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Department of Environmental Sciences
University of Gujrat, Pakistan

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

Environmental Significance Statement

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 green nanotechnologies to increase crop yields, safeguard ecosystems, and support the United Nations Sustainable Development Goals.

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

Qudrat Ullah[a], Waqas Haider[a], Muhammad Qasim[a], Muhammad Waqar[a], Thanet Khomphet[a], Mujahid Farid[b]*, Zaki ul Zaman Asam[2]

[a]*Food Technology and Innovation Research Center of Excellence, School of Agricultural Technology and Food Industry, Walailak University, Tha Sala, Nakhon Si Thammarat 80160, Thailand*

[b]*Department of Environmental Sciences, University of Gujrat, Hafiz Hayat Campus, Gujrat, 50700, Pakistan*

Corresponding Author: mujahid.farid@uog.edu.pk

Abstract

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 chlorophyll content, nutrient uptake, and disease resistance in crops. Nonetheless, differences in synthetic processes and composition may cause unstable efficacy, and field-level increase in yield is between 5-20% 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, 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.

Keywords: Crop; Chitosan; Agriculture; Nanotechnology; Fertilizers

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, decreases chemicals, and increases stress-resistance against crops by designing materials at 1-100 nm [2]. Chitosan-based nanoparticles

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(ChNPs) and nanofibers are unique nanomaterials since they are biocompatible, biodegradable, and applicable in multifunctional applications in the promotion of plant growth and in controlling pathogens [3]. The 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 increases, erratic rainfall, and soil degradation [5]. Due to biodegradability, non-cytotoxicity, and natural chitin origin, chitosan has been developed to become more sophisticated nanomaterials, such as nanoparticles and nanofibers, appropriate for use in vegetable crops [6]. Based on the accumulated data, one can assume that opportunities for enhancing the resistance of vegetable crops to various forms of stress exist in the case of using chitosan-based nanomaterials [7]. ChNPs are capable of raising tomatoes and lettuce chlorophyll by 15-25 percent under salinity stress when used at 50-100 mg/L during 7-14 days [8, 9]. Since they are cationic, they can bind to the negatively charged plant cell wall, but nutrient uptake efficiency is 25-30% higher compared to the chemical fertilizers [10]. For example, chitosan nanofibers elicitor, as mentioned earlier, has the capability of activating systemic resistance and reducing the rate of diseases such as Phytophthora that affects potatoes to a range of 50-60 percent through enhancing the defense genes. Chitosan's deacetylation degree, ranging from 70-95%, 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 resistance [12]. Bottom-up methods build nanomaterials from smaller units, like assembling Lego blocks. The most common 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 the bioactive compounds [15]. On the other hand, the bottom-up techniques such as milling and ultrasonication mainly involve the mechanical breakdown of chitosan particles into particles of size in the range of 200-300 nM but do not alter the morphological homogeneity of chitosan and there is only about 20-30%

variation in particle size distribution [16]. This is why the bottom-up strategies can offer a high level of accuracy; however, these methods cannot be implemented in crop farming at a large scale since they require some heavy mechanical energy.

Chemical synthesis approaches expand the fabrication of chitosan to a higher degree following the chemical process where chitin is liquefied by the usage of strong acids and bases to convert to chitosan and then in nanoscale form [17]. Another conventional method of thermo-chemical hydrolysis to get soluble and biologically active products is capable of producing an extent of deacetylation between 70-95% the result is a non-uniform molecular size of polymer of between 50-1000 kDa [15]. Although this kind of variability is industrially feasible, it reduces the effect in vegetable crops relative to fresh weight by up to 15-20% due to variability in deacetylation [18]. The enzymatic methods for chitin deacetylation include the use of purified chitin deacetylase, which is found in microorganisms such as *Bacillus* spp., and at moderate conditions, the degree of deacetylation aimed at 85% was achieved. However, it is reported to be expensive and 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 biotechnological application of various enzymes also involves an environmental factor in the process of microbial fermentation [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 of below 150 nm [21]. By synthesizing ChNPs biologically, there is a great potential to control plant fungal pathogens, with the example of growth inhibition of solani's mycelium to 70-80% by the ChNPs, which is higher than the chemically synthesized ChNPs by 10-15 [22]. However, there are also some limitations of this type of production, such as the yields, which are in the range of 20%-30% lower than those of chemical synthesis, which is due to slow fermentation [23].

