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RESPONSE OF AZOTOBACTER AND PHOSPHATE SOLUBILIZING BACTERIA IN COMBINATION WITH UREA AND SINGLE SUPER PHOSPHATE ON GROWTH AND YIELD UNDER RICE CROP IN ALLUVIAL SOILS OF AYODHYA DISTRICT U.P., INDIA

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ABSTRACT

There was also a field experiment conducted at Kharif season 2023-24 on the Student's Instructional Farm, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya (U.P.) to determine the impact of integrated application of Azotobacter and PSB in association with different levels of urea and SSP on growth, yield, and economics of rice. The experiment consisted of eight treatments with three replications in randomized block design, i.e., T_1 (Absolute control), T_2 (100% RDF), T_3 (100% RDF + Azotobacter), T_4 (100% RDF + PSB), T_5 (100% RDF + Azotobacter + PSB), T_6 (100% NK + 75% P + PSB), T_7 (75% N + 100% PK + Azotobacter), and T_8 (75% NP + 100% K + Azotobacter + PSB). Sarju-52' rice variety was employed as test crop.

The results of treatment revealed that co-inoculation of PSB and Azotobacter with 100% RDF (T_5) enhanced the tillering, plant height, biomass yield, yield characters, and grain as well as straw yield significantly with respect to the remaining treatments. T_5 had maximum grain yield (51.34 q/ha), straw yield (74.04 q/ha), and biological yield (125.38 q/ha), which was accompanied by enhanced uptake of nitrogen (64.46 kg/ha), phosphorus (12.02 kg/ha), and potassium (21.67 kg/ha) in grain. Economic appraisal revealed that T_5 recorded the highest gross return (Rs. 1,85,053.60), net return (Rs. 65,944.80), and benefit-cost ratio (1.24).

Treatment T_6, T_7, and T_8 were also observed as good in terms of yield and profitability that partial replacement of fertilizers with biofertilizers can be a great nutrient management practice. The study established that integrated use of Azotobacter and PSB with chemical fertilizers promotes productivity improvement, nutrient uptake, and profitability of rice in the alluvial soils of the prevailing scenario of eastern Uttar Pradesh.

***Keywords* :** Azotobacter, Phosphate Solubilizing Bacteria (PSB), Co-inoculation, Integrated Nutrient Management.

Introduction

Rice (*Oryza sativa* L.) is a crop for the diet of more than half the people in the world and still the backbone of India's national food security and rural livelihoods. The world's second highest producer and consumer, India cultivated rice on 40.73 million ha in 2023-24 with a yield of 113.26 million tonnes with a mean productivity of 2.78 t/ha (Anonymous, 2023-24). Uttar Pradesh contributes more than 15.86 million tonnes from 5.73 million hectares alone. But rising productivity at the expense of sustainability is a matter of concern, especially in the context of the type of Indo-Gangetic plain alluvial soils like Ayodhya.

Nitrogen (N) and phosphorus (P) are the significant limiting nutrients of rice. Nitrogen is required for vegetative growth, photosynthesis, and protein biosynthesis (Lea and Miflin, 2011), whereas phosphorus plays a role in energy transfer, root development, and grain production (Liu, 2021). However, nitrogen in rice is only 30% efficient, and enormous losses are through leaching, volatilization, and denitrification (Raghuram & Sharma, 2019). Phosphorus too is not efficient since 80-90% of the added P is fixed in insoluble forms in soil (Pereira & Castro, 2014). Excessive and indiscriminate application of fertilizers decrease not only the efficiency of nutrient uptake but also cause soil degradation, water eutrophication, and greenhouse gas emission (Ducousso-Détrez *et al.*, 2024).

Integrated nutrient management with chemical fertilizers and microbial inoculants is increasingly encouraged as a green option. Of the microbial biofertilizers, Azotobacter, a diazotroph of the rhizosphere found in soil, increases nitrogen availability by reducing atmospheric N□ to fixed state and excreting growth-regulating compounds such as IAA and gibberellins (Shahwar *et al.*, 2023). Its use has been found to have the capability to contribute 19-47% nitrogen required in rice, particularly under conditions of low-N or drought stress (Silletti *et al.*, 2021). Apart from yield enhancement, Azotobacter promotes root and microbial development, leading to enhanced tolerance and soil health (Kurrey *et al.*, 2018).

