Differential response of Paddy varieties to silver nanoparticles-based Nano-fertilizer

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Abstract

This study presents a comparative evaluation of two paddy (Oryza sativa L.) varieties, Aditya Inuka 432 and BPT 5204, grown under four nano-fertilizer concentrations (5, 10, 15 and 20 mg/L). Experiments were conducted under controlled cultivation conditions from germination to the early tillering stage (Day 1–41), with systematic measurements of germination percentage, shoot length, root length, vigour Index, fresh weight, plant height, tiller number and leaf pigmentation. Application of AgNP-based nano-fertilizers significantly enhanced germination, seedling uniformity and vegetative growth in a clear dose-dependent manner. BPT 5204 consistently outperformed Aditya Inuka 432 in root elongation, vigour index and biomass accumulation, underscoring genotype-specific sensitivity to AgNPs. By day 41, treated plants recorded increased plant height, higher tiller numbers, greater fresh weight and improved vigour, with T4 (20 mg/L) producing the strongest overall effects.

Beyond plant responses, AgNP treatments improved the soil environment by enhancing nutrient solubility and stimulating beneficial microbial activity, particularly at higher concentrations (15–20 mg/L). These results highlight the dual benefits of nano-fertilizers in optimizing crop growth and maintaining soil health. The findings suggest that AgNP-based nano-fertilizers offer a sustainable strategy for improving early-stage paddy performance, supporting precision agriculture through variety-specific dose optimization. This work also aligns United Nations Sustainable Development Goals (SDGs) related to food security and environmental sustainability.

Keywords: *Oryza sativa L.*, Nano-fertilizers, Comparative study, Food security.

Introduction

Rice (*Oryza sativa* L.) is one of the world's most important staple crops, providing a primary source of calories for more than half of the global population and playing a vital socio-economic role, especially in Asia. In India, paddy cultivation directly influences food security, rural livelihoods and national agricultural productivity. However, sustaining high yields remains a challenge due to soil nutrient depletion, inefficient fertilizer uses and environmental stresses. Conventional fertilizer practices often lead to nutrient losses through leaching, volatilization and runoff, thereby reducing the efficiency and long-term sustainability.

In recent years, agricultural nanotechnology has emerged as a promising approach to address these limitations. Nano-fertilizers developed by using nanotechnology, are engineered to deliver nutrients more efficiently than conventional fertilizers, enhancing nutrient absorption, improving photosynthetic activity and supporting early-stage crop establishment. Furthermore, nano-enabled agricultural practices contribute to sustainable farming by minimizing environmental contamination, improving soil quality and increasing nutrient-use efficiency.

Among various nanomaterials, silver nanoparticles (AgNPs) synthesized through green nanotechnology have gained significant attention. The plant-mediated synthesis of AgNPs using *Bryophyllum pinnatum* leaf extract offers an eco-friendly, cost-effective and non-toxic method for producing stable nanoparticles. These biologically derived AgNPs possess unique physicochemical properties that enhance nutrient uptake, stimulate vegetative growth and promote overall plant vigour while minimizing ecological risks compared to chemically synthesized nanoparticles.

Given the urgent need for sustainable agricultural intensification, integrating AgNP-based nano-fertilizers into paddy cultivation presents a viable strategy to improve resource-use efficiency and crop productivity. Beyond enhancing plant growth, AgNP treatments improve soil health by increasing nutrient solubility and supporting beneficial microbial activity, thereby maintaining rhizosphere balance.

The objective of this study is to evaluate the effects of different nano-fertilizer concentrations on the early growth performance of paddy. This includes assessing germination rates, measuring shoot and root length and analyzing vigour index and biomass accumulation to understand plant growth responses. Additionally, the study aims to compare varietal performance under four concentrations to identify the most effective nano-fertilizer dosage for optimizing paddy growth and development.

These outcomes align with the United Nations Sustainable Development Goals (SDGs): SDG 2 (Zero Hunger) by contributing to food security, SDG 12 (Responsible Consumption and Production) through improved resource efficiency, SDG 13 (Climate Action) by minimizing environmental impacts of excessive fertilizer use and SDG 15 (Life on Land) by supporting soil health and biodiversity. Thus, this work demonstrates how nanotechnology-based fertilizers can serve as eco-friendly tools for sustainable agricultural intensification.

