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# Rhizospheric Fungi And Silver Nanoparticles For Management Of Tomato Vascular Wilt In Prayagraj

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## Abstract

Tomato wilt limits crop growth and productivity, highlighting the need for effective disease management approaches. This study evaluated silver nanoparticles (AgNPs) and a rhizospheric fungal antagonist, individually and in combination, against a wilt-associated fungus under laboratory and pot conditions. Field observations were conducted at Nawawa Urf Nimikla Uperhar, Prayagraj, Uttar Pradesh, where disease incidence was 31.60%. Symptomatic plants exhibited yellowing, drooping, stunting, wilting and vascular browning. Fungal material was isolated from symptomatic tissues, while rhizospheric fungi were recovered and screened using dual culture. AgNP antifungal activity was assessed at concentrations of 50, 75, 100, 125 and 150 µg/mL. The pot experiment compared an infected untreated control, fungicide, antagonist alone, AgNPs alone and their combined application. AgNPs exhibited concentration-dependent inhibition, increasing from 31.4% at 50 µg/mL to 90.2% at 150 µg/mL. The combined treatment recorded the lowest disease severity index, 11.30 ± 0.85%, compared with 73.00 ± 3.24% in the infected control, representing 84.52% disease reduction. Corresponding area under the disease progress curve values were 148.55 ± 4.49 and 785.40 ± 10.25. The combined treatment recorded plant height of 41.95 ± 1.75 cm, fresh biomass of 33.51 ± 2.10 g/plant and dry biomass of 8.35 ± 0.20 g/plant. Fruit number reached 15.15 ± 0.23 per plant, and yield increased to 105.25 ± 3.98 g/plant, exceeding the control by 208.65%. These descriptive findings support further evaluation of the combined treatment. Future studies should optimize treatment doses and evaluate antagonist compatibility, field efficacy and environmental safety across different tomato-growing conditions.

Keywords: tomato; vascular wilt; Fusarium; Trichoderma; silver nanoparticles; biological control

## 1. Introduction

Tomato (Solanum lycopersicum L.) is an important vegetable crop, valued for its nutritional quality, culinary uses and contribution to farmer’s income. But its growth and productivity can be affected by soilborne diseases, especially vascular wilt. Infection may interfere with water transport in the plant leading to yellowing of leaves, progressive wilting, reduced vigour and poor fruit production. Wilt is difficult to manage because disease development involves interactions between the pathogen, the host plant and the surrounding soil environment. Consequently, an effective management strategy must consider the root environment, the appropriateness of the treatment and its mode of application. Recently, the rhizospheric and endophytic fungi have been investigated as biological alternatives or complements to the conventional fungicides, especially their potential to suppress the pathogens and improve the plant performance (Bandara & Kang, 2024; Haque et al., 2023; Muhorakeye et al., 2024).

Trichoderma species, as beneficial fungi, have been extensively studied for their potential to manage soilborne plant diseases. These fungi might restrict pathogen growth by competing for nutrients and space, by producing inhibitory compounds and by direct interactions with pathogenic fungi. They can also


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associate with plant roots, and may contribute to root development and activation of plant defence responses. But they're not equally effective. Differences in fungal isolates, tomato cultivars, growing conditions and treatment procedures can affect the extent of protection obtained. Therefore, strong inhibition of a pathogen in the laboratory does not necessarily lead to equally effective disease suppression in plants. Based on research on induced defence, microbial priming and strain selection, promising antagonists need to be tested in plant-based experimental conditions before recommending their field application (Hasna et al., 2025; Sorahinobar et al., 2025; Suwor et al., 2025; Zehra et al., 2023). Moreover, studies on nematode-associated wilt complexes highlight that the success of biological management is contingent on the organisms present and their interactions in the root environment (Anbalagan et al., 2025).

