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Chitosan in modern agriculture production

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Abstract: In the perspective of return to nature, using scientific and technical progress for improved living standards, people began to search for solutions to alleviate environmental pollution. Researchers intend to make clean, affordable products that are gentle yet effective. Chitosan derived from the exoskeleton of crustaceans, cuticles of insects, cell walls of fungi, and some algae are renowned for many decades to exhibit biotic properties, especially anti-microbial characteristics. Here we review each ingredient for sourcing organic chitosan, with clean raw materials that can make pure, rich, and powerful products working naturally. Our study elaborates advances and utilisation of chitosan for industrial control-release fertilisers by physical, chemical, and multifaceted formulations such as water-retaining super absorbent, polyacrylic acid, and resins. Plant growth-promoting properties of chitosan as a growth regulator, pest/disease resistance, signalling regulation, effect on nuclear deformation, and apoptosis. Chitosan can improve the plant defence mechanism by stimulating photochemistry and enzymes related to photosynthesis. Furthermore, electrophysiological modification induced by chitosan can practically enable it to be utilised as a herbicide. Chitosan has an excellent role in improving soil fertility and plant growth as well as plant growth promoters. It is concluded, chitosan can play a key role in modern agriculture production and could be a valuable source promoting agricultural ecosystem sustainability. Future suggestions will be based on current achievements and also notable gaps. In addition, chitosan has a huge contribution to reducing fertilisers pollution, managing agricultural pests and pathogens in modern-day agriculture.

Keywords: chitosan; fertiliser; pesticide; growth regulator; photochemistry

The overwhelming demand for food in line with the ever-increasing global population has given rise to additional exploration to produce sufficient food with sustainable agriculture to satisfy consumers' current nutritional needs (Zhang et al. 2017). Fertilisers are crucially important for delivering nutrients to plants to produce high-quality crops for food security (Kusumastuti et al. 2019). Similarly, pesticides are chemicals used to eliminate pests and pathogens. At the same time, fertilisers and pesticides are also identified as agricultural pollutants. Whereas, contamination became a considerable challenge in advanced industrial countries compared to undeveloped countries (Yu et al. 2021). Freshwater availability is affected due to the deposition of agricultural effluents hazardous to all living beings. The agriculture sector became a major contributor of damages to biodiversity, with intensifying influences due to altering consumption patterns and growing inhabitants by transforming natural habitats to extremely sophisticated arrangements and discharging pollutants and greenhouse gases. A massive percentage of organic pollutants infiltrate the soil, as well as several manufactured toxic substances. Besides, the enormous use of extremely destructive chemical pesticides has a drastic impact on human health and ecosystems (Gan and Ng 2012). These chemicals are capable of deposition, sorption with leaching tendencies that impact massive accumulation inside the soil particles, biological molecules, and metabolic transmutation

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of microorganisms. Farmers are still using a huge amount of agrochemicals (pesticides, fertilisers, and organometallics) and increasing these major issues (Chen 2020), like air pollution, soil toxicity, different agricultural degradation, residue buildup, pesticide tolerance in pests and microorganisms (Bargaz et al. 2018, Alengebawy et al. 2021).

Organic farming is an up-to-date and viable agriculture system that delivers fresh and natural farm produces to consumers. In the perspective of return to nature using scientific and technical progress for improved living standards, people began to search for solutions to alleviate environmental pollution. Researchers intend to make clean, affordable products that are gentle yet effective. Recently, several different polymers are introduced. Some innovative methodologies are being searched to control the release of fertilisers and pesticides for excellent agriculture, reducing the various hazardous impacts of these substances. Adopting several polysaccharides as delivery methodologies have presented considerable advantages like biocompatibility, non-toxicity, the propensity to biomolecules, excellent formulation, sustained release, and so on (Elsoud and El Kady 2019). However, most other concerns to encounter in agriculture research are diseases and pests, nutrient wastage, insufficient crop production because of water scarcity, fertilisers (nitrogenous, phosphoric, potassium, and organometal), and pesticide misapplication (Hamed et al. 2016). To tackle the concerns discussed from the widespread overuse of synthetic agrochemicals, this also becomes crucial to building alternative practices enabling the safe and productive use of such chemicals.

Numerous researchers assumed that restricting nutrient distribution using naturally degradable materials (Kumar et al. 2019) and rapidly developing smart nanomaterials can contribute a vital role in developing agricultural activities (Arruda et al. 2015), regarding the latest progress in nanotechnology, coating of such agrochemicals (fertilisers, pesticides, and herbicides) (Figure 1) which could deliver the most incredible platform to end it (Maghsoodi et al. 2019). Currently, the adoption of nano-carriers and nanosensors had attracted the interest of research groups from several areas of plant sciences; therefore, considerable scientific contributions are ongoing to focus on improving the formulation of

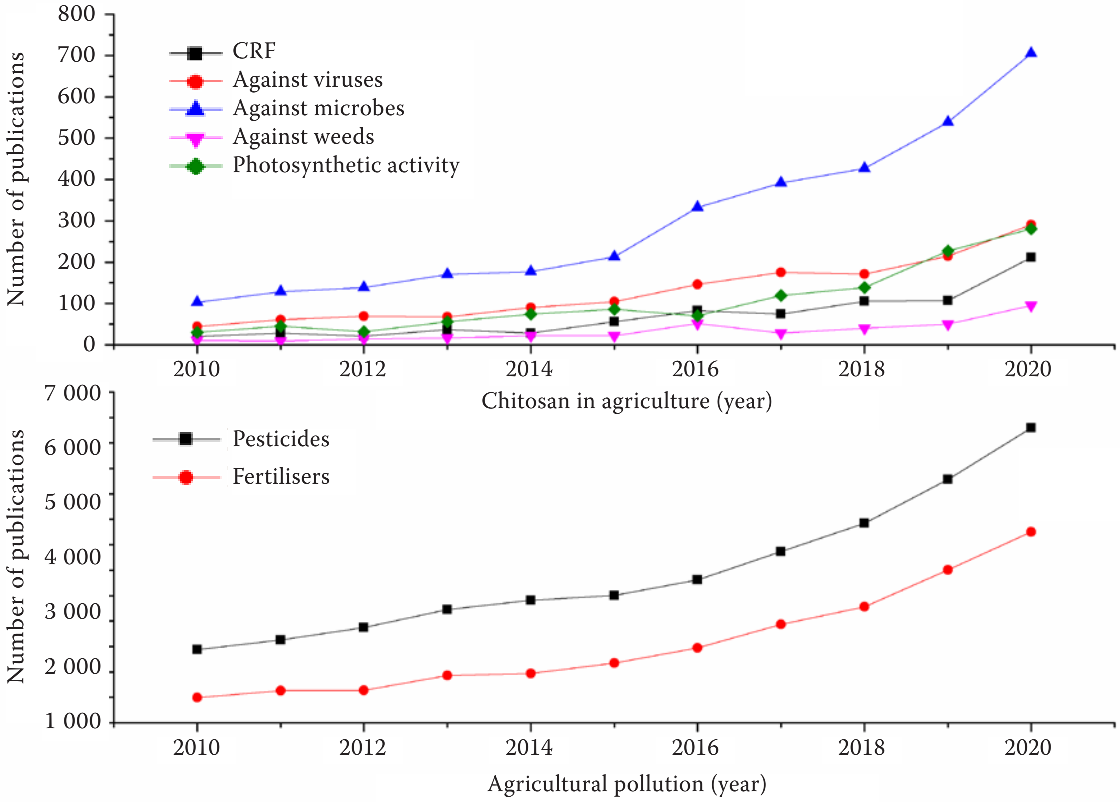

Figure 1. The number of publications reflecting the use of chitosan application in agriculture as per data of 2020 acquired from the Science Direct database. CRF – controlled-release fertilisers

biopolymer-based nano-carriers (Wani et al. 2019). Scientists seem to be eager to discover the capabilities of nanomaterials that enable it so convenient for promoting crop productivity (Raliya et al. 2015). Chitosan is a polycationic polymer synthesised deacetylation of chitin (a structural material present in multitudinous invertebrates) commonly collected by crustacean's exoskeletons, particularly shrimps and crabs, as well as fungus and yeast cell walls and diatom spines. Because it has been relatively hydrophobic, it is primarily insoluble in water and various organic solvents (Zargar et al. 2015, Nguyen and Wang 2017). This context has a tremendous potential and demand for advantageous and ecologically hospitable plant growth regulators within agriculture (Raliya et al. 2015).