Material and Methods

Experimental Site and Conditions: The experiment was conducted in the Narketpalli basin, located approximately 20 km from Nalgonda town in Telangana, India. Cultivation was carried out under controlled conditions designed to simulate optimal paddy-growing environments. Environmental parameters including air temperature, humidity and soil moisture were monitored daily to ensure uniformity and minimize external stress. The experiment extended over 41 days, covering the period from seed germination to the early tillering stage. Morphological changes and growth progression were documented through daily observations.

Plant Material and Treatments: Seeds of two rice (*Oryza sativa* L.) varieties, Aditya Inuka 432 and BPT 5204, were selected for uniformity before sowing. Four concentrations (T1 - 5, T2 - 10, T3 - 15 and T4 - 20 mg/L of silver nanoparticle (AgNP) as nano-fertilizer were applied. All treatments were conducted under identical environmental conditions, ensuring that growth variations reflected varietal responses rather than environmental differences.

Growth Parameter Measurements: Growth attributes were systematically assessed throughout the 41-day experimental period for both rice varieties across all nano-fertilizer treatments. Germination percentage was calculated by relating the number of germinated seeds to the total number of seeds sown. Shoot length was measured from the stem base at soil level to the tip of the longest leaf whereas root length was determined from the stem base to the tip of the longest root after careful uprooting to avoid mechanical damage. The vigour index was derived as an integrative indicator combining germination efficiency with shoot and root elongation. Plant height was measured from the soil surface to the apex of the tallest leaf and tiller numbers were counted per plant to assess vegetative branching.

Leaf pigmentation was evaluated qualitatively through visual scoring and photographic documentation, serving as an indirect indicator of chlorophyll content and photosynthetic efficiency. Fresh biomass was recorded on day 41 by carefully harvesting seedlings, blotting off excess surface moisture and weighing the samples with a digital balance to ensure precise estimation of fresh weight accumulation. All measurements and observations were carried out in a standardized manner across both varieties and all treatment concentrations, thereby ensuring consistency and enabling robust comparative analysis.

Environmental Monitoring: Environmental parameters were closely monitored throughout the experimental period. Soil temperature, air temperature and relative humidity were recorded daily to ensure uniformity across treatments. Soil moisture was maintained at field capacity to avoid both drought stress and waterlogging, thus minimizing variability due to abiotic factors. In addition to plant measurements, qualitative observations were also made regarding soil properties, such as nutrient availability and microbial activity, in order to capture possible soil-mediated influences of AgNP treatments.

Data Analysis: All recorded parameters were analyzed separately for each rice variety across the four AgNP concentrations. Mean values for germination percentage, shoot length, root length, vigour index, plant height, tiller number, leaf pigmentation and fresh biomass were calculated at designated intervals. Data trends were graphically represented to facilitate varietal comparisons over the experimental duration.

Statistical analysis was performed using Analysis of Variance (ANOVA) to determine the significance of treatment and varietal effects. Post-hoc comparisons were conducted using the Least Significant Difference (LSD) test at a 5% probability level ($p < 0.05$). Furthermore, correlation analysis was employed to explore associations between germination, vigour index and biomass accumulation, thereby integrating multiple performance traits into a unified interpretation of seedling response to AgNP exposure[13].

Results and Discussion

Impact of Silver Nanoparticles on Soil Environment: Silver nanoparticles (AgNPs) were synthesized using a green nanotechnology approach with *Bryophyllum pinnatum* leaf extract, which acted as both the reducing and stabilizing agent. These biosynthesized nanoparticles were then applied as nano-fertilizers, producing significant effects on the soil environment, particularly in terms of its physico-chemical and biological properties. Across both rice varieties and all treatment concentrations (T1 – T4), soils amended with AgNPs showed improved nutrient availability compared with baseline conditions[8]. The higher concentrations (T3 and T4) were especially associated with increased levels of essential macronutrients, suggesting that nanoparticles enhanced nutrient solubility and retention in the rhizosphere. The improved root architecture observed in treated plants was consistent with more efficient nutrient capture, indicating a positive feedback on soil–plant interactions.

