
Research Article

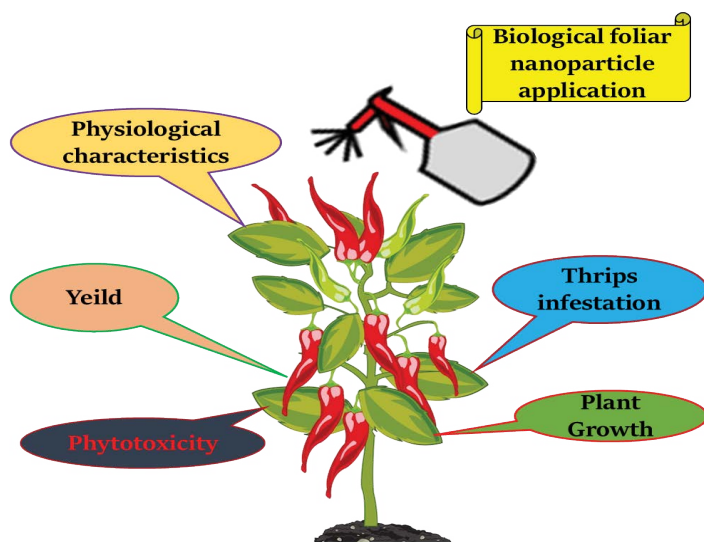
Nano Silver Foliar Treatment Substantially Mitigates the Incidence of Thrips Infestation in Chilli Plants

 Boregowda Nandini¹, Kiran Suresh Mawale^{1,3}, Parvatam Giridhar^{1,2*}

Abstract

The prevalence of thrips infestation in chilli (*Capsicum annum* L.) is a significant determinant that greatly hinders the overall quality and yield of the fruit. In the present study, we aimed an inclusive approach of the sequential application of synthesised Rhizopus elicitor-mediated silver (Ag) and silver thiosulfate ($\text{Ag}_2\text{S}_2\text{O}_3$) nanoparticles (AgNPs, STNPs) in order to combat thrips infestation in chilli plants. In a controlled greenhouse environment, a foliar spray treatment was conducted using different concentrations of bio-nanosilver particles, specifically AgNPs and STNPs (at concentrations of 20, 40, 60, 80, and 100 mgL^{-1}). The application of NPs through foliar spray at varying concentrations ranging from 20 to 100 mgL^{-1} exhibited a significant reduction in thrips population, surpassing the control treatment and also exemplified with no discernible signs of phytotoxic effects. The findings indicated that the Ag and ST NPs produced by biological means had a positive impact on the growth of seedlings and resulted in a considerable increase in crop yield compared to the control. This effect was attributed to the NPs ability to provide a protective barrier against thrips. The study indicates that NPs produced through biological processes are well-suited for commercially significant chilli plants. Additionally, they provide a new avenue for biopesticides to prevent thrips infestation, leading to sustainable agricultural practices.

Keywords: Infestations; Foliar spray; Thrips; Yield; Bionano-pesticide



Graphical abstract

Affiliation:

¹Plant Cell Biotechnology Department, CSIR-Central Food Technological Research Institute, Mysuru-570020, India

²The Director, CSIR-Central Food Technological Research Institute, Mysuru-570020, India

³Academy of Scientific and Innovative Research (AcSIR), Ghaziabad -201002, India

*Corresponding author:

Parvatam Giridhar, Plant Cell Biotechnology Department, CSIR-Central Food Technological Research Institute, Mysuru-570020, India.

Citation: Boregowda Nandini, Kiran Suresh Mawale, Parvatam Giridhar. Nanosilver Foliar Treatment Substantially Mitigates the Incidence of Thrips Infestation in Chilli Plants. Journal of Nanotechnology Research. 8 (2026): 18-26.

Received: January 06, 2026

Accepted: March 31, 2026

Published: April 21, 2026

Introduction

Capsicum annuum L., commonly known as chilli, exhibits remarkable nutraceutical properties, rendering it a formidable force in the realm of health promotion and nutrition [1]. Chilli is an annual herbaceous plant that are cultivated as a vegetive crops across the globe. It has high monetary value and adds flavour, aroma, and colour to cuisine. The chilli pepper plant is native to the Solanaceae family, which encompasses tropical and subtropical Africa, Central and Southern Europe, Asia, and North America [2]. Plant diseases and infestation have a considerable impact on agriculture, causing qualitative as well as quantitative deficits. Resistance in plant pathogenic microbes is one of several unintended effects of persistent pesticide usage. The decline in soil health is another consequence of the extinction of non-targeted species. Consequently, efforts are underway to develop biomaterial-based biodegradable agrochemicals that are both safe and practicable for use on crops. Moreover, contemporary studies suggest that the prevalence of synthetic pesticide application is on the rise, a development that carries significant ramifications for the economy, food safety, and public health [3]. Agriculturists employ chemical fertilisers as a means to augment agricultural productivity; however, the injudicious application of these substances poses a significant detriment to both the natural ecosystem and the vitality of cultivated flora. The unbridled and pervasive utilisation of synthetic agrochemicals in the realm of plant cultivation and safeguarding contributes significantly to the escalation of environmental pollution [1].