According to the literature, in this method of thermo-chemical hydrolysis, the degree of deacetylation ranges from 70-95% to increase the solubility and bioactivity of chitosan; the polymers' non-uniformity in molecular weight of 50 to 1000 kDa. This is still industrially possible but decreases the performance of vegetable crops since bioactivity is reduced by 15-20% due to irregular deacetylation [24]. Alternatively, an enzymatic process that employs chitin deacetylase from microbial sources, particularly *Bacillus* spp*,* achieves at most 85% deacetylation under gentle conditions. The high cost of the process was estimated to be 38-

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73% less expensive than that of the chemical method in utilizing agro-industrial waste [25]. Therefore, there is a need to balance the improvement of real-life productive, efficient, and sustainable bioprocesses that cater to the agriculture sector. However, their high surface area can cause agglomeration, reduce germination by up to 80%, and impact droplet size by 10-20% under field conditions unless stabilized with surfactants.

Further, enhanced controlled release is beneficial in the use of ChNPs as nutrient release sustains for about 30-60 days, 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, which shows that 50 nm is marginally greater than 200 nm, which might be hypothetical and challenging to standardize. This implies that there exists a large variation whereby accuracy when determined under laboratory conditions differs from that of field cropping; this deserves a boost for vegetable crops [27, 28].

This one can be considered as a conjugation with metals, particularly copper, as a technique of ''nanoengineering'' to enhance the function of chitosan nanomaterials [29]. This biocontrol system relates the chitosan's biocompatibility with copper to control the growth of Fusarium oxysporum, decreasing the growth by 85-90% in tomato crops. While Chitosan nanoparticles organically reduce the crop growth by 70-75%. This entry on copper loading of nano-fertilizer of between 5-10% w/w enhances the enzyme activation of pathogenicity and raises 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 microbial population may be reported to have been reduced by 5-10%. Often, such a trade-off is made to achieve perfect coordination with the necessary potency and non-carcinogenic effect on the natural environment to some extent.

Nano-fibering, an additional nano-engineering technique, enhances vegetable crop resilience by improving structural and functional properties. Chitin nanofiber with a size ranging from 10-20 nm in diameter exhibits eliciting activities that enhance the defense gene expression of cabbage and its resistance to *Alternaria brassicicola* by 60-70 % [31]. This has enhanced their mechanical properties; their tensile strengths are 2-3 times those of ChNPs, hence enhancing bioactivity with durability. However, the costs of fabricating covalent CNTs-TiO2 nanocomposites are still higher by 20–30% than the costs of nanoparticles, and this is a problem of marketability. This could be a new method of employing nanoparticles and nanofiber to enhance the durability of vegetable crops irrespective of the kind in question [32].

Consequently, they have the capability of achieving outstanding impacts, for example, an increased yield by 20-40 % on the foliar applied systems because of their surface area and controlled release [26]. The second type of improvement is nano-tailoring, which is also used where 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 the synthesis of these nanomaterials can meet the conditions in the field. The preparation of chitosan-based nanomaterials is fundamental to enhancing the resistance of vegetable crops since the various synthesis leads to different properties of the nanomaterials [33]. This variability is seen in **Table 1**; Ionotropic gelation offers 70-85% of Fusarium control in tomato at an optimal size of 50-100 nm ChNPs, while enzyme hydrolysis gives 30-40% Ni removal in lettuce at a 1.4 cost factor more. **Table 1** presents a detailed comparison of 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 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 [34]. Current research demonstrates that chitosan nanoparticles (ChNPs) inhibit 70-85% of the mycelial growth of *Fusarium oxysporum* Schltdl. In potato and tomato systems, outperforming bulk chitosan by 20-25% due to their nanoscale size, which enhances penetration of fungal cell walls [35]. This efficiency is attributed to the cationic nature of chitosan, and it interferes with the pathogen membranes as well as being a germination inhibitor of the spore in Phytophthora infestans by 90% [36]. However, in the case when the size of particles varies between 50 and 200 nm, the actions are unstable; this is due to the reasons that 10-15% action of smaller particles and at the same time the process of synthesis must be very accurate [37]. This brings ChNPs as the green solution to synthetic fungicides; however, the stability of these ChNPs at the field level remains a great challenge. As concluded from **Table 2**, a test of pathogen control efficiency for lettuce with Botrytis cinerea was between 60-70% while for okra it was 85-90% against *Fusarium oxysporum* when using Ch-CuNPs. 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. 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 the ChNPs on the foliage of discomfort, the defense enzymes and activities have been enhanced, where chitinase and peroxidase of tomatoes have increased by 30- 40% in 48 h [26]. This induction is in concordance with the increase of the endochitinase genes to decrease Ralstonia solanacearum by 50-60%. They also realized that it increased phenolic compounds by 25-35% which boosted its systemic resistance [38]. There is, however, the variance of nanomaterial concentration that ranges from 50 to 75 mg / L because beyond this range the efficiency drops by 10-15% due to phytotoxicity [39]. This ability of ChNPs to be both antimicrobial and an elicitor is proving the versatility of the compound; however, the need arises for an implementation of a proper amount of the ChNPs to elicit the required response [40].