Like PSB, phosphate solubilizing bacteria also have a significant function in mobilizing insoluble phosphorus pools by organic acids, phosphatases, and chelating compounds (Rawat *et al.*, 2022). PSB has been found to induce phosphorus uptake, enhance PUE, and enhance root vigour at early stages, ultimately leading to enhanced yields (Heuer *et al.*, 2017). They are especially effective in Uttar Pradesh alluvial soils with P deficiency because of excessive P fixation and low availability of native P pool (Hazra *et al.*, 2018).

Urea and single super phosphate (SSP) are still the largest N and P fertilizers applied by Indian farmers. But, in the absence of organic or biological inputs, they are inefficient. But, in such situations, synergistic application of urea and SSP with Azotobacter and PSB is a good method to improve the productivity of rice without burdening the environment excessively. The recent studies have shown that co-inoculation of the biofertilizers with the optimum amount of the fertilizers has been effective in maximizing the grain yield, nutrient uptake, and even the functioning of the soil microbial community (Rawat *et al.*, 2022).

Keeping all the above factors in view, the current research was conducted to examine the potential of Azotobacter and phosphate solubilizing bacteria to work in conjunction with urea and single super phosphate in promoting rice growth and yield achievement of *Oryza sativa* L. grown in Ayodhya's alluvial soil. The study is focused on making an input to the process of sustainable intensification and integrated nutrient management conducted in Eastern India's rice ecosystem.

Materials and Methods

Experimental Site and Soil Characteristics

The experiment was conducted during the Kharif season 2024-25 at Acharya Narendra Deva University of Agriculture and Technology, Student's Instructional Farm, Kumarganj, Ayodhya (U.P.), India. The experimental site is located at 26.47° N latitude and 82.12° E longitude and has an altitude of 113 meters (mean sea level). The soil of the experimental field was silt loam in nature. Pre-experimental soil analysis was pH 7.57 at a soil:water ratio of 1:2.5 and electrical conductivity of 0.39 dS m^{-1}. Organic carbon was 0.56% as measured by Walkley and Black's (1934) method. Available nitrogen was 215.8 kg ha^{-1} (alkaline $KMnO_4$ procedure), phosphorus 19.2 kg ha^{-1} (Olsen's procedure), and potassium 204.5 kg ha^{-1} (neutral normal ammonium acetate extraction and flame photometry). Its particle density and bulk density were 2.64 Mg m^{-3} and 1.39 Mg m^{-3}, respectively.

Experimental Design and Treatment Details

The experiment was conducted in a Randomized Block Design (RBD) with eight treatments replicated three times. Treatment options were: T_1 - Absolute Control, T_2 - 100% RDF, T_3 - 100% RDF + Azotobacter, T_4 - 100% RDF + PSB, T_5 - 100% RDF + Azotobacter + PSB, T_6 - 75% RDF + Azotobacter + PSB, T_7 - 50% RDF + Azotobacter + PSB, and T_8- Azotobacter + PSB. The fertilizer application rate suggested was 150 kg N, 60 kg P_2O_5, and 40 kg K_2O ha^{-1}, supplied by urea, SSP, and MOP, respectively. Root dips of biofertilizers Azotobacter and PSB at the dose of 250 g ha^{-1} for each were applied prior to transplanting.

Crop and Agronomic Practices

Rice cv. 'Sarju-52' was transplant on 12 July 2024 at a spacing of 20 cm × 10 cm, three seedlings per hill, and with the aid of 30-day-old seedlings. Plot size was 4 m × 3 m (12 m²) for each treatment. All treatments were uniformly followed with common agronomic practices such as puddling, irrigation, and weed management.

Growth and Yield Observations

Growth parameters like plant height, fresh weight, dry weight, number of tillers per hill, and dry matter accumulation were recorded at the respective growth stages. Plant height from soil level to the apex of the longest leaf was measured in five randomly chosen plants from each plot. Fresh and dry weights were determined by weighing the entire above-ground portion prior to and following oven drying at 65 ± 2°C to constant weight. The dry matter accumulation was derived from these weights. Yield components including number of panicles per hill, panicle length, number of grains per panicle, and test weight (1000-grain weight) were determined on five randomly selected hills. Grain and straw yield were taken from the net plot area and expressed as t ha^{-1}.