In the past ten years, significant progress has been made in the research and application of chitosan. In agriculture, chitosan is mainly used in degradable mulching, coating film, bio-pesticide, food preservation, and plant growth regulator (Figure 1). This review is written with the primary objectives of nanosize components, which facilitate a convenient penetration into the plant's external membranes *via* cuticles, stomata, trichomes, stigma, hydathodes, cuts, roots interconnections, etc. For example, the controllable delivery of agro-nutrients from nano-carriers tends to improve the performance of active elements that might minimise degradation *via* decreasing vaporisation while avoiding contaminating threats (environment and health). Thus, the desirable capabilities of biomaterials-based nano-carriers somehow become the leading factor supporting the rising demand in their several other possibilities in plants. The current review investigates the potential applications of chitosan, which can become more intuitive precipitously and eco-friendly in agriculture.

USE OF CHITOSAN AS CONTROLLED-RELEASE FERTILISER

The indiscriminate practice of chemical fertilisers application is a grave problem worldwide. The reasonable application of fertiliser and increased nutrient utilisation capability while limiting deleterious toxicity depends on nutrient delivery to plant requirements and sustaining nutrient absorption. Controlled-release fertilisers (CRF) are considered by the delayed release of nutrients that extends for a limited amount (Cole et al. 2016). However, the aspects, such as duration of release, can be potently affected by management situations such as storage, transportation, supply in the field, and soil state's moisture content and biological activity (Rajan et al. 2021). Recently, the application of chitosan in controlled-release fertiliser is still in the primary stage. However, it can be an excellent fertiliser based on its biodegradable, environment-friendly, and other excellent characteristics. In addition, the porous structure on the surface is conducive to water and nutrient permeation (Kalia et al. 2020). After the controlled-release microspheres made of chitosan, loaded with nitrogen elements in the microspheres could be slowly released into the soil to meet the nutrient requirements of plants at various stages and improve the utilisation rate of fertiliser and reduce the loss of chemical fertiliser (Giroto et al. 2017).

Preparation and formulation of CRF

Chitosan nanoparticles were initially synthesised in 1994, applying the emulsification and cross-linking technique used as drug carriers (Ohya et al. 1994). After that, various technologies such as ionic gelation, reversed micellar approach, precipitation, sieving, emulsion droplet coalescence, and spray drying were developed. These technologies have already been developed for agricultural purposes. The mechanism and function mostly determine the methodologies of preparation; for example, the rate of releasing such active components is usually determined by the size and morphology of the nanocomposites, the thermal-mechanical performance, and the level of hazardous materials effects of the degradable remnants. Chitosan-based controlled release techniques are mostly used as a CRF application. Some studies have determined that the water absorbency of chitosan-coated CRF influences its distribution characteristics. Whereas chitosan has been observed to possess tremendous biodegradability, according to the delayed-release rate of polymer linkages, it has a decreased swelling potential while forming a hydrogel. However, combining chitosan with all various hydrophilic polymeric materials enhances its gel-state water absorption capabilities (Jamnongkan and Kaewpirom 2010). Another study revealed that the emulsification and cross-linking method is an excellent methodology for preparing CRF (Chen et al. 2013). A study by Jonas J. Perez and Nora J. Francois showed dissolving chitosan (CS) powder in an aqueous lactic acid solution (1% *v*/*v*) with mechanical stirring. The potato starch gel was prepared by heating an 8% *wt*/*v* starch (ST) solution

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in deionised water with constant magnetic stirring. Gelatinisation was achieved at 76 °C in a boiling distilled water bath. The cross-linking solution was prepared by dissolving sodium tripolyphosphate (TPP) in distilled water to produce a final concentration of 1% *wt*/*v* (pH 8.6). Potassium nitrate in powder form was dissolved in deionised water at a final concentration of 20% *wt*/*wt*. Dry polymeric matrices were immersed in the fertiliser-saturated aqueous solution for 4 h at room temperature. After the swelling process, the macrospheres were dried at 40 °C for 48 h (Perez and Francois 2016).

The emulsification and cross-linking method is an excellent methodology for preparing CRF, stabilising a particle structure, and modifying the controlled-release characteristics of that particle. Modification of the degree of cross-linking in a particulate alters the permeability of fertilisers throughout this. Cross-linking improves the mechanical stability of the resulting particulate or chitosan microspheres (fertilisers loaded) *via* utilising a nano-emulsion. The procedure occurs with the chitosan solution's emulsion in an oil droplet (water-in-oil emulsion). Sufficient surfactants initially stabilise the chitosan phase before combining using a relevant cross-linking agent (e.g., formaldehyde, glutaraldehyde, genipin, glyoxal, etc.). After that, the chitosan microsphere-based controlled-release fertilisers are required to be washed and dried Figure 2 (Agnihotri et al. 2004, Lestari et al. 2021).

The controlled release mechanism of CRF

It is important to understand the controlled release process, which would be the direct assessment of a CRF's performance. In a broad sense, the controlled release system is challenging to conceive because it depends on various factors such as the composition of the coatings materials, the type of CRF, farming contexts, and more. Chitosan hydrogel-based CRF can improve soil water retention. Hydrophilic polymers, which constitute hydrogels (e.g., polyvinyl alcohol), release active chemical compounds through diffusion, whereas chitosan releases active components

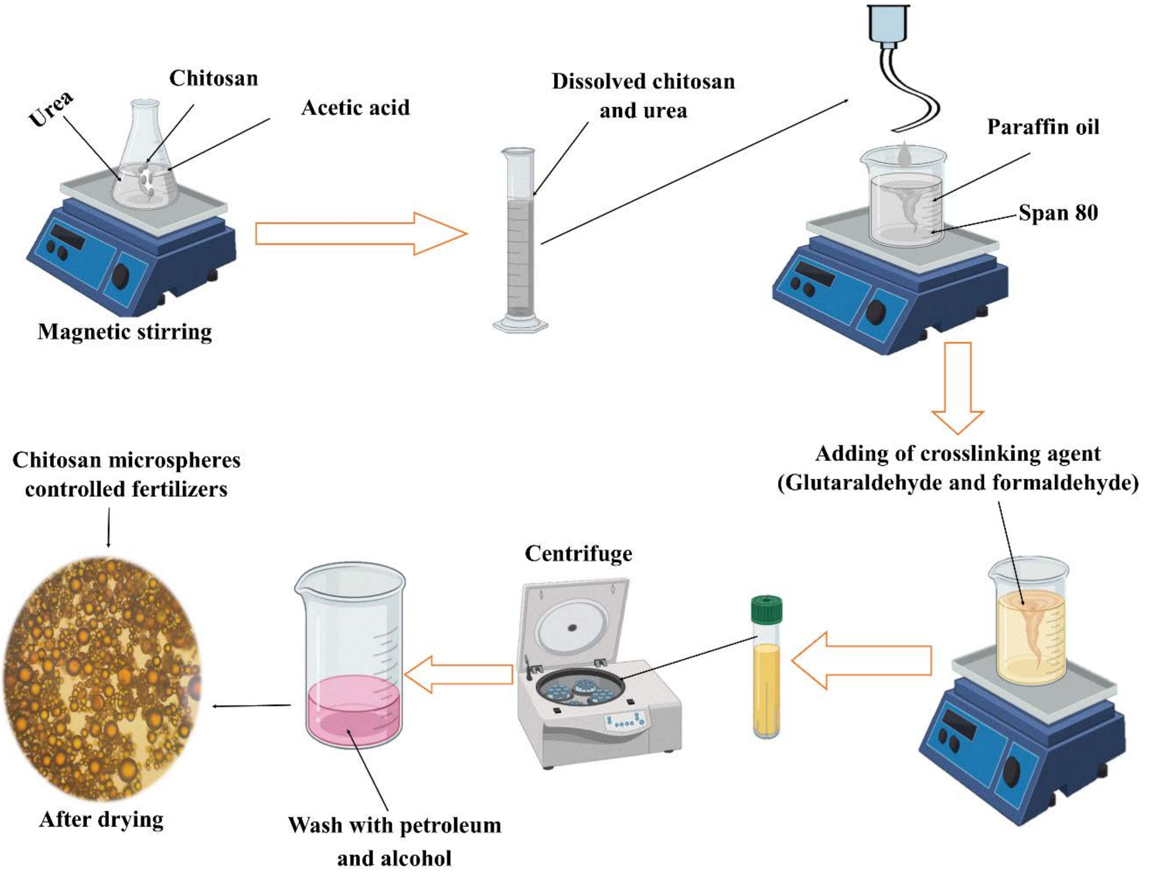

Figure 2. Preparation of chitosan microspheres-based controlled-release fertilisers through the emulsification and cross-linking method

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by degradation and diffusion. It is unusual to notice an immediate "burst" releasing active components from particulates that normally distribute them during diffusion or degradation.