As far as abiotic stress is concerned, the use of chitosan nanomaterials has 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 [41]. This could be attributed to the hydrophilic characteristic of chitosan to form a layer on the surfaces of the leaves This is in concordance with the findings of studies on potatoes, whereby the writers observed that the amount of chitosan must be dried to 50 mg/L and increased the root biomass of plants by 20-30% [42]. **Table 3** spells out the impact of chitosan nanomaterials on

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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, so there is a good check on the efficiency and the problems encountered. 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 scaling scores feasibility to be utilized.

The second one, which is highly associated with the salty stress test, is only comparable to salinity tolerance and mitigated by chitosan nanomaterials. ChNPs also have a defensive role in lettuce to decrease the adverse impact of sodium toxicity resulting from a 25-35 %reduction in ion leakage concentration at 100mM NaCl [43]. This became a result of the enhancement of the chlorophyll component by 15 to 20% through photosynthesis when the plant undergoes salt stress [44]. However, if the concentration of water is above 150 mM NaCl, these benefits are reduced up to 10-15%, as OS prevails over the positive impact of the nanomaterials [45]. Based on the comparative assessment, it has been found that the nano-chitosan is comparatively 20-25% more saline than the bulk forms, with restriction to the upper limit in saline areas [46].

Apart from improving the nutrient intake through its ChNP-based nano-carriers, it also confers an additional advantage of stress tolerance on the vegetables. As stated by [30] ChNPs used in onion systems to apply NPK fertilizers enhance the nutrient uptake by 30-40 % and bulb yield increases by between 20-25%. This is because of slow release, for it is processed gradually in a period of about one month to two months, compared to 5-10 days for normal fertilizers [47]. Similarly, nitrogen use efficiency has been improved by 25 to 30 % in Wheat Trials, yet the data on vegetable production are also variable. It shows a 10 to 15% times increase, particularly in nutrient-deficient soils [48]. Such differences particularly confirm the parameter of soil type as a constraint, the formulation of which demands the development of an effective nano-carrier to be used in the field.

These and other biotic things of resilience supplement the abiotic aspects to demonstrate a diverse utilization of chitosan nanomaterials, which, however, has a notable lack of research in past literature [49]. Antimicrobial effectiveness range is 70 to 90 percent; all the microorganisms are killed, but they can only work with a certain number of particles and in a certain fraction. Field results of the experiments are 10 to 20 percent less than the laboratory experiments [50, 51]. Concomitant to abiotic gains of between 15-25%, the effectiveness of water also depends on the climate, the lower being where temperatures are quite high [52]. Nutrient delivery works well

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in controlled conditions and badly in dynamic conditions, and that is why one has to work with adaptive strategies [30]. This variation implies that the ChNPs cannot be implemented as a generic concept, and thus, more attention will be paid to the usage of ChNPs in vegetable crops.

In summing up, 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 this material. This model defines ChNPs to encompass structures that help discourage pathogen invasions, for instance, the inability of Fusarium to penetrate by 70 – 85% and signaling molecules that trigger defense response, which are enzymes in the range of 30 – 40% [26]. For abiotic stress, the size of the shield addresses water loss (biotic and abiotic) in a range of 20-30% and nutrition lock, an improvement to nutrition availability by a range of 30-40%. It occupies plant tissue to form a shield [38]. However, it is moderate most of the time – highest at moderate stress levels and decreases by 10-20% at higher stress levels, which confirms the conditionality of the shield as provided above [45].

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% less effect if the formulation is not standardized [53, 54]. Monogenic abiotic stress yield loss avoidance is especially profitable in low-stress zones, which can be interpreted as low-stress yield improvement even such as between 20-25% in onions, in contrast to the stress zone assays in which it is unprofitable [47]. The nutrient enhancements would aid in sustainable yields; nevertheless, owing to the inconsistency in the texture of the soil, there is a 10-15 % lesser yield augmentation that needs calibration for the site [48]. 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 [55].

