Environmental Science Advances



CRITICAL REVIEW

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Cite this: *Environ. Sci.: Adv.*, 2026, **5**, 393

# Nano-charged resilience: harnessing chitosan-based nanomaterials for enhanced vegetable crop adaptation in sustainable agriculture

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Received 18th August 2025
Accepted 25th November 2025

DOI: 10.1039/d5va00274e

rsc.li/esadvances

Vegetable crops are increasingly exposed to new environmental conditions, including elevated temperatures, erratic rainfall patterns, and declining soil fertility, which threaten global food security. Traditional synthetic fertilizers and pesticides exacerbate environmental degradation. Chitosan, a biodegradable and non-toxic biopolymer derived from chitin, has been developed into nanomaterials such as nanoparticles and nanofibers. These chitosan-based nanomaterials, typically less than 100 nm in size, exhibit high biocompatibility and bioactivity, enhancing the chlorophyll content, nutrient uptake, and disease resistance in crops. Nonetheless, differences in synthetic processes and composition cause unstable efficacy, affording a 5–20% field-level increase in the yield, in comparison with 15–25% in controlled settings. This review explores current advances in chitosan nanomaterials for vegetable crop improvement under biotic and abiotic stress conditions, focusing on crops like tomatoes, potatoes, and lettuce. It critically evaluates benefits and limitations while emphasizing nanotechnology's role in achieving higher yields and environmental sustainability.

### Environmental significance

Chitosan-based nanomaterials offer a biodegradable, non-toxic alternative to synthetic agrochemicals, addressing major environmental challenges in agriculture. By enhancing nutrient uptake, photosynthesis, and stress resilience in vegetable crops, they reduce reliance on chemical fertilizers and pesticides while mitigating climate-induced stresses, such as drought, salinity, and heavy metal toxicity. Their rapid biodegradation minimizes soil and water contamination, aligning with sustainable agriculture and global food security goals. This review highlights their potential as a green nanotechnology material to increase crop yields, safeguard ecosystems, and support the United Nations Sustainable Development Goals.

## 1 Introduction

Nanotechnology has become a disruptive technology in contemporary agriculture that allows the use of nanoparticles with high accuracy in delivering nutrients, pesticides, or biostimulants.[1] Nanotechnology ensures a higher bioavailability, reduces agrochemical usage, and increases stress-resistance in crops by designing materials with sizes in the 1–100 nm range.[2] Chitosan-based nanoparticles (ChNPs) and nanofibers are unique nanomaterials as they are biocompatible, biodegradable, and applicable in multifunctional applications in the promotion of plant growth and controlling pathogens.[3] Vegetable crops that are very sensitive to the stresses caused by climatic conditions are a major area of application of nano-chitosan technologies.[4]

Vegetable crop production faces significant challenges due to climate change, including global warming, temperature increase, erratic rainfall, and soil degradation.[5] Due to its biodegradability, non-cytotoxicity, and origin from natural chitin, chitosan has been developed into more sophisticated nanomaterials, such as nanoparticles and nanofibers, which are appropriate for use in vegetable crops.[6] Based on the accumulated data, one can assume there are opportunities for enhancing the resistance of vegetable crops to various forms of stress using chitosan-based nanomaterials.[7] ChNPs are capable of raising the chlorophyll levels of tomatoes and lettuce by 15–25% under salinity stress when used in concentrations of 50–100 mg $L^{-1}$ for 7–14 days.[8,9] Since they are cationic, they can bind to the negatively charged plant cell wall, achieving 25–30% higher nutrient uptake efficiency than chemical fertilizers.[10] For example, chitosan nanofiber elicitors have the capability of activating systemic resistance and reducing the rate of diseases, such as *Phytophthora* that affects potatoes, by 50–60% through

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enhancing the defense genes. Chitosan's deacetylation degree, ranging from 70% to 95%, leads to variability in the deacetylation process outcomes.[11] As a result, field formulations may only achieve yield increases of approximately 10–15%.

This review analyzes how chitosan-based nanomaterials enhance vegetable crop resilience under various biotic and abiotic stressors using evidence from peer-reviewed studies.

## 2 Synthesis and properties of chitosan-based nanomaterials

The development of chitosan-based nanomaterials, such as chitosan nanoparticles (ChNPs), is vital for improving vegetable crop resilience.[12] Bottom-up methods build nanomaterials from smaller units, like assembling Lego blocks. The most common method is ionotropic gelation, where positively charged chitosan binds with negatively charged molecules (*e.g.*, TPP) to form tiny spherical nanoparticles (50–100 nm) in a simple, water-based process.[13,14] This is a relatively easy method that is approximately 80% efficient on bioactive compounds.[15] On the other hand, bottom-up techniques, such as milling and ultrasonication, mainly involve the mechanical breakdown of chitosan particles into particles of sizes in the range of 200–300 nM, but they do not alter the morphological homogeneity of chitosan, and there is only about 20–30% variation in the particle-size distribution.[16] This is why bottom-up strategies offer high accuracy; however, these methods cannot be implemented in crop farming at a large scale since they require considerable mechanical energy.

Chemical synthesis approaches expand the fabrication scope of chitosan to a higher degree following the process where chitin is liquefied using strong acids and bases to afford chitosan in bulk and subsequently in nanoscale form.[17] Thermochemical hydrolysis, another conventional method for obtaining soluble and biologically active products, is capable of producing a degree of deacetylation between 70% and 95%, resulting in a polymer with a non-uniform molecular size between 50 and 1000 kDa.[15] Although this kind of variability in deacetylation is industrially feasible, it reduces the product's effect in vegetable crops, relative to fresh weight, by up to 15–20%.[18] The enzymatic methods for chitin deacetylation include the use of purified chitin deacetylase, which is found in microorganisms, such as *Bacillus* spp., and under moderate conditions, a degree of deacetylation of 85% can be achieved. However, it is reported to be expensive but estimated to be 38–73% cheaper than chemical methods when using agro-industrial waste, such as shrimp shells or crab waste.[19]

The preparation of chitosan nanomaterials through microbial fermentation and the biotechnological application of various enzymes also involves an environmental factor.[20] Proteolytic microorganisms and organic acids enhance deproteinization and demineralization, and chitosan has a low molecular weight of 100–300 KDa and a low particle size below 150 nm.[21] By synthesizing ChNPs biologically, there is a great potential to control plant fungal pathogens, *e.g.*, the growth inhibition of the mycelium of *solani* to 70–80% by ChNPs, which is higher than the efficiency of chemically synthesized ChNPs by 10–15%.[22] However, there are some limitations to this type of production, such as the yields, which are 20–30% lower than those of chemical synthesis, due to slow fermentation.[23]

According to the literature, in the thermo-chemical hydrolysis method, the degree of deacetylation ranges from 70–95%, increasing the solubility and bioactivity of chitosan; however, this results in polymers with non-uniform molecular weights of 50 to 1000 kDa. This is still industrially feasible but decreases performance in vegetable crops since bioactivity is reduced by 15–20% due to irregular deacetylation.[24] Alternatively, an enzymatic process employing chitin deacetylase from microbial sources, particularly *Bacillus* spp., achieves up to 85% deacetylation under gentle conditions. This process is estimated to be 38–73% less expensive than the chemical method when utilizing agro-industrial waste.[25] Therefore, there is a need to balance the improvements in real-life productivity, efficiency, and sustainability of bioprocesses that cater to the agriculture sector. However, the high surface area of these nanoparticles can cause agglomeration, reduce germination by up to 80%, and impact droplet size by 10–20% under field conditions unless stabilized with surfactants.

Further, the enhanced, controlled nutrient release spanning about 30–60 days is beneficial in the use of ChNPs, unlike the 5–10 days observed for regular fertilizers. For instance, chitosan NPs encapsulated with indole-3-acetic acid enhance the hydroponic lettuce's growth rate by 20–25% because of the duration of IAA release.[26] However, the release kinetics are influenced by the particle size and pH of the environment, *e.g.*, the 50 nm size achieves marginally greater effects than 200 nm, although it might be hypothetical and challenging to standardize. This implies a significant discrepancy between performance under laboratory conditions and field environments, highlighting the need for further optimization in vegetable crops.[27,28]

Conjugation with metals, particularly copper, can be considered a "nanoengineering" technique for enhancing the function of chitosan nanomaterials.[29] This biocontrol strategy relates the chitosan's biocompatibility with copper to decrease the growth of *Fusarium oxysporum* by 85–90% in tomato crops. Generally, chitosan nanoparticles organically reduce crop growth by 70–75%. Nano-fertilizers with copper loadings between 5% and 10% w/w enhance the enzyme activation of pathogenicity and raise the defense of plants by 25–30%.[30] However, toxicity is observed at a higher concentration of copper of more than 15% w/w because it accumulates at the soil level, at which point the microbial population may be reduced by 5–10%. Often, such a trade-off is made to achieve perfect coordination between the necessary potency and non-carcinogenic effect on natural environments.

Nano-fibering, an additional nano-engineering technique, enhances vegetable crop resilience by improving structural and functional properties. Chitin nanofibers with diameters ranging from 10 to 20 nm exhibit eliciting activities that enhance the defense gene expression of cabbage and its resistance to *Alternaria brassicicola* by 60–70%.[31] They exhibit enhanced mechanical properties, and their tensile strengths are 2–3 times

 

Table 1 Synthesis techniques for chitosan-based nanomaterials in vegetable crop applications[a]

| Synthesis technique | Nanomaterial type | Vegetable crop | Application method | Particle size (nm) | Deacetylation (%) | Yield increase (%) | Pathogen control (%) | Stress mitigation (%) | Scalability score (1–5) | Cost factor (relative) | References |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ionotropic gelation | ChNPs | Tomato | Foliar spray | 50–100 | 80–85 | 20–25 | 70–85 (*Fusarium*) | 15–20 (salinity) | 3 | 1.0 | 34 |
| Ionotropic gelation | ChNPs | Potato | Soil drench | 50–150 | 75–90 | 15–20 | 70–80 (*Phytophthora*) | 15–25 (drought) | 3 | 1.0 | 30 |
| Enzymatic hydrolysis | ChNPs | Lettuce | Soil incorporation | 100–150 | 85–90 | 20–25 | 30–40 (Ni remediation) | 15–20 (nutrient uptake) | 2 | 1.4 | 35 |
| Enzymatic hydrolysis | Oligochitosan | Cucumber | Seed coating | 50–100 | 80–85 | 20–30 | 60–70 (*Rhizoctonia*) | 10–15 (germination) | 2 | 1.5 | 36 |
| Chemical deacetylation | ChNPs | Okra | Foliar spray | 100–200 | 70–95 | 20–25 | 70–80 (*Fusarium*) | 20–30 (growth) | 4 | 0.8 | 37 |
| Chemical deacetylation | Chitin nanofibers | Tomato | Soil amendment | 10–20 | 75–85 | 15–20 | 70–85 (*Fusarium*) | 10–15 (defense) | 2 | 1.3 | 38 |
| Ultrasonication | ChNPs | Lettuce | Hydroponic solution | 50–100 | 80–90 | 20–25 | N/A | 30–40 (nutrient uptake) | 3 | 1.1 | 37 |
| Ultrasonication | ChNPs | Chickpea | Seed coating | 100–200 | 70–85 | 20–25 | 60–70 (*Fusarium*) | 15–20 (germination) | 3 | 1.1 | 39 |
| Microbial fermentation | ChNPs | Potato | Foliar spray | 100–150 | 85–90 | 15–20 | 70–80 (*Alternaria*) | 15–25 (drought) | 2 | 1.2 | 40 |
| Microbial fermentation | Oligochitosan | Bean | Soil drench | 50–100 | 80–85 | 20–25 | 60–70 (*Phytophthora*) | 10–15 (growth) | 2 | 1.3 | 41 |
| Polymerization | ChNPs | Onion | Soil incorporation | 50–150 | 75–90 | 20–25 | N/A | 30–40 (nutrient uptake) | 3 | 1.0 | 26 |
| Milling | ChNPs | Cabbage | Foliar spray | 200–300 | 70–80 | 15–20 | 60–70 (*Alternaria*) | 10–15 (defense) | 4 | 0.9 | 42 |