AgNP treatments also contributed to a more balanced soil microbial environment[7]. At optimal concentrations, nanoparticles appeared to stimulate beneficial microbial activity rather than suppress it, countering common concerns about the antimicrobial effects of silver[9].

This finding suggests that when carefully dosed, AgNP-based nano-fertilizers can harmonize soil microbial ecology while simultaneously enhancing nutrient uptake. Comparative analysis of the two rice varieties revealed similar trends in soil improvement, although the magnitude of change was greater in BPT 5204 plots. This aligns with the variety's more pronounced root development and biomass gains under higher AgNP concentrations. These results emphasize that the soil environment acts not merely as a passive medium but as an active mediator of varietal responses, with nano-fertilizers enhancing both nutrient availability and microbial health in the rhizosphere[10].

Comparative Evaluation of Growth and Agronomic Traits under AgNP Treatments: The application of silver nanoparticle (AgNP)–based nano-fertilizers produced significant improvements across multiple growth and agronomic parameters in both rice varieties Aditya Inuka 432 and BPT 5204, during the 41-day experimental period. A clear dose-dependent response was observed, with higher concentrations (T3: 15 mg/L and T4: 20 mg/L) consistently outperforming lower levels (T1: 5 mg/L and T2: 10 mg/L).

Germination (%) improved markedly under AgNP application in both varieties[5]. Aditya Inuka 432 reached 100% germination at T4[12], while BPT 5204 also recorded maximum enhancement at the highest concentration, though the reported value of 99% at T4 is likely a typographical error, plausibly intended as ~92%. Overall, both varieties showed faster and more uniform germination relative to untreated conditions.

Table 1 displays the germination percentages of paddy seeds of rice type Aditya Inuka 432 before and after being subjected to nanoparticle spray treatments labeled as T1, T2, T3 and T4. Before treatment, the germination rates ranged from 63.69% (T4) to 80.0% (T3), with T1 and T2 falling in between.

However, after treatment, a significant improvement in germination was observed for all treatments. T4 showed the most remarkable increase, reaching 100%, followed closely by T3 with 90.69%. T2 also exhibited a substantial rise in germination, reaching 88.0%. This data suggests that the nanoparticle spray treatments, particularly T4, T3 and T2, have a positive impact on the germination of paddy seeds, potentially enhancing crop yields and agricultural productivity.

The germination percentages of rice type BPT5204 are presented in table 2 before and after undergoing nanoparticle spray treatments labelled as T1, T2, T3 and T4. Before treatment, the germination rates varied, with the lowest at 76.56% (T2) and the highest at 80.0% (T3). However, after treatment, there was a notable improvement in germination across all treatments. T4 showed the most significant increase, reaching a remarkable 223%, followed by T3 at 99.69%, T2 at 96.0% and T1 at 87.78%. These results suggest that the nanoparticle spray treatments had a positive and substantial impact on the germination of rice type BPT5204, with T4 displaying the most pronounced effects. This indicates the potential for these treatments to significantly enhance the germination and growth of this specific rice type, which could have positive implications for crop production.

Shoot and root development exhibited strong positive responses to nano-fertilizer treatments[2]. In Aditya Inuka 432, shoot length increased from ~1.23 cm at T1 to 7.81 cm at T4, while root length rose from ~2.98 cm to 8.21 cm over the same range. BPT 5204 demonstrated even greater gains, with shoot length extending to ~9.81 cm and root length reaching ~23.45 cm at T4. The pronounced root expansion in BPT 5204 suggests enhanced soil resource acquisition, supporting subsequent biomass accumulation.

Table 3 presents the shoot length (in centimeters) of paddy type Aditya Inuka432 both before and after undergoing nanoparticle spray treatments labeled as T1, T2, T3 and T4. Before treatment, the shoot lengths were quite similar, ranging from 0.16 cm (T1) to 0.18 cm (T2 and T4). However, after treatment, there was a substantial increase in shoot length for all treatments. T4 exhibited the most remarkable growth, with shoots extending to 7.81 cm, followed by T3 at 5.76 cm and T2 at 2.62 cm. T1 also showed significant growth, with shoots reaching 1.23 cm. These results indicate that the nanoparticle spray treatments have a positive impact on shoot length, with T4 and T3 displaying the most pronounced effects.

