Journal of Animal Environment

(E-ISSN 2717-1396, ISSN 2717-1388)

Original Research Paper

# A Controlled-Release AgNPs and Rhizobium-Based Nanobio-Fertiliser Improves Tomato Growth and Minimises Nitrogen Consumption

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**Abstract**

Biodegradable and soil-environment-safe controlled-release fertilizers (CRFs) represent a core, cutting-edge feasible pathway to enhance agricultural sustainability and reduce the production sector's dependence on petroleum-based synthetic materials. This study focused on the research and development of controlled-release rhizobium (CRR) biofertilizer. We synthesized silver nanoparticles (AgNPs) using an environmentally friendly aqueous extract from neem (*Azadirachta indica*) leaves, and combined these particles with a starch-based polysaccharide nanocomposite to prepare a fertilizer efficacy carrier. The core research objective of this work is to improve nitrogen use efficiency (NUE) to support the sustainable production of tomato (*Solanum lycopersicum L.*). We conducted field trials that included 5 CRR formulations, each matched with three application rate gradients: 100%, 50%, and 25% of the recommended rhizobium dose. Conventional fertilization was set as the control group, and we measured four core indicators: plant growth, yield attributes, fruit quality, and NUE. Trial results show that the NUE of CRR treatment groups ranged from 47% to 88%, while the conventional fertilization control group only recorded an NUE of 33%. Even the agronomic performance of the 25% dose CRR treatment outperformed that of conventional fertilization. These findings confirm that CRR can reduce chemical fertilizer inputs and lower environmental impacts, and that this type of polysaccharide-based nano-biofertilizer is well-suited for nutrient management in tomato cultivation.

***Key words:*** Silver nanoparticles; porous starch; targeted delivery; quality; nitrogen use efficiency; Rhizobium; nanofertilizer; eco-friendly

## INTRODUCTION

Worldwide, agriculture must improve the productivity of crops with less negative impact on the environment from extensive fertilizer usage. Nitrogen (N) is an essential macronutrient for plant growth and metabolism. Unfortunately, nitrogen use efficiency (NUE) is generally low in most agricultural systems, and loss of nutrients to leaching, volatilization, and microbial revolutions/runs-off all contribute to soil degradation, pollution, eutrophication, and greenhouse gas emissions. For these reasons, improving the usage of macronutrients and the early adoption of sustainable fertilization practices has been of the greatest concern to the recent agriculture. Controlled-release fertilizers (CRFs) and nanofertilizers are new technologies which, when compared to other fertilizer practices, have greater nutrient availability and uptake, and lessen the adverse environmental impacts caused by fertilizers (Nawadkar et al., 2024; Haydar et al., 2024; Govil et al., 2024; Mehta et al., 2024;Alotaibi et al., 2024).

Biological approaches like PGPR and Rhizobium spp. offer solutions to sustainable plant production and the improvement of nutrient uptake. Unfortunately, the effectiveness of microbial inoculants diminishes in the field due to poor survival and low colonization as well as susceptibility to different environmental stresses. Biodegradable, starch-based, and encapsulated systems are a great potential to offer microbial protection and controlled release. Green, synthesized silver nanoparticles from neem with an even better potential to lessen the environmental effects of using conventional synthesized nanomaterials when in support of plant growth and nutrient uptake (Biswas et al., 2024; Alotaibi et al., 2024). There is a lack of studies in this area, especially when considering field studies as conceptualized in the following study.

Tomato (*Solanum lycopersicum* L.), one of the world's most important vegetable crops, requires efficient nutrient management to achieve sustainable productivity. Therefore, the present study developed a biodegradable starch-based nanocomposite biofertilizer incorporating *Rhizobium* and neem-

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Received: 14th August, 2026; Revised: 26th August, 2026; Accepted: 2nd September, 2026

(DOI): 10.70102/AEJ.2026.18.4s.77

synthesized AgNPs and evaluated its performance under field conditions ((Molina-Cano et al., 2025).
The study investigated its effects on plant growth, yield, fruit quality, nitrogen use efficiency, and rhizosphere characteristics. So that the controlled-release delivery of *Rhizobium* through a biodegradable nanocomposite matrix would enhance microbial survival, improve nutrient utilization, increase crop productivity, and reduce dependence on conventional chemical fertilizers.