Thrips are significant crop pests and viral disease vectors and one of the major biotic constraints for the chilli crop production across the worldwide. In India, thrips have recently caused a lot of damage to agricultural and horticultural environments. Small size and slight physical changes make species identification difficult. Morphological and genetic investigations showed that thrips parvispinus, an invasive thrips, destroyed chilli in Telangana and Andhra Pradesh in 2021–22. Across chilli crops, thrips populations averaged 18.46 to 37.16 per five terminal leaves [4]. Chilli insect pests can be controlled eco-friendly, efficiently, and affordably with the Integrated Pest Management (IPM) components. Our farmers lack adequate IPM management of pests like, thrips, borer and mites [5]. Nanomaterials, including frankincense nanoparticles (FNPs) and carbon nanotubes (CNTs), has a major effect on the quantity of onion thrips. Additionally, it might lessen the likelihood of pesticide resistance [6].

The utilisation of nanoparticles (NPs) as biopesticides for the purpose of pest control has garnered significant interest in recent times [7]. Nano-fertilizers containing Titanium dioxide (TiO₂) NPs increase crop yield by promoting plant growth [8, 9]. Zinc oxide (ZnO) NPs have the potential to enhance the rate of seed germination, hence enhancing plant growth and increasing crop yield [10, 11, 12, 13]. Furthermore,

NPs possess antifungal and antibacterial qualities [14, 15]. Additionally, they can improve crop performance by stimulating the function of antioxidant enzymes, the production of chlorophyll, and the growth of efficient photosynthetic systems in plants [16, 17]. NPs of TiO₂ and ZnO study showed significant control of *Tetranychus urticae*, mites infesting cucumber plants in Egypt without causing any phytotoxic effect on foliage [18]. Allam et al. [19] stated that effective managing thrips, detrimental pest is the first step to establishing control techniques to monitor and reduce its inhabitants.

The improved surface-to-volume ratio of NPs results in higher efficiency compared to their bulk counterparts [20]. Consequently, their level of activity is exceedingly elevated. The utilisation of diverse NPs, including silver (Ag), gold (Au), zinc (Zn), iron (Fe), and cadmium (Cd), has proven to be highly effective in the management of pests [21, 22]. According to Zhang et al. (2021), biologically produced nanoparticles outperform chemically produced ones in terms of efficiency. Sharma et al. [23] have produced an Ag-nano composite mediated by stem extract of *Achyranthes aspera* for the purpose of suppressing the dengue vectors, *Aedes aegypti*. The objective of this study is to identify an IPM approach using silver (AgNPs) and silver thiosulfate (Ag₂S₂O₃) nanoparticles (STNPs) mediated by the *Rhizopus* elicitor, and to evaluate their potential as bio-shields against thrips infestation prevention without causing phytotoxicity to chilli plants.

Experimental Methods

Host plant and thrips

The ICAR-Indian Institute of Horticultural Research (IIHR), located in Bengaluru, provided three different varieties of pungent chilli (*Capsicum annuum* L.) seeds: Arka Sweta, Arka Meghana, and Arka Haritha. The collected seeds were washed thorough rinsing in flowing tap water, followed by a 3-minute surface sterilization with sodium hypochlorite (NaOCl). Subsequently, they were thoroughly rinsed with sterile distilled water and used further. Chilli plants with severe thrips infestations were kept in greenhouses throughout this study. We collected infected leaves for treatment. Greenhouse thrips control was evaluated with several NP treatments. In thrips-free sterile zones, perforated polythene bags kept chilli seedlings healthy for 30 days. A soft-bristled brush was used to gently infest plants with 25-30 thrips per plant after 15 days. All growth, thrips, and infestation indicators were monitored.

Nanoparticles and storage stability

Silver nitrate (1 mM AgNO₃) (AgNPs) and silver thiosulfate (0.1mM, Ag₂S₂O₃) (STNPs) were synthesized and characterized for all the basic physicochemical properties (unpublished data) (Available at SSRN 4578634 [24]).

The NPs were stored at ambient temperature ($26\pm 2^{\circ}\text{C}$) and in the refrigerator at 4°C . The stored samples were assessed for a period of 60 days to determine their active thermodynamic stability and to notice any aggregation of the nanoparticle's solution. To assess the processing stability, NPs they were autoclaved (121°C for 20 min) and heated in a water bath at 100°C for 20 min. After treatment, the tubes were chilled in ice and spectrum characteristics were recorded

Assessment of thrips infestation in chilli plants after foliar nanoparticle treatment

Chilli seedlings are transferred to pots after 30 days, in a greenhouse at 12 h photoperiod, $29 \pm 2^{\circ}\text{C}$, $75\pm 5\%$ relative humidity during light cycle, and $85\pm 5\%$ during darkness. During 45 days post-transplantation (anthesis time), biological NPs (20, 40, 60, 80 and 100 mgL^{-1}) were applied as a thin foliar spray. The positive control consisted of seeds treated with sterile distilled water. Further, the chilli plants were regularly examined for growth characteristics, including leaf colour, canopy width, height, spread, leaf area (cm^2), primary branch count, yield, and fruit yield per plant. Plants were evaluated for damage four weeks after the initial symptoms appeared, specifically focusing on the most vulnerable accessions that were significantly impacted. The assessment was conducted using a relative scale ranging from 0 (indicating no damage) to 3 (representing serious damage, characterised by prominently curled leaves, silvering, and black spots).