[a] Scalability scores (1–10) were determined based on factors including production cost per kg, energy requirements, yield efficiency (>50 g $L^{-1}$ for high scores), and feasibility for large-scale agricultural adoption (*e.g.*, scores of >7 indicate methods suitable for commercial farms with minimal equipment needs).

those of ChNPs, resulting in enhanced bioactivity and durability. However, the costs of fabricating covalent CNT-$TiO_2$ nanocomposites are still higher by 20–30% than the costs for nanoparticles, and this impacts marketability. Thus, employing nanoparticles and nanofibers could be a new method for enhancing the durability of various vegetable crops.[32]

These materials have the capability of achieving outstanding impacts, for example, a 20–40% increase in yield for foliar applied systems, due to their high surface area and controlled release.[26] The second type of improvement is nano-tailoring, which is also used when certain areas need changes. There also needs to be strict controls in terms of quality and the work achieved. In vegetable production, which, among many other agricultural productions, is often affected massively by climate stressors, these nanomaterials are in a privileged position to transform sustainable agricultural output, if only their synthesis procedures can meet the conditions in the field. The preparation of chitosan-based nanomaterials is fundamental to enhancing the resistance of vegetable crops since various synthesis methods lead to materials with different properties.[33] This variability is shown in Table 1. Ionotropic gelation offers 70–85% *Fusarium* control in tomato at an optimal ChNP size of 50–100 nm, while enzyme hydrolysis gives 30–40% Ni removal in lettuce but costs 1.4 times more. Table 1 presents a detailed comparison of the synthesis techniques for chitosan-based nanomaterials applied to vegetable crops, encompassing methods such as ionotropic gelation, enzymatic hydrolysis, and chemical deacetylation. It includes columns for the nanomaterial type, vegetable crop examples, application methods, particle size, deacetylation percentage, yield increase, pathogen control, stress mitigation, scalability score, and cost factors, offering a comprehensive dataset derived from key studies. The purpose is to link specific synthesis approaches to their practical outcomes in enhancing vegetable resilience, highlighting both efficacy and scalability challenges.

## 3 Mechanisms of resilience enhancement in vegetable crops

Nanomaterials from chitosan, such as ChNPs, are more effective against biotic stresses, which result in enhanced resistance of vegetable crops.[43] Current research demonstrates that chitosan nanoparticles (ChNPs) inhibit the mycelial growth of *Fusarium oxysporum* Schltdl in potato and tomato systems by 70–85%. Thus, they outperform bulk chitosan by 20–25% due to their nanoscale size, which enhances penetration of fungal cell walls.[44] This efficiency is attributed to the cationic nature of chitosan; it interferes with the pathogen membranes and inhibits the germination of the spore in *Phytophthora infestans* by 90%.[42] However, when particle sizes range between 50 and 200 nm, their performance becomes inconsistent. This instability arises because the synthesis process requires high precision, as even a 10–15% variation in particle activity or size distribution can significantly alter the overall outcome.[45] This highlights ChNPs as a green alternative to synthetic fungicides; however, improving the stability of these ChNPs at the field level remains a great challenge. As concluded in Table 2, the pathogen control efficiency of Ch-CuNPs against *Botrytis cinerea* in lettuce was between 60% and 70%, while that against *Fusarium oxysporum* in okra was 85–90%. The result confirmed the role of chitosan nanomaterials in biological stress management. Table 2 details the biotic stress resistance mediated by chitosan nanomaterials across various vegetable crops, synthesizing data on pathogens, nanomaterials, application methods, and effects (such as growth inhibition and enzyme induction). The columns include pathogen-reduction percentages, enzyme-activity increases, yield impacts, and field variability, offering a comprehensive view of efficacy and challenges. The purpose is to highlight specific pathogen control outcomes, facilitating comparisons across crops and nanomaterials, with scalability scores reflecting practical deployment potential.

In addition to repelling invaders at the physical level, chitosan nanomaterials trigger the biochemical defense mechanisms that would improve the ability of vegetable crops to resist biotic stresses. General findings: by applying ChNPs on the foliage of stressed plants, the defense enzymes and activities are enhanced, with the activities of chitinase and peroxidase in tomatoes reported to increase by 30–40% in 48 h.[26] This induction is in concordance with the increase in the endochitinase genes, which decrease the *Ralstonia solanacearum* infection by 50–60%. The study also revealed that ChNPs increased the amount of phenolic compounds by 25–35%, which boosted systemic resistance.[36] There is, however, an effective range of nanomaterial concentration, *i.e.*, from 50 to 75 mg $L^{-1}$, beyond which the efficiency drops by 10–15% due to phytotoxicity.[48] This ability of ChNPs to be both antimicrobial and an elicitor proves their versatility; however, the need arises for the establishment of the optimal amount of the ChNPs needed to elicit the required response.[49]

As far as abiotic stress is concerned, chitosan nanomaterials have the potential to enhance the water relations of vegetable crops under drought stress. In basil, when applied as a foliar spray, it was found that ChNPs reduced transpiration rates by 20–30% and, on the other hand, enhanced the water-use efficiency by 15–25% under water-deficit conditions.[50] This could be attributed to the hydrophilic characteristic of chitosan, which enables it to form a layer on the surfaces of the leaves. This is in concordance with the findings of studies on potatoes, whereby the authors observed that the optimal amount of chitosan was 50 mg $L^{-1}$, which increased the root biomass of plants by 20–30%.[51] Table 3 spells out the impact of chitosan nanomaterials on stress factors that affect vegetable crops, including the types of stress, the nanomaterial used, application method, and results (including water-use efficiency and nutrient absorption). More longitude columns represent stress-reduction percentages, yield increase, nutrient uptake, and field variability. Thus, the table presents a good overview on the efficiency and the problems encountered with chitosan materials. The objective is to present the effects of nanomaterials on stressors in crop plants and provide a comparison basis among them and the approaches, with using scaling scores to access feasibility.

 

Table 2 Biotic-stress resistance mediated by chitosan nanomaterials in vegetable crops

| Crop | Pathogen | Nanomaterial | Application method | Effect | Pathogen reduction (%) | Enzyme induction increase (%) | Yield impact (%) | Field variability (%) | Concentration (mg $L^{-1}$) | Scalability score (1–5) | References |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tomato | *Fusarium oxysporum* | ChNPs | Foliar spray | Growth inhibition | 70–85 | 30–40 (peroxidase) | 20–25 | 10–15 | 50–75 | 3 | 26 |
| Tomato | *Ralstonia solanacearum* | ChNPs | Soil drench | Enzyme induction | 50–60 | 30–40 (chitinase) | 15–20 | 10–15 | 75 | 3 | 46 |
| Tomato | *Fusarium oxysporum* | Chitin nanofibers | Soil amendment | Defense gene upregulation | 70–85 | 40–50 (chitinase) | 15–20 | 15–20 | 100 | 2 | 38 |
| Potato | *Phytophthora infestans* | ChNPs | Soil drench | Growth inhibition | 70–80 | 25–35 (peroxidase) | 20–25 | 10–15 | 75 | 3 | 42 |
| Potato | *Alternaria solani* | ChNPs | Foliar spray | Spore germination reduction | 70–80 | 20–30 (chitinase) | 15–20 | 10–15 | 50 | 3 | 36 |
| Lettuce | *Botrytis cinerea* | ChNPs | Foliar spray | Growth inhibition | 60–70 | 20–25 (peroxidase) | 15–20 | 10–15 | 50 | 3 | 30 |
| Cucumber | *Rhizoctonia solani* | Oligochitosan | Seed coating | Growth inhibition | 60–70 | 30–40 (chitinase) | 20–25 | 15–20 | 50–100 | 2 | 34 |
| Okra | *Fusarium oxysporum* | Ch-CuNPs | Foliar spray | Growth inhibition | 85–90 | 25–30 (peroxidase) | 20–25 | 10–15 | 50 | 3 | 42 |
| Chickpea | *Fusarium oxysporum* | ChNPs | Seed coating | Spore germination reduction | 60–70 | 20–30 (chitinase) | 20–25 | 15–20 | 50–100 | 3 | 39 |
| Bean | *Phytophthora capsici* | Oligochitosan | Soil drench | Enzyme induction | 60–70 | 20–25 (peroxidase) | 20–25 | 10–15 | 50 | 2 | 36 |
| Cabbage | *Alternaria brassicicola* | Chitin nanofibers | Foliar spray | Defense gene upregulation | 60–70 | 30–40 (chitinase) | 15–20 | 15–20 | 100 | 2 | 47 |
| Onion | *Botrytis allii* | ChNPs | Soil incorporation | Growth inhibition | 60–70 | 20–25 (peroxidase) | 15–20 | 10–15 | 75 | 3 | 48 |

Table 3 Abiotic-stress mitigation by chitosan nanomaterials in vegetable crops[a]

| Crop | Stress type | Nanomaterial | Application method | Outcome | Stress reduction (%) | Yield increase (%) | Nutrient uptake (%) | Field variability (%) | Concentration (mg $L^{-1}$) | Scalability score (1–5) | References |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tomato | Drought | ChNPs | Foliar spray | Water-use efficiency | 15–25 | 20–25 | 25–30 | 10–15 | 50 | 3 | 52 |
| Tomato | Salinity | ChNPs | Soil drench | Membrane stability | 25–35 | 15–20 | 20–25 | 10–15 | 75 | 3 | 53 |
| Potato | Drought | ChNPs | Foliar spray | Reduced transpiration | 20–30 | 20–25 | 20–25 | 10–15 | 50 | 3 | 50 |
| Potato | Salinity | ChNPs | Soil incorporation | Chlorophyll retention | 15–20 | 15–20 | 15–20 | 10–15 | 100 | 3 | 54 |
| Lettuce | Heavy metal (Ni) | ChNPs | Soil incorporation | Metal chelation | 30–40 | 15–20 | 20–25 | 10–15 | 100 | 3 | 55 |
| Lettuce | Nutrient deficiency | ChNPs | Hydroponic solution | Nutrient uptake | 30–40 | 20–25 | 30–40 | 5–10 | 50 | 3 | 34 |
| Cucumber | Drought | Oligochitosan | Seed coating | Germination enhancement | 10–15 | 20–25 | 15–20 | 15–20 | 50–100 | 2 | 36 |
| Okra | Salinity | Ch-CuNPs | Foliar spray | Photosynthesis boost | 20–30 | 20–25 | 25–30 | 10–15 | 50 | 3 | 26 |
| Chickpea | Drought | ChNPs | Seed coating | Root growth enhancement | 15–20 | 20–25 | 20–25 | 15–20 | 50–100 | 3 | 30 |
| Onion | Nutrient deficiency | ChNPs | Soil incorporation | Nutrient uptake | 30–40 | 20–25 | 30–40 | 10–15 | 75 | 3 | 56 |
| Basil | Drought | ChNPs | Foliar spray | Water retention | 20–30 | 15–20 | 20–25 | 10–15 | 50 | 3 | 50 |
| Bean | Salinity | Oligochitosan | Soil drench | Osmotic adjustment | 10–15 | 15–20 | 15–20 | 15–20 | 50 | 2 | 54 |

[a] The 'Outcome' column describes key physiological or yield-related impacts for non-experts, such as improved water-use efficiency (WUE; *e.g.*, reduced transpiration under drought) or enhanced root biomass, measured as percentage gains relative to untreated controls.