This occurs in response to active substances adsorbing over the exterior parts of the particulates. Whenever this bursting is exhausted, a sustainable release would be noticed, which increases while the particle-matrix proceeds to degrade. The synthesised chitosan-polyvinyl alcohol (PVA) particulates were utilised to evaluate the release of the active component throughout a variety of situations. Researchers determined diffusion-controlled releasing by investigating the linear interaction among the level of active component released and the square root of the time (Kweon and Kang 1999). The controlled-release fertilisers developed by chitosan hydrogels possess a quasi-Fickian diffusion process that controls potassium releasing kinetics and water absorption (Corradini et al. 2010). A strong connection is seen between accumulated drug released and the square root of duration, indicating that drug-releasing through the microcapsules is diffusion-controlled and follows the Higuchi equations (Jameela et al. 1998). The connection between matrix degradation and indomethacin releasing kinetics *via* chitosan microparticles. The retention time of chitosan inside the microcapsules and the pH of the released media have been revealed to be interrelated to release kinetics (Jameela et al. 1998). The *in vitro* discharge assessment of drug-loaded chitosan nanoparticles the dynamical swelling information of chitosan nanoparticles and indicated that the swelling of chitosan nanoparticles reduces as cross-linking accumulates. The expansion response of chitosan/poly (vinyl alcohol) hydrogels as a factor of pH, polymeric formulations, and cross-linking degrees (Agnihotri and Aminabhavi 2004).

Physically controlled fertilisers

Chitosan and its composites occur in several physical forms, including resins, microspheres, hydrogels, membranes, and fibres. The variety of one specific physical method depends on the system configuration for limited applications (Jiang and Fu 2013). Determining chitosan assortments into preferred physical form starts from mixing the blend components in the liquid form and applying the appropriate shaping method.

Coated fertilisers development has been progressively increased in the current decade, where 95% of them have controlled-release fertilisers. Matrix-based fertilisers, also known as the physical type of CRF, are unique, low-cost, and controlled release (Ni et al. 2013). Current advancements in fertilisers have been progressively increased, and 95% of them are controlled-release fertilisers. Matrix-based fertilisers are also classified as a physical type of CRF with unique, low cost, and controlled release properties (Yang et al. 2018).

Chemically controlled fertilisers

Chemically controlled-release fertilisers can delay-release by preventing fertiliser decomposition or nutrient transformation through chemical activity. The chemical type of CRF is divided into two categories: Chemically bonded fertilisers and chemically inhibited fertilisers. This category of slow-release fertiliser has a more significant impact, but its cost is comparatively high (Abdel-Aziz et al. 2018). Chemically bonded fertilisers allow fertilisers mixed with one or more chemical components *via* cross-linking or ionic linking to develop a partially soluble or unsolvable substance.

It delivers required nutrients through plant roots and biological activity. The amount of resources has often been assessed *via* the particle size-water content throughout the soil (Benckiser et al. 2013); chemically controlled fertilisers release where nitrogen could incorporate into controlled substances. Widely utilised are urease inhibitors and nitrifies, which reduce urea's hydrolysis, although the latter inactivates the nitrified of ammonium and several various sources (Habala et al. 2016).

Chitosan water-retaining controlled-release fertiliser

The water-retaining controlled-release fertiliser is a high-tech product that combines water-retaining agents with modern plant nutrition fertilisation theory and controlled release technology to determine the nutrient supply rate and fertiliser-effective period (Perez and Francois 2016). At present, most of the water-retaining controlled-release fertilisers on the market are coated with water-retaining agents as the coating material. The microspheres on the coating material are used to realise the controlled release of nutrients (Fang et al. 2018).

Chitosan superabsorbent resin

The primary preparation method of chitosan superabsorbent resin is solution polymerisation (Essawy

https://doi.org/10.17221/332/2021-PSE

et al. 2016). Under initiator and cross-linking agent (Wu et al. 2010). The hydrophilic monomer is copolymerised with chitosan to produce a three-dimensional network structure (Ullah et al. 2021). At present, the most commonly used initiators are mainly persulfate (Naim et al. 2013), under the condition of heat decomposition or by redox reaction to produce free radicals. These free radicals at certain temperatures are free active centres with hydrophilic monomer copolymerisation (Moreno-Vásquez et al. 2017). The cross-linking agent containing vinyl double bond [N, N'methylene double acrylamide (MBA)] issued by the action of the biochemistry of cross-linking and physical cross-linking, forming a three-dimensional network structure (Kumar et al. 2019).

Polyacrylic acid/chitosan superabsorbent resin

Several publications on polyacrylic acid/chitosan synthesis of superabsorbent resin that can absorb the distilled water. Most of the mass fraction of NaCl solution and the addition of chitosan for absorbent resin has, it is prominent and not easy to tear after absorbing water, has good gel intensity, and has the characteristics of non-toxic and harmless (Spagnol et al. 2012). The chitosan water-absorbing and water-retaining material with a water absorption rate of more than 800 times of distilled water, water absorption rate of more than 500 times of water, and absorption mass fraction of 0.9% NaCl solution 130 times was prepared by aqueous solution polymerisation method (Peng et al. 2020). The material has outstanding biodegradability, no environmental pollution, and the preparation process is simple and low-cost.

CHITOSAN AND PLANT GROWTH REGULATORS

Agriculture suffers several challenges because it attempts to fulfil the increasing demand for sustainable food supply and ensure sufficient nutrition for a constantly increasing population. To achieve large crop yields, agricultural land must be improved (Aftab and Hakeem 2021). An approach to fulfil this objective has been the utilisation of growth regulators to modulate plant growth. Plant growth regulators (PGRs) are biological or chemical components that positively impact and influence plant health and growth (Rostami and Azhdarpoor 2019). These are frequently implemented in various plants to reduce internode elongation and produce a denser, more compact, and smaller plant. PGRs helps improve plant growth in ways that enhance branching, decrease shoot development, expand returning bloom, avoid excess fruit, and improve fruit growth (Table 1). There are five main and important PGRs (auxins, gibberellins, cytokinins, abscisic acid, ethylene) found in crops and fruit plants. Besides that, these components are synthesised inside the plants, referred to as plant hormones, although these materials can be utilised in hormone levels as synthetic or natural compounds. Recently in agriculture, they have mostly been used for different reasons, such as delaying or expediting processing, inducing roots, and weed management (Rostami and Azhdarpoor 2019). In addition, chitosan and plant growth regulators positively affect culture medium in *Serapias vomeracea*, decreasing this necessity for complex and particular nutrition. Even the medium can be modified until the excessive browning took place, it appears that when jasmonic acid (JAS) or indole acetic acid (IAA) is being used, the browning trend for *S. vomeracea* roots should not be unavoidable. Chitosan can boost the effectiveness of culture medium in *S. vomeracea* cultures, thus decreasing the demand for complex and other supplements (Głąb et al. 2020).

