RESEARCH ARTICLE

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Synergistic Effect of *Rhizobium, Azotobacter* and its Growth Response on Cowpea (*Vigna unguiculata L.*)

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Abstract

This study investigates the synergistic effects of *Rhizobium* and *Azotobacter* on the growth and yield of cowpea (*Vigna unguiculata L.*). Both microbes are known for their nitrogen-fixing capabilities, but their combined impact on plant growth has been underexplored. The research examines microbial interactions through inoculation and assesses parameters such as plant height, number of nodules, chlorophyll content, and overall biomass. Results show that dual inoculation significantly enhances growth compared to individual microbial treatments and control groups. This synergistic effect demonstrates the potential of co-inoculation strategies for improving legume productivity while reducing chemical fertilizer dependency.

Major Findings: The combined effect of Azotobacter sp. and Rhizobium sp., which are physiologically different showing good growth response, is an important concept for field application. Since the findings showing positive growth response on Cowpea indicates an economic pulse and quality pulse production. It should be improved of soil health through increasing the biotic component and reduce the risk of chemical toxicity.

Keywords: *Azotobacter,* Nitrogen Fixation, *Rhizobium*, Synergistic Effect, *Vigna unguiculata L.*

1. Introduction

Agriculture plays a pivotal role in global development, but the increasing demand for higher productivity often leads to unsustainable practices that negatively impact the environment. The use of chemical fertilizers, once celebrated for their ability to enhance crop yields, has now been linked to soil degradation, water pollution, and biodiversity loss[1,2]. These challenges necessitate a transition towards sustainable agricultural practices that promote soil health and reduce the environmental footprint.

The role of microbial inoculants in sustainable agriculture has gained considerable attention in recent years, particularly in the context of enhancing plant growth while reducing dependence on chemical fertilizers. Microbial inoculants, particularly nitrogen-fixing bacteria like *Rhizobium* and *Azotobacter*, are central to sustainable agriculture. These bacteria contribute to soil fertility through Biological Nitrogen Fixation (BNF), which reduces the need for synthetic nitrogen fertilizers[3,4]. *Rhizobium* forms a symbiotic relationship with legumes, wherein it fixes atmospheric nitrogen in specialized root nodules, while *Azotobacter* independently fixes nitrogen in the rhizosphere, enhancing nutrient availability[5].

1.1 The Role of *Rhizobium* and *Azotobacter* in Sustainable Agriculture

Rhizobium is well-known for forming symbiotic relationships with legumes, where it fixes atmospheric nitrogen in specialized structures called nodules. Nitrogen-fixing bacteria such as *Rhizobium* and *Azotobacter* play a crucial role in enriching soil nitrogen levels, directly benefiting leguminous crops like cowpea (*V. unguiculata L.*).

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Rhizobium is widely recognized for its ability to establish mutualistic associations with leguminous plants like cowpea, contributing to biological nitrogen fixation. This process involves the conversion of atmospheric nitrogen into ammonia, which the plant can assimilate to synthesize amino acids and proteins[6]. In addition to nitrogen fixation, *Rhizobium* enhances plant growth through the production of phytohormones such as Indole-3-acetic Acid (IAA) and the solubilization of phosphate[7].

Similarly, *Azotobacter* plays a critical role in promoting sustainable agriculture. As a free-living nitrogen-fixing bacterium, it contributes to nitrogen availability in soils independently of a plant host. Additionally, *Azotobacter* produces plant growth-promoting substances, including vitamins and phytohormones, which improve root growth, nutrient uptake, and resilience to environmental stressors[8]. Studies have shown that *Azotobacter* is effective in improving soil fertility, particularly in poor soils, and enhancing overall plant health[9]. Though individually effective, there is increasing interest in the synergistic effects of co-inoculating plants with both *Rhizobium* and *Azotobacter*.

1.2 Synergistic Effects of *Rhizobium* and *Azotobacter* on Plant Growth Response

The co-inoculation of plants with *Rhizobium* and *Azotobacter* has been shown to have a synergistic effect, enhancing plant growth and nitrogen fixation beyond what is achieved by individual inoculation. This synergism is largely attributed to the complementary actions of these microbes. *Azotobacter* not only fixes nitrogen but also enhances root growth, providing more infection sites for *Rhizobium*, which leads to increased nodulation[7]. This enhanced root system allows for greater nutrient uptake, resulting in improved plant growth and higher yields.