Nutrient Uptake and Analysis

Grain and straw were cut and oven-dried, ground, and analyzed for nutrient levels. Nitrogen was estimated using the Kjeldahl technique. For phosphorus and potassium estimation, samples were digested by acid treatment using a triacid mixture (HNO_3:H_2SO_4:$HClO_4$ in 9:3:1 ratio). Phosphorus was estimated colorimetrically by vanadomolybdate yellow colour technique and potassium by flame photometry. Uptake of nutrients was obtained by multiplying grain and straw yields with their corresponding nutrient concentrations and summation of the two.

Economic Analysis

An economic assessment of all the practices was conducted through the calculation of cost of cultivation, gross return, net return, and benefit-cost (B:C) ratio. Minimum Support Price (MSP) ruling in 2024-25 at 2,320 per quintal of paddy was used for the calculation of gross return. Net return was obtained by subtracting total cost of cultivation from gross return. B:C ratio was derived as ratio of gross return and cost of cultivation.

Statistical Analysis

Statistical comparison of data collected were carried out using the Analysis of Variance (ANOVA) suitable for the RBD. The differences due to treatment were tested for significance at 5% level by using Critical Difference (CD) values as per Gomez and Gomez (1984) method. Tabulation and charting of data were carried out in Microsoft Excel 2019, while statistical analysis was conducted using OPSTAT software.

Results

Growth Parameters

Plant Height

Impact of different integrated nutrient management treatments on height of rice plants at various stages of crop development is indicated in Table 1. Analysis revealed that plant height varied significantly between the treatments at all the growth stages (30, 60, 90 DAT and harvest).

At 30 DAT, the maximum height was noted in T_5 (100% RDF + Azotobacter + PSB) at 45.63 cm followed by T_8 (45.52 cm) and T_7 (45.48 cm) at close proximity, all of the highest statistical category 'A'. These treatments realized small but meaningful statistical increases over T_1 (Absolute Control: 45.08 cm), with T_5 being 1.22% higher than it. Increases were noted also over T_2 (100% RDF: 45.15 cm), with T_5 recording a 1.06% increase.

Differences became clear at 60 DAT. T_5 exhibited maximum plant height (90.57 cm) that was 17.5% higher than T_1 (77.07 cm) and 12.0% higher than T_2 (80.90 cm). T_8 and T_7 exhibited 87.63 cm and 87.41 cm, respectively, also higher than RDF. T_3, T_4, and T_6 exhibited intermediate values (84.00, 83.87, and 84.43 cm, respectively).

At 90 DAT, T_5 once more had the tallest plants (119.63 cm) with increments of 16.5% and 16.4% over T_1 (102.73 cm) and T_2 (107.35 cm), respectively. T_8 and T_7 were statistically still equal to T_5 but numerically lower by a slight margin (118.35 cm and 117.57 cm). T_3, T_4, and T_6 still had intermediate performance with 113.62, 111.50, and 113.13 cm.

At harvest, T_5 was still at the top with 120.43 cm plant height. T_8 (118.70 cm) and T_7 (117.87 cm) were also preferred well and recorded 10-15% over control and 9-10% over RDF. Other treatment such as T_3 (113.97 cm), T_4 (111.67 cm), and T_6 (113.35 cm) represented moderate increases over T_1 and T_2.

Plant Weight

The values in Table 1 indicate that the fresh and dry plant weights were greatly affected by the use of biofertilizers and chemical fertilizers at every growth stage.

At 30 DAT, maximum fresh weight was recorded for T_5 (51.09 g), followed by T_8 (47.64 g) and T_7 (47.03 g). Lowest value was for T_1 (29.51 g). The same pattern was noted for dry weight, with maximum being for T_5 (14.33 g), followed by T_8 (14.14 g) and T_7 (14.04 g), and the minimum being that of T_1 (8.85 g). Statistical clustering grouped T_5, T_8, and T_7 into group 'A' for both fresh and dry weight.

On 60 DAT, T_5 still maintained maximum fresh (85.59 g) and dry (22.61 g) weight, followed by T_8 and T_7. T_1 was the lowest. For fresh weight, T_5 and T_8 were statistically within group 'A', whereas for dry weight, T_5, T_8, and T_7 were within group 'A'.

At 90 DAT, T_5 had the highest again for fresh (106.99 g) and dry weight (25.35 g), followed by T_8 and T_7. T_1 was still statistically lowest. T_5 and T_8 were in the top group for fresh weight, and T_5, T_8, T_7, and T_6 made up the top group for dry weight.