## MATERIALS AND METHODS

***Materials***

Silver nitrate ($AgNO_3$)was sourced from Merck, Mumbai, India. Sodium alginate (SA), carboxy-methyl chitosan (CMC) and chitosan was procured from Sigma-Aldrich (India). KBH (India) was ordered and sourced from local supplier as commercial Rhizobium biofertilizer. Fresh *Azadirachta indica* leaves were harvested and washed with distilled water before use. All chemicals and reagents employed in this study were of analytical grade and utilized without additional purification.

***A-Green synthesis A silver nanoparticles***

Using the method outlined in reference, 10mL of freshly made Azadirachta indica leaf extract was mixed with 90mL of 1mM AgNO3 solution, producing a solution with a leaf extract to silver salt ratio of 1:9. The mixture was then stirred and heated to 80°C and held at that temperature for 3 hours. The color of the mixture shifted from pale yellow to dark brown, showing the formation of silver nanoparticles (AgNPs). The AgNPs were separated from the solution by centrifugation at 15,000g for 20 minutes. The AgNPs were washed 3 times with deionized water, then freeze dried. The AgNPs were kept at 4°C for storage until required for use (Gawai et al., 2023).

***Synthesis of A-AgNPs–Rhi***

*Rhizobium*-loaded A-AgNPs were prepared by mixing equal volumes of Rhizobium suspension (5 mM) and A-AgNP solution (5 mM) under magnetic stirring for 10 min at room temperature. Formation of the A-AgNP–Rhizobium complex was confirmed by a visible change in suspension appearance. Encapsulation efficiency was determined indirectly by measuring unbound Rhizobium in the supernatant after centrifugation at 12,000 × g for 60 min. The supernatant was freeze-dried and weighed, and encapsulation efficiency was calculated following standard protocols. The nanoparticles exhibited an encapsulation efficiency of approximately 52% (Abdelkhalek et al., 2023).

***Encapsulation of A-AgNPs–Rhi in a polysaccharide matrix***

A starch-based polysaccharide (PS) matrix was used to prepare the controlled-release formulation. A-AgNPs–Rhizobium (1:100) suspension (10 mg $mL^{-1}$) was sonicated for 10 min and mixed with PS at a 1.5:1 (w/w) ratio, followed by stirring for 12 h at room temperature to achieve encapsulation. After gel formation, the mixture was centrifuged at 4,000 × g for 15 min. Encapsulation efficiency was determined by measuring the absorbance of the supernatant at 770 nm and confirmed using the Folin–Ciocalteu assay. The resulting encapsulated material was dried at 40 °C for 12 h and stored in a desiccator until further analysis (Velloso et al., 2024).

***Preparation of Controlled-Release Beads***

Polysaccharide interpenetrating polymer network beads were prepared using sodium alginate (SA), carboxymethyl chitosan (CMC), and cellulose nanofibers (CNF). The polymers were dissolved in distilled water and homogenized to obtain a uniform solution. The PS-encapsulated A–AgNPs–Rhizobium formulation was then incorporated and mixed thoroughly. After degassing under vacuum, the mixture was extruded dropwise into 2% (w/v) $CaCl_2$ solution to form beads through ionic crosslinking. The beads were cured for 30 min, washed twice with distilled water, air-dried, and stored for subsequent characterization and field evaluation (Firmanda et al., 2024).

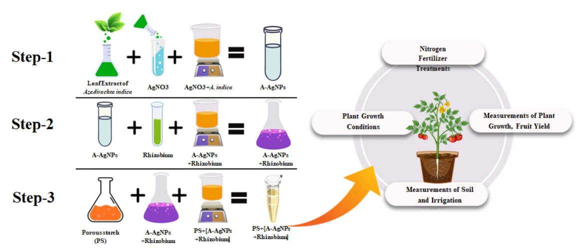


Fig. 1: Schematic Overview of the Synthesis and Characterisation of a Bio-nano Fertiliser Affecting Nutrient Use Efficiency and Nutritional Quality and Productivity of Tomato Fruits