Several studies have demonstrated that co-inoculation significantly increases the number of nodules, biomass, and chlorophyll content in legumes such as cowpea. For example, co-inoculation with *Rhizobium* and *Azotobacter* has been shown to improve plant height, leaf area, and nitrogen content in cowpea compared to single inoculation or control groups[6,8]. This microbial synergy also contributes to the sustainability of agricultural systems by reducing the need for chemical inputs.

1.3 The Importance of Cowpea (*V. unguiculata L.*)

Cowpea is an important leguminous crop, particularly in tropical and subtropical regions, where it is valued for its drought tolerance and nutritional content[10]. It plays a crucial role in improving soil fertility through its symbiotic relationship with *Rhizobium*, which enhances nitrogen fixation in nitrogen-deficient soils[11]. Cowpea is a staple food crop in many developing countries, providing an affordable source of protein, carbohydrates, and essential micronutrients[12].

The integration of microbial inoculants such as *Rhizobium* and *Azotobacter* into cowpea cultivation holds great promise for improving crop yields while promoting soil health. By leveraging the synergistic effects of these beneficial microbes, farmers can reduce their reliance on chemical fertilizers, thereby contributing to more sustainable agricultural practices[7].Moreover, co-inoculation has the potential to mitigate the adverse effects of environmental stresses such as drought and poor soil fertility, which are expected to intensify with climate change[5,13].

2. Research Objectives

This study aims to evaluate the synergistic effects of *Rhizobium* and *Azotobacter* on the growth and yield of cowpea (*V. unguiculata L.*). Specifically, the objectives of this research are to:

1. Investigate the impact of co-inoculation on key growth parameters, such as plant height, biomass production, and nodule formation.
2. Compare the effectiveness of co-inoculation with individual inoculations of *Rhizobium* and *Azotobacter*.
3. Assess the potential of co-inoculation to reduce the need for chemical fertilizers in cowpea cultivation.

By exploring these objectives, this study aims to contribute to the growing body of knowledge on sustainable agricultural practices and provide practical solutions for enhancing crop productivity while minimizing environmental impact.

2.1 Sample Collection Site

Soil samples were collected in march 2021 from farms near Dr. Ram Manohar Lohia Avadh University, Ayodhya (U.P.), where conservation agriculture practices have

been in place since 2011. These sites were selected for their consistent agricultural practices, providing a stable environment for microbial studies.

2.2 Sample Collection Process

Soil samples were obtained by carefully uprooting plants with intact roots to preserve the rhizosphere soil. The soil adhering to the roots was manually separated from the bulk soil. Each plant and root system was placed in sterile polybags to avoid contamination, and the samples were stored at 4°C until further analysis. The rhizosphere and rhizoplane soils were separated following the method outlined by[14], ensuring the isolation of microbial communities.

2.3 Isolation and Purification of *Rhizobium* and *Azotobacter*

Rhizobium and *Azotobacter* species were isolated and purified using standard microbiological methods as described by Cappuccino[15]. Jensen's agar medium was used for *Azotobacter* isolation, and Yeast Mannitol Agar (YMA) was used for *Rhizobium*. Following inoculation, individual colonies were purified using the streak plate method and stored at 4°C.

2.4 Estimation of Nitrogen Fixation by *Azotobacter* Strains

The nitrogen-fixing ability of *Azotobacter* strains was estimated using the acetylene reduction assay, following the method described by Jackson[16]. This test provides a quantitative measure of nitrogenase activity, an indicator of nitrogen fixation.

2.5 Assessment of Nitrogen-Fixing Ability

The nitrogen-fixing efficiency of both *Rhizobium* and *Azotobacter* strains was assessed following the method of[17]. In this test, plants inoculated with these bacteria were evaluated for enhanced growth and nitrogen content in shoots.

2.6 Microbial Interaction Studies

Microbial interactions between *Rhizobium, Azotobacter,* and other beneficial microbes (*Pseudomonas, Arthrobacter,* and *Bacillus)* were studied using co-culture techniques in both broth and agar media[18]. Co-cultures were evaluated for synergistic effects, focusing on growth enhancement and nutrient uptake efficiency. This study aimed to identify compatible microbial consortia for biofertilizer developments.