At the time of harvest, T_5 had the greatest fresh (128.39 g) and dry (26.08 g) weight, followed by T_8 and T_7. T_1 was the least. Statistical classification grouped T_5 and T_8 in group 'A' for fresh weight, whereas T_5, T_8, T_7, and T_6 were statistically equivalent for dry weight.

Table 1: Effect of co-inoculation of N-fixer and Phosphate solubilizing bacteria (PSB) on growth parameters of paddy crop at various growth intervals.

Treatments	Plant height (cm)				Plant fresh weight (g)				Plant dry weight (g)			
	30 DAT	60 DAT	90 DAT	At harvest	30 DAT	60 DAT	90 DAT	At harvest	30 DAT	60 DAT	90 DAT	At harvest
T_1 Absolute Control	45.08^f	77.07^e	102.73^e	103.20^e	29.51^d	55.63^e	69.54^e	83.45^e	8.85^d	15.17^e	15.76^d	16.12^c
T_2 100% RDF	45.15^{ef}	80.90^d	107.35^{de}	107.83^{de}	43.59^c	71.23^d	89.05^d	106.86^d	13.08^c	19.97^d	19.00^c	19.74^b
T_3 100% RDF + *Azotobacter*	45.29^{cd}	84.00^{cd}	113.62^{bc}	113.97^{bc}	44.43^c	74.27^{cd}	92.84^{cd}	111.40^{cd}	13.33^c	20.25^{cd}	21.29^b	20.33^b
T_4 100% RDF + PSB	45.25^{de}	83.87^{cd}	111.50^{cd}	111.67^{cd}	43.76^c	72.90^{cd}	91.13^{cd}	109.36^{cd}	13.13^c	19.34^d	21.18^b	20.41^b
T_5 100% RDF + *Azotobacter* + PSB	45.63	90.57^a	119.63^a	120.43^a	51.09	85.59^a	106.99^a	128.39^a	14.33^a	22.61^a	25.35^a	26.08^a
T_6 100% NK + 75% P + PSB	45.39^{bc}	84.43^{bc}	113.13^{bcd}	113.35^{bcd}	45.71^b	76.96^{bc}	96.20^{bc}	115.45^{bc}	13.94^b	21.32^{bc}	24.11^a	24.77^a
T_7 75% N + 100% PK + *Azotobacter*	45.48^{ab}	87.41^{ab}	117.57^{ab}	117.87^{ab}	47.03^a	80.05^b	100.06^b	120.07^b	14.04^b	21.72^{ab}	24.18^a	24.92^a
T_8 75% NP + 100% K + *Azotobacter* + PSB	45.52^a	87.63^a	118.35^{ab}	118.70^{ab}	47.64^a	81.60^{ab}	102.00^{ab}	122.41^{ab}	14.14^{ab}	21.95^{ab}	25.07^a	25.92^a
SEm±	**0.03**	**1.05**	**1.98**	**2.71**	**0.56**	**1.54**	**1.92**	**2.31**	**0.09**	**0.41**	**0.60**	**0.55**
C.D. at 5%	**0.10**	**3.21**	**6.00**	**5.93**	**1.04**	**4.70**	**5.83**	**6.99**	**0.27**	**1.32**	**1.82**	**1.67**

Number of Tillers per hill

Data presented in table 2 indicate that tiller hill number was greatly influenced by various nutrient management practices at all stages of growth (30, 60, 90 DAT, and harvest).

T_5 had the maximum mean tiller number at 30 DAT (4.10), followed by T_8 (4.03) and T_7 (4.01), all falling within statistical group 'A'. T_2 (3.42) was within group 'C', while T_1 (2.93) was the minimum in group 'F'. T_3 (3.67) and T_4 (3.52) were in 'D' and 'E', respectively.

At 60 DAT, the number of tillers was significantly higher. T_5 (8.20) was highest and fell in group 'A' together with T_8 (8.00), T_7 (7.87), and T_6 (7.72). T_2 (7.20) belonged to group 'B', while T_1 (5.33) was the lowest in group 'C'.

At 90 DAT, T_5 once more gave the highest tillers (13.27), followed by T_8 (12.40), T_7 (11.92), and T_6 (11.77), all of which belonged to the top statistical group. T_2 (11.07), T_3 (11.10), and T_4 (10.88) belonged to the middle group, and T_1 (5.80) was the lowest in group 'D'.