## CHARACTERIZATION AND GREENHOUSE EVALUATION

***Characterization of PS-[Rhi+A-AgNPs] Nanocomposite Beads***

Preparation of PS-[Rhi+A-AgNPs] nanocomposites and biosynthesized AgNPs were characterized in terms of their optical properties by a UV–vis spectrophotometer (Shimadzu UV-1800, Japan) over the wavelength range from 200 to 800 nm. Dynamic light scattering (DLS; Spectroscatter 201) was used for particle size distribution measurement. Fourier-transform infrared (FTIR; PerkinElmer 1750, USA) spectroscopy was used to identify the functional groups that were involved in both nanoparticle synthesis and encapsulation. X-ray diffraction (XRD; Rigaku Ultima IV, Japan) was used to determine the crystalline structure of AgNPs using Cu Kα radiation (λ = 1.5406 Å) across a range of 2θ from 10–80° (Thomas et al., 2024).

***Greenhouse Experiment***

Thirty-three tomato (Solanum lycopersicum L.) seedlings were raised in peat moss and vermiculite at a 1:1 volume ratio, under greenhouse conditions for 45 days before the transplantation into plastic pots containing 5 kg of clay loam soil (Table 1). Phosphorus and potassium fertilizers were applied according to recommended agronomic practices. During the entire study, soil moisture was kept around 75% of field capacity. The greenhouse conditions included 25 ± 2°C (day), 15 ± 2°C (night, relative humidity of) at levels between muffled 65–75%, and photosynthetic photon flux density ranging from muzzle-800 to muzzle-1000 µmol m$^{-2}$ scM (Khan et al., 2024).

***Experimental Design and Fertilizer Treatments***

The experiment was conducted in randomized complete block design (RCBD) with factorial arrangement comprised of five controlled-release Rhizobium (CRR) formulations (T1–T5) and three levels of nitrogen application (100%, 50% and 25% of the recommended dose). The recommended rate of commercial Rhizobium fertilizer was used as control. Fertilizer applications were done on 15, 40 and 60 days after transplanting. Six replicate tests were performed for each treatment (Isabel et al., 2024).

***Table of Contents Plant Growth, Yield and Fruit Quality Assessment***

Fifteen days after the last application of chemical fertilizers, we measured growth parameters (plant height, leaf number, stem diameter, number of branches and chlorophyll content. Harvesting leaves as fresh and dry biomass. Yield parameters comprised the number of fruit per plant, average fruit weight, yield per plant and marketable yield. Standard analytical procedures were used to determine parameters of quality: fruit length, diameter, TSS, titratable acidity and vitamin C content. The Nitrogen concentration in plant tissues was analyzed according to the Kjeldahl method.

***Statistical Analysis***

Statistical analysis: Data were analyzed by two-way ANOVA using MSTAT-C Version 2.1. At a threshold of $p \leq 0.05$, treatment means were compared using Tukey's honestly significant difference (HSD) test. Heat maps and graphical analyses were produced in SPSS Version 21.

**Table 1: Tomato pot experiment soil chemical and physical qualities..**

| **pH** | **TCC* %** | **OC** %** | **Available Nutrients (mg/kg)** | | | **Coarse Sand** | **Fine Sand** | **Silt** | **Clay** |
|---|---|---|---|---|---|---|---|---|---|
| | | | N | P | K | % | % | % | % |
| 7.34 | 2.6 | 1.55 | 110.2 | 13.3 | 219 | 4.4 | 30 | 26.8 | 36.9 |

* Total calcium carbonate, ** total organic carbon.

## RESULT

***Characterization of PS-[Rhi+A-AgNPs]***

The yellowish-brown coloration of the azadirachta indica-mediated agNP solution confirmed the successful synthesis of AgNPs. The presence of surface plasmon resonance (SPR) was confirmed by UV-Vis spectroscopy at 448 nm. The absorption of the Rhi+A-AgNPs in the range of 400–450 nm (Fig. 2A) was indicative of the formation and stability of the nanoparticles (Thomas et al., 2024).

X-ray diffraction (XRD) confirmed that the A-AgNPs were crystalline (Fig. 2B). Four diffraction peaks at 2θ of 36°, 41°, 48°, and 76° were suggestive of the formation of crystalline AgNPs.