Studies on the foliage features of chilli plants infested with thrips

In our study, we separated foliage/leaves showing curled symptoms caused by thrips from that caused by thrips/mites, as the standard score provided in 1980 by Niles was typically used to determine upward curling and downward curling, respectively. For each treatment, five plants were chosen at random and their thrips damage was assessed visually by looking for signs of upward leaf curling. According to the conventional approach, the rating was recorded every 30 days with visual symptoms on the leaves using a 0–4 scale. At the height of the population's activity following transplantation, five separate observations were recorded. Grade 0: No leaf curling symptoms; Grade 1: Mild curling on 1-25% leaves; Grade 2: Moderately curling, puckering symptom on 26-50% leaves with stunting of plant growth; Grade 3: Severe curling, puckering symptom on 51-75% leaves with stunting of plant growth; Grade 4: Severe curling, puckering symptom on >75% leaves with severe stunting of plant growth, bushy appearance.

Study of sap inoculation

A sap inoculation test was performed by obtaining the leaves from a 15-day-old plant that exhibited fourth-grade symptoms of foliage curling, including upward (abaxial)

curling and a boat-shaped appearance. After rinsing the collected leaves in distilled water, they were marinated in the pestle and mortar with a 100 to 200 ml of distilled water. The fluid was filtered through muslin cloth and promptly applied to the three uppermost, fully opened, healthy leaves of chilli plants that were 45 days old. For abrasive purposes, treated leaves were sprinkled with a small amount of carborundum powder prior to sap inoculation. Following the inoculation with sap, the plants were carefully covered using polypropylene covers in order to prevent any potential infestation by thrips. A total of 15 plants were inoculated, while an additional 15 plants were kept as control (untreated). Observations were made on the leaf curling appearance for a period of 30 days on both the treated and untreated plants.

Detached Leaf Tests

The detached leaf tests were performed with the intact leaves from each treatment were placed with their petioles were put in a jar. Jars were closed using muslin cloth and placed in a climate room at $24\pm 2^{\circ}\text{C}$, 16 h light, 70% RH. There were six replicates for each treatment. The extent of NPs protection, damage and destruction by thrips feeding, oviposition and secretion were rated together using a relative scale from 0 (no damage) to 3 (severe damage) two days after incubation.

The assessment of feeding damage infected by thrips

The observed feeding damage includes multiple signs on the leaf disc, resulting from the feeding activities of thrips. These signs include discolorations such as necrosis, dark green areas indicating recent damage, and the characteristic silver leaf damage. After finding thrips in the chilli crop, weekly observations were taken of the leaves and fruits until the crop was 60 days old. Each treatment had 10 healthy plants in sterile zones without pests as controls to measure pest occurrence. Thrips populations were observed in treatment pots. Each replication selects five plants from separate treatment plots. Thrips (nymphs and adults) were counted on each plant's top, middle, and bottom leaves using a magnifying hand lens. Average thrips per leaf were calculated in each treatment plot. Observations were taken 5, 10, and 15 days following each spray. Total acceptable green chilli yield was calculated from each treatment NPs. The percentage of thrips decrease was determined using a formula. Significant difference values were used to compare the substantial impact of the treatments on thrips mortality at the 5% level of significance ($p \leq 0.05$). The mean percentage decrease values from the several treatments were tabulated.

Percent reduction in thrips inhabitants = $\frac{\text{Average post treatment thrips incidence} - \text{Average pretreatment thrips incidence}}{\text{Average pretreatment thrips incidence}} \times 100$.

Effect of NPs on Yield

The number of fruits on both control and treatment plants

was monitored. Once the fruits achieved their optimal level of maturity, they were cleaned to eliminate any impurities and were subsequently weighed. The fruits' yield mass was recorded using a digital balance. The formula was employed to calculate the percentage yield of fruits.

Yield increase (%) = ((Yield in Treated – Yield in Control)/ Yield in Control) X 100.

Phytotoxicity assessment

Under greenhouse conditions, the phytotoxicity of synthesized NPs at various concentrations to chilli plants was assessed. The randomized block design was utilized to replicate the interventions four times with three different varieties of chilli seeds: Arka sweta, Arka meghana, and Arka haritha.

Method of evaluation: Leaf damage, wilting, vein clearing, necrosis, epinasty, and hyponasty were among the symptoms of phytotoxicity that were noted 1, 3, 5, 7, 10, 14, 21, and 28-days following treatment. After being sown for fifteen days in an insect-free area of the greenhouse, the chilli seedlings received treatment. The percentage of leaves exhibiting these phytotoxicity symptoms was reported, and the Central Insecticide Board (C.I.B.) prescribed a scale for grading the degree of phytotoxicity. Grade 0 with no phytotoxicity symptoms; Grade 1 with 1-10% phytotoxicity symptoms; Grade 2 with 11-20% phytotoxicity symptoms; Grade 3 with 21-30% phytotoxicity symptoms; Grade 4 with 31-40% phytotoxicity symptoms; Grade 5 with 41-50% phytotoxicity symptoms; Grade 6 with 51-60% phytotoxicity symptoms; Grade 7 with 61-70% phytotoxicity symptoms; Grade 8 with 71-80% phytotoxicity symptoms; Grade 9 with 81-90% phytotoxicity symptoms; Grade 10 with 91-100% phytotoxicity symptoms. Percent toxicity = [total grade points/ (maximum grade × average number of foliage recorded)] × 100.

Statistical analysis

For all experiments, experimental findings are reported as the mean, and standard deviation of triplicate assays. For the statistical test, Tukey's multiple range test ($p \leq 0.05$) was used to compare treatment means.