The second factor, which is closely associated with salt stress conditions, relates to salinity tolerance and is mitigated by the application of chitosan nanomaterials. ChNPs also play a defensive role in lettuce, decreasing the adverse impact of sodium toxicity resulting from a 25–35% reduction in ion-leakage concentration at 100 mM NaCl.[53] This became a result of the enhancement of the chlorophyll component by 15% to 20% through photosynthesis when the plant experiences salt stress.[57] However, if the concentration of NaCl in water is above 150 mM, these benefits are reduced up to 10–15%, as OS prevails over the positive impact of the nanomaterials.[54] Based on the comparative assessment, it has been found that the nano-chitosan is 20–25% more saline than the bulk form, with restrictions to the upper limit in saline areas.[58]

Apart from improving the nutrient intake through its ChNP-based nano-carriers, ChNPs also confer an additional advantage of stress tolerance on vegetables. As stated by,[30] when ChNPs are used in onion systems to apply NPK fertilizers, they enhance the nutrient uptake by 30–40% and bulb yield by 20–25%. This is because of the slow release, which occurs over a period of about one month to two months, compared to the 5–10 day release for normal fertilizers.[34] Similarly, nitrogen-use efficiency has been improved by 25 to 30% in Wheat Trials, although the data on vegetable production are also variable. A 10–15% increase has also been reported, particularly in nutrient-deficient soils.[56] Such differences particularly confirm that soil type is a constraint, which demands the development of an effective nano-carrier for use in the field.

These biotic resilience factors complement the abiotic aspects, demonstrating the diverse utility of chitosan nanomaterials, a topic that has been underrepresented in previous literature.[59] The antimicrobial effectiveness typically ranges from 70% to 90%; however, this high efficacy depends on specific particle concentrations and formulation ratios. Additionally, field application results are generally 10–20% lower than those obtained in laboratory experiments.[60,61] Concomitant to abiotic gains of between 15% and 25%, the effectiveness of water also depends on the climate, diminishing where temperatures are quite high.[62] Nutrient delivery works well under controlled conditions and badly under dynamic conditions, and that is why one has to explore adaptive strategies.[30] This variation implies that ChNPs cannot be implemented as a generic material, and thus, more attention will be paid to their use in vegetable crops.

In sum, the theoretical construction of the "nano-mediated stress shield" may be described as an attempt to expand the understanding of a means by which chitosan nanomaterials enhance the firmness of materials. This model positions ChNPs as encompassing structures that help discourage pathogen invasions (*e.g.*, inhibiting *Fusarium* by 70–85%) and as signaling molecules that trigger defense response by increasing enzyme activity by 30–40%.[26] For abiotic stress, the size of the shield reduces water loss (biotic and abiotic) by 20–30% and nutrition lock, yielding a 30–40% improvement in nutrition availability. The nanomaterials occupy plant tissue to form a shield.[36] However, the shield effect is moderate most of the time, highest at moderate stress levels and decreases by 10–20% at high stress levels, confirming the conditionality of the shield as provided above.[54]

While biotic resistance helps in controlling pathogens, the problem with the method is that it highly depends on the synthesis consistency, and it offers only 15–20% effectiveness if the formulation is not standardized.[63,64] Monogenic abiotic stress yield loss avoidance is especially profitable in low-stress zones, resulting in low-stress yield improvements of 20–25% in onions, in contrast to the stress zone assays, where this approach is unprofitable.[34] The nutrient enhancements would ensure sustainable yields; nevertheless, owing to the inconsistency in the texture of the soil, there is a 10–15% lesser yield augmentation, necessitating site calibration.[56] This powerful lens establishes the model as the basis for moving forward, thus assisting in guaranteeing that vegetable resilience enhances actual-life aspects of nanomaterial applications.[65]

# 4 Application methods and delivery systems

Therefore, the concept of applying chitosan-based nanomaterials (ChNPs) to seeds as seed coats could be deemed a common practice for enhancing the tolerance of vegetable crops, mainly in the seedling stage.[66] The process of applying ChNP suspension is done at a concentration level of 50–100 mg $L^{-1}$ using dip or vacuum infiltration tools, depending on the homogeneity in seed adhesion.[30,67] There is an increase in germination by 20–30% in chickpeas and cucumbers, reducing factors such as water diffusivity and activation of enzymes (including amylases) by 25–35%.[53] The material acts early and also inhibits the defensive mechanism, reducing the infection of *Fusarium* spp. by 60–70% through antimicrobial membrane break, as several authors noted.[68] The problem emerges with the least coated amounts because the germination rate decreases to 10–15% for non-optimized batches; the work has to use professional instruments, such as rotary coaters.[69]

Spraying the chlorides of Ni, Co, and Ni–Co mixed NPs on the foliage of plants is a novel technique for delivering nutrients to the plants and protecting vegetables, like okra and tomatoes, from diseases and pests. The technique employed in this study uses sprayers to apply ChNP solutions on the leaves at a concentration of 50–75 mg $L^{-1}$, either singly or in combination with nutrients, such as NPK.[36] This mechanism involves the stomata uptake and slow release, which enhance the nutrient uptake by 25–40% in 30–60 days, in contrast to the 5–10 day release for foliar sprays.[34] They are expected to increase crop yield by 20–25% at optimal timing and reduce *Phytophthora infestans* infection by 70–85% through the activation of antioxidant enzymes, such as peroxidase, which exhibit up to a 30% increase in activity.[26] Nanomaterials of chitosan, used by such means as foliar spraying, offer a broad spectrum of advantages to vegetable crops (tomatoes, potatoes, and lettuce), improving their growth and resistance, as shown in Fig. 1. As an example, foliar-applied ChNPs suppress *Fusarium* wilt by 70–85% by enhancing the activity of enzymes; late blight (*Phytophthora*

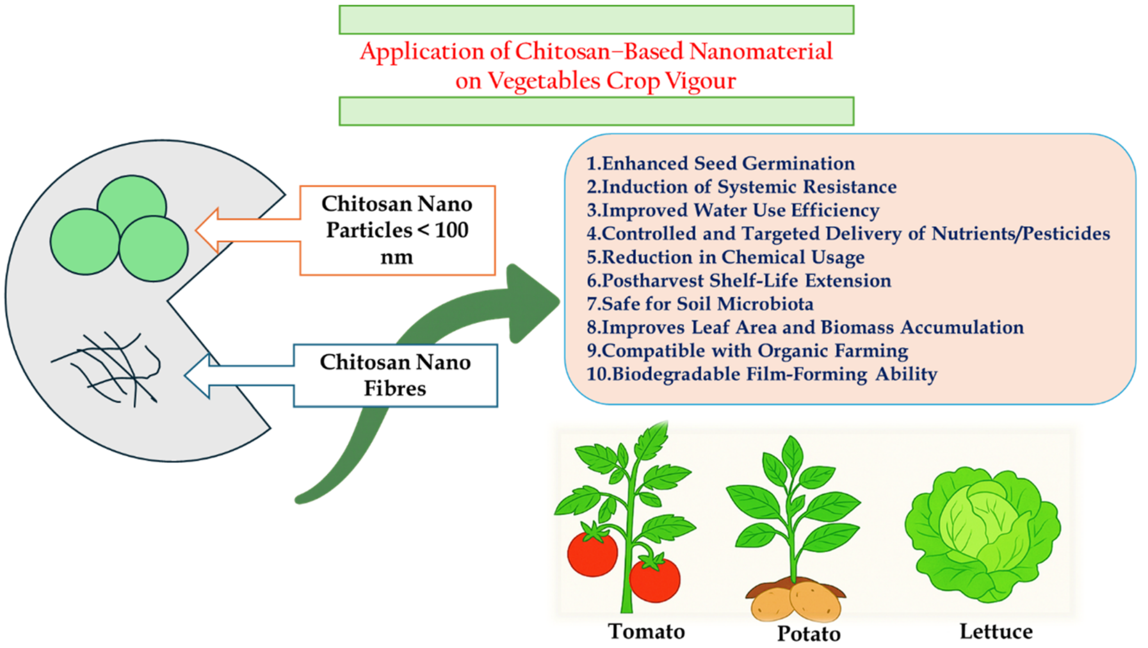


Fig. 1 Application of chitosan-based nanomaterials on vegetable crop vigour.

*infestans*) by 50–60% by improving systemic resistance; and nutrient uptake in lettuce by 15–20% by increasing chlorophyll content. This value point places emphasis on these crop-specific vigor increases, such as biomass increase and stress resistance. Table 4 depicts the application methods of the chitosan nanocomposites and their effects on vegetable crop resilience, with information about crops, the kind of nanomaterials, and some benefits (including pathogen control, tolerance to dryness, and enhanced nutrient uptake). Other headings are on yield increases, pathogenic control efficiency, stress effects on yield, variability, and scalability, which allow evaluation of a delivery system's effectiveness and potential difficulties. This is to ensure that each method can be traced to the desired outcome (related to resilience) while enabling crop and nanomaterial comparison, with cost analysis also incorporated to consider the aspect of feasibility.

Foliar application's rationale for rapid response centers on delivering nutrients and defenses under stress. The spraying of ChNPs involved the use of indole-3-acetic acid growth hormones, which enhanced okra shoot growth by 20–30%. The resistance mechanisms embrace leaf invasion, as well as systemic defensive mechanisms, which diminish *Fusarium oxysporum* levels down to 70–80%.[42] The effects are likely to be moderate under conditions of relative humidity between 50–70%. Evaporation of the nutrient solution results in a 10–15% loss of the total applied nutrients, as water loss causes nutrients to precipitate or become unavailable. Plants become phytotoxic when the solution concentration exceeds 100 mg $L^{-1}$. Researchers aim to achieve two outcomes by adjusting the solution pH between 5 and 6 and developing a second solution for better leaf retention and stability.