Moreover, chitosan may help in promoting root development while preventing browning. An excellent transmission system with γ-PGA and chitosan polymers is used for the GA_3 plant hormones. The nano-particles had been outstanding in concepts of size, polydispersity, zeta potential, and encapsulation performance (Pereira et al. 2017).

Furthermore, the consistent release technique will support the active agent's actual release and defending against degradation processes. The procedure is more viable than the free hormone during bioactivity assays, encouraging germination in less than 24 h and expanding leaf area and root development (containing lateral roots material) (Campos et al. 2015). Latest advancements in pesticide delivery, depending on chitosan-containing solutions of microcapsules (identified or not with elements), copolymeric concentration, and nanomicellar, are the most attractive for both pesticide formulations (Al-Dhabaan et al. 2018).

The majority of these experiments are sensible formulas that prevent ecological dangers, including photo-degradation. Furthermore, they generally prefer a higher concentration of bioactive compounds and pH-responsive and can be released by enzyme activity. Thus, chitosan can encourage better precision in pest management and a decrease in actively working in the field.

https://doi.org/10.17221/332/2021-PSE

Table 1. Recent progress in chitosan and various applications on different species of plants

Species	Matrices	Installation method	Summary of study		References
			nutrition	protection	
Medicinal plant (*Sphaeranthus indicus*)	fabrication of chitosan nanocrystals	CH-NP formulation, with multiple concentrations	improved root, shoot and leaf commencement as a plant growth promoter	effective against filariasis vectors, Zika virus, and malaria	Thamilarasan et al. (2018)
Irish potato (*Solanum tuberosum*)	chitosan nanoparticles	chitosan spray	increased shoot height, number of nodes, chlorophyll, carotenoids, proline, and sugar content	applicable in drought conditions and helpful in drought stress resistance	Muley et al. (2019)
Chickpea (*Cicer arietinum*)	chitosan nanoparticles (biologica prepared)	vitro release, treatments applied (control and chitosan nanoparticle)	increased the seed vigour index, and plant biomass	effective against phytopathogens	Sathiyabama and Parthasarathy (2016)
Purpletop verbena (*Verbena bonariensi*)	chitosan, gellan gum, iota-carrageenan	foliar application; treatments used (control, chitosan, gellan gum, iota-carrageenan)	increased plant height, number of inflorescences, leaves, shoots, enhanced stomatal conductance, fresh weight of roots		Salachna et al. (2017)
Maize (*Zea mays*)	Cu-Chitosan NPs	*in vitro* release of Cu-chitosan nanoparticles NPs applied as an antifungal		chitosan promoted plant immune expression, better deal with manipulating plant infections, promising plant defence and growth performer, a productive and beneficial agent	Choudhary et al. 2017)
Finger millet (*Eleusine coracana*)	copper-chitosan nano-particle	induction into a plant; foliar spray, seed coat + foliar spray; treatments applied in 30, 40 and 50 days		CuChNp enhanced defence enzymes and effectively improved enzymes against blast infection	Sathiyabama and Manikandan (2018)

Chitosan in photosynthetic activity

Several abiotic factors affect crop production, and the sunlight is critical because it is required for photosynthesis. It is the highly complex biochemical and biophysical mechanism that comprises the formulation of photosynthetic components. Calvin cycle, light-driven electrons movement, and light leaves (solar chloroplasts) are suitable to transform massive amounts of photosynthetic light quantum systems inside the plant (Mao et al. 2021). Plants perceive sunlight *via* various photoreceptors, such as cryptochromes and phytochromes. There are two main components of light: (1) light quality (generally refers to colour or light wavelength); (2) photometric value, which significantly affects the function

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Continued Table 1. Recent progress in chitosan and various applications on different species of plants

Species	Matrices	Installation method	Summary of study		References
			nutrition	protection	
Soybean (*Glycine max*), rice (*Oryza sativa*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*)	chitosan particles	chitosan irradiated in 1% solution with concentration of 0.0, 10.0, 30.0, 50.0 kiloGray (kGy)	radiation-degraded chitosan effectively prevented vanadium (V) absorption, transportation inside roots, activated seedling, improved growth and reduced heavy metal toxicity		Tham et al. (2001)
Strawberry (*Fragaria* × *annanasa*)	chitosan solution	foliar application with concentrations, 0, 125, 250, 500 and 1 000 ppm of chitosan solution	improved plant growth, production of total antioxidants, flavonoids, phenolics, carotenoids, and anthocyanins		Rahman et al. (2018)
Chilli, potato, and soybean	chitosan particles	foliar application (8 times) and irradiating chitosan using gamma rays at a dose of 75 kGy.		maximize the growth of chilli, potato, and soybean crops, and be effective against viruses, bacteria, and fungus	Darwis et al. (2014)
Maize (*Zea mays* L.)	–	foliar application with various concentration 0, 50, 75, 100, and 125 ppm	chitosan promoted plant growth, yield, components.		Mondal et al. (2013)
Cucumber (*Cucumis sativus*)	–	foliar application with inoculated *Colletotrichum* sp. conidia after four days adjusted the concentration of 50 000 ± 5 000 conidia per mL with a haemocytometer. Positive and negative controls were used.		The study proved that chitosan can control the *Colletotrichum sp.* and is also excellent for reducing toxicity in the environmental.	Dodgson and Dodgson (2017)

and structure of plant photosynthetic machinery of plants, as well as overall growth and yield capability. Chitosan is an important amino-polysaccharide and a deacetylated, modified version of chitin. It has great advantages, including non-toxicity, biocompatibility, and biodegradability (Cardona and Rutherford 2019). A study by Zong et al. (2017) indicated that chitosan application improved plant growth, chlorophyll (*Chl*) contents, plant productivity, and reduced the malondialdehyde (MDA) in the plant's leaves during the cadmium (Cd) stress. Salachna and Zawadzińska (2014) discovered that chitosan increased the *Chl* levels in leaves to 13.4%, compared to water-treated plants. Through comparative analysis with the control foliar spray of chitosan (MW = 2.5 kDa) in chilli enhanced chlorophyll content was about 13% (DDW) (Rahman et al. 2018).

Further, another experiment on peanut and coffee plants utilising chitosan (MW = 2 kDa and DP 8–16) concluded a much higher chlorophyll content (Dzung et al. 2011). Besides that, chitosan adoption protects *Chl* content during intense situations. Chitosan, supposed to serve in fenugreek to uptake 1 g/L, has been noticed to continue raising chlorophyll content

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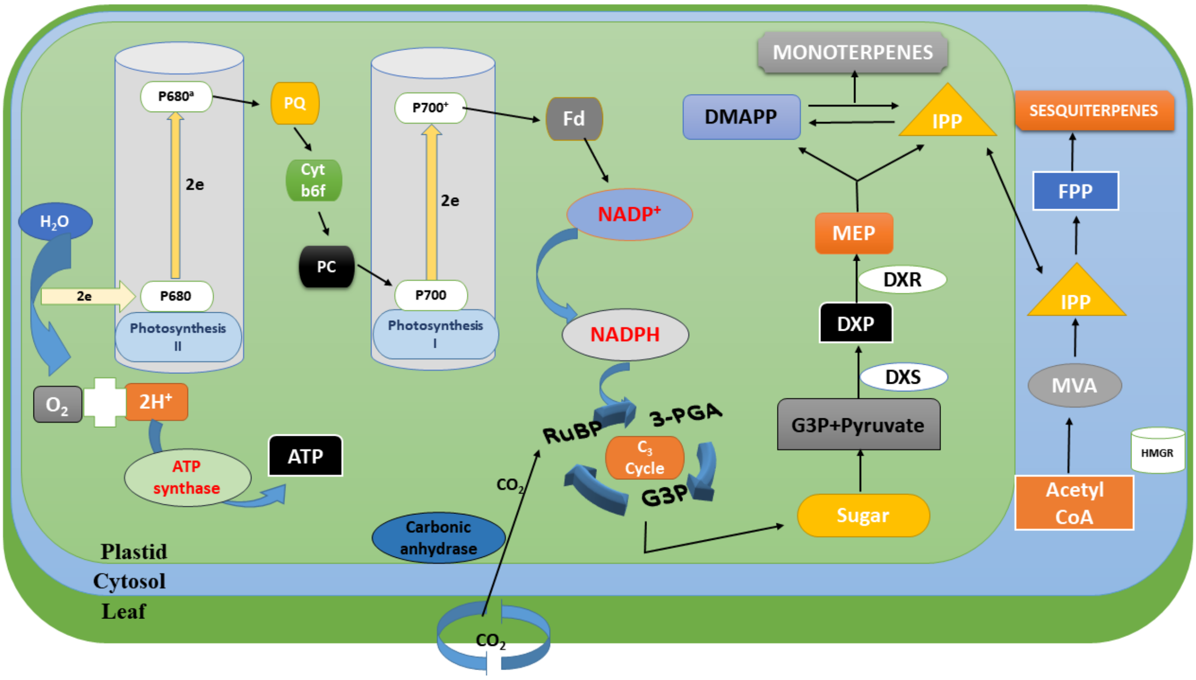