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 in enhancing the tolerance of vegetable crops, mainly in the seedling stage [56]. The process of applying ChNP suspension is done at a concentration level of 50-100 mg/L through dip or vacuum infiltration tools, depending on the homogeneity in seed adhesion [30, 57]. 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% [43]. It acts early It also inhibits the defensive mechanism, reducing the

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infection of *Fusarium* spp by 60-70 through antimicrobial membrane break, as several authors noted [58]. The problem emerges with the least coated amounts because the germination decreases to 10-15 % for non-optimized batches; the work has to use professional instruments such as rotary coaters [59].

Spraying the chlorides of Ni, Co, and Ni-Co mixed NPs on the foliage of the plant is a novel technique for delivering nutrients to the plant and protecting vegetables like okra and tomatoes from diseases and pests. The technique employed in this study is the sprayers that are used to spray ChNP solutions, most of which are in the concentration of 50-75 mg/L singly or in combination with nutrients such as NPK on the leaves [38]. This mechanism involves the stomata uptake and slow releasing ability, which enhances the nutrient uptake by 25-40% in 30-60 days, in contrast to 5-10 days in foliar sprays [47]. 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 either 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 being used to enhance the activity of enzymes; late blight (Phytophthora infestans) by a factor of 50-60 by being used to systemic resistance; and nutrient uptake in lettuce by 15-20% by being used to increase 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 that include 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 around resilience and enable crop and nanomaterial comparison, with cost analysis also considering the aspect of feasibility in terms of cost.

Foliar application's rationale for rapid response centers on delivering nutrients and defenses under stress. The spraying tools 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% [36]. The effects are likely to be moderate during conditions of relative humidity between 50 – 70 percent. Evaporation of solution nutrients costs between 10 and 15% of the entire nutrient application, as nutrients from the solution could soil through evaporation. Plants become phytotoxic when the solution exceeds 100 mg/L concentration. Researchers aim to achieve two outcomes by adjusting the solution pH between 5 and 6 and developing solution 2 for better leaf retention and stability.

Soil incorporation's purpose long-term support targets nutrient efficiency and soil health in vegetable systems. Drip irrigation tools apply ChNPs, and the controlled release mechanisms maintain nutrient accessibility within the property to result in 20-25% heavier tomato fruits than the standard control [47]. ChNPs exhibited equal importance in remediation by adsorbing cadmium from lettuce, making it 25-35% less available to uptake [60]. The degradation time spans from 60-90 days, together with minimal functionality under acidic conditions, having a pH level below 5, creates a 10-20% reduction of benefits, thus hindering broader ChNP adoption [50]. 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 nanoparticles (ChNPs) in increasing nutrient accessibility and uptake in vegetable crops, including application techniques (foliar, soil, seed) and interaction processes (binding, controlled release, chelation) to resulting benefits (improved yield and stress resistance) [61]. 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; resulting in (4) Depending on the crop, either 20-25% higher nutrient efficiency in tomatoes or 15-20% lower transpiration in drought-stressed potatoes 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 [62]. 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 [63]. As an example, tomatoes covered with nano-chitosan coatings accelerated the loss of weight by 30-40 percent and postponed the process of ripening by 7-10 days at 20 °C [64]. Chitosan-nanoZnO films reduced

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the E. coli and L. monocytogenes by 85-95 percent in 14 days in lettuce [65]. These applications are in line with the zero-waste 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 [40]. The physical defense layer created through seed coating ranges between 50 to 100 nm in thickness, yet becomes ineffective because of inconsistent application methods [66]. The enzyme enhancement activities of ChNPs applied to plant leaves reach 30% intensification, and their dose-dependent effects open concerns about excessive plant stimulation. Soil chitosan NPs effectively remediate and fertilize the ground while facing challenges with gradual chemical release during conditions of high stress [60]. The implementation of remote sensors intends to improve the performance of techniques by adjusting application amounts through a system of measurements.

A new intelligent nano-delivery system combines sensors with the vegetable crops' stress response, ChNPs for application. The smart nano-delivery system combines ChNPs with embedded sensors (pH, moisture, or conductivity) that can be released only under the conditions of sensing stress (e.g., soil moisture below 50%) [67]. 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%, and lessen waste [38, 68]. 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 [47]. Biodegradable polymers remain usable for designing prototype smart clothing systems that monitor elderly health status according to [55].