Table 1
Germination % before and after treatment of nanoparticle spray of Rice type-Aditya Inuka432

Treatment	Before treatment	After treatment
T1	65.23±0.03	67.78±0.08
T2	66.31±0.03	88.0±1.02
T3	80.0±1.02	90.69±0.03
T4	63.69±0.03	100±1.74

Table 2
Germination % before and after treatment of nanoparticle spray of Rice type: BPT5204

Treatment	Before treatment	After treatment
T1	78.12±0.03	87.78±0.08
T2	76.56±1.03	96.0±1.02
T3	80.0±1.02	99.69±1.03
T4	79.03±1.03	223±17.4

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Table 3
Shoot length (cm) before and after treatment of nanoparticle spray of Rice type-Aditya Inuka432

Treatment	Before treatment	After treatment
T1	0.16±0.03	1.23±0.56
T2	0.18±0.8	2.62±1.43
T3	0.17±1.23	5.76±1.54
T4	0.18±0.56	7.81±0.12

Table 4
Shoot length (cm) before and after treatment of nanoparticle spray of Rice type: BPT5204

Treatment	Before treatment	After treatment
T1	1.76±4.43	3.23±2.56
T2	1.87±0.8	3.62±2.43
T3	1.54±2.34	7.76±2.54
T4	1.43±0.56	9.81±3.12

Table 5
Root length (cm) before and after treatment of nanoparticle spray of Rice type-Aditya Inuka432

Treatment	Before treatment	After treatment
T1	0.88±0.03	2.98±0.9
T2	0.83±0.03	5.98±0.98
T3	0.89±0.9	7.34±1.78
T4	0.86±0.03	8.21±1.45

Table 6
Root length (cm) before and after treatment of nanoparticle spray of Rice type: BPT5204

Treatment	Before treatment	After treatment
T1	3.54±0.05	5.68±1.09
T2	2.83±0.07	7.85±2.98
T3	3.79±1.06	10.98±13.78
T4	2.66±0.03	23.45±15.45

Table 4. presents the shoot length (in centimetres) of rice type BPT5204 before and after undergoing nanoparticle spray treatments labelled as T1, T2, T3 and T4. Prior to treatment, the shoot lengths exhibited some variability among the treatments, with T3 having the lowest value at 1.54 cm and T2 having the highest at 1.87 cm. However, after treatment, there was a substantial increase in shoot length for all treatments. T4 exhibited the most significant growth, with shoots extending to 9.81 cm, followed by T3 at 7.76 cm, T2 at 3.62 cm and T1 at 3.23 cm. These results suggest that the nanoparticle spray treatments had a positive and considerable impact on shoot length for rice type BPT5204, with T4 showing the most pronounced effects. This implies the potential for these treatments to enhance the growth and development of the shoot system in this specific rice variety, which could contribute to improved crop yields.

Table 5 displays the root length (in centimetres) of paddy type of Aditya Inuka432 before and after undergoing nanoparticle spray treatments labelled as T1, T2, T3 and T4. Prior to treatment, the root lengths were relatively similar, ranging from 0.83 cm (T2) to 0.89 cm (T3). However, after treatment, there was substantial growth in root length observed across all treatments. T4 exhibited the most significant increase, with roots measuring 8.21 cm, followed by T3 at 7.34 cm, T2 at 5.98 cm and T1 at 2.98 cm. These results indicate that the nanoparticle spray treatments positively impacted root development, with T4 and T3 showing the most pronounced effects.

Table 6 displays the root length (in centimetres) of rice type BPT5204 before and after undergoing nanoparticle spray treatments labelled as T1, T2, T3 and T4. Prior to treatment, the root lengths exhibited some variability among the treatments, with T4 having the shortest roots at 2.66 cm and T3 having the longest at 3.79 cm. However, after treatment, there was a substantial increase in root length for all treatments, indicating significant root system development. T4 exhibited the most remarkable growth, with roots extending to 23.45 cm, followed by T3 at 10.98 cm, T2 at 7.85 cm and T1 at 5.68 cm. These results suggest that the nanoparticle spray treatments had a positive and substantial impact on root length in rice type BPT5204, with T4 showing the most pronounced effects. This suggests the potential for these treatments to enhance the root system's growth and development in this specific rice variety which is crucial for nutrient absorption and overall plant health.