The involvement of phenol, amines and hydroxyls in the reduction and capping of the AgNPs were suggested by the FTIR spectra of the samples (Fig. 2C). Following the formation of AgNPs, a slight shift in the region of the FTIR absorption peaks was indicative of the formation of the AgNPs and the presence of the biocomponents of the Ethiopian basil leaf extract. FTIR also revealed that encapsulation of the nanoparticles was achieved through non-covalent physical interactions, with no new chemical bonds formed after nanoparticle incorporation (Nkosi et al., 2024).

The dynamic light scattering (DLS) of the biosynthesized A-AgNPs (Fig. 2D) revealed a hydrodynamic diameter of 90 nm, a polydispersity index (PDI) of 0.30, and a zeta potential of −36.7 mV. These results imply that the nanoparticles were relatively homogenous and exhibited good colloidal stability (Thomas et al., 2024; Nkosi et al., 2024).

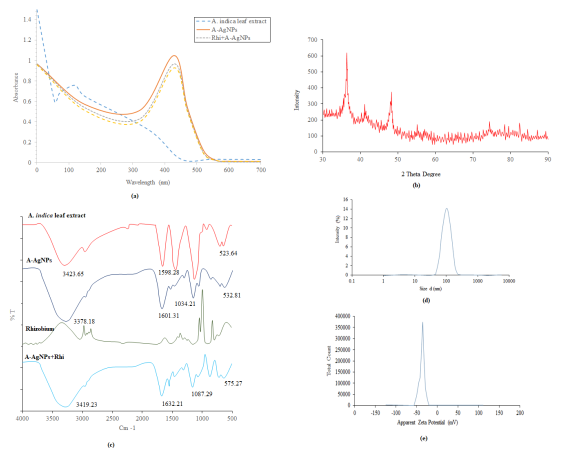

Figure 2. Biosynthesis of silver nanoparticles: UV spectra of the aqueous leaf extract and A-AgNPs synthesized from the A. *indica* leaf extract (a); XRD pattern of the synthesized A-AgNPs (b); FTIR spectra of the A. *indica* leaf extract and A-AgNPs, Rhizobium, A-AgNps+Rhi (d); Nanoparticle size measurements: (A) size and PDI analysis; (B) ζ-potential of the biosynthesized A-AgNPs (e).

***pH-Responsive Swelling Behavior of PS-[Rhi+A-AgNPs] Beads***

The swelling behavior of the bead formulations was strongly influenced by the pH of the surrounding medium (Fig. 3). Under acidic conditions (pH 1.2), all formulations exhibited limited swelling, with swelling ratios ranging from approximately 150% to 204%, and no significant increase was observed after 2 h of incubation. In contrast, substantial swelling occurred at pH 6.8, where the PS-[Rhi+A-AgNPs] beads showed a swelling ratio of 1378.60 ± 19.08%, while SCT beads exhibited the highest swelling ratio (1512.30 ± 26.94%). The swelling ratio increased progressively with incubation time, indicating enhanced water uptake and matrix expansion under near-neutral conditions.

The decreased swelling at low pH may be due to the formation of stronger intermolecular forces within polymer chains which limits water diffusion; in contrast at pH 6.8, ionization of the functional groups forces relaxation of the polymer chains and increases water absorption. pH-responsive swelling behavior has also been observed in hydrogel systems based on alginate–chitosan and cellulose, which can be described by a phenomenon of low swelling at acidic pH and a dramatic increase of swelling at neutral pH, in a way that allows for the controlled release of the materials that are encapsulated (Chen et al., 2024; Liu et al., 2024). From the swelling analysis, it can be inferred that the PS-[Rhi+A-AgNPs] beads have the appropriate pH-sensitive characteristics for agricultural systems to enable sustained and controlled release of the bioactive constituents.

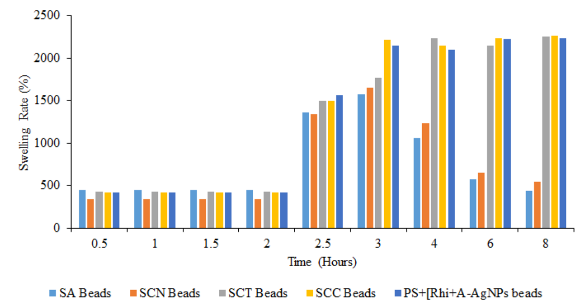


Fig. 3: Impact of pH on the swelling rate of four beads (SA, SCN, SCT, SCC) and PS+[Rhi+A-AgNPs] .