At harvest, T_5 (13.33) was the highest, statistically equivalent to T_8 (12.43), T_7 (12.05), and T_6 (11.83), which were in group 'A'. T_2 (11.12), T_3 (11.13), and T_4 (10.92) were in group 'B', while T_1 (5.92) was in group 'C'.

Dry Matter Accumulation

Data presented in table 2 illustrate that dry matter accumulation (DMA) was dramatically affected by nutrient management practices throughout all the stages of growth.

On 30 DAT, T_5 had the greatest dry matter (202.93 g m^{-2}), followed closely by T_8 (199.98 g m^{-2}); both were in statistical group 'A'. These two treatments exceeded T_2 (186.81 g m^{-2}, group 'E') by 8.6% and 7.0%, respectively. T_7 (194.95 g m^{-2}) and T_6 (193.17 g m^{-2}), in group 'B', also exceeded T_2 by 4.4-6.6%. T_3 (190.36 g m^{-2}) and T_4 (188.14 g m^{-2}) were under groups 'C' and 'D'. The control (T_1) had the lowest value of 180.29 g m^{-2}, which was 11.9% below T_2 and 12.6% less than T_5.

At 60 DAT, T_5 (547.38 g m^{-2}) still led, statistically equal with T_8 (542.56 g m^{-2}) and T_7 (531.30 g m^{-2}), in the highest group 'A'. They surpassed T_2 (490.66 g m^{-2}, group 'C') by 8.3-11.6%. T_6 (510.37 g m^{-2}) and T_3 (501.53 g m^{-2}) were in group 'B', whereas T_1 posted the lowest (462.56 g m^{-2}), 15.9% lower than T_5.

At 90 DAT, T_5 (917.95 g m^{-2}) was highly significant compared to all others, followed by T_8 (893.62 g m^{-2}) and T_7 (879.34 g m^{-2}), all of group 'A' and 10.6-13.2% greater than T_2 (830.06 g m^{-2}). T_3 (873.58 g m^{-2}) and T_4 (863.24 g m^{-2}) were of group 'B', whereas T_6 (838.53 g m^{-2}) and T_2 were in group 'C'. T_1 had the minimum (778.19 g m^{-2}), 15.2% less than T_2.

At maturity, cumulative dry matter accumulation was highest in T_5 (961.54 g m^{-2}), T_8 (958.71 g m^{-2}), and T_7 (934.73 g m^{-2}), all statistically belonging to group 'A'. These were 8.0-11.1% better than T_2 (865.64 g m^{-2}, group 'D'). T_6 (928.28 g m^{-2} and T_3 (916.51 g m^{-2}) belonged to group 'B', and T_4 (896.40 g m^{-2}) belonged to group 'C'. The control T_1 possessed the lowest dry matter at 828.66 g m^{-2}, being 13.5% lower than T_2.

Table 2: Effect of co-inoculation of N-fixer and Phosphate solubilizing bacteria (PSB) on growth attributes of paddy crop at various growth intervals.

Treatments	No. of tillers hill^{-1}				Dry matter accumulation (g m^{-2})			
	30 DAT	60 DAT	90 DAT	At harvest	30 DAT	60 DAT	90 DAT	At harvest
T_1 Absolute Control	2.93^{f}	5.33^{c}	5.80^{d}	5.92^{c}	180.29^{f}	462.56^{d}	778.19^{e}	828.66^{e}
T_2 100% RDF	3.42^{e}	7.20^{b}	11.07^{bc}	11.12^{b}	186.81^{e}	490.66^{c}	830.06^{d}	865.64^{d}
T_3 100% RDF + *Azotobacter*	3.67^{cd}	7.57^{ab}	11.10^{bc}	11.13^{b}	190.36^{cd}	501.53^{bc}	873.583^{bc}	916.51^{bc}
T_4 100% RDF + PSB	3.52^{de}	7.43^{ab}	10.88^{c}	10.92^{b}	188.14^{de}	495.19^{bc}	863.24^{bcd}	896.40^{cd}
T_5 100% RDF + *Azotobacter* + PSB	4.10^{a}	8.20^{a}	13.27^{a}	13.33^{a}	202.93^{a}	547.38^{a}	917.95^{a}	961.537^{a}
T_6 100% NK + 75% P + PSB	3.82^{bc}	7.72^{ab}	11.77^{abc}	11.83^{ab}	193.17^{bc}	510.37^{b}	838.53^{cd}	928.28^{abc}
T_7 75% N + 100% PK + *Azotobacter*	4.01^{ab}	7.87^{ab}	11.92^{abc}	12.05^{ab}	194.95^{b}	531.30^{a}	879.34^{ab}	934.73^{ab}
T_8 75% NP + 100% K + *Azotobacter* + PSB	4.03^{ab}	8.00^{ab}	12.40^{ab}	12.43^{ab}	199.98^{a}	542.56^{a}	893.62^{ab}	958.71^{a}
SEm±	**0.07**	**0.31**	**0.50**	**0.50**	**1.16**	**5.84**	**13.38**	**11.37**
C.D. at 5%	**0.22**	**0.94**	**1.52**	**1.52**	**3.51**	**17.72**	**40.50**	**34.50**