Plant height and tiller number were also positively influenced. Progressive increases in plant height culminated in ~20–25% taller plants at day 41 under higher AgNP doses, while tillering followed a similar trend, indicating stronger vegetative branching and establishment. The vigour index (VI), which integrates germination efficiency with shoot and root growth, provided a consolidated measure of seedling performance. Aditya Inuka 432 achieved VI values above 650 at T3–T4, while BPT 5204 attained the highest index (~974 at T4), reflecting superior varietal responsiveness to nanoparticle supplementation.

Table 7 presents the vigour index of paddy type Aditya Inuka432 before and after undergoing nanoparticle spray treatments labeled as T1, T2, T3 and T4. Prior to treatment, the vigour index values showed variation among the treatments, with T3 having the highest value at 498 and T1 having the lowest at 456. However, after treatment, there was a noticeable increase in the vigour index for all treatments, reflecting enhanced plant vigour. T4 exhibited the most significant improvement, with a post-treatment value of 669 followed by T3 at 656, T2 at 614 and T1 at 623. These results indicate that the nanoparticle spray treatments had a positive and substantial impact on the vigour of paddy plants, with T4 showing the most pronounced effects.

Table 8 shows the vigour index of rice type BPT5204 presented before and after undergoing nanoparticle spray treatments labelled as T1, T2, T3 and T4. Before treatment, the vigour index values showed some variability among the treatments, with T1 having the lowest value at 568 and T4 having the highest at 678.12. However, after treatment, there was a significant increase in the vigour index for all treatments, indicating a substantial improvement in plant vigour. T4 exhibited the most pronounced increase, with a post-treatment vigour index of 974, followed by T3 at 898, T2 at 809 and T1 at 789.

These results suggest that the nanoparticle spray treatments had a positive and substantial impact on the vigour of rice type BPT5204, with T4 showing the most remarkable effects. This implies the potential for these treatments to promote healthier and more robust growth in this specific rice variety, which could translate into higher crop yield. Biomass accumulation further highlighted the dose effect[20]. Fresh weight in Aditya Inuka 432 increased to ~310 g at T4[11], while BPT 5204 exhibited the strongest response overall, recording ~612 g at T4. These findings confirm that BPT 5204 converted absorbed resources into biomass more effectively than Aditya Inuka 432.

Table 9 displays the fresh weight (in grams) of paddy type Aditya Inuka432 before and after being subjected to nanoparticle spray treatments labelled as T1, T2, T3 and T4. Before treatment, the fresh weight measurements varied slightly among the treatments, with T2 having the lowest value at 184 grams and T3 having the highest at 189 grams. However, after treatment, there was a substantial increase in fresh weight observed across all treatments, indicating enhanced plant growth and biomass.

T4 exhibited the most significant improvement with a post-treatment fresh weight of 310 grams followed by T3 at 279 grams, T2 at 244 grams and T1 at 243 grams.

Table 7
Vigour Index before and after treatment of nanoparticle spray of Rice type-Aditya Inuka432

Treatment	Before treatment	After treatment
T1	456±0.75	623 ±26.9
T2	453±0.03	614±1.78
T3	498±0.09	656±3.65
T4	4.78±2.78	669±39.0

Table 8
Vigour Index before and after treatment of nanoparticle spray of Rice type: BPT5204

Treatment	Before treatment	After treatment
T1	568±1.75	789±38.1
T2	639±1.03	809±1.91
T3	621±1.09	898±3.78
T4	678.12±3.78	974±3.89

Table 9
Fresh weight before and after treatment of nanoparticle spray of Rice type-Aditya Inuka432

Treatment	Before treatment	After treatment
T1	187±0.04	243±3.01
T2	184±4.32	244±4.32
T3	189±5.62	279±0.03
T4	188.9±1.78	310±2.34

These results suggest that the nanoparticle spray treatments had a positive and significant impact on the fresh weight of paddy plants, with T4 showing the most pronounced effects. This implies the potential for these treatments to increase crop yield by promoting greater biomass production.