***Effect of PS-[Rhi+A-AgNPs] on Tomato Growth Attributes***

At 100, 50 and 25% N, PS+[Rhi+A-AgNPs increased tomato plant stem diameter, height, branches, leaves number as well as fresh and dry weight compared to the other treatments. From 25 to 100% of the recommended dose, PS+[Rhi+A-AgNPs increased all growth parameters in tomato (Table 2). The number of branches was significantly larger for all treatments, although there was a minor interaction at the N level.

**Table 2: Examination of variance of tomato growth qualities.**

| Source | No | Plant Height (cm) | No. of Branches | No. of Leaves | Stem Diameters (mm) | Plant Fresh Weight (g) | Plant Dry Weight (g) |
|---|---|---|---|---|---|---|---|
| Treatments (T) | 4 | 572.5*** | 2.01*** | 34.42*** | 0.07*** | 45785.75*** | 2763.43*** |
| Leaves (L) | 3 | 154*** | 5.88*** | 47.5*** | 0.03* | 17362.17*** | 365.56*** |
| T X L | 12 | 38.92*** | 0.25ns | 9.74*** | 0.01* | 13884.22*** | 235.41*** |

ns: not statistically significant. *, **, ***: statistically significant at p < 0.05, ≤ 0.01, and ≤ 0.001, respectively

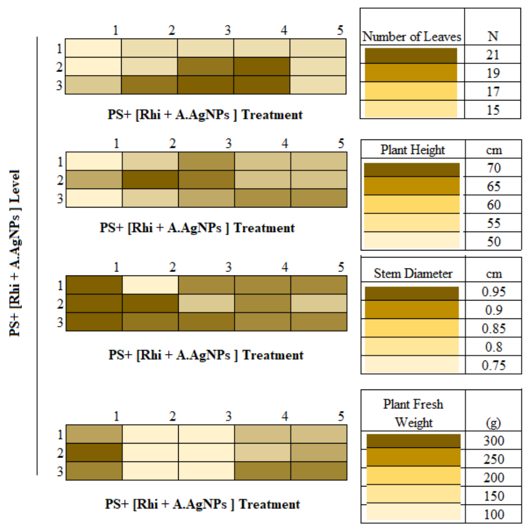


Fig.4. Heat map graph visualisation illustrates the interaction between the PS+[Rhi+A-AgNPs treatments and the nitrogen levels applied (25%, 50% and 100%, dose) concerning the following plant development characteristics: (A) leaf count, (B) plant height, (C) stem diameter, and (D) fresh plant weight.

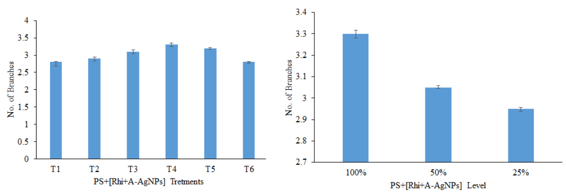


Fig. 5: The quantity of branches in tomato plants influenced by PS+[Rhi+A-AgNPs: (A) treatments and (B) nitrogen application levels. Distinct letters signify substantial variations among the levels as per Tukey's multiple range test ($p \leq 0.05$).

Application of PS-[Rhi+A-AgNPs] significantly improved vegetative growth parameters compared with the 25% N treatment (Figure 4). The highest leaf number was monitored in treatments T3 and T4 under both 100% and 50% nitrogen levels, while stem diameter increased markedly in T1, T3, and T5 compared with the control. Enhanced growth performance may be attributed to the controlled release of nutrients and improved , which promoted nutrient uptake and plant vigor.

Most PS-[Rhi+A-AgNPs] treatments improved shoot fresh and dry biomass across all nitrogen levels, with T3-T5 showing the most improvement. Treated plants had a higher branch count than the control, especially with 100% and 50% N, but the branch count differences were not statistically significant. These results show that the nanocomposite biofertilizer has potential to improve growth with even lower nitrogen. Other studies have shown that controlled release biofertilizers and PGPR-based formulations enhance growth and biomass in tomatoes by improving nutrient availability and increasing photosynthetic and nitrogen use efficiency (Fadiji et al., 2024;Munda et al., 2024). The findings seen with 50% N show that the PS-[Rhi+A-AgNPs] system helps counterbalance minimal fertilizer use and still leads to healthy growth.