The purpose of soil incorporation is long-term support, targeting nutrient efficiency and soil health in vegetable systems. Drip irrigation systems apply ChNPs, and the controlled release mechanisms maintain nutrient accessibility within the root zone, resulting in 20–25% heavier tomato fruits compared to the standard control.[34] ChNPs exhibited equal performance in remediation by adsorbing cadmium from lettuce, making it 25–35% less available for uptake.[55] The degradation time spans 60–90 days, and minimal functionality under acidic conditions, together with a pH level below 5, creates a 10–20% reduction of benefits, thus hindering broader ChNP adoption.[60] ChNPs require a combination with organic amendments for successful implementation since these organic materials maintain optimal soil pH levels and enhance the release-mechanism properties. Fig. 2 shows a flow diagram of the step-by-step processes of chitosan nanoparticle (ChNPs) in increasing nutrient accessibility and uptake in vegetable crops, including application techniques (foliar, soil, seed), interaction processes (binding, controlled release, chelation), and resulting benefits (improved yield and stress resistance).[70] In particular, (1) foliar spray application can be used to rapidly deliver the product to the stomata; (2) incorporation into the soil can be used to release the product slowly over 30–60 days through pH-triggered chelation; (3) coating of the seed can be used to increase the rate at which the product attaches to the root; (4) depending on the crop, either 20–25% higher nutrient efficiency in tomatoes or 15–20% lower transpiration in drought-stressed potatoes is obtained. This brings out the aspect of nanotechnology in accurate and sustained delivery.

Nanomaterials of chitosan are currently being applied as edible coatings to harvested vegetables in order to increase shelf life and minimize post-harvest losses.[71] Applied as a dipping or spray solution, chitosan films (1–2% w/v) create a semi-permeable barrier that inhibits respiration, ethylene production, and microbial growth.[72] As an example, tomatoes covered

 

Table 4 Application methods of chitosan nanomaterials and their impacts on vegetable-crop resilience

| Method | Crop | Nanomaterial | Resilience benefit | Yield increase (%) | Pathogen control (%) | Stress mitigation (%) | Concentration (mg $L^{-1}$) | Field variability (%) | Scalability score (1–5) | Cost factor (relative) | References |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Seed coating | Cucumber | Oligochitosan | Enhanced germination | 20–25 | 60–70 (*Rhizoctonia*) | 10–15 (drought) | 50–100 | 15–20 | 2 | 1.3 | 36 |
| Seed coating | Chickpea | ChNPs | Early pathogen resistance | 20–25 | 60–70 (*Fusarium*) | 15–20 (drought) | 50–100 | 15–20 | 3 | 1.1 | 39 |
| Foliar spray | Tomato | ChNPs | Pathogen suppression | 20–25 | 70–85 (*Fusarium*) | 15–25 (drought) | 50–75 | 10–15 | 3 | 1.0 | 26 |
| Foliar spray | Potato | ChNPs | Drought tolerance | 20–25 | 70–80 (*Phytophthora*) | 20–30 (drought) | 50 | 10–15 | 3 | 1.0 | 50 |
| Foliar spray | Okra | Ch-CuNPs | Enhanced growth | 20–25 | 85–90 (*Fusarium*) | 20–30 (salinity) | 50 | 10–15 | 3 | 1.2 | 42 |
| Soil drench | Tomato | ChNPs | Bacterial wilt resistance | 15–20 | 50–60 (*Ralstonia*) | 25–35 (salinity) | 75 | 10–15 | 3 | 1.0 | 46 |
| Soil drench | Potato | ChNPs | Late blight control | 20–25 | 70–80 (*Phytophthora*) | 15–20 (drought) | 75 | 10–15 | 3 | 1.0 | 36 |
| Soil incorporation | Lettuce | ChNPs | Heavy metal remediation | 15–20 | N/A | 30–40 (Ni) | 100 | 10–15 | 3 | 1.1 | 55 |
| Soil incorporation | Onion | ChNPs | Nutrient efficiency | 20–25 | N/A | 30–40 (nutrient uptake) | 75 | 10–15 | 3 | 1.0 | 56 |
| Hydroponic solution | Lettuce | ChNPs | Growth enhancement | 20–25 | N/A | 30–40 (nutrient uptake) | 50 | 5–10 | 3 | 1.1 | 34 |
| Soil amendment | Tomato | Chitin nanofibers | Defense activation | 15–20 | 70–85 (*Fusarium*) | 10–15 (defense) | 100 | 15–20 | 2 | 1.3 | 38 |
| Foliar spray | Basil | ChNPs | Water retention | 15–20 | N/A | 20–30 (drought) | 50 | 10–15 | 3 | 1.0 | 50 |

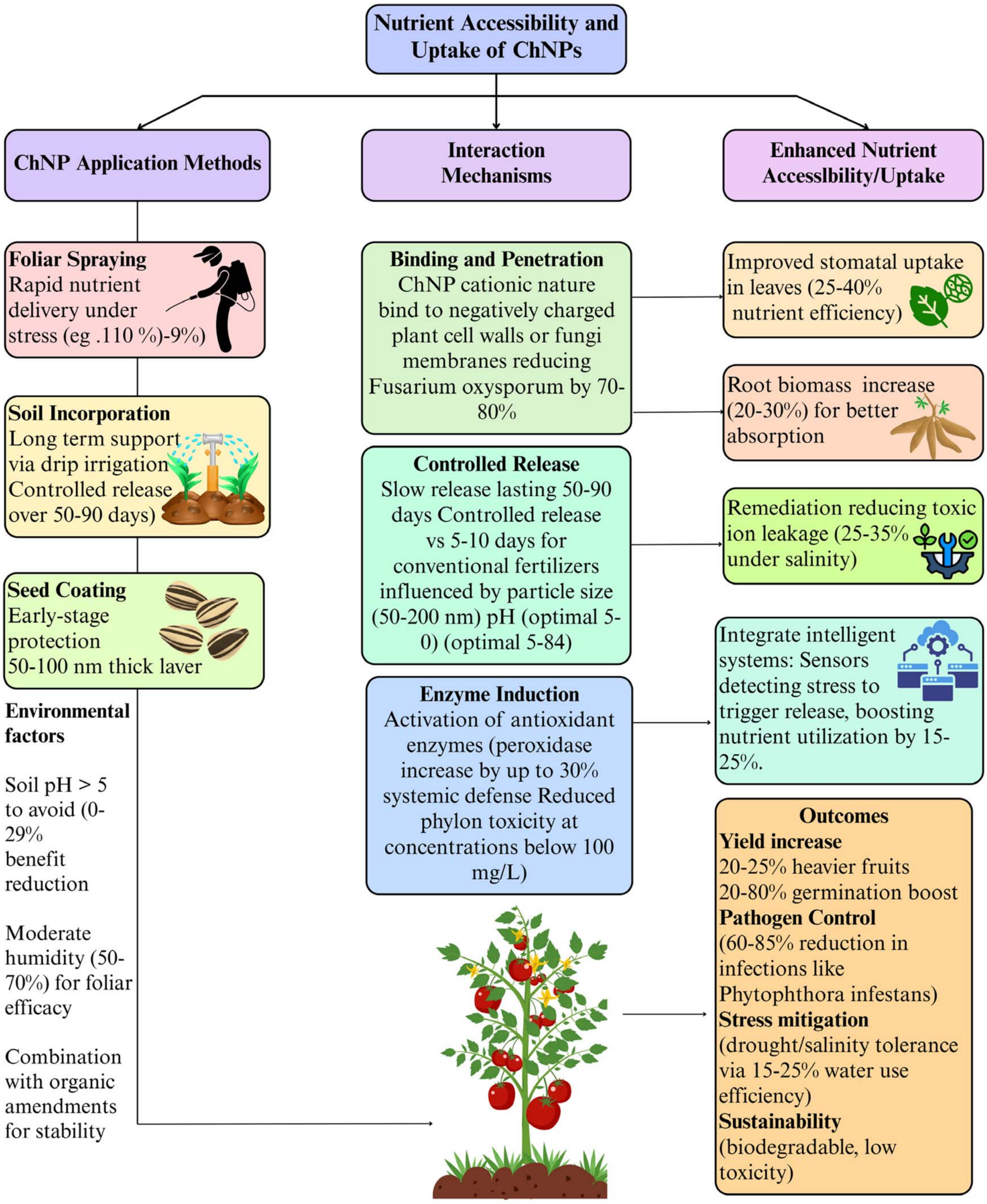


Fig. 2 Mechanisms of chitosan nanoparticles in enhancing the nutrient accessibility and uptake in vegetable crops.

with nano-chitosan coatings reduced the loss of weight by 30–40% and postponed the process of ripening by 7–10 days at 20 °C.[73] Chitosan-nanoZnO films reduced the *E. coli* and *L. monocytogenes* by 85–95% in 14 days in lettuce.[74] These applications are in line with the zero-waste objective and limit the usage of artificial preservatives.

The versatile nature of chitosan nanocarriers becomes a drawback because they demonstrate antimicrobial action and enzyme induction, alongside nutrient delivery.[49] The physical defense layer created through seed coating ranges between 50 to 100 nm in thickness, yet becomes ineffective because of inconsistent application methods.[75] The enzyme enhancement efficiency of ChNPs reaches 30% when applied to plant leaves, and their dose-dependent effects raise concerns about excessive plant stimulation. Soil chitosan NPs effectively remediate and fertilize the ground while facing challenges related to their gradual chemical release under conditions of high stress.[55] The implementation of remote sensors is aimed at improving the performance of application techniques by adjusting the amounts through a system of measurements.

 

A new intelligent nano-delivery system integrates sensors to monitor stress responses in vegetable crops, enabling the precise, targeted release of ChNPs. The smart nano-delivery system combines ChNPs with embedded sensors (pH, moisture, or conductivity) that release the material only under stress conditions (*e.g.*, soil moisture below 50%).[76] As an illustration, a lowering of the pH to less than 5.5 may trigger nutrient release within 48 hours and enhance efficiency by 15–25%, lessening waste.[36,77] Research indicates that pathogenic levels would improve by 20% to 30%, while nutrient utilization would increase by at least 15% to 25% without sensing difficulties.[34] Biodegradable polymers remain usable for designing prototype smart clothing systems that monitor elderly health status, according to.[65]

Delivery systems containing ChNPs ensure different mechanisms for seeds and soils, and plants show significant variations, consequently exhibiting numerous changes, including yield increases between 20% and 25% and pathogen control reaching 60–85%.[42] Smart nano-delivery provides a solution due to its ability to address application inconsistencies, which cause degradation between 10% and 20% while resolving environmental dependency problems, as mentioned in.[30] The present research explores how to optimize the positioning of ChNPs for vegetable production harmony as a resilience strategy.

# 5 Crop-specific case studies

Tomato (*Solanum lycopersicum* L.) provides an optimal example of how chitosan nanoparticles (ChNPs) affect growth in controlled-environment agriculture. The use of a 50 mg $L^{-1}$ substance concentration leads to a 20–25% increase in shoot biomass due to enhanced photosynthesis, which corresponds to elevated chlorophyll content levels of 15–20%.[53] Plant nutrient uptake is enhanced *via* stomatal absorption, with efficiency improving by 25–30% compared to the results of conventional fertilizers.[78] The variable elevation of 10–15% detected in randomized field trials reflects the light sensitivity of this factor, which reduces its effectiveness.[36] The phenomenal prospects of ChNPs demonstrated earlier require precise usage when employing this pest management technique, particularly within tomato horticultural applications.