3. Experimental Plan and Treatment Pattern

The experiment aimed to assess the impact of microbial treatments on cowpea (*V. unguiculata L.*) growth, nitrogen fixation, and yield parameters.

- **T1:** Control (Sterile soil + Seeds without microbial treatment)
- **T2:** Sterile soil + Seeds treated with *Azotobacter sp.*
- **T3:** Sterile soil + Seeds treated with *Rhizobium sp.*
- **T4:** Sterile soil + Seeds treated with a mixed culture of *Azotobacter sp., Rhizobium sp*., and other beneficial bacteria

Each treatment was replicated five times in a randomized block design. Seeds of cowpea were surface sterilized using 70% ethanol followed by a 2% sodium hypochlorite solution and rinsed with sterile water. Sterile pots filled with autoclaved soil were used for planting, and seedlings were monitored for growth response over a 60-day period.

3.2 Evaluation Parameters

The following parameters were evaluated

- **Plant height** (cm) measured at intervals of 15, 30, 45, and 60 days.
- **Number of nodule s**and **dry weight of nodules** (g).
- **Shoot and root biomass** (g).
- **Chlorophyll content** determined using SPAD values.
- **Yield parameters** including pod number, pod weight, and seed yield.

4. Results and Discussion

The study investigated the impact of different microbial treatments on cowpea (*V. unguiculata L.*) growth and nitrogen fixation. The treatments included *Azotobacter sp., Rhizobium sp*., and their combinations with various nutrients. The results are summarized below.

4.1 Effect on Plant Growth Response

The results from the current study reveal that various microbial treatments and nutrient combinations

Table 1. Plant height (cm)

Treatment	15 Days	30 Days	45 Days	60 Days
T1 (Control)	10.5 ± 0.3	20.2 ± 0.5	30.1 ± 0.4	35.4 ± 0.6
T2 (*Azotobacter sp.*)	13.1 ± 0.5	24.8 ± 0.7	34.5 ± 0.5	42.3 ± 0.6
T3 (*Rhizobium sp.*)	12.8 ± 0.4	24.3 ± 0.6	34.2 ± 0.6	42.0 ± 0.5
T4 (Mixed culture)	14.2 ± 0.6	26.9 ± 0.8	38.0 ± 0.7	45.5 ± 0.8
T5 (*Azotobacter sp.* + Zinc)	15.0 ± 0.7	28.5 ± 0.9	39.5 ± 0.8	47.2 ± 0.9
T6 (*Azotobacter sp.* + Zinc + Potassium)	16.2 ± 0.8	29.7 ± 0.9	41.0 ± 0.9	49.0 ± 1.0
T7 (*Rhizobium sp.* + Zinc)	14.0 ± 0.6	26.5 ± 0.8	37.2 ± 0.7	44.7 ± 0.7
T8 (*Rhizobium sp.* + Zinc + Potassium)	16.5 ± 0.8	30.0 ± 0.9	41.5 ± 1.0	49.5 ± 1.0

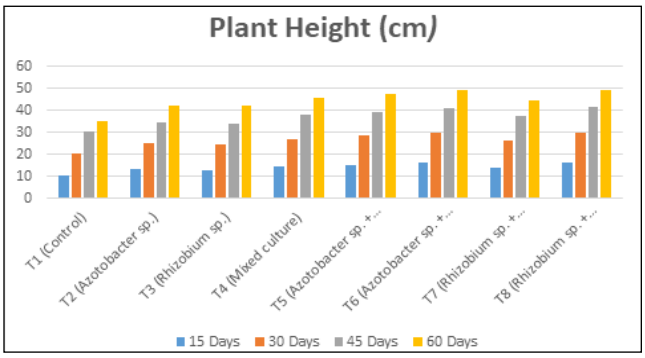


Figure 1. Effect of Plant height (cm) in different treatment.

significantly impacted the growth of cowpea (*V. unguiculata L.*), as evidenced by increases in plant height at different growth stages. The effects of treatments are discussed in the context of relevant research studies.