The delivery systems containing ChNP ensure different mechanisms for seeds and soils, and plants show significant variations, thus achieving numerous changes, including yield increases between 20-25 % with pathogen control reaching between 60-85% [36]. Smart nano-delivery provides a solution due to its ability to address application inconsistency issues, which cause degradation rates between 10- 20% while also 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 50 mg/L substance concentration leads to a 20-25% increase in shoot biomass due to enhanced photosynthesis

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rates, which correspond to elevated chlorophyll content levels of 15-20% [43]. Plant nutrient uptake is enhanced via stomatal absorption, with efficiency improving by 25–30% compared to conventional fertilizers [69]. The variable elevation of 10-15% detected in randomized field trials reflects the light sensitivity of this factor, which reduces its effectiveness [38]. 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 ChNPs reach a 75 mg/L concentration in the soil, according to [26]Through their 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 [70]. The stability of ChNP experiences a decrease of 10-15% in acidic soiling conditions with pH levels below 5 units [50]. 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 70-85% when the nanofiber treatment reaches 100 mg/L, while gene expression of chitinase reaches between 40-50% levels [71]. The fibrous 10–20 nm structure of ChNPs produces superior eliciting results than ChNPs according to laboratory tests by about 15–20% [72]. Their high production costs, which amount to 20-30% more than ChNPs, combined with 50-60% reduced effectiveness in field conditions, according to [73]. Represent the main limitations for 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 in areas with water scarcity problems in drought conditions on potatoes (*Solanum tuberosum* L.). A 50 mg/L guttation spraying results in a 20-30% decrease in transpiration rate and enhances water use efficiency by 15-25% during conditions of 50% dry soil [74]. It has been proven that this micro-coating method increases leaf water retention, so plants produce 20-25% additional tubers [41]. The osmotic stress experienced during excessive dry soil conditions results in decreased benefits of 5-10% [45]. This system provides favorable drought resistance, although it functions in a specific, limited time frame and needs irrigation systems to function.

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Nano-chitosan provides effective biological management of Phytophthora infestans, which threatens potatoes as a major disease agent. The fertilization of soil at 75 mg/L ChNPs results in minimal mycelial expansion of 70-80 percent and time-limited spore germination of 85-90 percent due to membrane breakdown processes [36]. The microbiological activity of peroxidase defense enzymes rises by 25-35% while late blight disease incidence decreases by 50-60% [38]. The current field application rate of between ten and fifteen percent reduction in efficacy stems from the recent variation of particle size from 50 – 200 nm, which requires further improvement in synthesis techniques [75]. 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 the soil used for the restoration of heavy metal-contaminated soils. 100 mg/kg ChNPs reduced Ni concentration in leaves by 30-40% at the molecular level because their large surface area quantity of 100 m^2/g allowed better ion interaction [60]. The root growth increases up to 15-20% when hydroponic systems utilize this mechanism, which functions through chelation [30]. The remediation capability of ChNP treatment in clayey soil falls to a 10-15% range [50]. 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 the 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 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 percent in tomatoes during pathogen assault or 20-30 percent in lettuce during salinity and prevents cell death and enhances 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 [47]. The mechanism functions with fifty

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to hundred-nanometer root-bound particle adsorption to maintain nutrient concentration levels better than standard five to ten-day fertilizers, according to [26]. The concentration of solution above one hundred milligrams per liter leads to root clogging, which reduces the gain by 10 to 15 percent and therefore requires better concentration control [45]. The growth enhancement technique works efficiently in hydroponics, although appropriate measures need attention to achieve optimal outcomes because the acceleration rate sometimes slows down, 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 simultaneously boosting growth through a 20-25% improvement in biomass development. Potatoes show positive drought resilience characteristics between 15-25% and Phytophthora resistance at 70-80% levels. Lettuce functions well at Ni reduction by 30-40% combined with 20-25% hydroponic yield enhancement. The degree of variation, including field outcomes, which decreases between 10-20% stems from production processes alongside environmental factors and variable defense levels from strong to moderate between hydroponic systems and open fields [73]. The novel framework adopts ChNPs as crop-differentiated tools while demanding additional research to enhance the practical utilization [55].

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. 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 [76]. The biodegradation efficiency of microbial action amounts to 95-100% for chitosan nanoparticles, while organophosphates only achieve 20-30% degradation within the corresponding periods [77]. Biodegradable matter effectively reduces environmental pollution by 50-60% more than chemical fertilizer programs, 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 [50].