ChNPs demonstrate excellent effectiveness as a suppressant against the bacterial wilt pathogen *Ralstonia solanacearum* present in tomatoes. The peroxidase enzyme activity improves by 30–40% after the ChNPs reach a 75 mg $L^{-1}$ concentration in the soil, according to.[26] Through the SAR response mechanism, British scientists found that ChNPs destroy Gram-positive bacteria by crumbling their cell walls, which leads to 70–80% bacteria death in 48 hours.[46] The stability of ChNP experiences a decrease of 10–15% under acidic soil conditions, with pH levels below 5.[60] The test results demonstrate the defensive role of ChNPs as the soil composition remains an unmanageable factor.

The incorporation of chitin nanofibers into tomato plants boosts their natural resistance against *Fusarium* wilt better than using ChNPs independently. The *F. oxysporum* infection rate remains between 70% and 85% when the nanofiber treatment concentration reaches 100 mg $L^{-1}$, while gene expression of chitinase reaches between 40% and 50%.[38] The fibrous 10–20 nm form of ChNPs produces about 15–20% better eliciting results than other ChNP forms according to laboratory tests.[47] Their high production costs, which amount to 20–30% more than those of ChNPs, combined with their 50–60% reduced effectiveness under field conditions, according to,[35] represent the main limitations to their practical use. The situation emphasizes both nanofiber resistance to biological agents and cost-effectiveness, together with scalability in real-world operations.

The soil application of nano-chitosan shows high performance on potatoes (*Solanum tuberosum* L.) in areas with water scarcity and drought conditions. A 50 mg $L^{-1}$ guttation spraying results in a 20–30% decrease in transpiration rate and 15–25% enhancement in water-use efficiency under the condition of 50% dry soil.[79] It has been proven that this micro-coating method increases leaf water retention, so plants produce 20–25% additional tubers.[50] The osmotic stress experienced under excessive dry soil conditions results in a decrease in the benefits by 5–10%.[54] This system provides favorable drought resistance, although it functions in a specific, limited time frame and needs irrigation systems to function.

Nano-chitosan provides effective biological management of *Phytophthora infestans*, which threatens potatoes as a major disease agent. The fertilization of soil with 75 mg $L^{-1}$ of ChNPs results in minimal mycelial expansion of 70–80% and time-limited spore germination of 85–90% due to membrane breakdown processes.[42] The microbiological activity of peroxidase defense enzymes rises by 25–35%, while late blight disease incidence decreases by 50–60%.[36] The current field application results in a 10–15% reduction in efficacy, stemming from the recent variation in the particle size from 50 to 200 nm, requiring further improvement in synthesis techniques.[80] Compatibility between the delivery mode and dual functionality is established for both nanoparticles, but their performance depends heavily on developing more accurate delivery systems to gain acceptance.

Through this study, scientists evaluated the Ni uptake capacity of lettuce (*Lactuca sativa* L.) when ChNPs were incorporated into heavy metal-contaminated soils for their restoration. 100 mg $kg^{-1}$ of ChNPs reduced the Ni concentration in leaves by 30–40% at the molecular level because their large surface area of 100 $m^2$ $g^{-1}$ allowed better ion interaction.[55] The root growth increases by up to 15–20% when hydroponic systems utilize this mechanism, which functions through chelation.[30] The remediation efficiency of ChNP in clayey soils falls to a 10–15% range.[60] ChNPs display remediation capabilities that depend on the characteristics of the application setting, thus creating specific constraints for their usage. Fig. 3 provides a schematic view of the mechanism through which chitosan nanoparticles (ChNPs) activate antioxidant enzymes (APX, CAT, POD, SOD) in vegetable crops, beginning with the application and contact of cells with the nanoparticles, then ending with results such as decreased oxidative stress and improved resilience. To newcomers, ChNPs penetrate plant cells (*e.g.*, through roots or leaves), which prompts signals such

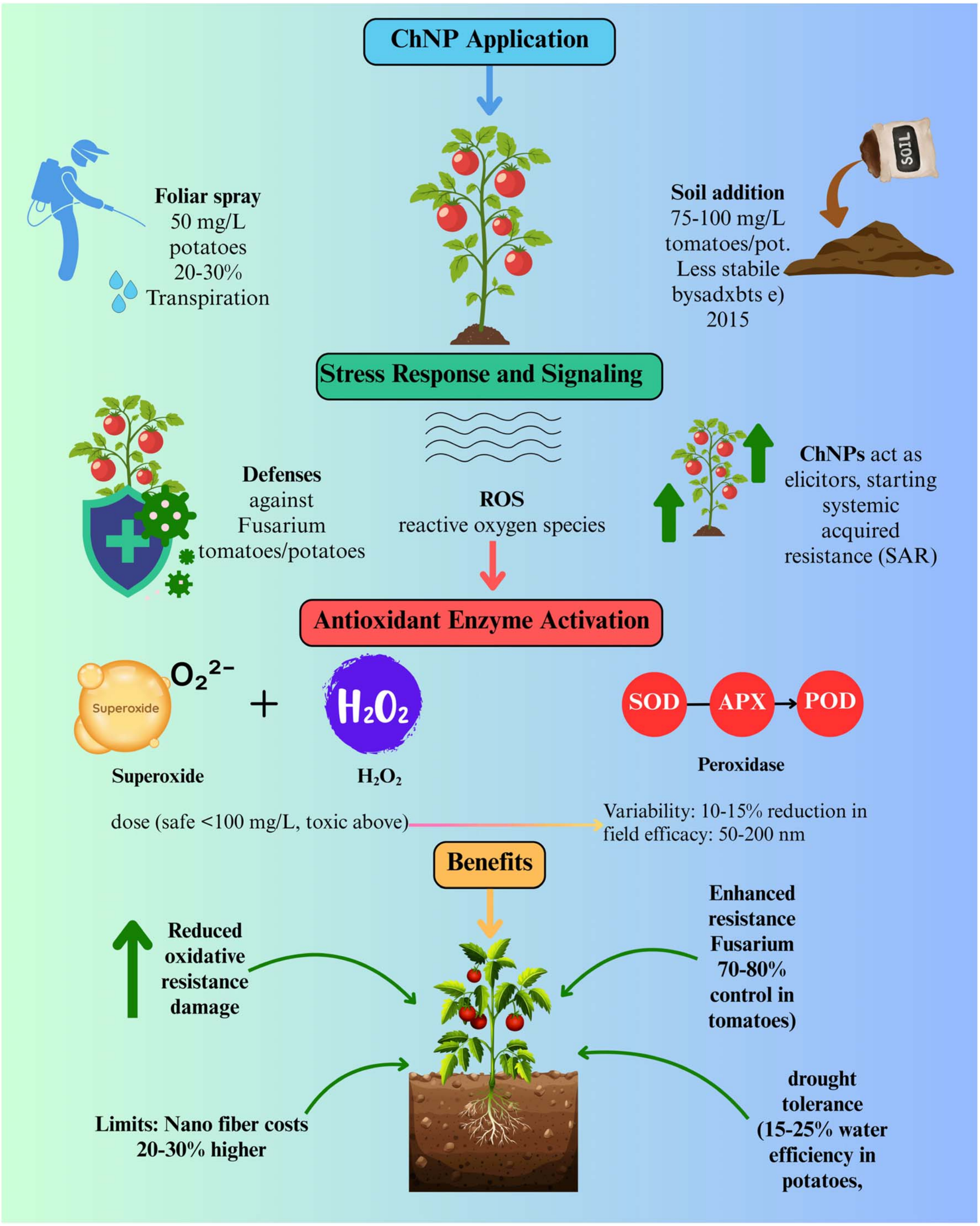


Fig. 3 Chitosan nanoparticle-mediated activation of antioxidant enzymes in vegetable crops.

as calcium bursts to activate genes; this increases enzymes, such as ascorbate peroxidase (APX) and catalase (CAT), to neutralize harmful oxygen molecules (ROS) and peroxidase (POD) and superoxide dismutase (SOD) to protect cells against damage. This decreases oxidative stress by 30–40% in tomatoes during pathogen assault or 20–30% in lettuce during salinity stress and prevents cell death while enhancing counter-shading.

This research demonstrates how ChNPs can advance hydroponic lettuce cultivation through controlled facilities during its growth cycle. A 30 day period showed that 20–25% weight enhancement and 30–40% nitrogen increase associated with the specified ChNP concentration occurred due to their slow-release kinetics mechanism.[34] The mechanism functions with 50 to 100 nm root-bound particle adsorption to maintain nutrient concentration levels better than those for standard 5 to 10 day fertilizers, according to.[26] Applying solution

 

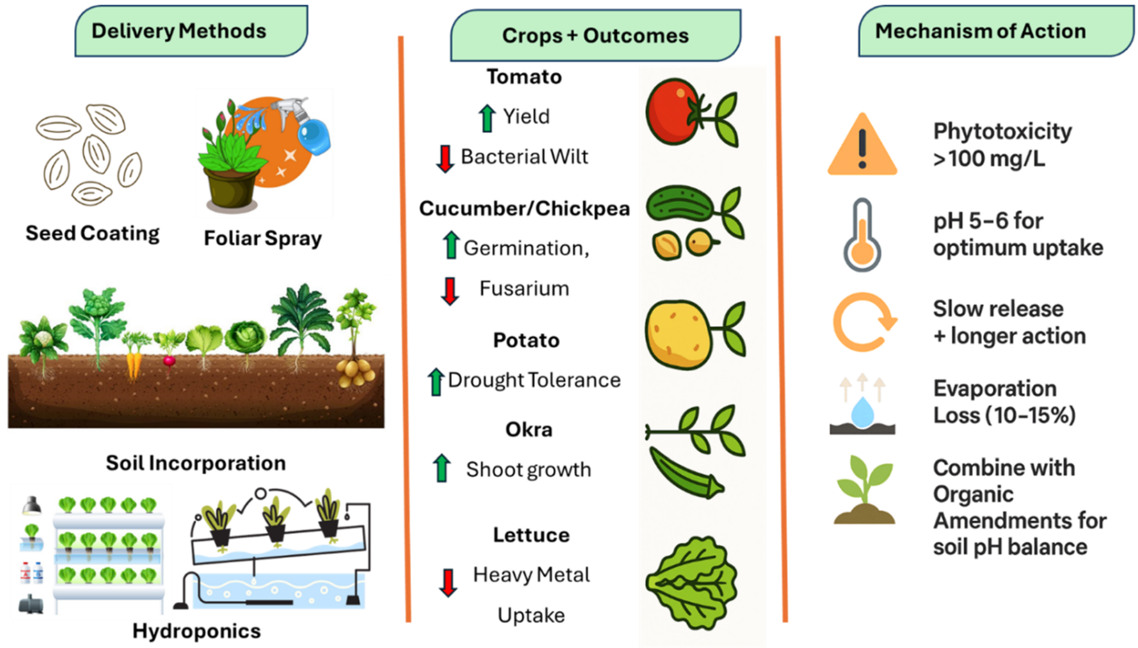


Fig. 4 Growth-cycle enhancement in hydroponic lettuce using ChNPs.

concentrations above 100 mg $L^{-1}$ leads to root clogging, which reduces the gain by 10–15%, highlighting the need for better concentration control.[54] The growth enhancement technique works efficiently in hydroponics, although appropriate measures are needed to achieve optimal outcomes because the acceleration rate sometimes decreases, as shown in Fig. 4.