Results

Nanoparticles synthesis and its storage stability

In our preliminary study, we prepared silver nitrate (AgNO_3) and sodium thiosulfate ($\text{Na}_2\text{S}_2\text{O}_3$) nanoparticles (NPs) at concentrations of 1 mM and 0.1 mM, respectively. These synthesised NPs were subjected to various characterization techniques, including UV-visible spectrum, zetapotential, Fourier-transform infrared spectroscopy (FTIR), and transmission electron microscopy (TEM) analysis [24]. The results revealed an absorption peak at 426 nm in the UV-visible spectrum, with a size range of 18-35 nm. We performed greenhouse studies to examine the impact of synthesised NPs on chilli plants. Specifically examined on the effects of different concentrations of Ag and ST NPs on thrips infestation and the modulation of phyto-biochemical constituents in chilli plants. In this study, we will focus on the storage stability and the effects of synthesized nanoparticles on thrips infestation (Fig. 3-Effect of synthesized nanoparticles on chilli plants against thrips infestation). Specifically, we will examine the physio-morphological changes in plants caused by thrips infestation and observe the damage caused by thrips feeding.

The storage stability is evaluated at ambient temperature, refrigeration, and 100°C temperature. Visually and spectrally, there are no discernible alterations in morphology during the initial 60 days of refrigeration storage. Visibly, we detected slight colour alterations during incubation at room temperature; however, the spectrum peak remained constant and did not exhibit any substantial changes. After 20 minutes in a water bath at 100°C, no significant changes were observed visually, and the absorption spectrum also revealed no notable changes (Fig.1-Schematic view of silver). Based on the collective observation, it can be inferred that the synthesized NPs exhibited stability throughout the storage period at varying temperatures, with no substantial alterations.

Relative scale chilli plant thrips assessment with post-foliar nanoparticle treatment

The data collected after the initial application of all three treatments consistently demonstrated that the use of NPs

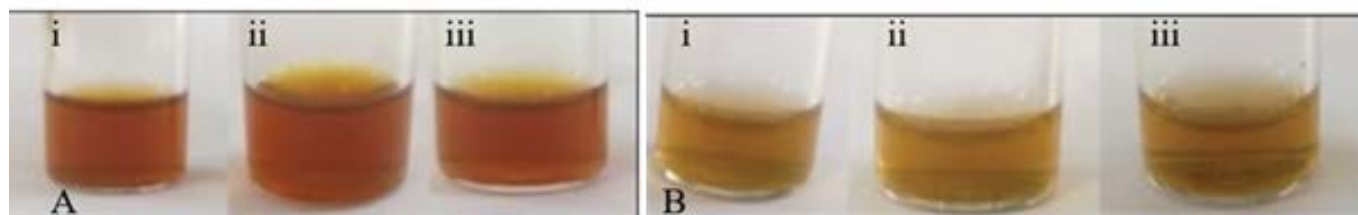


Figure 1: Schematic view of silver (A) and silver thiosulfate (B) nanoparticles following a 60-day storage stability incubation period at (i) room temperature ($26 \pm 2^\circ\text{C}$), (ii) 4°C , and (iii) 100°C

was highly effective in decreasing the thrips population compared to the untreated control. The STNPs (0.1mM) at a concentration of 60 mgL⁻¹ had the highest efficacy and were considerably superior to the other treatments on the 3rd, 7th, and 10th day following application. The mean of three observations demonstrated that this treatment recorded lowest surviving population i.e. 1.27 thrips/10 leaves. The subsequent efficacious treatment was the application of AgNPs at a concentration of 80 mgL⁻¹, resulting in a density of 2.7 thrips/10 leaves. This treatment was equally as effective as the application of Na₂SO₄ NPs at the same concentration, which resulted in a density of 3.2 thrips/10 leaves. The subsequent treatments observed thrips population ranging from 1.7 to 3.4 thrips/10 leaves, compared to 30 to 35 thrips/10 leaves in the untreated control. The data clearly indicates that 3, 5, and 7 days after the initial spray treatment, the Ag and ST NPs were the most efficient in reducing the thrips population. On average, ST NPs showed a reduction of 97%, while AgNPs showed an 94% of reduction. Figure 2 (Chilli plant thrips assessment with relative scale with post-foliar nanoparticle treatment in all the three varieties) illustrates a mean assessment of the relative scale of the percent thrips in all three varieties of chilli.

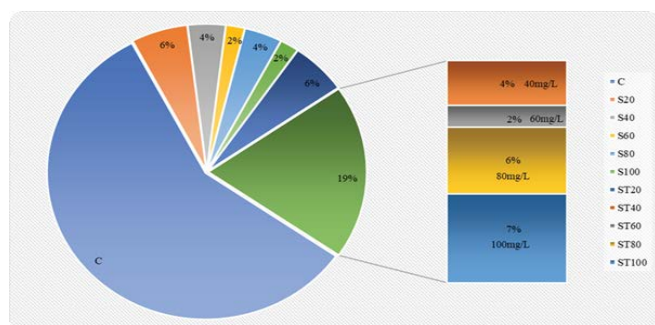


Figure 2: Chilli plant thrips assessment with relative scale with post-foliar nanoparticle treatment in all the three varieties. S20 to S100 are different concentration of AgNPs from 20 to 100mg/L; ST20 to ST100 are different concentration of STNPs from 20 to 100mg/L.