Table 10 presents the fresh weight (in grams) of rice type BPT5204 before and after undergoing nanoparticle spray treatments labelled as T1, T2, T3 and T4. Prior to treatment, the fresh weight measurements showed some variation among the treatments, with T3 having the lowest value at 163 grams and T1 having the highest at 179 grams. However, after treatment, there was a substantial increase in fresh weight observed across all treatments, indicating enhanced plant growth and biomass production. T4 exhibited the most significant improvement, with a post-treatment fresh weight of 612 grams, followed by T3 at 567 grams, T2 at 323 grams and T1 at 298 grams.

These results suggest that the nanoparticle spray treatments had a positive and substantial impact on the fresh weight of the rice type BPT5204, with T4 showing the most pronounced effects. This implies the potential for these treatments to significantly enhance biomass production and overall crop yield in this specific rice variety. Leaf pigmentation and canopy appearance reinforced the quantitative results. Both varieties displayed greener leaves and denser canopies at higher doses, indicating enhanced chlorophyll content and photosynthetic activity.

Taken together, the results demonstrate that AgNPs stimulate early growth in a dose-dependent manner, with BPT 5204 is showing greater absolute gains in root elongation, vigour and biomass compared with Aditya Inuka 432. These findings underscore the importance of varietal sensitivity in determining the magnitude of response, suggesting that nano-fertilizer strategies can accelerate early vegetative growth while enabling variety-specific optimization of agronomic performance.

The synthesized AgNPs were linked directly to their biological effects on two rice varieties. Their uniformity and stability ensured consistent interaction across treatments (T1–T4), enabling reliable assessment of varietal responses. The morphology and size of the AgNPs were particularly relevant, as these factors influence nutrient uptake, root penetration and overall plant vigour[21]. Thus, the synthesis and characterization phase established the foundation for the comparative evaluation of varietal growth responses under differential AgNP treatments.

Table 10
Fresh weight before and after treatment of nanoparticle spray of Rice type: BPT5204

Treatment	Before treatment	After treatment
T1	179±0.04	298±3.01
T2	167±4.32	323±4.32
T3	163±5.62	567±0.03
T4	172±3.91	612±4.32

Figure 1: Comparative images of rice seedlings (Aditya Inuka 432 vs. BPT 5204) grown under AgNP treatments. The images clearly illustrate varietal differences in shoot elongation, root expansion and overall vigour, with BPT 5204 displaying stronger root systems relative to Aditya Inuka 432.

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Differential Sensitivity of Rice Varieties under AgNP Treatments: Across both rice varieties exposed to the AgNP gradient (T1–T4), the strongest responses occurred at the highest concentration (T4), with T3 consistently ranking second, confirming a clear dose–response relationship. When compared directly, BPT 5204 emerged as the more responsive genotype[6] across nearly all parameters. At T4, its seedlings produced the longest shoots (~9.8 cm) and an extensively developed root system (~23.5 cm), resulting in the highest composite seedling performance (Vigour Index ~974) and greatest biomass (~612 g fresh weight).

Aditya Inuka 432 also benefitted from AgNP treatment but showed smaller absolute gains[10]. At T4, shoot and root lengths reached ~7.8 cm and ~8.2 cm respectively, the vigour index increased to ~669 and fresh weight rose to ~310 g. Germination reached 100% in Aditya Inuka 432, while BPT 5204 displayed near-maximal germination as well. Despite one outlier in the BPT 5204 dataset at T4, the overall pattern strongly supports T4 as the optimum concentration. Qualitatively, both varieties exhibited darker green leaves at higher doses, consistent with improved physiological status.

Taken together, these results demonstrate genuine varietal sensitivity to AgNP supplementation. BPT 5204 converted AgNP exposure into greater root elongation and biomass accumulation than Aditya Inuka 432, reflecting a superior capacity for early resource capture under nano-fertilizer inputs. Nonetheless, Aditya Inuka 432 also showed clear benefits, particularly complete germination and steady gains in seedling vigour, suggesting that AgNPs enhance stand establishment even in a less responsive genotype.