Silver nanoparticles (AgNPs) have also been investigated for their potential to inhibit pathogens related to tomato wilt. Recent studies have been performed on plant mediated and fungal synthesis, concentration dependent antifungal activity and treatment performance under greenhouse conditions (Ahmad et al., 2022; Ashraf et al., 2025; Jana et al., 2025; Macías Sánchez et al., 2023; Tabassum et al., 2024). Because concentrations that inhibit a pathogen may also affect beneficial microorganisms, their potential use in disease management needs careful dose selection. Thus, laboratory screening is useful to identify a range of effective concentrations, while pot experiments can determine whether the selected treatment supports disease suppression and plant growth under more complex biological conditions. Integration of AgNPs with a fungal antagonist could be a potential approach for integrated wilt management. But the worth of such a combination is dependent upon the degree to which the parts fit together. The concentration of nanoparticles chosen should be able to show antifungal activity against the pathogen and at the same time allow the beneficial fungus to survive and perform. In addition to the individual components, a combined treatment should be evaluated to see if it provides an added benefit. The fact that both parts work when tested individually does not mean that you can assume that improvements will occur.

In this respect, the current study integrates field observation of tomato wilt incidence, fungal observations, antifungal screening, compatibility assessment and pot-treatment responses using the experimental records provided. Field observations confirmed the occurrence of wilt in the surveyed sites. Laboratory experiments are used to evaluate the activity of treatments and pot evaluation is used to examine the response of tomato plants to the treatments. The present study aims to link these stages for evaluation of the potential of a selected fungal antagonist and AgNP treatment applied alone and in combination for management of tomato wilt and support of plant growth.

### 1.1. Novelty statement

In present study, the novelty is that field observations on tomato wilt have been combined with antifungal screening, assessment of compatibility between antagonists and AgNPs and pot evaluation. The study evaluates whether an effective AgNP dose is compatible with the selected beneficial fungus and enhances treatment performance when used in combination, rather than focusing solely on the inhibition of the pathogen. This method links the laboratory screening to the suppression of disease and growth responses of tomato plants. It offers an experimental basis for the development of a complementary integrated wilt management strategy.

## 2. Materials and methods

Field observations were conducted in a tomato-growing field at Nawawa Urf Nimikla Uperhar, Prayagraj, Uttar Pradesh, India. The GPS coordinates displayed in the field photographs ranged from approximately 25.384809–25.384855° N and 81.949568–81.949664° E (figure 1). Tomato plants were inspected for lower-leaf yellowing, drooping, stunting and wilting.