Chilli foliage traits, Sap inoculation studies and Detached leaf tests

It was evident that none of the three studied varieties (Arka Sweta, Arka Haritha, and Arka Meghana) met the criteria for grades I and II in terms of resistance to thrips when an initial assessment was performed. Both varieties were classified between grades III and IV, which correspond to characteristics that are vulnerable to infestation by thrips. The assessed characteristics of the three cultivars during thrips infestation were, on average, classified as grade III, which denotes susceptibility. After conducting a foliar spray treatment of NPS, it was observed that the leaves exhibited varying degrees of curling, depending on the concentration of NPs applied. Upon careful examination of the samples treated with silver and silver thiosulfate nanoparticles at concentrations

below 20 mgL⁻¹, we observed a noticeable change in quality. Grade I symptoms were observed, characterized by a mild curling of leaves, with the presence of thrips in the middle and bottom lines. When encountering the concentrations of 40, 60, 80, and 100 mgL⁻¹ of both NPs foliar spray treatment, no noticeable leaf curling symptoms were observed during the 60-day growth period of chilli plants. Therefore, the leaf quality can be considered significant, as indicated by the rich leaf colour gauge displaying a dark green appearance without any necrotic lesions owing from the foliar spray application. Additionally, the NPs perform as a protective barrier against thrips infestation, preventing their attachment and subsequent reproductive and infestation activities (Figure 3).



Figure 3: Effect of synthesized nanoparticles on chilli plants against thrips infestation.

a -thrips infestation maintained under greenhouse conditions; b – maintenance of chilli seedlings; c – foliar spray treatment; d – Arka haritha variety of chilli seedlings with (i) 20mg/L (ii) 40mg/L (iii) 60 mg/L silver nanoparticles treatment.

The plants inoculated with sap did not display any symptoms of leaf curl for a duration of one month. Nevertheless, it is worth noting that plants that were not protected exhibited a significant occurrence of pronounced leaves curling up, with a prevalence of 79% thrips incidence. The results illustrated that the thrips-borne virus was not responsible for the leaf curling observed in chilli plants, which is in conformity with Patel and Gupta [25].

The detached leaf assay yields similar results to the leaf curl index. None of the NPS treatments exhibited any necrotic or wilting on the chilli leaf plants. Additionally, in treatments containing 40, 60, and 80 mgL⁻¹ of NPs, no significant damage was observed, and thrips feeding and oviposition were observed with relative scale from 0 (no damage). Whereas in untreated control, complete foliage necrotic, thrips oviposition and dryness were observed after two days of incubation with relative scale of 3 (severe damage) in all the three chilli varieties. Foliar treatment yielded the most effective control of thrips grazing on all NP treatments (Fig.4-Green house studies on the characteristics attributes of chilli foliage, detached leaf, yield and phytotoxicity) with post-foliar nanoparticle treatment).



Figure 4: Greenhouse studies on the characteristics attributes of chilli foliage, detached leaf, yield and phytotoxicity) with post-foliar nanoparticle treatment

Evaluation of thrips-infected feeding damage, fruit yield and phytotoxicity assessment

Following the initial application of NPs, no significant changes were observed until the fifth day of post-treatment. Subsequently, a noticeable decrease in the population of thrips was frequently observed, indicating a dependency on the NPs treatment. A similar trend of reduced thrips incidence was observed on both the tenth and fifteenth day of visual observation under greenhouse conditions across all treatments. At concentrations of 40, 60, and 80 mgL⁻¹ of Na₂S₂O₃ NPs treatment study demonstrated notable effects on plant growth parameters and a significant reduction in thrips. The most substantial reduction, at 87.7% and 93.6%, was observed in the 40 and 60 mgL⁻¹ ST NPs treatments, respectively. Following closely behind was the 60 mgL⁻¹ NPs treatment, which exhibited a 79% reduction compared to the control on the 15th day of post treatment. There is a notable occurrence of thrips incidents in NPs treatment plants after the 22-25th day of post NPs treatment. There is a minor observation of thrips in the plants, which was effectively mitigated and diminished in the subsequent growth period.

Further, no discernible incidents of thrips were observed in the treated plants at the 60th day of the growth period. All the plants subjected to NPs treatment exhibited a significant All the plants subjected to NPs treatment exhibited a significant impact on plant height growth, plant canopy, leaf color, and plant vigor. Additionally, there was an evident improvement in fruit yield compared to the control group.

When compared to the untreated control, the fruit yield was significantly affected by the application of Ag and Na₂SO₄ nanoparticles. Furthermore, compared to control plants, those treated with Ag and ST NPs nanoparticles yielded larger fruits. Fruit yield varies from 60 to 90 number of pods depends of the concentration of NPs and variety of chilli plants. and Percent increase of yields in AS, AH, and AM on an average of significantly improved by 28%, 20%, and 16% over control (Fig. 5-Effect of foliar spray on yield of chilli plants treated with various nanoparticle concentrations).