***Tomato Plant Biomass and Leaf Chemical Composition***

Table 2 shows treatments PS+[Rhi+A-AgNPs] which included various N levels and their effect on dry matter, leaf potassium and N concentration, and leaf chlorophyll spadometer reading. With the exception of T5 at 50 and 25% N, all PS+ [Rhi+A-AgNPs] treatments showed increased dry matter relative to control. Dry matter for control and other PS+[Rhi+A-AgNPs] treatments was less than that for T2, which was surpassed by T5 at 100% N. All PS+[Rhi+A-AgNPs] treatments SPAD values were greater than the control. SPAD values were the highest for T4 and T3 at 100% N (Figure 6). Most PS+[Rhi+A-AgNPs] treatments, at the maximum N levels, showed that tomato plants absorbed greater leaf K and N than the control. T1 at 100, 50, and 25% N (Figure 6) absorbed the highest amounts of K and N.

**Table 2: Variance analysis of leaf chlorophyll, dry matter, nitrogen and potassium content**

| **Source** | **No.** | **Total Yield/Plant (g)** | **Marketable/Yield (%)** | **Number of Fruits/Plants** | **Mean of Fruits Weight (g)** | **Mean of Fruits Diameter (cm)** | **Mean of Fruits Length (cm)** |
|---|---|---|---|---|---|---|---|
| Treatments (T) | 4 | 1499274.23 *** | 171.12 * | 81.79 *** | 946.11 *** | 4.02 *** | 1.112 *** |
| Levels (L) | 3 | 606345.32 *** | 134.69 ns | 61.01 *** | 1232.31 *** | 0.421 * | 0.131 ns |
| T × L | 12 | 237776.61*** | 30.89 ns | 9.01 * | 285.21 *** | 0.829 * | 0.279 ns |

ns: not statistically significant. *, **, ***: statistically significant at $p < 0.05$, $p \leq 0.01$, and $p \leq 0.001$, respectively.

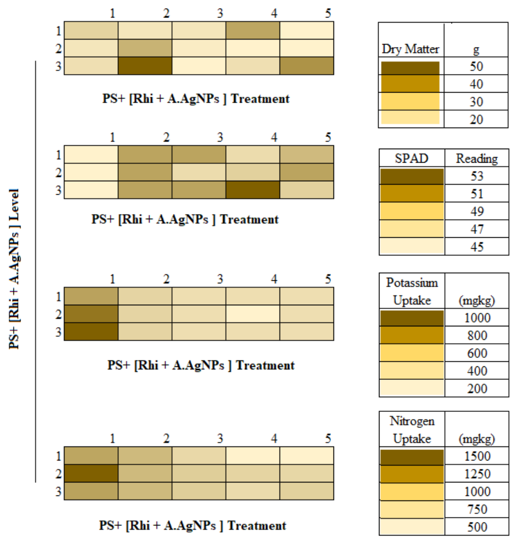


Fig. 6: Two-dimensional heat map displays interaction : PS+[Rhi+A-AgNPs treatments and applied N levels (25%,50% and 100% suggested dose) affect tomato plant dry matter, potassium uptake, SPAD reading, and nitrogen absorption.

***Effect of PS-[Rhi+A-AgNPs] on Yield and Fruit Characteristics***

The PS-[Rhi+A-AgNPs] treatments significantly improved total yield, fruit number, fruit weight, and fruit size compared with the control (Table 3). Increasing nitrogen application from 25% to 100% generally enhanced fruit production; however, several PS-[Rhi+A-AgNPs] treatments maintained high yields even under reduced nitrogen levels. Treatments T2 and T5 produced the highest fruit yields at 100% N, while T1, T2, and T3 recorded significantly greater marketable yields than the control. Fruit diameter and length were also improved in most PS-[Rhi+A-AgNPs] treatments, indicating enhanced fruit quality. The likely reason for the improved yield performance could be linked to the controlled-release traits of the nanocomposite formulation, which result in the availability of nutrients, reduced nutrient depletion, and improved nitrogen use. Tomato yield and fruit quality showing the same improvements after application of controlled-release fertilizers and microbial biofertilizers have been reported (Fadiji et al., 2024;Munda et al., 2024). Of PS-[Rhi+A-AgNPs] treatments, many were able to achieve similar or better yields with only 25% of the recommended dose of nitrogen, meaning that the formulation is able to greatly lessen the need for nitrogen fertilizers while still improving the yield of the crop. The bio-nanocomposite fertilizer form that was created has great potential for use in nutrient management and improving tomato production in a sustainable manner.