Figure 3. Chitosan activates organelles (responsible for photosynthesis) present in the chloroplast. Chitosan increases chlorophyll fluorescence parameters (F_v/F_m, qP, PSII, and ETR), improves ATP production, and decreases potential (NADPH), all of which are used during the Calvin cycle. Through the rising trend in stomatal conductance (g_s), CO_2 dissipation boosts, contributing to the advancement in inner CO_2 content that connects *via* rubisco in the involvement of Carbonic anhydrase (CA) but is limited in carbohydrates. As the potential outcome expands the P_n, the average carbohydrate level grows. Sugars synthesised deliver like a base to secondary metabolites (monoterpenes). DXR behaviour promotes and correlates to higher monoterpene development. The figure adapted from Ahmed et al. (2020) with minor modification

under a saline environment (Yahyaabadi et al. 2016). Therefore, chitosan can help reduce the breakdown of *Chl*, which could contribute to a more excellent photosynthetic activity. Xue et al. (2004) described that the chitosan applications could increase the antioxidant enzyme activity and the proline and solvable protein levels of cucumber leaves at cold temperatures. Moreover, CS has the potential to defend the membranes, help to improve the efficiency to eliminate active oxygen species (AOS), Figure 3 and alleviate damages to the photosynthetic system at cold pressures (Xue et al. 2004). However, still, some studies are required to clarify how irradiated chitosan (ICH) relates its bioactivity to citronella. Afterwards, surely the ICH has the potential as a plant-growth regulator to perk up crop yield.

With the help of recent studies, chitosan was identified as an effective component for increasing shoot height, nodes, and membrane sustainability. Therefore, chlorophyll, carotenoids, proline, and sugar content were significantly increased (Rahman et al. 2018). Chitosan application with gellan gum helps enhance stomatal conductance by about 13.8% and 16.3%. The number of shoots per plant increased by 29.4% to 37.5%. Gellan gum responded well across the chitosan and gellan and delivered an increased fresh weight of the terrestrial portion and root between 34.3% to 114%, well above control (Table 1) (Mondal et al. 2013).

Chitosan in photochemistry

Photochemistry is one of the earliest practices in the advanced molecular that occurs due to light absorption. The exploration of photochemical mechanisms that rely upon sunlight catalyzes important chemical activities or produces energy for various developmental sectors. Chlorophyll fluorophore is indeed a critical indicator of photosynthetic activity commencing (Shafiq et al. 2021). The optimum photosynthetic behaviour, also identified as the maximum PSII efficiency (F_v/F_m) average, is a variable for determin-

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ing PSII viability in leading photochemical interactions relevant to leaf photosynthesis performance (Figure 3). Photosynthesizing performance is closely linked towards leaf F_v/F_m and its significance to plants during ordinary ecological situations (Zou et al. 2015). Elongation release of chitosan in crops also increases the proteins such as the oxygen-evolving enhancer protein 1 (OEE1) and light-harvesting chlorophyll *a*/*b*-binding (LHCB) proteins, which is one of the most important elements of light to maintaining the compounds in plants and performs an essential role in the uptake of sunlight and convert of excitation energy to the photochemical reaction central core (Chamnanmanoontham et al. 2015). Although the OEE1 is needed for oxygen-transforming activities and PSII stabilisation, its translation is assumed to be the level-limiting step inside the formation of PSII components.

Photochemical and non-photochemical quenching

Cyanobacteria seem to be the earliest microorganisms capable of oxygenic photosynthesis and are the developmental originators of the chloroplast inside plants. In plants, cyanobacteria apparatus supporting photosynthetic light processes contains protein compounds installed within chloroplast's locked and slightly folded membrane system (thylakoid) in the chloroplast (Harbinson et al. 2018). Photochemical quenching (qP) transforms light energies delivered through pigment compounds *via* chemical energy required to process photosynthetic activity. The better index of qP fundamentally symbolises the quite effectively the plant absorbs energy (Vredenberg et al. 2009). In agriculture, chitosan (CS) also performs various activities degree of acetylation (DA) with

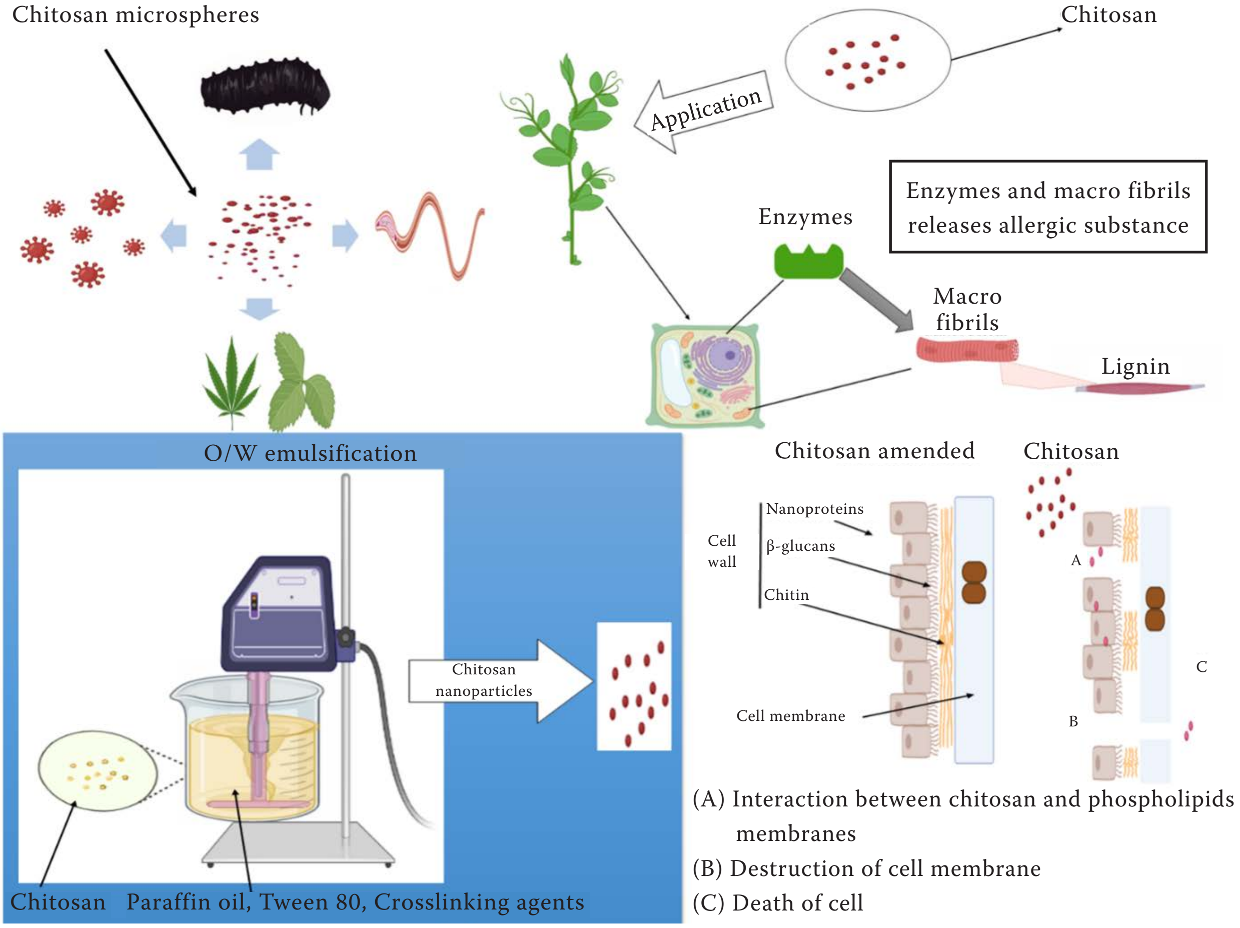

Figure 4. Emulsification of chitosan, applications to different species, hazardous impacts to plant growth, and act as a plant resistance material

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the crucial feature. In the plant leaves, moderately N-acetylated CS elicitor action has greater than that of homo-oligomers of either GlcNAc or GlcN. Moreover, it was demonstrated that the activity of CS in increasing plant resistance towards abiotic stress is strongly related to DA (Li et al. 2020b).