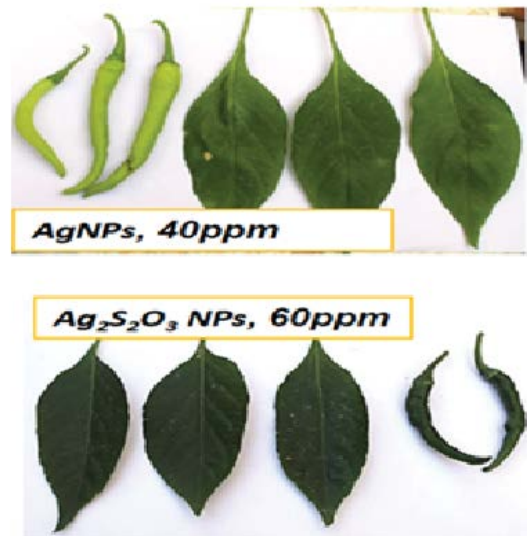


Figure 6: Comparative view of chilli leaves and fruits after treatment (Arka haritha).

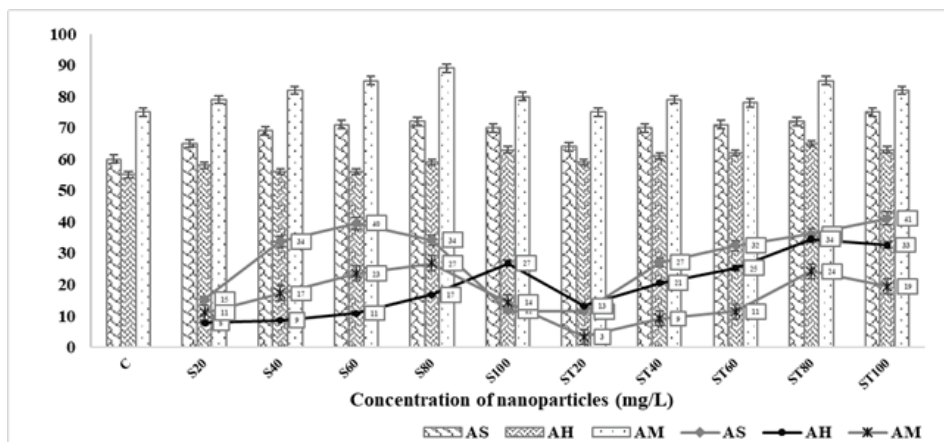


Figure 5: Effect of foliar spray on yield of chilli plants treated with various nanoparticle concentrations. Bar graph indicated the number of fruits per plant; line graph indicates the percent yield increase over control. Values ± SD (standard deviation) (n=5) means five independent replicates. (AS- Arka Sweta, AH- Arka Harita, AM- Arka Meghana). According to Tukey’s Multiple Range Test ($p \leq 0.05$).

Upon NPs application, it has been noted that no notable grade of phytotoxicity was observed in any of the five distinct concentrations of NPs that were administered to the chilli plants (Fig. 6- Comparative view of chilli leaves and fruits after treatment). These concentrations varied from 20 to 100 mgL⁻¹. The prevalence of this result was observed across all three varieties of chilli.

Discussion

The present study aimed to assess the efficacy of silver nanoparticles (AgNPs) and silver thiosulfate nanoparticles (STNPs) derived from *Rhizopus* elicitor in mitigating thrips infestation in chilli plants using a foliar enrichment method. The current progress in integrating nanoparticles shows promising potential in offering effective bio-shielded protection against thrips through the reduction of thrips adherence, prevention of oviposition, and inhibition of multiplication, all without causing any harmful phytotoxic effects on plants, even at low concentrations. The use of the cellular part of microorganisms is consistently regarded as more beneficial in the production of NPs, as opposed to employing the entire microorganism. The utilization of living microorganisms hinders the ability to control the size of NPs due to the significant influence the development stage and period of incubation on the size and characteristics of NPs [26].

In our experimental observations, a notable disparity was observed between the Ag and STNPs in terms of their distinct capacity to inhibit the sporulation of thrips on chilli leaves, as well as their reproductive activity. According to Nandini et al. [27], the phenomenon of SeNPs being observed to be effective against the downy mildew pathogen in pearl millet may be attributed to the changing characteristics of the protein. Studies conducted by Pal et al. [28] on the shape-dependent activity of silver nanoparticles (AgNPs) with *E. coli* found that truncated triangular AgNPs significantly suppressed the growth of bacteria in comparison to spherical and rod-shaped AgNPs. Ajitha et al. [29] demonstrated that the antimicrobial activity of AgNPs is dependent on the particle size of the particles. They made the observation that a reduction in the size of the AgNPs led to an increase in the antibacterial activity against *E. coli*, *Pseudomonas* spp., *Aspergillus niger*, and *Penicillium* spp. The findings indicate that there exists an inverse relationship between the size of NPs and their effectiveness in combating thrips biopesticide activity. Nanometals show promise as a non-chemical pesticide alternative for plant disease management. The study conducted by Ocoy et al. [30] found that DNA-directed AgNPs produced on graphene oxide (Go) effectively suppressed *Xanthomonas perforans* bacterial spot in tomatoes, whereas Lamsal et al. [31] found that a foliar spray applied at a concentration of 100 ppm effectively inhibited powdery mildew in cucurbits.