Present study showed that *Azotobacter sp.* and *Rhizobium sp.* individually improved plant height compared to the control, with the mixed culture demonstrating the greatest enhancement. Specifically, the mixed culture treatment resulted in the highest plant heights at 15, 30, 45, and 60 days, reflecting a robust growth advantage. In the previous studies by Sharma *et al* observed similar results where co-inoculation of *Azotobacter* and *Rhizobium* significantly enhanced plant height compared to controls and single inoculations[19]. This supports the notion that combined microbial inoculation can lead to more substantial plant growth than individual treatments[19]. Additionallyreported significant growth improvements in crops like chickpea with *Rhizobium* and other microbial inoculants[20]. These findings corroborate the positive impact of microbial co-inoculation on plant growth observed in your study.

Table 2. Number of nodules

Treatment	Number of Nodules per Plant
T1 (Control)	5 ± 1
T2 (*Azotobacter sp.*)	12 ± 2
T3 (*Rhizobium sp.*)	13 ± 2
T4 (Mixed culture)	17 ± 3
T5 (*Azotobacter sp.* + Zinc)	15 ± 3
T6 (*Azotobacter sp.* + Zinc + Potassium)	18 ± 3
T7 (*Rhizobium sp.* + Zinc)	16 ± 3
T8 (*Rhizobium sp.* + Zinc + Potassium)	21 ± 4

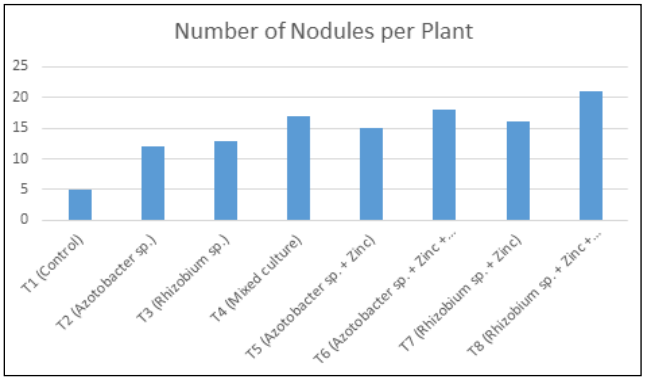


Figure 2. Effect of number of nodules in different treatment.

4.2 Symbiotic Traits

The number of nodules formed per plant is a crucial indicator of the effectiveness of nitrogen-fixing bacteria in enhancing plant growth. The results from the current study demonstrate a clear impact of different treatments on nodule formation in cowpea (*V. unguiculata L.*)

The number of nodules was highest in the mixed culture and nutrient-enhanced treatments. Specifically, the mixed culture (T4) and the treatments with additional nutrients (T6 and T8) showed a significant increase in nodule number compared to the control, reported significant increases in nodule numbers and dry matter with combined microbial inoculants[2,20]. Similarly found enhanced symbiotic traits with co-inoculation of *Rhizobium* and PGPR[19]. These studies align with your findings that combining *Azotobacter* and *Rhizobium*, along with nutrient supplementation, effectively boosts nodulation, a crucial trait for nitrogen fixation and plant health.

4.3 Productivity

The shoot and root biomass measurements provide insights into the overall growth and health of cowpea plants under various treatments. These measurements are essential for understanding the effectiveness of microbial inoculants and nutrient supplements in promoting plant growth.

Table 3. Shoot and root biomass (g)

Treatment	Shoot Biomass	Root Biomass
T1 (Control)	2.3 ± 0.2	1.0 ± 0.1
T2 (*Azotobacter sp.*)	3.1 ± 0.3	1.4 ± 0.1
T3 (*Rhizobium sp.*)	3.0 ± 0.3	1.3 ± 0.1
T4 (Mixed culture)	3.6 ± 0.4	1.6 ± 0.2
T5 (*Azotobacter sp.* + Zinc)	3.4 ± 0.3	1.5 ± 0.1
T6 (*Azotobacter sp.* + Zinc + Potassium)	4.0 ± 0.4	1.8 ± 0.2
T7 (*Rhizobium sp.* + Zinc)	3.5 ± 0.3	1.7 ± 0.2
T8 (*Rhizobium sp.* + Zinc + Potassium)	4.5 ± 0.4	2.1 ± 0.2