Non-photochemical quenching (NPQ) is an apparatus devoted by plants and algae to secure themselves from the adversative consequences of extreme light intensity (Murchie and Ruban 2020). It comprises quenching single excited situation chlorophylls through improving interior transformations to the ground condition (non-radiative decay), thereby dispersing surplus excitation potential inoffensive heat *via* molecular vibrations. NPQ is involved in virtually all photosynthetic eukaryotic organisms (algae and plants). Recently chitosan has been applied against the different stresses caused by abiotic factors. In this study, we included some hypotheses for the evidence. The Zou et al. (2015) experimented with observing the effects of chitosan to reduce salt stress. However, the chitosan oligosaccharides (COS) treatments help minimise an acceptable degree, the value rises, which is not enough to allow any broad movement (Zou et al. 2015). However, the NPQ level increased during salt stress. On the other hand, Zhang et al. (2017) indicated remarkable advancements in the PSII membrane's fluorescent sensitivity (Figure 3), has been described the implementation of CS-Chitoheptose (GlcN) 7, as CS-Chitoheptose (GlcN) 7 is appreciated to sustain the energy transmission for PSII (Zhang et al. 2017).

CHITOSAN UTILISATION AGAINST PESTS AND PATHOGENS

More than 30 types of chitosan biological pesticides are registered by 30 companies in various countries (China, Pakistan, Canada, and India). The primary dosage forms are water agent, powder, suspension agent and micro-emulsion, etc. In recent years some studies showed that chitosan (chitooligosaccharides) was synthesised from marine sources, which have been utilised to control agricultural pests and different pathogens (Figure 4). In this section, we are going to discuss the chitosan application capabilities towards pests and pathogens.

Recent used multiple concentrations of CH-NPs have been examined as growth promoters for shootlets reconstituted *in vitro* in root gel trials. CH-NPs greatly enhanced root and shoot progress and leaf commencement in *Sphaeranthus indicus* explants 15–30 days after the investigation. Moreover, the CH-NPs had LC_{50} values of less than 15 μg/mL against three important mosquito species: filariasis vectors, Zika virus, and malaria (Thamilarasan et al. 2018).

Chitosan utilisation as pesticides

Agriculture science had made tremendous advancements over the last century, introducing pesticides for quicker pest reduction. Moreover, developed countries realised the disadvantages during the initial phases but continued to use pesticides at a high level. Unfortunately, these countries have not informed other countries about hazardous impacts until they exported sold pesticides at low cost and delivered chemicals to undeveloped countries in the name of AIDS. Awareness about pesticide's side effects appeared globally. Several countries' scientists started research on this topic. According to the researchers, United Nations also became active on these issues and banned several groups where organochlorine pesticides are a good example (Sah et al. 2020, Arisekar et al. 2021). Recently, scientists are focusing on returning to nature, and several methods are being tested to reduce the pesticides in agricultural lands and control the pest population. In this context, chitosan has been utilised in different agricultural sectors as well as modification in pesticides. Chitosan is assumed to be a natural green source since considers the benefits of lignocellulosic biomass (Álvarez et al. 2017). Over the past few years, several studies have elucidated the formation and use of chitosan nano-particles to deliver the pesticide (Bandforuzi and Hadjmohammadi 2019). Pesticides have been used aggressively in earlier years to counter pests and microorganisms, mainly in expanding agricultural yields (Maluin and Hussein 2020). On the other hand, pesticide overuse poses a significant risk to human beings and livestock (who take advantage of agricultural products) and poisoning groundwater water. Modification and application development, including level and release in the agriculture sector, are suggestive.

The latest contributions played a significant part in material-controlled release adaptable to the operator's ecological or intrinsic factors (Yoon et al. 2020). The increasing procedures of action loading and the invention in controlled release particles can help as a shield towards photosensitive and unstable components are being followed. Chitosan nanomicellar methods and related co-polymers may be advanced and incorporate spinosad fungicides, and the research findings will be beneficial to preventing photo-degradation (Zhou et al. 2020). The interaction by nanomicella encouraged a productive delivery that had been easier around pH 6.4 than pH 7.0, revealing that the formulation seems pH-responsive. The performance against fungi significantly increased utilising the encapsulated formulations in contrast to the un-encapsulated spinosad. Coated nanocrystals of *Bacillus thuringienses* with chitosan determined how chitosan affects the sustainability of such nano-particles to ecological challenge but was reactive towards alkaline pH, proposing its capability to target particular insects during its larval period while it might release bioactive throughout the environment (He et al. 2017).

Paula et al. (2011) reported chitosan/cashew tree gum microparticles covered with *Lippia sidoides* (LS) essential oil as a biological pesticide. However, once the microparticles were cross-linked was the LS was released quietly slowly. As the outcome, the charged particles were successful pest prevention (Paula et al. 2011). Guan conducted another research where chitosan/alginate microspheres were preloaded using imidacloprid, a photodegradable pesticide. The technique has been using meticulous step-by-step self-assembly encapsulation to synthesise imidacloprid (IMI) microcrystals employing chitosan (CHI) and sodium alginate (ALG). Different IMI microcapsule formations initial acetone addition. The colloidal stabilising of the polyelectrolyte multilayers (PEM) attempting to coated resulted in excellently well-isolated crystals (Guan et al. 2008). The non-coated microcrystals presented a semi-transparent shape and size. If initially, the proportion of PEM films began to increase, similarly went the instability of such crystal top layer. PEM depositing polished the layer of the coated crystal while the coating was consistent. Ag nano-particles in rice grains seemed to be transferred mostly on TiO_2 nano-particles; however, SDS aggregation modified the TiO_2 particles. IMI delivery *via* microparticles examined using deionised water at 25 °C and pH 7.4. The pesticide starts releasing ratio through the microspheres remained vastly lower than the uncontrolled insecticide exposure ratio (Guan et al. 2008, 2009).

The future challenge concerning botanicals for agricultural compounds is mainly associated with photosensitivity and excessive volatility, and the development of beta-cyclodextrin. Moreover, chitosan nanomaterials for incorporation compound synthesis containing linalool and carvacrol and an enhancement within compounds longevity.

Chitosan utilised as plant disease resistance

Fungal pathogens are recognised as pestilential microbes, which is an increasing threat to worldwide food production; however, microbes that caused infections in plants have seriously influenced Europe and North America's urban and forestry landscape last centuries. Chitosan is a key element for the fungus cell walls and a promising elicitor of plant resistance (Gong et al. 2020). We will now analyse the massive expansion and awareness of chitosan sensing and signalling in the plants, nuclear deformation, apoptosis, defence-related enzymes, electrophysiological modifications by the chitosan in plants (Figure 4). The chitosan-induced plant disease resistance mechanism and the reaction caused by chitosan in plant-pathogen interaction have not been well understood (El Hadrami et al. 2010). Plants recognise elicitors through transmembrane receptors. However, particular receptors for chitosan detection have not been determined yet. The protein kinase cascade responsible for transmitting signals to transcription factors (TFs) has not been implicit (Yin et al. 2016). Several models have been suggested to elucidate the chitosan role responsible for the trigger in the plant *via* defence genes. In these models, the up-regulation of plant defence genes induced by chitosan involves the direct interaction between chitosan and DNA. These models recommend that chitosan induces the triggering of defense genes by changing the DNA (chromatin structural recombination) structure, accompanied by the decrease of high mobility group (HMGA) or the interaction with DNA polymerase complex (Hadwiger 2013). The defence response evoked by chitosan treatment can depend on the variability in the plant-pathogen system. Even for the crops, defence responses differ depending on the treatment time and method.