Yield Attributes

Yield Parameters

Data provided in Table 3 indicate substantial variations in rice plant establishment and density characteristics-i.e., number of hills per m², productive tillers per m², plant population per m², and panicles per plant-under various nutrient management treatments.

T_5 always exhibited the maximum performance in terms of all the parameters. Harvest hill density was highest under T_5 (58.33 hills m^{-2}), falling in group 'A', which was 23.2% and 15.1% higher than T_1 (47.33 hills m^{-2}) and T_2 (50.67 hills m^{-2}), respectively. Treatments T_8 (56.33) and T_7 (55.33) belonged to group 'B', indicating 18.9% and 16.9% increases over the control. T_6 (54.00) and T_3 (53.33) were placed in group 'C', then came T_4 (52.00) and T_2 in group 'D'. T_1 was always lowest, indicating poor initial growth without nutrient application.

Productive tillers per m² also mimicked this trend, where T_5 (376.36) in group 'A' surpassed T_1 (298.55) and T_2 (321.60) by 26.1% and 17.0%, respectively. T_8 (367.02) and T_7 (350.57) were placed in 'B', and these had improvements of 22.9% and 17.4% over the control. T_6 (345.45) and T_3 (341.77), in group 'C', had increases of 15.7% and 14.5%. T_4 (333.17) and T_2, both belonging to group 'D', reported relatively small rises of 11.6% and 7.7%, whereas T_1 continued to be placed in the lowest statistical group 'F'.

Plant population per m² was maximum in T_5 (91.67), statistically equal to T_8 (89.33) and T_7 (87.33), all falling under 'A'. T_5 had 41.7% more than T_1 (64.67) and 17.5% over T_2 (78.00). T_6 (84.00), T_3 (82.00), and T_4 (80.33), falling under groups 'B' and 'C', had 24.3-29.9% gain over T_1. T_2 had 20.6% gain over T_1 but was poorer than microbial-integrated treatments statistically.

Panicles per plant, a critical yield determinant, were highest under T_5 (18.53), placed in group 'A'. This represented a 58.8% and 19.8% increase over T_1 (11.67) and T_2 (15.47), respectively. T_8 (17.93) and T_7 (17.73), both in group 'A', showed 53.7% and 51.9% increases over control. T_6 (16.87), T_3 (15.93), and T_4 (15.73), grouped under 'B', recorded 36.5-44.6% increases. T_2, at 15.47, was 32.5% higher than control but nevertheless statistically lower than the best. T_1 was placed in 'C', still being lowest on all establishment parameters related to yield.

Table 3: Effect of co-inoculation of N-fixer and Phosphate solubilizing bacteria (PSB) on yield attributes at harvest of paddy crop.

Treatments	No. of hills m^{-2}	No. of effective tillers m^{-2}	No. of plants m^{-2}	No. of panicles plant^{-1}
T_1 Absolute Control	47.33^{f}	298.55^{f}	64.67^{e}	11.67^{c}
T_2 100% RDF	50.67^{e}	321.60^{e}	78.00^{d}	15.47^{b}
T_3 100% RDF + *Azotobacter*	53.33^{cd}	341.77^{c}	82.00^{cd}	15.93^{ab}
T_4 100% RDF + PSB	52.00^{de}	333.17^{d}	80.33^{cd}	15.73^{ab}
T_5 100% RDF + *Azotobacter* + PSB	58.33	376.36	91.67^{a}	18.53^{a}
T_6 100% NK + 75% P + PSB	54.00^{bc}	345.45^{bc}	84.00^{bc}	16.87^{ab}

T_7 75% N + 100% PK + *Azotobacter*	55.33[ab]	350.57[b]	87.33[ab]	17.73[ab]
T_8 75% NP + 100% K + *Azotobacter* + PSB	56.33[a]	367.02[a]	89.33[a]	17.93[ab]
SEm±	**0.59**	**2.04**	**1.53**	**0.95**
C.D. at 5%	**1.81**	**6.14**	**4.63**	**2.84**

Grain Characteristics

Table 4 indicate that the nutrient management strategies, specifically the integrated microbial inoculants, significantly impacted the test weight and protein content of rice grains at harvest. These two parameters are crucial measures of physical grain quality and nutritional improvement.