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The low toxicity levels found in ChNPs make them an ideal choice for applications around vegetable crops, together with the ecosystem, instead of standard chemical fertilizers. The seedling vigor remains unaffected when exposed to ChNPs at 50-100 mg/L concentrations, yet the fungicides produced a seedling vigor decline by 15 to 20 percent at matching concentrations, according to [30]. The oral LD50 of 5000 mg/kg or above-reported chitosan is non-toxic in mammals, even when compared against chlorpyrifos pesticide with values ranging from 300 to 500 mg/kg [21]. The low toxicity level of ChNPs enables them to reduce ecological risks by 70-80% so they are eligible for food crop applications, including tomatoes and lettuce [36].

ChNPs show resistance against biotic stress elements as a primary factor that gives them market superiority over alternative treatments [78]. 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% [38]. Under trial conditions, the efficacy reached rates of 20-25% better than chemical control yields or when applied in controlled environments [47]. 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 [36].

Current data demonstrate that ChNPs handle abiotic stress with superior capability than traditional methods under certain conditions [34]. 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 [79]. Lettuce plants absorb higher amounts of fertilizer when treated with ChNP nano-carriers, reaching 30-40% instead of 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 [45]. 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 70-95% resulted in a 15-20% variation of solubility and bioactivity between different production batches, yet higher deacetylation negatively affected pathogen inhibition. The effectiveness of

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nanomaterials between 50-200 nm increases by 10-15% but the synthesis implementation becomes more difficult [80]. The variability in tomato Ralstonia control drops from 60 percent to 45 percent 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 higher costs and equipment requirements [47]. Simultaneously, laboratory platforms generate 50-100 g/L productivity. Enzymatic synthesis, while eco-friendly, produces 20-30% fewer ChNPs than chemical methods, with costs 20-40% higher per kg [73]. Nanobiotechnology application at field locations results in a 10-20% reduction in effectiveness because spraying across extensive areas becomes inconsistent [38]. 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 100mg/kg, and foliar spray approaches 50 mg/L, although crop-specific and stress condition changes may influence these rates and result in output decreases up to 10-15% [39]. Current reaction parameters are inconsistent regarding pH and temperature conditions because minimal deviations below 5-10% have been reported to reduce bioactivity. The effectiveness of Ni reduction in Lettuce lies between 30-40% using different ChNP sizes; however, it falls within the 10- 15% range [60]. Lack of standardization guides 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:

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 (foliar), 100 mg/kg (soil)
4. **Quality checks**: Zeta potential >+30 mV, PDI <0.3

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Additions 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 for foliage and 100 mg/kg for soil usage [55]. Research indicates 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 [47]. The establishment costs for ChNPs remain in place even after the initial investment, due to the challenges indicated by [81].

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 achieves success rates between 70-85% for tomatoes, yet lettuce demonstrates nutrient sorption levels between 30-40% and the analysis of stomatal uptake kinetics and root absorption rates remains poorly investigated, showing variations between 10-20% [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 [36]. The 70-95% deacetylation range in moderate synthesis degree requires specific protocol development because it affects bioactivity by 15-20% [50]. 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% [38]. Better environmental impact assessments can be achieved by studying the current degradation rates spanning from 95-100% over 60-90 days, yet reducing to 10-15% under acidic soil conditions [76]. The innovative strategies implemented in laboratory conditions should be applied towards pilot-scale testing of diverse large-scale oils, while a 10-20% reduction in field effectiveness occurs; enzymatic manufacturing costs 20-30% more than conventional methods, but requires a cost-benefit evaluation [73]. 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

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effective, sustainable agriculture method since it meets international standards for green agriculture [55].

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 60-90 % Phytophthora and Fusarium pathogens in tomatoes and potatoes, and okra, and 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 chill peppers and lettuce. Environmental impact following the use of post-heritage release pesticides would decrease up to 70%-80% because microbial breakdown reaches 95 to 100% while hazardous measures surpass LD50 >5000 mg/kg. Such challenges, including 10-15% variability across fields and scaling obstacles (e.g., enzymatic costs rise 1.4 times), need resolution before establishing the "nano-standardization framework," which addresses particle size (50-100 nm) and application rates (50-100 mg/L). 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, and elicitor mechanisms to produce chitinase from tomatoes with efficiency reaching between 40-50%. Smart technologies will be integrated into future developments to integrate efficient yield with sustainable soil health through the main component use of chitosan nanomaterials in crop sustainability [82].

Data Availability Statement

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

Disclosure Statement

No potential conflict of interest was reported by the author(s).

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Conflicts of Interest

The authors declare no conflict of interest.

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Department of Environmental Sciences
University of Gujrat, Pakistan

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Data Availability Statement

All the data is provided in the manuscript file.