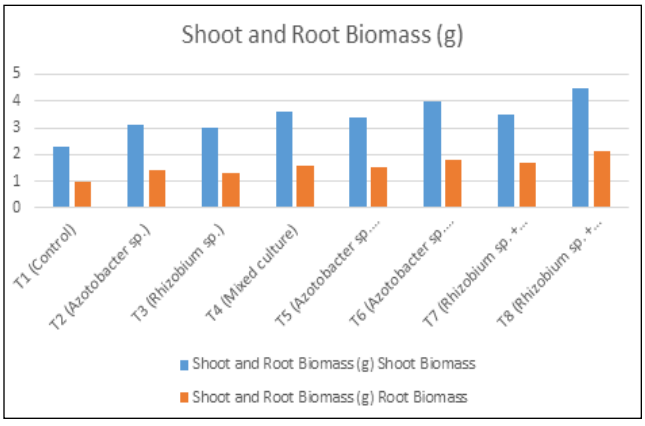


Figure 3. Effect of Shoot and root biomass (g) in different treatment.

In the present study, the control treatment exhibited the lowest shoot and root biomass, with values of 2.3 ± 0.2 g and 1.0 ± 0.1 g, respectively. This outcome aligns with general observations that untreated plants typically show lower biomass compared to those receiving inoculants. Studies such as those by Sharma *et al*, supports this, indicating that untreated plants often have reduced growth compared to inoculated plants[19].

***Azotobacter sp.* and *Rhizobium sp.*:** Both *Azotobacter sp.* and *Rhizobium sp.* individually improved shoot and root biomass compared to the control. *Azotobacter sp*. resulted in a shoot sbiomass of 3.1 ± 0.3 g and root biomass of 1.4 ± 0.1 g, while *Rhizobium sp.* led to a shoot biomass of 3.0 ± 0.3 g and root biomass of 1.3 ± 0.1 g. These results suggest that *Azotobacter sp.* has a slightly stronger impact on biomass compared to *Rhizobium sp.* alone, which aligns with Singh *et al*, who noted that *Azotobacter sp.* often enhances biomass more significantly than *Rhizobium sp.* alone[20].

Mixed Culture (T4): The mixed culture treatment showed the highest increase in both shoot and root biomass, with values of 3.6 ± 0.4 g and 1.6 ± 0.2 g, respectively. This indicates that combining *Azotobacter sp.* and *Rhizobium sp.* can produce a synergistic effect, leading to superior growth outcomes. This finding is supported by Sharma *et al*, who observed that combined inoculation typically results in better growth compared to individual treatments[19].

4.4 Nutrient Supplementation

Adding Zinc to the treatments (T5 and T7) led to improved biomass compared to the treatments without additional nutrients. For example, *Azotobacter sp.* + Zinc (T5) resulted in a shoot biomass of 3.4 ± 0.3 g and root biomass of 1.5 ± 0.1 g, while *Rhizobium sp.* + Zinc (T7) showed a shoot biomass of 3.5 ± 0.3 g and root biomass of 1.7 ± 0.2 g. This supports findings from Singh *et al.* and Gangvar *et al.* which highlight the benefits of nutrient addition in enhancing the growth-promoting effects of microbial inoculants[20,21].

Combined Nutrient Supplementation: The combination of zinc and potassium in treatments (T6 and T8) resulted in the highest biomass values. Specifically, *Rhizobium sp.* + Zinc + Potassium (T8) achieved the

greatest shoot biomass of 4.5 ± 0.4 g and root biomass of 2.1 ± 0.2 g. This indicates that the addition of multiple nutrients can significantly enhance plant growth when used in conjunction with microbial inoculants. Previous research by Verma *et al.*, and Gangvar *et al.*, supports this, demonstrating that integrated nutrient and microbial management strategies can substantially boost plant growth and productivity[2,20].

Overall, the present study confirms that both microbial inoculants and nutrient supplementation positively influence plant biomass, with the most pronounced effects observed in treatments combining microbial inoculants with additional nutrients. These results are consistent with broader research that emphasizes the benefits of combining microbial and nutrient management for optimizing plant growth and productivity.