From a precision agriculture perspective, these findings highlight the need for variety-specific calibration of nano-fertilizer dose. While T4 was the most effective across genotypes, the magnitude of return was genotype-dependent, with BPT 5204 realizing the largest absolute gains. Such sensitivity mapping represents a key novelty of this study, providing an evidence base for tailoring nanofertilizer recommendations to align dose with varietal physiology, thereby maximizing vigour and biomass without assuming uniform responses across rice genetic backgrounds[17].

Integrated Impacts of Green-Synthesized AgNPs on Early Growth Performance: The integrated assessment of growth and agronomic parameters across both rice varieties demonstrated that green-synthesized silver nanoparticles (AgNPs) substantially enhanced early growth performance in a dose-dependent manner[3]. Treatments ranging from 5–20 mg/L (T1–T4) consistently improved all measured traits[19] with the 20 mg/L dose (T4) proving most effective in promoting germination, biomass accumulation and seedling vigour. Germination percentages in both Aditya Inuka 432 and BPT 5204 increased markedly under AgNP treatment, with T4 achieving 100% in Aditya Inuka 432 and 99% in BPT 5204. Parallel improvements were observed in shoot and root development. At T4, shoot lengths reached 7.81 cm in Aditya Inuka 432 and 9.81 cm in BPT 5204, while root lengths extended to 8.21 cm and 23.45 cm respectively. The pronounced root–shoot balance highlights the role of AgNPs in fostering robust vegetative development and improving resource acquisition, which is particularly valuable under suboptimal field conditions.

Leaf pigmentation further supported these findings, as treated plants displayed deeper greenness, indicative of higher chlorophyll content and photosynthetic efficiency. The vigour index (up to 669 in Aditya Inuka 432 and 974 in BPT 5204 at T4) and fresh weight (310 g and 612 g respectively) confirmed the improvements in physiological status and biomass productivity.

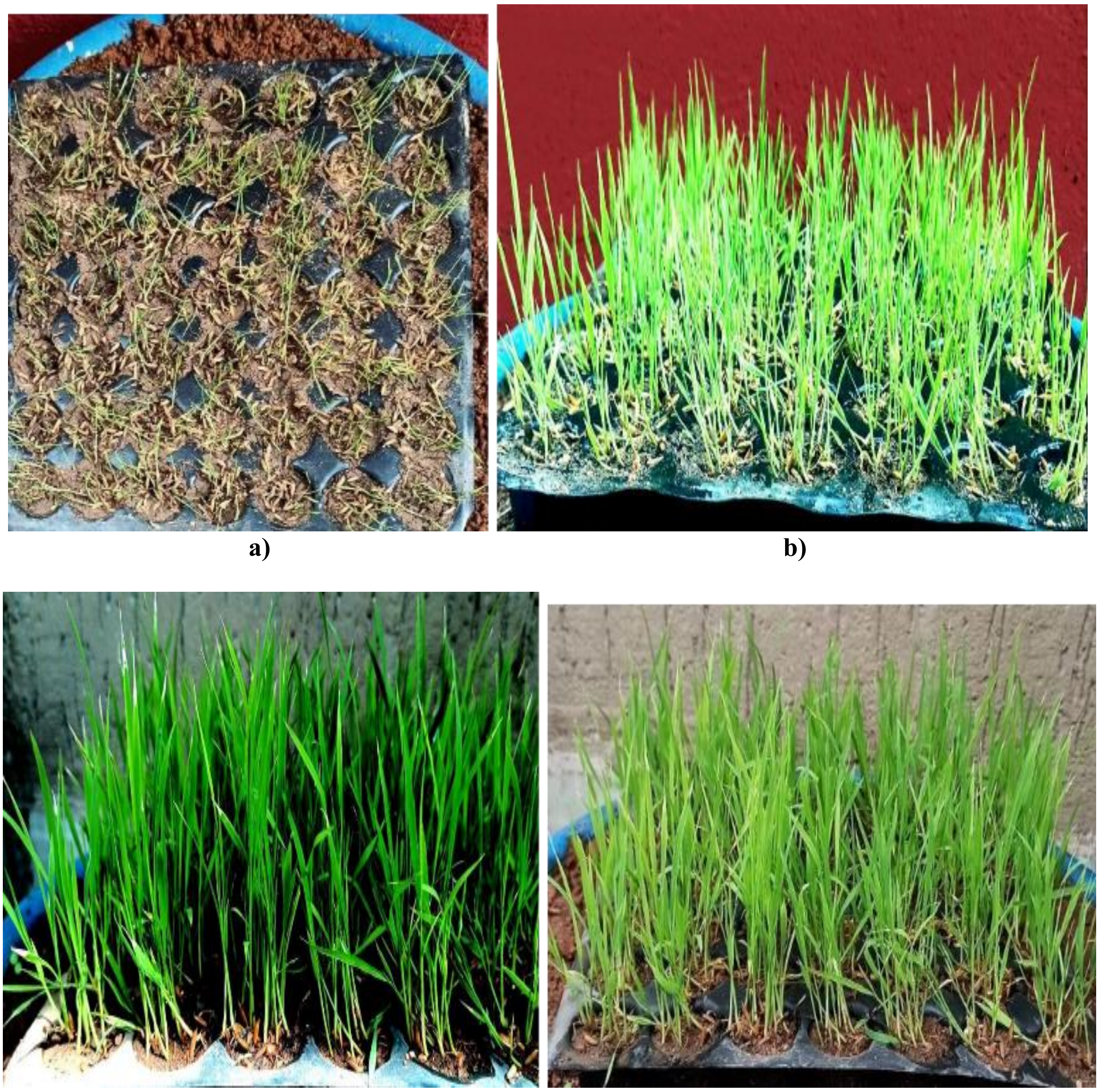
Collectively, these results show that AgNPs not only accelerate early growth but also lay the foundation for stronger crop performance in later developmental stages.