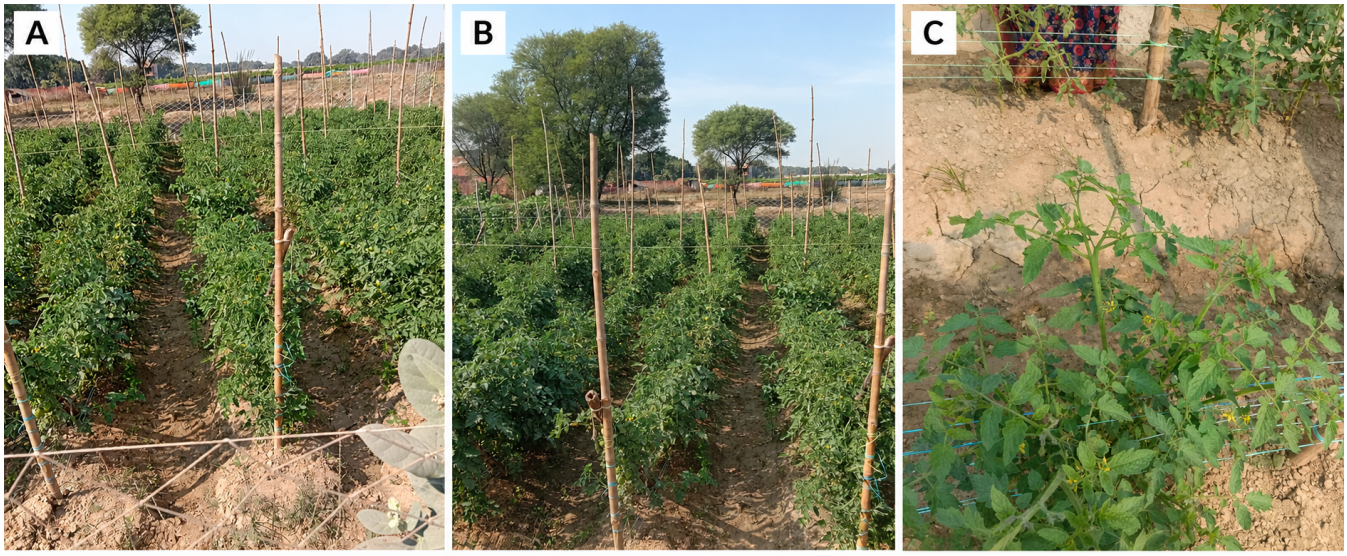



Figure 1. Field documentation of tomato cultivation at Nawawa Urf Nimikla Uperhar, Prayagraj, Uttar Pradesh, India. (A–B) General views showing tomato rows and the staking system. (C) Closer view showing tomato foliage, support strings and soil-surface cracking.

Symptomatic plants were examined for internal vascular browning. Photographs documented the field layout, crop appearance and visible soil conditions. Disease incidence was calculated using the following formula:

Disease incidence (%) = (Number of symptomatic plants / Total number of plants examined) × 100

Wilt-associated fungal material was isolated from symptomatic tomato tissues on potato dextrose agar. The cultures were incubated at approximately 25 ± 2°C and purified for subsequent antifungal assays. The recovered material was designated as the wilt-associated fungus for the present evaluation.

Rhizospheric fungi were recovered through serial dilution plating and root-associated isolation. Candidate fungal antagonists were evaluated against the wilt-associated fungus using the dual-culture technique. Pathogen growth in the presence of an antagonist was compared with growth in an antagonist-free control. Percentage inhibition was calculated as:

Here, C represents pathogen growth in the control and T represents pathogen growth in the treated plate. The antifungal activity of silver nanoparticles (AgNPs) was evaluated using amended agar at concentrations of 50, 75, 100, 125 and 150 µg/mL.

Growth inhibition (%) = [(C - T) / C] × 100

The pot experiment comprised five treatments: infected untreated control (T0), fungicide treatment (T1), fungal antagonist alone (T2), AgNPs alone (T3), and AgNPs combined with the fungal antagonist (T4). Treatment performance was assessed using disease severity index, area under the disease progress curve, plant height, fresh biomass, dry biomass, fruit number and fruit yield. Disease reduction and yield improvement were calculated relative to the infected untreated control:

Disease reduction (%) = [(DSI of control - DSI of treatment) / DSI of control] × 100

Yield improvement (%) = [(Treatment yield - Control yield) / Control yield] × 100

## 3. Results

### 3.1. Field incidence and symptoms

The incidence of wilt-associated symptoms in the surveyed tomato field at Nawawa Urf Nimikla Uperhar, Prayagraj, Uttar Pradesh, was 31.60%. Affected plants exhibited yellowing of lower leaves, drooping, reduced vegetative vigour, stunting and wilting. Brown discoloration of vascular tissues was observed during internal examination of symptomatic stems. Together, these observations documented the occurrence of vascular wilt symptoms at the study site. Field photographs showed tomato plants cultivated in rows with stakes and supporting strings. Soil-surface cracking was visible in parts of the field. These observations provided a record of crop appearance and field conditions at the time of inspection (figure 2).

### 3.2. Antifungal activity of silver nanoparticles

Silver nanoparticles inhibited the growth of the wilt-associated fungus at all tested concentrations. Growth inhibition increased consistently with increasing AgNP concentration, ranging from 31.4% at 50 µg/mL to 90.2% at 150 µg/mL (Table 1).