Signal regulation

Chitosan is a biopolymer, is considered a potent inducer of phytoalexin synthesis and aggregation in different host cells, and stimulates callose, lignification formation, and production protease inhibitor (Singh et al. 2019). It is well-identified that chitosan and its derivatives are used as potential elicitors to boost plant resistance (Li et al. 2020a). It forms

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a barrier at the injection site to prevent the spread of pathogens. It alerts other healthy plant tissues to produce early signal defence response, including the accumulation of metabolites and proteins related (PR) to immune response (such as plant defences and PR-related proteins). Chitosan also has been applied to regulate plant disease resistance has been reported in many plant disease systems (Figure 4) (El Hadrami et al. 2010), including different plants and a series of different pathogens, such as viruses, viroids, bacteria, fungi, nematodes, and other microorganisms (Chakraborty et al. 2020).

Effect on nuclear deformation and apoptosis

The latest research has found that chitosan can induce programmed cell necrosis (PCD) and hypersensitivity-related resistance reactions in plants (Zhang et al. 2012). It can also cause chromatin condensation and marginalisation, destroying the nucleus and dissociating nucleosome DNA (Samuilov et al. 2019). However, chitosan does not affect stomatal guard cells but affects epidermal cells. It was found that chitosan could prevent the destruction of the epidermis cell nucleus under anaerobic conditions (Figure 4). The antioxidants aztrezole and mannitol are inhibited by chitosan, H_2O on epidermal cells (Vasil'ev et al. 2011). The researchers used a series of inhibitors to elucidate the apoptosis of epidermal cells induced by chitosan (Malerba and Cerana 2016), including reactive oxygen species produced by NADPH oxidase in the plasma membrane (Figure 4). It also found that chitosan could cause the epidermal nucleus on the leaves to disintegrate (Lopez-Moya et al. 2021).

Defence-related enzymes

Chitosan application can infiltrate yeast and damage and exterior of the grape, spore germination, and mycelial development of *Penicillium expansum* in grape injuries would be avoided (Romanazzi et al. 2017, Godana et al. 2020). In addition, *P. anomala*, individually or in combined effects using chitosan, stimulated grapes diseases defence-related enzyme actions like APX and CHI and diminished MDA and H_2O_2 synthesis, damaging fruit degradation (Godana et al. 2020).

As a physiologic elicitor, chitosan can encourage target resistance through the enzyme's enhanced function associated with the defensive system (Figure 4), including phenylalanine ammonia-lyase and peroxidase polyphenol oxidase catalase and superoxide dismutase (Siddaiah et al. 2018). Another study showed that Cu-chitosan nanoparticles (Cu-ChNp) dosages for millet plants contributed to a noticeable enhancement in defence enzymes that could be identified subjectively and quantitatively. Furthermore, blast infection influence corresponds effectively with improved defensive enzymes in CuChNp-treated millet plants (Table 1) (Sathiyabama and Manikandan 2018).

This review suggests that treating the seeds with chitosan has accelerated their germination and can increase their resistance to stress factors. The concomitant increases in chitosan-induced catalase activity in fish indicate that chitosan has antioxidant potential. Additionally, any rise in catalase levels helps eliminate free radicals.

Electrophysiological modifications by chitosan

Several researchers used chitosan in the soaking medium of *M. pudica pulvini* as its potential role in causing spontaneous depolarisation of the motor cell membrane depending on concentration manner at concentration > 10 g/mL and up to 100 g/mL. Demonstration time sequences of bioelectric activity were recorded over this dose range: the depolarisation took place after a time gap, and it went on decreasing when prescribed concentrations increased with its peak at; 10–15 min, and returned to its original resting capability after; 30–40 min even when chitosan appears (Pospieszny et al. 1991). O-chitosan nano-particles were completely arranged using the oil-in-water (O/W) emulsification technique (Figure 4). The nano-article preparation had a spherical shape with an average diameter of 296.962 nm. Chitosan nano-particles also displayed well dispersal in the PDA medium (El-Mohamedya et al. 2019). However, for *Gibberella zeae* and *Fusarium culmorum*, the evolution of mycelium of *Nigrospora sphaerica*, *Botryosphaeria dothidea*, *Novosphingobium oryzae*, and *Alternaria tenuissima* was reduced by adding chitosan (Xing et al. 2016). Fatty acid studies have shown that plasma membranes of chitosan-sensitive fungi possess lower unsaturated fatty acid levels than chitosan-resistant fungi (Palma-Guerrero et al. 2010).

The phylogenetic ITS gene classification analysis shows two chitosan-resistant strains of fungi had a close phylogenetic relationship which suggests some of the collective structural factors that may lead to their resistance to chitosan. Based on these results, O-chitosan nano-particles can be used as an antifungal dispersion system to control pathogenic fungi (Xing et al. 2016). However, more reviews on this topic are needed to describe the sensitive aspect of some pathogenic fungi concerning chitosan, but the others are resistant. Furthermore, the anti-microbial action methods of chitosan and its derivatives have not yet been determined, and the investigation continues to search for facts.

Chitosan utilisation against viruses

Chitosan has great antibacterial capabilities because of its insoluble characteristics in water. Therefore, chitosan can be easily dissolved in mild acids such as acetic and uric acid. The anti-microbial activity of chitosan was first studied in the medical field (Perinelli et al. 2018), such as wound inflammation, dermatitis, beriberi, fingernails, and so on (Maxwell et al. 2017). Based on recent research, chitosan application expanded in agricultural production (Table 1) and could find that chitosan and its derivatives have suitable bactericidal and antibacterial activities and have killing or inhibiting effects on fungi, bacteria, and viruses (Figure 4) (Badawy and Rabea 2011). It was found that chitosan could inhibit the spore germination and mycelium growth of pathogenic fungi of plant diseases (Saharan et al. 2013) and induce the plant to develop a protective function against pathogen infection (El Hadrami et al. 2010). Chitosan's antiviral efficacy has been reviewed in microorganisms and plants (Katiyar et al. 2015). Chitosan promoted tolerance to viral diseases in plants. It suppressed the widespread transmission of viruses and viroid so that most or all treated plants with chitosan did not acquire systemic viral infectivity. The lower molecular weight of chitosan prevents tobacco mosaic virus development provoked local necroses by 50% to 90% (Davydova et al. 2011). The direct protective action of chitosan on viruses had been expressed primarily during the inactivation of viruses. It was active in preventing coliphage infectivity and replicating 1–97 A phage in *Bacillus thuringiensis* culture. When chitosan is applied to a mutation suspension, its titer is reduced with chitosan. Electron microscopic analyses revealed that chitosan induced massive reforms in mutation particles and destabilised their stability (Alghuthaymi et al. 2020).