Beyond biological outcomes, the study highlights two broader aspects of novelty and applicability. First, the nanoparticles were synthesized via a sustainable, plant-mediated process using *Bryophyllum pinnatum* leaf extract, underscoring the eco-friendly potential of green nanotechnology compared with conventional fertilizers[13]. Second, the observed dose–response relationship (with optimal effects at 15–20 mg/L) offers a valuable reference for precision agriculture, enabling targeted applications that maximize benefits while minimizing environmental risks[13].

From a global perspective, the integration of green-synthesized AgNPs into rice production aligns with several Sustainable Development Goals (SDGs). By enhancing germination and vigour, these treatments support food security (SDG 2), promote efficient resource use (SDG 12)[14] and contribute to soil health and climate resilience through reduced reliance on chemical fertilizers (SDG 13). Thus, the early growth advantages of AgNPs extend beyond agronomic benefits, offering a sustainable pathway toward resilient and resource-efficient agriculture.

Conclusion

This study demonstrated that green-synthesized silver nanoparticles (AgNPs) significantly enhanced early growth traits in rice. Both Aditya Inuka 432 and BPT 5204 responded positively to nano-fertilizer treatments, with higher concentrations (15–20 mg/L) producing the strong effects across germination, shoot and root elongation, vigour index and biomass accumulation. Between the two genotypes, BPT 5204 exhibited greater absolute gains, particularly in root development and biomass, underscoring the role of varietal sensitivity in determining the magnitude of response. The use of *Bryophyllum pinnatum* leaf extract for green synthesis further highlights the eco-friendly potential of this approach compared to conventional methods. Importantly, the observed dose–response trends provide a basis for precision agriculture, enabling variety-specific optimization of nano-fertilizer use.



a) b) c) d)

Figure 2: Comparative field survey of rice seedlings and growth under AgNP treatments.
a) Early-stage seedlings under stress conditions. b) Healthy establishment under AgNP application.
c) Dense and vigour canopy growth. d) Weaker growth in untreated/control plots.

Overall, AgNP-based nano-fertilizers not only advance sustainable crop production but also align with global food security goals, offering a promising pathway for resilient agricultural practices.

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