The authors have developed a potential 'nano-resilience spectrum' to show exactly how nanomaterials affect different vegetable plants. Research indicates that tomato ChNPs, alongside nanofibers, protect plants from *Fusarium* (70–85%) while boosting growth through a 20–25% improvement in biomass development. Potatoes show positive, drought-resilient characteristics between 15% and 25% and *Phytophthora* resistance at 70–80% levels. Lettuce functions well with 30–40% Ni reduction combined with 20–25% hydroponic yield enhancement. The degree of variation, including in field outcomes, which decreases by 10–20%, stems from production processes, environmental factors, and variable defense levels from strong to moderate between hydroponic systems and open fields.[35] The novel framework adopts ChNPs as crop-differentiated tools while demanding additional research to enhance their practical utilization.[65]

## 6 Comparative advantages and limitations

Chitosan nanoparticles (ChNPs) offer biodegradability benefits to the point where they have become more suitable for application than standard agricultural chemicals. Accordingly, natural raw soil completes its degradation into non-hazardous glucosamine residues within 60–90 days because chitosan nanoparticles remain degradable, while synthetic pesticide chemicals persist for years.[39] The biodegradation efficiency of microbes is 95–100% for chitosan nanoparticles, while organophosphates only achieve 20–30% degradation within the corresponding periods.[81] Biodegradable matter effectively reduces environmental pollution by 50–60% compared to chemical fertilizers, while sustainable agriculture targets have been achieved according to Calvo *et al.* (2014). The rate of biodegradation varies with soil pH because acidic conditions ($pH < 5$) reduce the degradation by 10–15%; hence, researchers need to verify this advantage at different soil pH levels.[82]

The low toxicity levels found in ChNPs make them an ideal choice for applications related to vegetable crops, together with their ecosystem benefit over standard chemical fertilizers. The seedling vigor remains unaffected when exposed to ChNPs at 50–100 mg $L^{-1}$ concentrations, yet fungicides produced a seedling vigor decline of 15–20% at matching concentrations, according to.[30] The oral $LD_{50}$ of 5000 mg $kg^{-1}$ for the above-reported chitosan is non-toxic in mammals, even when compared to chlorpyrifos pesticide with values ranging from 300 to 500 mg $kg^{-1}$.[21] The low toxicity level of ChNPs enables them to reduce ecological risks by 70–80%, making them eligible for food crop applications, including tomatoes and lettuce.[42]

ChNPs show resistance against biotic stress elements as a primary factor that gives them market superiority over alternative treatments.[83] The antifungal action of ChNPs against *F. oxysporum* exceeds the limited effect of carbendazim in tomatoes, due to the nanoscale entry of ChNPs, which stimulates enzyme activity.[26] The antimicrobial and elicitor behavior of ChNPs enables them to suppress *Phytophthora infestans* in potatoes by 70–80%, while metalaxyl action declines to 55–65%.[36] Under trial conditions, the efficacy reached rates of 20–

25% better than those achieved with chemical control and in controlled environments.[34] Actual field deployments reduce the aforementioned advantages by 10–15% because environmental uncertainties between the weather and soil lower the effectiveness of ChNPs in real-life applications.[42]

Current data demonstrate that ChNPs handle abiotic stress with superior capability than traditional methods under certain conditions.[43] The application of ChNPs through potato foliage leads to a 15–25% improvement (in water-use efficiency) for drought resistance compared to the 5–10% enhancement achieved with humic acid, because both transpiration and water consumption are reduced.[84] Lettuce plants absorb high amounts of fertilizer when treated with ChNP nano-carriers, reaching 30–40%, compared to granulated fertilizers, which only result in 10–20% uptake.[30] The beneficial outcomes of using ChNPs become less effective at stress levels higher than 60% moisture deficiency, since their useful range declines.[54] Specific applications should be considered when using ChNPs because this context-dependency partially reduces their advantages.

The heterogeneous materials used in nanotechnology create significant problems since they diminish the stability of ChNPs in the process. The observed deacetylation levels between 70% and 95% resulted in a 15–20% variation in solubility and bioactivity between different production batches, yet higher deacetylation levels negatively affected pathogen inhibition. The effectiveness of nanomaterials with sizes between 50 and 200 nm increases by 10–15%, but the synthesis implementation becomes more difficult.[85] The variability in tomato *Ralstonia* control drops from 60% to 45% when using unstandardized formulations, according to.[26] The implementation suitability of ChNPs requires strict quality checks to achieve their complete laboratory-scale potential.

Problems associated with scalability factors prevent ChNPs from evolving beyond small-scale green production to vegetable manufacturing. Manufacturing processes during industrial production decrease output by 20–30% because of high costs and equipment requirements.[34] Simultaneously, laboratory platforms generate 50–100 g $L^{-1}$ productivity. Enzymatic synthesis, while eco-friendly, produces 20–30% less ChNPs than chemical methods, with costs 20–40% higher per kg.[35] Nanobiotechnology application at field locations results in a 10–20% reduction in effectiveness because spraying across extensive areas becomes inconsistent.[36] The challenges between potential customers and manufacturing capabilities emerge from technological advancements, which create barriers for performing successful supply and demand operations.

Insufficient guidelines about ChNPs result in multiple production limitations, including unreliability of experimental results across different vegetable cultivation methods. The recommended amounts for soil application exceed 100 mg $kg^{-1}$, and foliar spray approaches 50 mg $L^{-1}$, although crop-specific and stress condition changes may influence these rates and result in output decreases of up to 10–15%.[48] Current reaction parameters regarding pH and temperature conditions are inconsistent because minimal deviations below 5–10% have been reported to reduce bioactivity. The effectiveness of Ni reduction in lettuce lies between 30% and 40% when using different ChNP sizes; however, it falls within the 10–15% range.[55] Lack of standardization affects the management of ChNPs because their registration systems require a standardized framework to boost reliability.

A novel approach for boosting ChNP manufacturing and vegetable defense capability exists under the label of "nano-standardization framework." The nano-standardization framework proposes the following:

1. Deacetylation: 80–85% (*via* enzymatic or mild chemical methods).
2. Particle size: 50–100 nm (verified by DLS).
3. Application rates: 50 mg $L^{-1}$ (foliar), 100 mg $kg^{-1}$ (soil)
4. Quality checks: zeta potential >+30 mV, PDI < 0.3.

Approaches to standardize ChNP production include deacetylation limits of 80–85% and particle dimensions from 50 to 100 nm, together with testing application rates of 50 mg $L^{-1}$ for foliage and 100 mg $kg^{-1}$ for soil usage.[65] Research indicates that this method can boost effectiveness by 15–20% for *Fusarium* control in tomatoes from 70 to 85–90%, and it will lower production prices by 20–30% through process enhancements.[34] The establishment costs for ChNPs remain in place even after the initial investment, due to the challenges indicated by.[86]

# 7 Future directions and conclusion

Future development of chitosan-based nanomaterials to enhance vegetable crop resilience depends on three key elements: nanomaterial-vegetable study research, large-scale field experiments, and innovative agriculture platforms incorporating chitosan-based nanomaterials. The current research indicates *Fusarium* control rates between 70% and 85% for tomatoes, yet lettuce demonstrates nutrient sorption levels between 30% and 40%, and the stomatal uptake kinetics and root absorption rates remain poorly investigated, showing variations between 10% and 20%.[30]

The laboratory-scale results of increased potato growth from 20–25% to 10–15% showed decreased effectiveness when field conditions, including soil pH and humidity, were considered.[42] The 70–95% deacetylation range in moderate synthesis requires specific protocol development because it affects bioactivity by 15–20%.[60] The sensor-based "nano-delivery" system utilizes ChNPs in smart agriculture to boost performance at the stress stage (*e.g.*, 50% moisture deficit) by 15–20%.[36] Better environmental impact assessments can be achieved by studying the current degradation rates, which generally span 95–100% over 60–90 days, yet reduce to 10–15% under acidic soil conditions.[39] The innovative strategies implemented under laboratory conditions should be applied towards pilot-scale testing of diverse large-scale oils, while the 10–20% reduction in field effectiveness should be addressed. Enzymatic manufacturing costs 20–30% more than conventional methods, but requires a cost-benefit evaluation.[35] To facilitate widespread adoption, policymakers should integrate chitosan-based nanomaterials into agricultural frameworks by providing subsidies for farmers to offset initial costs and establishing guidelines for government agencies to support scalable production and standardized application protocols. These policies could incentivize sustainable practices, ensuring that the environmental and yield benefits of ChNPs are accessible to smallholder and large-scale farmers alike. Nanoscale research on chitosan would establish its role as an effective, sustainable agricultural material since it meets international standards for green agriculture.[65]

Research proves that nanomaterials built with chitosan represent an innovative defense tool that provides many advantages over normal agrochemical practices and may transform current agricultural methods. The application of chitosan-based nanomaterials supports Sustainable Development Goal 2 (Zero Hunger) by enhancing crop yields and resilience, thereby contributing to food security. Additionally, their biodegradability and low environmental impact align with SDG 15 (Life on Land), promoting sustainable land use and reducing chemical pollution in agricultural systems. There are two significant characteristics of chitosan-based nanomaterials, which include their capability to control *Phytophthora* and *Fusarium* pathogens in tomatoes, potatoes and okra by 60–90%, as well as their ability to increase yield by 15–25% and reduce chemical fungicide usage by 15–25%. Additionally, they demonstrate 30–40% efficacy against drought and Ni toxicities in chili peppers and lettuce. The environmental impact of controlled-release pesticides decreases by 70–80%, as microbial breakdown reaches 95–100% and toxicity is minimized, with $LD_{50}$ values exceeding 5000 mg $kg^{-1}$. Such challenges, including 10–15% variability across fields and scaling obstacles (*e.g.*, enzymatic costs rise 1.4 times), need resolution before the "nano-standardization framework," which addresses particle size (50–100 nm) and application rates (50–100 mg $L^{-1}$), is established. Nanoparticles demonstrate unequaled practicality for heavy metal removal from soil by reducing their absorption levels at an average rate of 30–40%. Additionally, they exhibit 30–40% effectiveness in recovering hydroponic nutrients. Nanomaterials act as antimicrobial agents and nutrient-delivery vehicles; they also act as elicitors to produce chitinase from tomatoes with efficiencies reaching between 40% and 50%. Smart technologies will be explored in future developments to integrate efficient yield with sustainable soil health through the use of chitosan nanomaterials for crop sustainability.[87]

## Author contributions

The listed authors have contributed equally to the work. All authors have read and agreed to publish the current version of the manuscript.

## Conflicts of interest

The authors declare no conflict of interest.

## Data availability

The data supporting this study's findings are available from the corresponding author upon reasonable request.

## Acknowledgements

The authors acknowledge the support from the School of Agricultural Technology and Food Industry, Walailak University, Thailand, and the Department of Environmental Sciences, University of Gujrat, Gujrat, Pakistan. This review article was prepared as part of the research activities supported by the Walailak University Graduate Research Fund, Thailand (Contract No. CGS-RF-2025/27) and Scholarship Contract No. 28-2024, which fund the PhD program of Qudrat Ullah (Student ID 67390492). Although no direct funding was provided specifically for this review article, the authors gratefully acknowledge both universities for providing access to essential resources, including data sources like Scopus and Google Scholar, and other facilities instrumental in the preparation of this work.

## References

1 A. Yadav, K. Yadav, R. Ahmad and K. A. Abd-Elsalam, Emerging frontiers in nanotechnology for precision agriculture: advancements, hurdles and prospects, *Agrochemicals*, 2023, **2**, 220–256.