Enhanced plant development could potentially serve as a rationale for the observed augmentation in growth, plant vitality, fruit production, and secondary metabolite synthesis in *Capsicum annuum* plants treated with Ag and ST-based NPs in the contemporary work. The study conducted by Buchman et al. [32] revealed a noteworthy augmentation in the Silicon (Si) concentration of watermelon seeds subsequent to the application of 500 mg/L of mesoporous SiNPs. Numerous research examining the way NPs induce defense genes and/or enzymes in agricultural plants have been published. Pungent metabolites serve a range of physiological purposes in addition to protecting against pathogens, such as facilitating the growth of pathogen seeds and attracting frugivorous (fruit-eating) predators [33]. Kang et al. [34] found that SiNPs of different dissolving rates increased leaf Si content in healthy and Fusarium-infected *Citrullus lanatus* plants over a 4-week growth period. In greenhouse circumstances, mesoporous SiNPs induce dose-dependent hormetic effects in chilli plants [35]. In summary, the act of stimulating plant defence mechanisms represents an ecologically advantageous approach to managing pest populations. Nevertheless, it is worth noting that insects/pests have developed counteractive mechanisms in response to the adaptive abilities of plants, as a result of their prolonged interactions with plant defence mechanisms [36]. Zhang et al. [37] established a benchmark for subsequent investigations concerning the integration of induced plant insect resistance and RNA interference as a means to diminish the anti-adaptive capacity of insects and enhance the efficacy of pest control.

Conclusion

In summary, the proliferation of resistance to chemical pesticides has been attributed to the overapplication of such substances, which has also substantially exacerbated environmental contamination. Numerous endeavors have been undertaken to identify substitute materials capable of eliciting favorable outcomes in substitute of chemical-based pesticides. Our results provide further support for the claim that NPs derived from Ag and ST are more efficacious in facilitating the growth and development of seedlings, while additionally possessing pesticidal properties. This research demonstrated that NPs were produced by microorganisms using a biological method, in which *Rhizopus* extract is used as a stabilizing and reducing agent during NP biosynthesis. Analyses of comparative data on plant growth and yield, sap inoculation, and phytotoxicity assessment in greenhouse environments indicate that proactive shielding of plants against thrips infestation with significant improved seed quality parameters. Implementing NPs can, in general, increase crop yield, improve the efficacy with an act as a pesticide, and stimulate plant growth.

Acknowledgments

The authors thankfully acknowledge the support and encouragement provided by Director, CSIR-CFTRI for the work. NB would like to thank for SERB N-PDF (PDF/2017/001197) Government of India, New Delhi, for National Post Doctoral fellowship and KSM would like to thank CSIR-JRF (31/005(0560)2018-EMR-I). This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Authorship Contribution Statement

NB: Conceptualization, Methodology, Investigation, Validation, Writing original draft & editing, **KSM:** Methodology, Investigation, Data curation, Formal analysis, Visualization, Validation, Writing original draft & editing, **PG:** Conceptualization, Supervision, Resources, Investigation, Data curation, Visualization, Validation, Editing.

Availability of Data and Materials

Not applicable.

Declarations

Ethics Approval and Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Competing Interests

The authors declare that they have no competing interests.

References

- Reddy KM. Capsicums for Nutrition and Entrepreneurship. In: Vegetables for Nutrition and Entrepreneurship. Singapore: Springer Nature Singapore (2023): 297-309.
- Tripodi P, Kumar S. The capsicum crop: an introduction. The Capsicum Genome (2019): 1-8.
- Lougraimzi H, Bouaichi A, Kholssi R, et al. The Study of Post-Harvest Cereal Practices and Socio-Economic Impacts of Chemicals Used For Grain Storage In Morocco. Tekirdağ Ziraat Fakültesi Dergisi 19 (2022): 465-472.
- Raghavendra KV, Ramesh KB, Rachana RR, et al. Genetic diversity analysis of severely infesting invasive thrips, *Thrips parvispinus* (Karny) in chilli (*Capsicum annuum* L.) in India. Phytoparasitica 51 (2023): 227-239.
- Rashid MH, Dutta NK, Sarkar MA, et al. Integrated management of thrips-mite and borer complex attacking chilli. J Entomol Zool Stud 10 (2022): 216-220.
- Abdulla AL, Jawad S, Mohammed A. Carbon Nanotubes (CNTS) and Frankincense Nanoparticles as Promising Insecticides to Control Onion Thrips. Tekirdağ Ziraat Fakültesi Dergisi 20 (2023): 773-783.
- Athanassiou CG, Kavallieratos NG, Benelli G, et al. Nanoparticles for pest control: current status and future perspectives. Journal of Pest Science 91 (2018): 1-15.
- Lyu S, Wei X, Chen J, et al. Titanium as a beneficial element for crop production. Frontiers in Plant Science 8 (2017): 597.
- Gohari G, Mohammadi A, Akbari A, et al. Titanium dioxide nanoparticles (TiO₂ NPs) promote growth and ameliorate salinity stress effects on essential oil profile and biochemical attributes of *Dracocephalum moldavica*. Scientific Reports 10 (2020): 912.
- de la Rosa G, López-Moreno ML, de Haro D, et al. Effects of ZnO nanoparticles in alfalfa, tomato, and cucumber at the germination stage: root development and X-ray absorption spectroscopy studies. Pure and Applied Chemistry 85 (2013): 2161-2174.
- Burman U, Kumar P. Plant response to engineered nanoparticles. In: Nanomaterials in Plants, Algae, and Microorganisms. Academic Press (2018): 103-118.
- Laware SL, Raskar S. Influence of zinc oxide nanoparticles on growth, flowering and seed productivity in onion. International Journal of Current Microbiology Science 3 (2014): 874-881.
- García-López JI, Zavala-García F, Olivares-Sáenz E, et al. Zinc oxide nanoparticles boosts phenolic compounds and antioxidant activity of *Capsicum annuum* L. during germination. Agronomy 8 (2018): 215.
- Huang L, Yang H, Zhang Y, et al. Study on synthesis and antibacterial properties of Ag NPs/GO nanocomposites. Journal of Nanomaterials (2016).
- Boxi SS, Mukherjee K, Paria S. Ag doped hollow TiO₂ NPs nanoparticles as an effective green fungicide against *Fusarium solani* and *Venturia inaequalis* phytopathogens. Nanotechnology 27 (2016): 085103.
- Shabbir A, Khan MM, Ahmad B, et al. Efficacy of TiO₂ NPs nanoparticles in enhancing the photosynthesis, essential oil and khusimol biosynthesis in *Vetiveria zizanioides* L. Nash. Photosynthetica 57 (2019).
- Landa P. Positive effects of metallic nanoparticles on plants: Overview of involved mechanisms. Plant Physiology and Biochemistry 161 (2021): 12-24.
- Senbill H, Hassan SM, Eldesouky SE. Acaricidal and biological activities of Titanium dioxide and Zinc oxide nanoparticles on the two-spotted spider mite, *Tetranychus*