Mechanism of chitosan as anti-microbial

Chitosan and its impacts had wide-spectrum anti-microbial effects. Subsequently, the antibacterial

Table 2. Inhibitory influences of chitosan on different fungal pathogens

Pathogen	Molecular weight (m) of chitosan	The concentration of chitosan (dissolved in acetic acid)	Experimental method	Bacteriostatic effect	References
Candida albicans	32 kDa with degree of deacetylation (94%)	1.25 mg/mL	tissue culture test plates	–	Tayel et al. (2010)
Botrytis cinerea	7.6×10^3 with degree of deacetylation (97%)	0.5 and 1.0 mg/mL	potato dextrose agar (PDA)	–	Guo et al. (2008)
Escherichia coli	1.21×10^6 with degree of deacetylation (82.33%)	1.0 mg/mL	nutrient medium	85%	Li et al. (2016)
Fusarium graminearum	28 kDa	1.0 mg/mL	agar culture	–	No et al. (2002)
Magnaporthe grisea	10.0 kDa with DA (~13.4–18.8%)	0.5 mg/mL	agar (HiMedia)	57%	Vishu Kumar et al. (2007)
Alternaria solani	42.5 to 135 kDa with DA 50 mol%	0.1% with 50 µL of the chitosan solution	Muller–Hinton agar and PDA	24%	Younes et al. (2014)
Xanthomonas oryzae	607 KD	2 000 mg/L	PDA	76.47%	Li et al. (2013)

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effect of chitosan was further studied (Li et al. 2019). The isolated chitosan was used against the root rot's pathogens and treated the root with chitosan (Akter et al. 2018). Furthermore, several studies revealed that different molecular weights of chitosan had a particular inhibitory effect on the pathogen of *Isatis indigotica* root rot. The effects of acid-soluble chitosan and two kinds of water-soluble chitosan on 15 kinds of plant pathogenic fungi, such as *Fusarium oxysporum*, *Rhizoctonia cerealis*, and *F. graminearum* (Table 2), were determined on potato glucose agar. The results showed that three kinds of chitosan could inhibit 15 kinds of plant pathogenic fungi to a certain extent. However, the inhibition intensity was different due to the physicochemical properties of chitosan and different pathogenic fungi, and expanse the resistance to plants promotes the host's immune response to infection (Lopez-Moya and Lopez-Llorca 2016, Gong et al. 2020).

Moreover, protease blockers are more often acquired to prevent the pathogen's enzymes involved in attacks. In addition to providing toward the early stage of pest and pathogen identification, plant chitinases have been noticed to support fighting against fungal growth and are considered to be a regulated defence strategy in their own right and are recognised as pathogen-related (PR) proteins in this context (Yu et al. 2021). Whereas, analysis on whether plant chitinases effectively against fungal pathogens and proven that these pathogens can be prevented. However, a rice chitinase was differentially expressed in rice, and the converted plants had no tolerance, which the fell armyworm moth caterpillars attacked (*Spodoptera frugiperda*) (Carozzi 1997).

Studies have shown that chitosan has a significant inhibitory effect on various pathogens. However, its antibacterial activity depends on its molecular weight, de-acetylation, solution pH value, solvent type and concentration, and other factors. The molecular weight and de-acetylation degree of chitosan are the two critical physicochemical properties. Different molecular weights and de-acetylation degrees of chitosan have different bacteriostatic effects on plant pathogens Table 2 (Kulikov et al. 2006).

The direct inhibition of virus and viroid activity by chitosan is closely related to its molecular weight (Wang et al. 2012). It has been reported in several literatures that chitosan inactivates the replication of pathogenic bacteria (El Hadrami et al. 2010, Udayangani et al. 2017). This may be due to when the pathogen penetrates the plant tissue (El Hadrami et al. 2010). Chitosan nano-particles are tightly combined with nucleic acid, causing a series of damage and selective inhibition of pathogens. For example, selective inhibition may result in mRNA's inactivation encoding essential genes in viral or viroid metabolism and infection. These properties of chitosan are widely used in gene therapy and gene silencing. However, for bacteria, fungi, oomycetes, and other harmful microorganisms, chitosan may indirectly exert its antibacterial effect by enhancing host plant's resistance.

At the same time, further studies have shown that chitosan can achieve its activity by pathogenic chelating elements, minerals, or directly exerting toxicity (Kulikov et al. 2006, Rubina et al. 2017). Due to chitosan's biological high polymer characteristics, it can directly form a physical barrier where the pathogen penetrates and prevents the pathogen from spreading to the healthy leaves. In addition, the study also found that chitosan can directly inhibit plant pathogenic bacteria (Rubina et al. 2017). Yang et al. (2012) added different concentrations of chitosan to PDA medium for cultivation of *Monilia fusticola*. The results showed that when chitosan concentration was 2 mg/mL, the organelles of *M. fusticola* were reduced, and the cavity was increased. When the concentration was 4 mg/mL, the cells of peach rot were seriously damaged, which was mainly caused by the invasion of extracellular material or the leakage of intracellular protoplasm due to the rupture of the cell wall (Yang et al. 2012). Falcón et al. (2008) studied the effects of chitosan on tobacco (*Phytophthora capsici*) Table 2. They found that after chitosan treatment, its hyphae appeared abnormal, cell wall structure was destroyed, and its normal metabolism was affected.

Moreover, chitosan can encourage the plant to produce a resistance response and promote the activation of the plant defence mechanism. Once the defence system is activated, the plant disease resistance has effectively enhanced. Some researchers believed that because the major components of the fungal cell wall were chitin (Figure 4) and glucan, chitosan and its derivatives could induce the production of pathogenic related proteins such as PR in pathogenic pathogens in plants. It may help to stimulate the development of phytoalexins, chitinase, and β-1,3-glucanase into the plants, etc. The production of these enzymes can damage the cell walls of fungal diseases, inhibiting their growth and thus providing protection (Figure 4).

Chitosan advancement in herbicides

The use of herbicide in advanced agriculture has significantly mitigated to enhance plant species loss of productivity (Figure 4). However, some studies revealed that this superfluous application caused dangerous environmental and human health long-term issues (Pundir and Chauhan 2012), herbicides presence the phytochemicals maximum polluting in hydrological systems (Malerba and Cerana 2016). To control these issues, the exploitation of natural polysaccharides such as chitosan was probed. Several scientists developed and tested updated chitosan nano-particles to transport paraquat, the most widely utilised herbicide. Alginate/chitosan nano-particles replace the herbicide release and its linkage with the soil (dos Santos Silva et al. 2011). Besides, chitosan/tripolyphosphate nano-particles decreased paraquat harmful effects (Grillo et al. 2014), and enhanced herbicide response was observed for *Eichhornia crassipes* paraquat was articulated in silver/chitosan nano-particles (Namasivayam et al. 2014).

Moreover, methodology based on chitosan nano-particles could control and suppress undesired herbicides or toxic substances from soil and water (Celis et al. 2012). The herbicide Clopyralid available in water and soil was adsorbed and extracted with a nanocomposite substance of chitosan and Montmorillonite. It expressed that chitosan helps improve chiral herbicide dichlorvos' bioactivity regarding the green algae *Chlorella pyrenoidosa* (Wen et al. 2011). A plant esterase-chitosan/gold nanoparticles-graphene nano-sheet composite-based component was proven entirely on behalf of ultra-sensitive exposure of organophosphate pesticides in various experiments (Bao et al. 2015).

CONCLUSION

Following all of the latest developments achieved during ten years of applying and synthesising chitosan-based nanomaterials, it is assumed to be safe and tremendous progress has been accomplished in this domain. Chitosan has an excellent role in improving soil fertility and plant growth as well as plant growth promoters. Chitosan can play a key role in modern agriculture production and could be a valuable source promoting agricultural ecosystem sustainability. Future suggestions will be based on current achievements and also notable gaps. In addition, chitosan has a huge contribution to reducing fertilisers pollution, managing agricultural pests and pathogens in modern-day agriculture, due to its biologically degradation, biocompatibility, and non-toxic characteristics. Furthermore, a systematic study of chitosan's relationship with the plant's vascular system is required that would assist in the development of crop or species-based chitosan microspheres for controlled release. Moreover, chitosan employment within the sector is still limited and requires additional testing and analysis. Whenever assessing the mechanism between chitosan and chitosan oligosaccharides (COS) as biopesticides, it seems interesting to examine microbial tolerance strategies to these molecules, which must be justified. Implementing chitosan and associated products within integrated pest management (IPM) activities throughout agricultural production, specifically towards crop pathogenic bacteria and fungus, still needs to be used. In the modern world, it could be needed to elucidate the composition of COS utilising through various methods like FTIR, UV visible, XRD, NMR, and MS in an attempt to develop the varieties of responsive groups in chitosan oligo-saccharides, the ratio of monomeric segments, their level of de-acetylation, as well as concerns in oligo-saccharides, which is mandatory required for the inclusion and interaction of scientific institutes and agricultural corporations.

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