Highest test weight was recorded in T_5 (25.85 g), which was in group 'A', and a 22.0% increase over the control (T_1: 21.19 g) and 13.6% over RDF alone (T_2: 22.75 g). T_5 statistically matched T_8 (25.62 g), T_7 (25.33 g), and T_6 (24.91 g), all of group 'A', with 17.5-20.9% gains over T_1 and 9.5-12.6% gains over T_2. This supported that full and truncated RDF levels, when co-inoculated with Azotobacter and PSB, had significantly increased grain filling and density.

T_3 (23.84 g), which had RDF and Azotobacter treatment, fell under category 'B' and showed a 12.5% increment over T_1 and 4.8% over T_2, thereby signifying that inoculation of Azotobacter alone also contributed to grain weight but less so than consortia. T_4 (23.36 g), with PSB + RDF, fell under category 'C' and showed a 10.2% increase over T_1 but minor 2.7% increase over T_2. T_1 (21.19 g), the control, was shortest and occurred in group 'D', which means poor grain development under deficient conditions.

Under grain protein content, T_5 also recorded the maximum (7.85%), followed by T_3 (7.79%), both from group 'A'. These reflected 36.0% and 34.9% increases over the control (T_1: 5.77%) and 8.6% and 7.8% over T_2 (7.23%), respectively. T_8 (7.67%) ranked in group 'B' and reflected 32.9% and 6.1% improvement over T_1 and T_2, respectively. T_7 (7.48%) and T_6 (7.44%) were statistically on par in group 'C', reflecting 28.9-29.6% and 2.9-3.5% improvement over T_1 and T_2, respectively.

T_4 (7.31%) and T_2 (7.23%) were in group 'D', with moderate increases of 26.7% and 25.2% over control. T_1 (5.77%) was singular in group 'E', representing low nitrogen uptake and amino acid synthesis without microbial or nutrient input.

Table 4: Effect of co-inoculation of N-fixer and Phosphate solubilizing bacteria (PSB) on grain weight and protein (%) at harvest of paddy crop.

Treatments	Test weight (g)	Grain protein (%)
T_1 Absolute Control	21.19[d]	5.773[e]
T_2 100% RDF	22.75[c]	7.230[d]
T_3 100% RDF + *Azotobacter*	23.84[bc]	7.793[a]
T_4 100% RDF + PSB	23.36[c]	7.313[cd]
T_5 100% RDF + *Azotobacter* + PSB	25.85[a]	7.853[a]
T_6 100% NK + 75% P + PSB	24.91[ab]	7.440[cd]
T_7 75% N + 100% PK + *Azotobacter*	25.33[a]	7.480[bc]
T_8 75% NP + 100% K + *Azotobacter* + PSB	25.62[a]	7.670[ab]
SEm±	**0.34**	**0.08**
C.D. at 5%	**1.12**	**0.23**

Panicle Characteristics

Values in Table 5 indicated that integrated nutrient management, especially microbial consortia treatments with full or partial chemical fertilization, significantly impacted fresh weight, dry weight, panicle length, and grains per panicle.

Highest panicle fresh weight was found in T_5 (3.85 g) which was statistically better and fell under group 'A'. It had a 42.6% increase over absolute control (T_1: 2.70 g) as well as an increase of 17.7% over RDF alone (T_2: 3.27 g). T_8 (3.78 g) and T_7 (3.65 g), even though lower, were also in the top group with 40.0% and 35.2% increases over T_1, and 15.6% and 11.6% over T_2, respectively. T_6 (3.60 g) and T_3 (3.57 g) belonged to group 'B' and registered 33.3% and 32.2% increases over T_1. T_4 (3.34 g) and T_2 (3.27 g) both belonged to group 'C' and were related to relatively minor increases of 23.7% and 21.1% over control, while T_1 was lowest in group 'D'.