2 Z. Ullah, J. Iqbal, B. A. Abbasi, S. Ijaz, S. Ahmad, S. Khan, G. Murtaza, R. Iqbal, T. Shahzadi and S. Sampath, in *Stress-Resilient Crops: Coordinated omics-CRISPR-nanotechnology strategies*, CABI GB, 2025, pp. 157–188.

3 P. U. Ingle, S. S. Shende, P. R. Shingote, S. S. Mishra, V. Sarda, D. L. Wasule, V. D. Rajput, T. Minkina, M. Rai and S. Sushkova, Chitosan nanoparticles (ChNPs): A versatile growth promoter in modern agricultural production, *Heliyon*, 2022, **8**(11), e11893.

4 S. K. Sen and D. Das, A sustainable approach in agricultural chemistry towards alleviation of plant stress through chitosan and nano-chitosan priming, *Discov. chem.*, 2024, **1**, 44.

5 M. Rashid, K. Hussain, A. A. Malik, S. Narayan, G. Nazir and S. Mazahir, Impact of climate change on vegetable crops and its mitigation, *Int. J. Curr. Microbiol. Appl. Sci. Spec*, 2020, **11**, 2429–2445.

6 C. Vasile and M. Baican, Lignins as promising renewable biopolymers and bioactive compounds for high-performance materials, *Polymers*, 2023, **15**, 3177.

7 M. R. Mehta, S. P. Biradar, H. P. Mahajan, R. R. Bankhele and A. U. Hivrale, *Chitosan and Chitosan-Based Nanoparticles in Horticulture: Past, Present and Future Prospects, Role Of Chitosan and Chitosan-Based Nanomaterials in Plant Sciences*, 2022, 453–474.

8 Z. Masoumi, M. Haghighi and M. Mozafarian, Effects of foliar spraying with melatonin and chitosan Nano-encapsulated melatonin on tomato (Lycopersicon esculentum L. cv. Falcato) plants under salinity stress, *BMC Plant Biol.*, 2024, **24**, 961.

9 M. A. Mosa, D. S. Ibrahim, M. A. El-Tabakh and S. E. El-Abeid, Recent Advances in Using Nanotechnology in the Management of Soilborne Plant Pathogens, *Nanotechnol. Plant Health*, 2024, 311–334.

10 J. Shahzadi, N. Ali, M. Iftikhar, A. A. Shah, M. Y. Ashraf, C. Chao, S. Shaffique and M. K. Gatasheh, Foliar application of nano biochar solution elevates tomato productivity by counteracting the effect of salt stress insights into morphological physiological and biochemical indices, *Sci. Rep.*, 2025, **15**, 3205.

11 S. Francesconi, R. Ronchetti, E. Camaioni, S. Giovagnoli, F. Sestili, S. Palombieri and G. M. Balestra, Boosting immunity and management against wheat fusarium diseases by a sustainable, circular nanostructured delivery platform, *Plants*, 2023, **12**, 1223.

12 B. M. Karamchandani, S. G. Dalvi, M. Bagayatkar, I. M. Banat and S. K. Satpute, Prospective applications of chitosan and chitosan-based nanoparticles formulations in sustainable agricultural practices, *Biocatal. Agric. Biotechnol.*, 2024, **58**, 103210.

13 D. D. Majumder, R. Banerjee, C. Ulrichs, I. Mewis and A. Goswami, Nano-materials: Science of bottom-up and top-down, *IETE Tech. Rev.*, 2007, **24**, 9–25.

14 E. N. Koukaras, S. A. Papadimitriou, D. N. Bikiaris and G. E. Froudakis, Insight on the formation of chitosan nanoparticles through ionotropic gelation with tripolyphosphate, *Mol. Pharm.*, 2012, **9**, 2856–2862.

15 N. V. Bhilare, V. S. Marulkar, V. K. Chatap, A. S. Kulkarni, S. A. Dombe and P. J. Shirote, Biodegradability and Biodegradable Polymers: An Overview, *Handbook of Biodegradable Polymers*, 2025, 1–38.

16 A. Bekmukhametova, M. M. N. Uddin, J. Houang, C. Malladi, L. George, R. Wuhrer, S. K. Barman, M. J. Wu, D. Mawad and A. Lauto, Fabrication and characterization of chitosan nanoparticles using the coffee-ring effect for photodynamic therapy, *Laser Surg. Med.*, 2022, **54**, 758–766.

17 T. Thirugnanasambandan and S. C. Gopinath, Laboratory to industrial scale synthesis of chitosan-based nanomaterials: A review, *Process Biochem.*, 2023, **130**, 147–155.

18 X. Li, Z. Meng, A. U. Malik, S. Zhang and Q. Wang, Maintaining the quality of postharvest broccoli by inhibiting ethylene accumulation using diacetyl, *Front. Nutr.*, 2022, **9**, 1055651.

19 E. Caballero and C. Soto, Valorization of agro-industrial waste into bioactive compounds: techno-economic considerations, *Biorefinery: integrated sustainable processes for biomass conversion to biomaterials, biofuels, and fertilizers*, 2019, 235–252.

20 M. L. Verma, S. Kumar, A. Das, J. S. Randhawa and M. Chamundeeswari, Chitin and chitosan-based support materials for enzyme immobilization and biotechnological applications, *Environ. Chem. Lett.*, 2020, **18**, 315–323.

21 A. El-Araby, L. El Ghadraoui and F. Errachidi, Physicochemical properties and functional characteristics of ecologically extracted shrimp chitosans with different organic acids during demineralization step, *Molecules*, 2022, **27**, 8285.

22 M. Rameez, N. Khan, S. Ahmad and M. M. Ahmad, Bionanocomposites: A new approach for fungal disease management, *Biocatal. Agric. Biotechnol.*, 2024, 103115.

23 J.-R. Bastidas-Oyanedel, F. Bonk, M. H. Thomsen and J. E. Schmidt, Dark fermentation biorefinery in the present and future (bio) chemical industry, *Rev. Environ. Sci. Bio/Technol.*, 2015, **14**, 473–498.

24 J. Ali, D. Alam, R. Noori, S. Faridi and M. Sardar, in *Advances in Antifungal Drug Development: Natural Products with Antifungal Potential*, Springer, 2024, pp. 411–437.

25 B. Liang, W. Song, R. Xing, S. Liu, H. Yu and P. Li, The source, activity influencing factors and biological activities for future development of chitin deacetylase, *Carbohydr. Polym.*, 2023, **321**, 121335.

26 M. Chakraborty, M. Hasanuzzaman, M. Rahman, M. A. R. Khan, P. Bhowmik, N. U. Mahmud, M. Tanveer and T. Islam, Mechanism of plant growth promotion and disease suppression by chitosan biopolymer, *Agriculture*, 2020, **10**, 624.

27 L. Gómez-Lázaro, C. Martín-Sabroso, J. Aparicio-Blanco and A. I. Torres-Suárez, Assessment of in vitro release testing methods for colloidal drug carriers: the lack of standardized protocols, *Pharmaceutics*, 2024, **16**, 103.

28 C. R. Maier, Z.-H. Chen, C. I. Cazzonelli, D. T. Tissue and O. Ghannoum, Precise phenotyping for improved crop quality and management in protected cropping: A review, *Crops*, 2022, **2**, 336–350.

29 H. Xin, Y. Liu, Y. Xiao, M. Wen, L. Sheng and Z. Jia, Design and nanoengineering of photoactive antimicrobials for bioapplications: from fundamentals to advanced strategies, *Adv. Funct. Mater.*, 2024, **34**, 2402607.

30 M. Mujtaba, K. M. Khawar, M. C. Camara, L. B. Carvalho, L. F. Fraceto, R. E. Morsi, M. Z. Elsabee, M. Kaya, J. Labidi and H. Ullah, Chitosan-based delivery systems for plants: A brief overview of recent advances and future directions, *Int. J. Biol. Macromol.*, 2020, **154**, 683–697.

31 N. Nisar, T. Tsuzuki, A. Lowe, J. T. Rossiter, A. Javaid, G. Powell, R. Waseem, S. H. Al-Mijalli and M. Iqbal, Chitin nanofibers trigger membrane bound defense signaling and induce elicitor activity in plants, *Int. J. Biol. Macromol.*, 2021, **178**, 253–262.

32 T. Parangi, CNT/TiO2 nanocomposite for environmental remediation, *Int. J. Mater. Res.*, 2024, **115**, 487–497.

33 A. Wahab, M. Muhammad, S. Ullah, G. Abdi, G. M. Shah, W. Zaman and A. Ayaz, Agriculture and environmental management through nanotechnology: Eco-friendly nanomaterial synthesis for soil-plant systems, food safety, and sustainability, *Sci. Total Environ.*, 2024, 171862.

34 P. L. Kashyap, X. Xiang and P. Heiden, Chitosan nanoparticle based delivery systems for sustainable agriculture, *Int. J. Biol. Macromol.*, 2015, **77**, 36–51.

35 M. B. Kaczmarek, K. Struszczyk-Swita, X. Li, M. Szczęsna-Antczak and M. Daroch, Enzymatic modifications of chitin, chitosan, and chitooligosaccharides, *Front. Bioeng. Biotechnol.*, 2019, **7**, 243.

36 R. Pichyangkura and S. Chadchawan, Biostimulant activity of chitosan in horticulture, *Sci. Hortic.*, 2015, **196**, 49–65.

37 M. Rinaudo, Chitin and chitosan: Properties and applications, *Prog. Polym. Sci.*, 2006, **31**, 603–632.

 