Table 1: Effect of AgNP concentration on growth inhibition of the wilt-associated fungus.

| AgNP concentration (µg/mL) | Growth inhibition (%) |
|---|---|
| 50 | 31.4 |
| 75 | 43.1 |
| 100 | 59.8 |
| 125 | 77.2 |
| 150 | 90.2 |

At 75 µg/mL, growth inhibition reached 43.1%, while 100 µg/mL inhibited fungal growth by 59.8%. Increasing the concentration to 125 µg/mL produced 77.2% inhibition. The highest concentration, 150 µg/mL, produced the strongest suppression, although complete inhibition was not recorded.

The overall increase in inhibition across the tested range was 58.8 percentage points. The largest increase between consecutive concentrations occurred from 100 to 125 µg/mL, when inhibition increased by 17.4 percentage points. These results showed a clear concentration-dependent antifungal response under laboratory conditions.

### 3.3. Disease suppression under pot conditions

All treatments recorded lower disease severity and cumulative disease development than the infected untreated control (Table 2). The control treatment (T0) recorded a disease severity index (DSI) of 73.00 ± 3.24% and an area under the disease progress curve (AUDPC) of 785.40 ± 10.25.

Table 2: Effects of treatments on disease severity and disease progress in tomato.

| Treatment | DSI (%) | AUDPC | Disease reduction (%) |
|---|---|---|---|
| T0 | 73.00 ± 3.24 | 785.40 ± 10.25 | — |
| T1 | 23.40 ± 2.10 | 293.40 ± 7.95 | 67.95 |
| T2 | 38.95 ± 1.90 | 451.50 ± 10.10 | 46.64 |
| T3 | 32.45 ± 2.45 | 381.10 ± 8.95 | 55.55 |
| T4 | 11.30 ± 0.85 | 148.55 ± 4.49 | 84.52 |

Note. T0 = infected untreated control; T1 = fungicide; T2 = fungal antagonist alone; T3 = AgNPs alone; T4 = AgNPs combined with the fungal antagonist. Disease reduction was calculated relative to the DSI of

T0.

The combined treatment (T4) recorded the lowest DSI, 11.30 ± 0.85%, representing an 84.52% reduction relative to the infected control. Fungicide treatment (T1) recorded the next lowest DSI, 23.40 ± 2.10%, followed by AgNPs alone (T3; 32.45 ± 2.45%) and the antagonist alone (T2; 38.95 ± 1.90%). The corresponding disease reductions were 67.95%, 55.55% and 46.64%, respectively.

AUDPC followed the same treatment ranking. The lowest value occurred under T4 (148.55 ± 4.49), followed by T1 (293.40 ± 7.95), T3 (381.10 ± 8.95) and T2 (451.50 ± 10.10). Relative to T0, T4 recorded an 81.09% reduction in AUDPC.

Compared with the individual components, T4 recorded a DSI that was 27.65 percentage points lower than T2 and 21.15 percentage points lower than T3. Thus, the combined application showed the most favourable disease-suppression response among the evaluated treatments.

### 3.4. Plant growth and biomass

The combined treatment recorded the highest plant height and fresh and dry biomass (Table 3). Plant height under T4 reached 41.95 ± 1.75 cm, compared with 19.95 ± 2.10 cm under T0. Among the remaining treatments, height was greatest under T3 (32.18 ± 0.00 cm), followed by T1 (30.98 ± 1.95 cm) and T2 (28.99 ± 2.21 cm).

Table 3: Effects of treatments on tomato growth, biomass and productivity.