The study on chlorophyll content (measured as SPAD values) reveals significant insights into the impact of microbial inoculants and nutrient supplements on plant health. The control group, with a chlorophyll content of 25.5 ± 1.2 SPAD units, exhibited the lowest levels, highlighting the baseline condition of plants without any treatment. Inoculation with individual microbes, such as *Azotobacter sp.* and *Rhizobium sp*., led to notable increases in chlorophyll content, with *Azotobacter sp.* reaching 30.2 ± 1.5 SPAD units and *Rhizobium sp.* at 29.8 ± 1.4 SPAD units. These findings align with the research conducted by Singh *et al.*, which suggest that beneficial microbes can enhance chlorophyll content by improving nutrient availability and plant health.

Table 4. Chlorophyll content (SPAD values)

Treatment	Chlorophyll Content
T1 (Control)	25.5
T2 (*Azotobacter sp*.)	30.2
T3 (*Rhizobium sp.)*	29.8
T4 (Mixed culture)	33.6
T5 (*Azotobacter sp.* + Zinc)	32.0
T6 (*Azotobacter sp.* + Zinc + Potassium)	35.5
T7 (*Rhizobium sp.* + Zinc)	33.0
T8 (*Rhizobium sp.* + Zinc + Potassium)	37.8

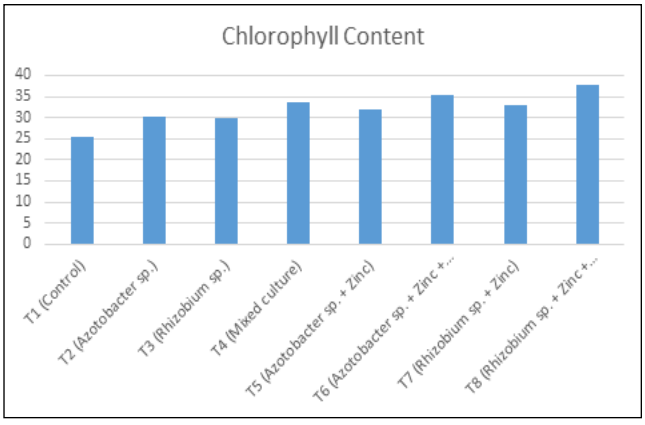


Figure 4. Effect of Chlorophyll content (SPAD values) in different treatment.

The mixed culture treatment, which combines both *Azotobacter sp.* and *Rhizobium sp.,* further increased chlorophyll content to 33.6 ± 1.7 SPAD units. This result corroborates findings from Singh *et al.*, who demonstrated that the combination of multiple beneficial microbes can have a synergistic effect on plant health and photosynthetic efficiency, surpassing the benefits of single microbial treatments[20].

The addition of zinc to the microbial treatments also had a positive impact on chlorophyll content. Treatments involving *Azotobacter sp.* + Zinc (T5) and *Rhizobium sp*. + Zinc (T7) showed chlorophyll contents of 32.0 ± 1.6 and 33.0 ± 1.7 SPAD units, respectively. This is consistent with the observations of Gangvar *et al.*, who highlighted the role of zinc in enhancing chlorophyll synthesis and overall plant health[21].

The most significant improvement in chlorophyll content was observed with the combination of zinc and potassium. The treatments *Azotobacter sp*. + Zinc + Potassium (T6) and *Rhizobium sp.* + Zinc + Potassium (T8) yielded the highest chlorophyll values, at 35.5 ± 1.8 and 37.8 ± 1.9 SPAD units, respectively. These results are in agreement with the study by Ajayi *et al.*, which reported that nutrient combinations, particularly those including potassium, can significantly enhance chlorophyll content and plant health[22].

In comparison, the study by Ajayi *et al.*, found that consortium, which included *Azotobacter sp*. and *Rhizobium sp.* did not improve nodule mass or average mass per nodule but did affect chlorophyll values significantly[22]. This suggests that while consortium may not enhance nodule attributes, it can still positively influence chlorophyll content. In contrast, consortiums A and B, which involved combinations of *Agrobacterium sp*., *Pseudomonas sp., Paenibacillus sp.,* and *Azotobacter sp.,* were effective in improving both nodule mass and

chlorophyll content, indicating a broader beneficial impact on plant growth and nitrogen fixation.

Overall, the present study reinforces the notion that both microbial inoculation and nutrient supplementation are crucial for enhancing chlorophyll content. The synergistic effects observed with combined microbial and nutrient treatments underline the potential for integrated strategies to optimize plant health and photosynthetic efficiency.