**Table 3: Variance analysis of fruits yield characteristics.**

| Source | No. | Total Yield/Plant (g) | Marketable/Yield (%) | No. of Fruits/Plants | Mean of Fruits Weight (g) | Mean of Fruits Diameter (cm) | Mean of Fruits Length (cm) |
|---|---|---|---|---|---|---|---|
| Treatments (T) | 4 | 1499274.23 *** | 171.12 * | 81.79 *** | 946.11 *** | 4.02 *** | 1.112 *** |
| Levels (L) | 3 | 606345.32 *** | 134.69 ns | 61.01 *** | 1232.31 *** | 0.421 * | 0.131 ns |
| T × L | 12 | 237776.61*** | 30.89 ns | 9.01 * | 285.21 *** | 0.829 * | 0.279 ns |

ns: not statistically significant. *, ***: statistically significant at a p-value of ≤ 0.05 and ≤ 0.001, respectively.

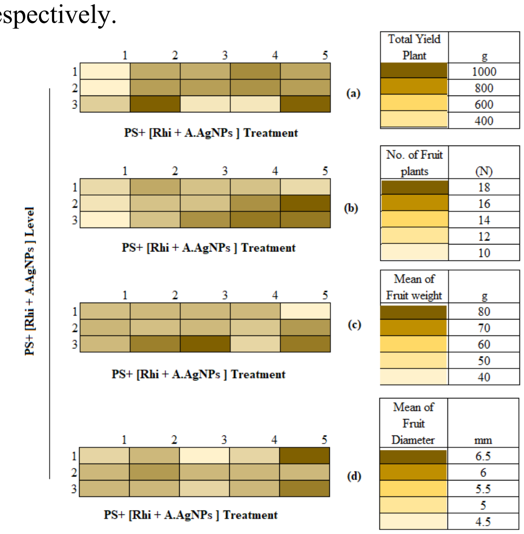


Fig 7 : Two-dimensional heat map displays interaction: PS+[Rhi+A-AgNPs treatments and applied N levels (25% , 50% and 100 % suggested dose) affect plant development metrics (A) total yield/plant, (B) number of fruits/plant, (C) mean fruit weight, and (D) mean fruit diameter.

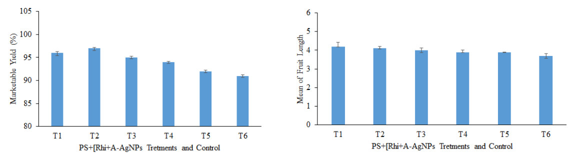


Fig. 8: illustrates the impact of PS+[Rhi+A-AgNPs interventions on the mean of fruit length (B) and marketable yield (A). Tukey's multiple range test ($p \leq 0.05$) indicates that the regimens exhibit significant differences

***Nitrogen Uptake Efficiency and Fruit Quality***

PS-[Rhi+A-AgNPs] treatments significantly influenced fruit quality attributes and nitrogen uptake efficiency (NUpE) (Table 4). The highest total soluble solids (TSS) were observed in T3 at 50% N, while fruit firmness showed no significant differences among treatments. Most PS-[Rhi+A-AgNPs] treatments maintained higher vitamin C and acidity levels than the control, even under reduced nitrogen application. Importantly, fruit quality was preserved or improved at 25% N, indicating that reduced fertilizer inputs did not adversely affect tomato quality.

Nitrogen uptake efficiency was markedly enhanced by PS-[Rhi+A-AgNPs], reaching a maximum of 88% compared with 33% in the control. Across all nitrogen levels, treated plants exhibited substantially higher NUpE, demonstrating improved nitrogen acquisition and utilization. These findings suggest that the controlled-release nanocomposite system effectively synchronizes nutrient availability with plant demand, thereby reducing nutrient losses and improving fertilizer efficiency.