| Treatment | Plant height (cm) | Fresh mass (g/plant) | Dry mass (g/plant) | Fruit number/plant | Yield (g/plant) |
|---|---|---|---|---|---|
| T0 | 19.95 ± 2.10 | 12.92 ± 0.98 | 3.60 ± 0.19 | 5.00 ± 0.01 | 34.10 ± 1.11 |
| T1 | 30.98 ± 1.95 | 25.02 ± 1.11 | 5.95 ± 0.25 | 9.90 ± 0.52 | 66.95 ± 4.10 |
| T2 | 28.99 ± 2.21 | 21.00 ± 0.85 | 5.64 ± 0.25 | 7.61 ± 0.45 | 57.25 ± 1.93 |
| T3 | 32.18 ± 0.00 | 23.50 ± 1.00 | 4.75 ± 0.15 | 8.92 ± 0.05 | 58.98 ± 3.02 |
| T4 | 41.95 ± 1.75 | 33.51 ± 2.10 | 8.35 ± 0.20 | 15.15 ± 0.23 | 105.25 ± 3.98 |

Fresh biomass ranged from 12.92 ± 0.98 g/plant under T0 to 33.51 ± 2.10 g/plant under T4. The intermediate treatments ranked T1 (25.02 ± 1.11 g/plant), T3 (23.50 ± 1.00 g/plant) and T2 (21.00 ± 0.85 g/plant).

Dry biomass was also highest under T4 (8.35 ± 0.20 g/plant), followed by T1 (5.95 ± 0.25 g/plant), T2 (5.64 ± 0.25 g/plant) and T3 (4.75 ± 0.15 g/plant). The infected untreated control recorded the lowest dry biomass (3.60 ± 0.19 g/plant).

Relative to T0, T4 recorded increases of 110.28% in plant height, 159.37% in fresh biomass and 131.94% in dry biomass. Although T3 produced taller plants than T1 and T2, its dry biomass was lower than both treatments, indicating that treatment rankings differed between plant height and biomass accumulation.

### 3.5. Fruit production and yield

Fruit number and yield were highest under the combined treatment. T4 recorded 15.15 ± 0.23 fruits/plant, compared with 5.00 ± 0.01 fruits/plant under T0. Fruit number under T1, T3 and T2 was 9.90 ± 0.52, 8.92 ± 0.05 and 7.61 ± 0.45 fruits/plant, respectively.

Yield followed the same ranking as fruit number. The highest yield, 105.25 ± 3.98 g/plant, occurred under T4, followed by T1 (66.95 ± 4.10 g/plant), T3 (58.98 ± 3.02 g/plant) and T2 (57.25 ± 1.93 g/plant). T0 recorded the lowest yield, 34.10 ± 1.11 g/plant.

Compared with the infected control, yield increased by 96.33% under T1, 67.89% under T2, 72.96% under T3 and 208.65% under T4. The combined treatment produced approximately 3.09 times the control

yield, alongside the lowest DSI and AUDPC and the highest recorded biomass.

Across the measured parameters, the combined AgNP–antagonist treatment consistently recorded the most favourable overall response.

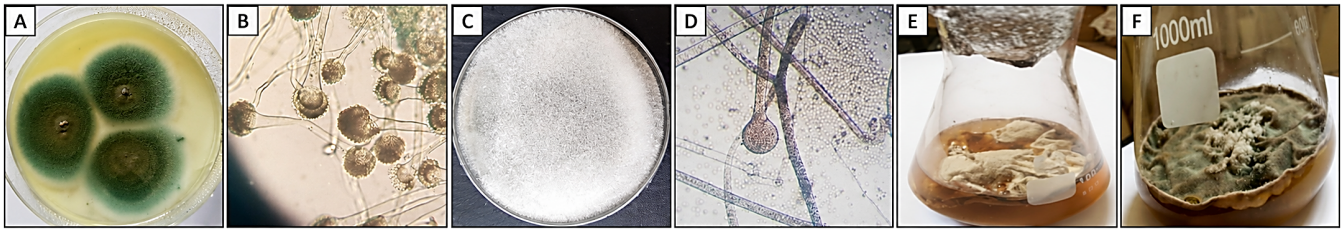



Figure 2. (A) Green fungal colonies on agar medium; (B) microscopic view of stalked, rounded reproductive structures; (C) white mycelial growth on agar medium; (D) microscopic view of hyphae and a rounded reproductive structure; (E) cream-coloured mycelial mat in liquid culture; (F) greenish fungal surface growth in liquid culture.