- urticae Koch and their side effects on the predatory mite. *Journal of Asia-Pacific Entomology* 26 (2023): 102027.
19. Fahmy AM, Allam RO, Ibrahim EG. Silver Nanoparticles as a New Trend for Controlling Subterranean Termite in Qena Region, Egypt. *Journal of Plant Protection and Pathology* 14 (2023): 359-365.
 20. Khodashenas B, Ghorbani HR. Synthesis of silver nanoparticles with different shapes. *Arabian Journal of Chemistry* 12 (2019): 1823-1838.
 21. Chenthamara D, Subramaniam S, Ramakrishnan SG, et al. Therapeutic efficacy of nanoparticles and routes of administration. *Biomaterials Research* 23 (2019): 1-29.
 22. Narayanan M, Devi PG, Natarajan D, et al. Green synthesis and characterization of titanium dioxide nanoparticles using leaf extract and larvicidal activity on *Aedes aegypti*. *Environmental Research* 200 (2021): 111333.
 23. Sharma A, Kumar S, Tripathi P. A facile method for green synthesis of *Achyranthes aspera* stem extract-mediated silver nanocomposites against *Aedes aegypti*. *Saudi Journal of Biological Sciences* 26 (2019): 698-708.
 24. Nandini B, Mawale KS, Parvatam G. Forestalling the Thrips infestation in chili plants by bio-nanosilver particles treatment. SSRN (2023).
 25. Patel VN, Gupta HC. Investigations into the causes of leaf curl of chillies in Rajasthan. *Indian Journal of Applied Entomology* 6 (1992): 1-3.
 26. Fernández-Llamas H, Castro L, Blázquez ML, et al. Biosynthesis of selenium nanoparticles by *Azoarcus* sp. CIB. *Microbial Cell Factories* 15 (2016): 1-10.
 27. Nandini B, Hariprasad P, Prakash HS, et al. Trichogenic-selenium nanoparticles enhance disease suppressive ability of *Trichoderma*. *Scientific Reports* 7 (2017): 2612.
 28. Pal S, Tak YK, Song JM. Does the antibacterial activity of silver nanoparticles depend on shape? *Applied and Environmental Microbiology* 73 (2007): 1712-1720.
 29. Ajitha B, Reddy YA, Reddy PS. Biosynthesis of silver nanoparticles using *Momordica charantia* leaf broth and evaluation of antimicrobial activity. *Journal of Photochemistry and Photobiology B* 146 (2015): 1-9.
 30. Ocoy I, Paret ML, Ocoy MA, et al. Nanotechnology in plant disease management: DNA-directed silver nanoparticles on graphene oxide. *ACS Nano* 7 (2013): 8972-8980.
 31. Lamsal K, Kim SW, Jung JH, et al. Inhibition effects of silver nanoparticles against powdery mildews. *Mycobiology* 39 (2011): 26.
 32. Buchman JT, Elmer WH, Ma C, et al. Chitosan-coated mesoporous silica nanoparticle treatment of watermelon. *ACS Sustainable Chemistry & Engineering* 7 (2019): 19649-19659.
 33. Tewksbury JJ, Nabhan GP. Directed deterrence by capsaicin in chillies. *Nature* 412 (2001): 403-404.
 34. Kang H, Elmer W, Shen Y, et al. Silica nanoparticle dissolution rate controls suppression of fusarium wilt of watermelon. *Environmental Science & Technology* 55 (2021): 13513-13522.
 35. Magaña-López E, Palos-Barba V, Zuverza-Mena N, et al. Nanostructured mesoporous silica materials induce hormesis on chili pepper. *Heliyon* 8 (2022).
 36. Zhu-Salzman K, Zeng RS. Molecular mechanisms of insect adaptation to plant defense. *Insect Science* 15 (2008): 477-481.
 37. Zhang T, Liu L, Jia Y, et al. Induced Resistance Combined with RNA Interference Attenuates the Counteradaptation of the Western Flower Thrips. *International Journal of Molecular Sciences* 23 (2022): 10886.



This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC-BY\) license 4.0](https://creativecommons.org/licenses/by/4.0/)