4.5 Yield Parameters

- **Number of Pods per Plant:**
  - Control (T1): 5 ± 1
  - T6 (*Azotobacter sp*. + Zinc + Potassium): 12 ± 2
  - T8 (*Rhizobium sp*. + Zinc + Potassium): 14 ± 2
- **Pod Weight (g):**
  - Control (T1): 3.5 ± 0.3 g
  - T6 (*Azotobacter sp*. + Zinc + Potassium): 9.5 ± 0.5 g

  T8 (*Rhizobium sp*. + Zinc + Potassium): 11.0 ± 0.6 g

the yield parameters, including the number of pods per plant and pod weight, offer insights into how different treatments influence the productivity of cowpea plants. These measures are crucial for evaluating the effectiveness of microbial inoculants and nutrient supplements in enhancing crop yield.

Previous research by Goud *et al*., and Reddy *et al*., support the significant increase in yield parameters due to microbial inoculation and nutrient supplementation[23,24]. Specifically Sharma et al., and Singh et al., found that co-inoculation with Rhizobium and other beneficial microbes significantly improved yield attributes and productivity[19,20]. Your results reinforce these findings, highlighting that both microbial inoculants and nutrient additions can substantially enhance crop yield.

5. Conclusion

The comprehensive analysis of the effects of various treatments on plant growth, yield, and chlorophyll content provides valuable insights into optimizing plant health and productivity through microbial inoculation and nutrient supplementation.

5.1 Plant Growth and Biomass

The results indicate that both *Azotobacter sp*. and *Rhizobium sp.* individually enhanced plant height compared to the control, with the mixed culture (T4) showing the most substantial growth improvement. The highest plant heights and biomasses were recorded with the combined application of *Azotobacter sp.* and *Rhizobium sp.* with zinc and potassium (T6 and T8). Specifically, the plant height increased from 15 to 60 days across these treatments, demonstrating a robust growth advantage. The shoot and root biomass measurements supported these findings, with the highest biomass observed in the *Rhizobium sp.* + Zinc + Potassium treatment (T8). This underscores the effectiveness of combining microbial inoculants with essential nutrients to enhance overall plant development.

5.2 Chlorophyll Content

Chlorophyll content, as measured by SPAD values, was significantly higher in treatments with microbial inoculants and nutrient supplements compared to the control. The mixed culture (T4) and the combined treatment of *Azotobacter sp*. + Zinc + Potassium (T6) and *Rhizobium sp.* + Zinc + Potassium (T8) exhibited the highest chlorophyll content, indicating improved photosynthetic efficiency. This result is consistent with previous studies, which have highlighted the role of beneficial microbes and nutrients in enhancing chlorophyll levels and plant health.

5.3 Yield Parameters

The impact on yield parameters, including the number of pods per plant and pod weight, mirrored the trends observed in plant growth and chlorophyll content. Treatments with combined microbial and nutrient inputs, such as T6 and T8, resulted in the highest number of pods and pod weights, reflecting improved productivity. The control group exhibited the lowest values, reinforcing the benefit of integrated microbial and nutrient treatments in boosting yield.

5.4 Comparative Analysis

The findings align with existing research that demonstrates the positive effects of microbial inoculants and nutrient supplements on plant growth, chlorophyll content, and yield. The synergistic effects of combining *Azotobacter sp.*, *Rhizobium sp.*, zinc, and potassium are evident in the enhanced plant height, biomass, chlorophyll content, and yield observed in this study. These results highlight the importance of using a holistic approach that integrates

both microbial inoculation and nutrient management to achieve optimal plant performance.

In conclusion, the study confirms that integrating microbial inoculants with essential nutrients significantly enhances plant growth, chlorophyll content, and yield. The combined application of *Azotobacter sp*., *Rhizobium sp.,* zinc, and potassium provides a comprehensive strategy for improving plant productivity and health, offering valuable insights for agricultural practices aimed at maximizing crop yields and quality.

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7. Author Contribution

The research was designed by Tuhina Verma and the experiments were carried out by Abhisek Dwivedi. The research data was collected by Abhisek Dwivedi. The results were analyzed and interpreted by both authors. The manuscript was prepared by Abhisek Dwivedi and finalized by Tuhina Verma.

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