## 4. Discussion

The field incidence of 31.60% shows that a considerable proportion of tomato plants in the study site suffered from wilt-associated symptoms. Yellowing, drooping, stunting and vascular browning indicated vascular dysfunction. But these symptoms alone are not enough to identify the pathogen. The observations are in accordance with the assessment of management options suitable for local growing conditions. Bandara and Kang (2024) demonstrated the effect of Trichoderma application methods on the growth of tomato, rhizosphere communities and soil suppressiveness, emphasising the significance of the delivery of the treatments.

The inhibition of AgNPs was concentration dependent and increased from 31.4% at 50 µg/mL to 90.2% at 150 µg/mL. This pattern is similar to Shendge et al. (2024) who reported increasing inhibition of tomato Fusarium with increasing concentrations of AgNPs. Nevertheless, it is not possible to directly compare effective doses across studies due to differences in nanoparticle preparation, fungal isolates and assay conditions. The results obtained here represent laboratory inhibition and not the optimum application rate for plants. The treatment of antagonist alone reduced the disease severity up to 46.64% indicating useful biological suppression. Also, Haque et al. (2023) demonstrated the role of selected Trichoderma isolates in reducing tomato Fusarium wilt and improving plant growth. Such responses may be mediated by competition, mycoparasitism and metabolite production, although these mechanisms were not measured in the present study.

The combined treatment recorded the lowest disease severity and AUDPC with a reduction of 84.52% and 81.09% respectively. The performance indicates that the combination of the two components is worthy of further investigation. Sidharthan et al. (2023) showed that compatible combinations of microbes could lead to improved wilt suppression and tomato growth. The results obtained are in favour of performing compatibility testing, but not of establishing compatibility or synergy for the present AgNP–antagonist combination.

The combined treatment resulted in a higher biomass, fruit number and yield with a lower severity of the disease. Yield was 105.25 g/plant with an increase of 208.65% compared to the infected control. In another study, Ashraf et al. (2025) reported wilt suppression and enhanced tomato performance after application of AgNPs. So, enhanced productivity here may be linked to reduced disease pressure, but direct growth promoting effects cannot be separated from disease suppression. On the whole, the results support integrated treatment as a promising experimental approach. Field recommendations require replicated trials, determined treatment doses and evaluation of the beneficial-fungus survival.

## 5. Conclusion and Future Prospects

The present study documented a wilt incidence of 31.60% in the surveyed tomato field at Nawawa Urf Nimikla Uperhar, Prayagraj. Silver nanoparticles exhibited concentration-dependent antifungal activity, with growth inhibition increasing from 31.4% at 50 µg/mL to 90.2% at 150 µg/mL. Under pot conditions, the combined application of AgNPs and the fungal antagonist recorded the most favourable overall response. Disease severity declined to 11.30%, representing an 84.52% reduction relative to the infected untreated control. The combined treatment also recorded the highest plant height, fresh and dry biomass, fruit number and yield. Yield reached 105.25 g/plant, compared with 34.10 g/plant in the control. These findings identify the combination as a promising experimental approach for managing tomato wilt, although statistical significance and synergistic interaction remain unestablished.

Future investigations should prioritize replicated greenhouse and field trials across different soils, seasons and tomato cultivars. Antagonist identity, pathogen confirmation and compatibility with AgNPs require documentation. Dose optimization should determine the lowest effective concentration that maintains antagonist survival and plant performance. Further work should examine treatment persistence, soil microbial responses, silver accumulation in edible tissues and production costs. Such evidence would establish whether the observed disease suppression and productivity gains can support practical, economical and environmentally responsible application.

Conflict of Interest: Authors declare no conflict of interest.

Author Contributions: Arati Yadav collected the field data, conducted laboratory work jointly with Shakti Nath Tripathi, and drafted the manuscript. Shakti Nath Tripathi designed the research, jointly conducted the laboratory work, and supervised the entire study.

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