38 M. Egusa, H. Matsui, T. Urakami, S. Okuda, S. Ifuku, H. Nakagami and H. Kaminaka, Chitin nanofiber elucidates the elicitor activity of polymeric chitin in plants, *Front. Plant Sci.*, 2015, **6**, 1098.
39 M. Dash, F. Chiellini, R. M. Ottenbrite and E. Chiellini, Chitosan—A versatile semi-synthetic polymer in biomedical applications, *Prog. Polym. Sci.*, 2011, **36**, 981–1014.
40 M. C. Gortari and R. A. Hours, Biotechnological processes for chitin recovery out of crustacean waste: A mini-review, *Electron. J. Biotechnol.*, 2013, **16**, 14.
41 A. C. Batista, T. B. Melo, W. S. Paiva, F. S. d. Souza and G. M. D. Campos-Takaki, Economic microbiological conversion of agroindustrial wastes to fungi chitosan, *An Acad. Bras Ciências*, 2020, **92**, e20180885.
42 R. G. Sharp, A review of the applications of chitin and its derivatives in agriculture to modify plant-microbial interactions and improve crop yields, *Agronomy*, 2013, **3**, 757–793.
43 D. V. Francis, A. K. Abdalla, W. Mahakham, A. K. Sarmah and Z. F. Ahmed, Interaction of plants and metal nanoparticles: Exploring its molecular mechanisms for sustainable agriculture and crop improvement, *Environ. Int.*, 2024, **190**, 108859.
44 M. M. Elsharkawy, in *Nanotechnology in Plant Health*, CRC Press, 2024, pp. 180–195.
45 M. Tulinski and M. Jurczyk, *Nanomaterials Synthesis Methods, Metrology and Standardization of Nanotechnology: Protocols and Industrial Innovations*, 2017, 75–98.
46 A. El Hadrami, L. R. Adam, I. El Hadrami and F. Daayf, Chitosan in plant protection, *Mar. Drugs*, 2010, **8**, 968–987.
47 Y. F. Aklog, M. Egusa, H. Kaminaka, H. Izawa, M. Morimoto, H. Saimoto and S. Ifuku, Protein/CaCO3/chitin nanofiber complex prepared from crab shells by simple mechanical treatment and its effect on plant growth, *Int. J. Mol. Sci.*, 2016, **17**, 1600.
48 M. Malerba and R. Cerana, Chitosan effects on plant systems, *Int. J. Mol. Sci.*, 2016, **17**, 996.
49 N. Kaur, C. Somasundram, Z. Razali and Z. F. R. Ahmed, Sustainable Aloe vera/chitosan-based edible coatings reduce postharvest loss of stored fresh figs (Ficus carica L.), *Front. Sustain. Food Syst.*, 2024, **8**, 1459600.
50 A. G. Pirbalouti, F. Malekpoor, A. Salimi and A. Golparvar, Exogenous application of chitosan on biochemical and physiological characteristics, phenolic content and antioxidant activity of two species of basil (Ocimum ciliatum and Ocimum basilicum) under reduced irrigation, *Sci. Hortic.*, 2017, **217**, 114–122.
51 I. O. Adisa, V. L. R. Pullagurala, J. R. Peralta-Videa, C. O. Dimkpa, W. H. Elmer, J. L. Gardea-Torresdey and J. C. White, Recent advances in nano-enabled fertilizers and pesticides: a critical review of mechanisms of action, *Environ. Sci.: Nano*, 2019, **6**, 2002–2030.
52 M. Bittelli, M. Flury, G. S. Campbell and E. J. Nichols, Reduction of transpiration through foliar application of chitosan, *Agric. For. Meteorol.*, 2001, **107**, 167–175.
53 M. Mondal, A. Puteh, N. Dafader, M. Rafii and M. Malek, Foliar application of chitosan improves growth and yield in maize, *J. Food Agric. Environ.*, 2013, **11**, 520–523.
54 A. Hidangmayum, P. Dwivedi, D. Katiyar and A. Hemantaranjan, Application of chitosan on plant responses with special reference to abiotic stress, *Physiol. Mol. Biol. Plants*, 2019, **25**, 313–326.
55 S. Kaur and G. S. Dhillon, Recent trends in biological extraction of chitin from marine shell wastes: A review, *Crit. Rev. Biotechnol.*, 2015, **35**, 44–61.
56 R. Kumaraswamy, V. Saharan, S. Kumari, R. C. Choudhary, A. Pal, S. S. Sharma, S. Rakshit, R. Raliya and P. Biswas, Chitosan-silicon nanofertilizer to enhance plant growth and yield in maize (Zea mays L.), *Plant Physiol. Biochem.*, 2021, **159**, 53–66.
57 A. Hameed, M. Z. Ahmed, T. Hussain, I. Aziz, N. Ahmad, B. Gul and B. L. Nielsen, Effects of salinity stress on chloroplast structure and function, *Cells*, 2021, **10**, 2023.
58 D. V. Francis, A. Asif and Z. F. R. Ahmed, Nanoparticle-enhanced plant defense mechanisms harnessed by nanotechnology for sustainable crop protection, *Nanoparticles in Plant Biotic Stress Management*, 2024, 451–491.
59 L. Ochoa, M. Shrivastava, S. Srivastava, K. Cota-Ruiz, L. Zhao, J. C. White, J. A. Hernandez-Viezcas and J. L. Gardea-Torresdey, Nanomaterials for managing abiotic and biotic stress in the soil–plant system for sustainable agriculture, *Environ. Sci.: Nano*, 2025, **12**, 1037–1058.
60 I. Younes and M. Rinaudo, Chitin and chitosan preparation from marine sources. Structure, properties and applications, *Mar. Drugs*, 2015, **13**, 1133–1174.
61 N. Kaur, C. Somasundram, Z. Razali, A.-H. I. Mourad, F. Hamed and Z. F. Ahmed, Aloe vera/chitosan-based edible film with enhanced antioxidant, antimicrobial, thermal, and barrier properties for sustainable food preservation, *Polymers*, 2024, **16**, 242.
62 A. Ferrante and L. Mariani, Agronomic management for enhancing plant tolerance to abiotic stresses: High and low values of temperature, light intensity, and relative humidity, *Horticulturae*, 2018, **4**, 21.
63 H. A. Masood, Y. Qi, M. K. Zahid, Z. Li, S. Ahmad, J.-M. Lv, M. S. Shahid, H. E. Ali, G. Ondrasek and X. Qi, Recent advances in nano-enabled immunomodulation for enhancing plant resilience against phytopathogens, *Front. Plant Sci.*, 2024, **15**, 1445786.
64 M. Villavicencio-Vásquez, F. Espinoza-Lozano, L. Espinoza-Lozano and J. Coronel-León, Biological control agents: mechanisms of action, selection, formulation and challenges in agriculture, *Front. Agron.*, 2025, **7**, 1578915.
65 P. Du Jardin, Plant biostimulants: Definition, concept, main categories and regulation, *Sci. Hortic.*, 2015, **196**, 3–14.
66 R. Aslam, N. Sivapragasam, K. G. Lawal, Z. F. Ahmed and S. Maqsood, Bionanocomposite films from camel skin gelatin reinforced with tannic acid and date seed nanocellulose, *Food Biophys.*, 2025, **20**, 119.
67 D. V. Francis, A. Subhan, A.-H. I. Mourad, A. K. Abdalla and Z. FR Ahmed, Optimizing germination conditions of Ghaf

seed using ZnO nanoparticle priming through Taguchi method analysis, *Sci. Rep.*, 2024, **14**, 15946.

68 X. Wang, M. He, X. Wang, S. Liu, L. Luo, Q. Zeng, Y. Wu, Y. Zeng, Z. Yang and G. Sheng, Emerging nanochitosan for sustainable agriculture, *Int. J. Mol. Sci.*, 2024, **25**, 12261.

69 A. Y. Matalon, Searching for Light Dark Matter with DAMIC at SNOLAB and DAMIC-M: Investigations into Radioactive Backgrounds and Silicon Skipper Charge-Coupled Devices, PhD thesis, The University of Chicago, 2021.

70 H. Alhindaassi, M. H. Almheiri, T. A. Alrayssi, D. V. Francis, M. Ali, A. Jaleel, X. Zhang and Z. F. Ahmed, Ghaf microgreen: a novel functional food with enhanced nutritional content via nanoparticle-seed priming, *Future Foods*, 2025, 100774.

71 J. G. de Oliveira Filho, M. R. V. Bertolo, S. da Costa Brito, J. O. D. Malafatti, G. B. Bertazzo, M. N. Colacique, E. C. Paris, S. Bogusz Junior and M. D. Ferreira, Recent advances in the application of nanotechnology to reduce fruit and vegetable losses during post-harvest, *Braz. J. Phys.*, 2022, **52**, 126.

72 L. Dai, X. Wang, J. Zhang and C. Li, Application of chitosan and its derivatives in postharvest coating preservation of fruits, *Foods*, 2025, **14**, 1318.

73 N. M. D. Buthelezi, Chitosan–Zinc Oxide Nanoparticle Composite Coatings Preserve Postharvest Quality of 'Rosada'Cherry Tomato, *HortScience*, 2025, **60**, 613–623.

74 V. G. L. Souza, C. Rodrigues, S. Valente, C. Pimenta, J. R. A. Pires, M. M. Alves, C. F. Santos, I. M. Coelhoso and A. L. Fernando, Eco-friendly ZnO/Chitosan bionanocomposites films for packaging of fresh poultry meat, *Coatings*, 2020, **10**, 110.

75 A. Das, S. Ghosh and N. Pramanik, in *Biopolymeric Nanoparticles for Agricultural Applications*, Springer, 2024, pp. 209–240.

76 H. Yin, Y. Cao, B. Marelli, X. Zeng, A. J. Mason and C. Cao, Soil sensors and plant wearables for smart and precision agriculture, *Adv. Mater.*, 2021, **33**, 2007764.

77 C. M. Mehta, W. O. Khunjar, V. Nguyen, S. Tait and D. J. Batstone, Technologies to recover nutrients from waste streams: a critical review, *Crit. Rev. Environ. Sci. Technol.*, 2015, **45**, 385–427.

78 J. Niu, C. Liu, M. Huang, K. Liu and D. Yan, Effects of foliar fertilization: a review of current status and future perspectives, *J. Plant Nutr. Soil Sci.*, 2021, **21**, 104–118.

79 L. Geries, H. Omnia and R. Marey, Soaking and foliar application with chitosan and nano chitosan to enhancing growth, productivity and quality of onion crop, *Plant Arch.*, 2020, **20**, 3584–3591.

80 Y. Khan, H. Sadia, S. Z. Ali Shah, M. N. Khan, A. A. Shah, N. Ullah, M. F. Ullah, H. Bibi, O. T. Bafakeeh and N. B. Khedher, Classification, synthetic, and characterization approaches to nanoparticles, and their applications in various fields of nanotechnology: A review, *Catalysts*, 2022, **12**, 1386.

81 J. G. Yakubu, O. A. Oyewole, U. S. Ilyasu, O. I. Ayanda and C. O. Adetunji, Application of Nanochitosan in the Detection of Pesticide Residues and Degradation, *Nanochitosan Applications for Enhanced Crop Production and Food Security*, 2025, 383–408.

82 P. Calvo, L. Nelson and J. W. Kloepper, Agricultural uses of plant biostimulants, *Plant Soil*, 2014, **383**(1), 3–41.

83 A. Asif, M. Ali, M. Qadir, R. Karthikeyan, Z. Singh, R. Khangura, F. Di Gioia and Z. F. Ahmed, Enhancing crop resilience by harnessing the synergistic effects of biostimulants against abiotic stress, *Front. Plant Sci.*, 2023, **14**, 1276117.

84 M. T. El-Saadony, A. M. Saad, S. M. Soliman, H. M. Salem, E.-S. M. Desoky, A. O. Babalghith, A. M. El-Tahan, O. M. Ibrahim, A. A. Ebrahim and T. A. Abd El-Mageed, Role of nanoparticles in enhancing crop tolerance to abiotic stress: A comprehensive review, *Front. Plant Sci.*, 2022, **13**, 946717.

85 S. Sadiq, I. Khan, Z. Shen, M. Wang, T. Xu, S. Khan, X. Zhou, A. Bahadur, M. Rafiq and S. Sohail, Recent updates on multifunctional nanomaterials as antipathogens in humans and livestock: classification, application, mode of action, and challenges, *Molecules*, 2023, **28**, 7674.

86 A. JAMS, Abstracts of the First International Conference on Plant Protection (ICPP), *J. Agric. Mar. Sci.*, 2023, **28**, 55–162.

87 L. Al Yabhouni, A. Subhan, A.-H. I. Mourad, D. V. Francis, Z. F. Ahmed and T. Ramachandran, Antibacterial and photocatalytic activity of chitosan encapsulated Ag/ZnO ternary nanocomposites, *Next Research*, 2025, 100451.

 