The observed improvements are consistent with previous studies reporting enhanced nutrient uptake, fruit quality, and nitrogen use efficiency following the application of controlled-release fertilizers and microbial biofertilizers in tomato production (Liu et al., 2024; Fadiji et al., 2024;Munda et al., 2024). The ability of PS-[Rhi+A-AgNPs] to maintain fruit quality while substantially reducing nitrogen inputs highlights its potential as a sustainable strategy for improving resource-use efficiency and reducing fertilizer dependency in vegetable production systems.

**Table 4: Nitrogen uptake efficiency and tomato fruit quality variance analysis.**

| **Source** | **No.** | **TSS** | **Firmness (N)** | **Vitamin C (mg/100 g)** | **Acidity (%)** | **NUpE** |
|---|---|---|---|---|---|---|
| Treatments (T) | 4 | 2.79 ** | 0.713 ** | 71.720 *** | 0.065 *** | 5173.71 *** |
| Levels (L) | 3 | 0.414 ns | 0.822 * | 20.511 *** | 0.248 *** | 2521.67 *** |
| T × L | 12 | 0.475 * | 0.668 *** | 28.313 *** | 0.117 *** | 431.47 *** |

(ns): Not statistically important. **, *, and *** mean that the difference is statistically significant at $p < 0.05$, 0.01, and 0.001, respectively.

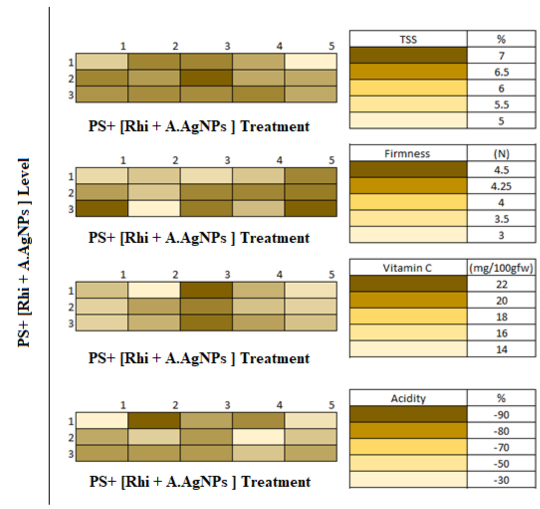


Fig. 9: Interaction between the PS+[Rhi+A-AgNPs treatments and applied N levels (100, 50, and 25% suggested concentration) for plant growth attributes (a) TSS, (b) firmness, (c) vitamin C, and (d) acidity is illustrated in a two-dimensional heat-map image.

**CONCLUSION**

This study create a new type of controlled-release nanobiofertilizer that incorporates Rhizobium, neem-synthesized silver nanoparticles, and a starch-based polysaccharide matrix that is also biodegradable. The formulation demonstrated advantageous physicochemical characteristics, satisfactory pH-responsive swelling, and effective nutrient delivery. PS-[Rhi+A-AgNPs] showed an enhancement over the traditional practices of fertilizing when looking at the growth, biomass, yield, quality of tomatoes, and nitrogen uptake efficiency. The efficiency showed an increase to 88%, while several practices sustained and/or improved the overall productivity using only 25% of the suggested nitrogen. Additionally, the created nanocomposite fertilizer has the potential to decrease the use of nitrogen fertilizers by 75% while maintaining the same performance of the crops. The

PS-[Rhi+A-AgNPs] system is an attractive, environmentally friendly system that has the potential to improve the efficiency of sustainable tomato production, while reducing the negative impacts to the environment.

**Acknowledgement**
We thank the higher authorities of Department of chemical engineering , GIET University Gunpur Raygada odisha authorities for their constant support and encouragement.

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**Author Contributions**
Shantanu Kumar Sahu: conceptualization, conducted the study, collected the data, analysis, interpreted the data, drafted the manuscript, Santosh Kumar Bindhani : conceptualization, and Diptikanta Achariya: conceptualization, analysis, interpreted the data. All three authors critically reviewed the final manuscript.

**Conflict of Interest**
The author declares no conflict during the study.

**Funding**
No funds were received to conduct the study.

**Data Availability Statement**
The datasets generated and/or analyzed during the current study are not publicly available because they are being used for ongoing research. However, the data are available from the corresponding author upon reasonable request.

**Author Declaration**
The authors confirm that this manuscript has not been published previously, is not under consideration elsewhere, and has been approved by all co-authors.

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