Panicle dry weight too followed the same trend with T_5 (1.48 g) once highest, closely followed by T_8 (1.44 g) and T_7 (1.40 g) of group 'A', recording increases of 32.1%, 28.6%, and 25.0% over T_1 (1.12 g), and 15.6%, 12.5%, and 9.4% over T_2 (1.28 g), respectively. Treatments T_6 (1.38 g) and T_3 (1.36 g) belonged to groups 'B' and 'C', while T_4 (1.31 g) and T_2 (1.28 g) recorded slight improvements, with T_1 once more the lowest (1.12 g), falling under group 'E'.

Panicle length was also maximized in T_5 (26.86 cm), showing a 40.4% rise over T_1 (19.13 cm) and 18.5% over T_2 (22.67 cm). T_8 (26.04 cm) and T_7 (24.96 cm) were clubbed with T_5 in group 'A', showing 36.2% and 30.5% increases over T_1. T_6 (24.08 cm), T_3 (23.64 cm), and T_4 (22.88 cm) were in groups 'B' and 'C' with 25.9%-19.7% rises, with T_2 and T_1 coming serially.

As far as number of grains per panicle is concerned, T_5 (153.87) was the highest yielding, statistically equal to T_8 (151.93) and T_7 (151.53) under group 'A'. These treatments were 62.1%, 60.1%, and 59.6% higher in grains than T_1 (control: 94.93) and 20.7%, 19.1%, and 18.8% higher than T_2 (127.53), respectively. T_6 (147.13) and T_3 (141.67) fell under groups 'B' and 'C', which were 55.0% and 49.3% higher than T_1, respectively. T_4 (137.67) and T_2 (127.53) constituted group 'D', whereas T_1 stayed in group 'E'.

Table 5: Effect of co-inoculation of N-fixer and Phosphate solubilizing bacteria (PSB) on panicle characteristics after harvesting of paddy crop.

Treatments	Panicle fresh weight (g)	Panicle dry weight (g)	Panicle length (cm)	No. of grains panicle^{-1}
T_1 Absolute Control	2.70^{d}	1.12^{e}	19.13^{d}	94.93^{e}
T_2 100% RDF	3.27^{c}	1.28^{d}	22.67^{c}	127.53^{d}
T_3 100% RDF + *Azotobacter*	3.57^{b}	1.36^{c}	23.64^{abc}	141.67^{bc}
T_4 100% RDF + PSB	3.34^{c}	1.31^{d}	22.88^{bc}	137.67^{cd}
T_5 100% RDF + *Azotobacter* + PSB	3.85^{a}	1.48	26.86^{a}	153.87^{a}
T_6 100% NK + 75% P + PSB	3.60^{b}	1.38^{bc}	24.08^{abc}	147.13^{abc}
T_7 75% N + 100% PK + *Azotobacter*	3.65^{ab}	1.40^{ab}	24.96^{abc}	151.53^{ab}
T_8 75% NP + 100% K + *Azotobacter* + PSB	3.78^{ab}	1.44^{a}	26.04^{ab}	151.93^{ab}
SEm±	**0.07**	**0.02**	**1.10**	**3.65**
C.D. at 5%	**0.22**	**0.05**	**3.32**	**10.74**

Nutrients Data

Nutrient Content in Grain and Straw

Results from Table 6 showed that integrated nutrient management had a significant impact on nitrogen (N), phosphorus (P), and potassium (K) levels in both rice straw and grain. Co-inoculation treatments of Azotobacter and PSB, especially T_5, performed better than other mixtures.

For nitrogen in grain, maximum content (1.26%) was noted in T_5, statistically at par with T_3 (1.25%) and T_8 (1.23%), all under group 'A'. This treatment had a significant 37.0% rise over control (T_1: 0.92%) and 8.6%-10.3% improvement above RDF alone (T_2: 1.16%). Treatments T_7 (1.20%), T_6 (1.19%), and T_4 (1.17%) were next in groups 'B' and 'C', while T_2 belonged to group 'D' and T_1 to the lowest in group 'E'.

Phosphorus in grain also reached the peak in T_5 (0.23%) and was statistically on par with all treatments save T_1 (0.13%), which belonged to group 'B' alone. Treatments T_2 through T_8 varied between 0.20% and 0.21% and belonged to group 'A', revealing that full RDF and partial RDF plus biofertilizers held high grain P content.

With regard to potassium content in grain, T_5 had the maximum value (0.42%), but was statistically at par with treatments T_2 to T_8 (0.34%-0.37%), which belonged to group 'A'. T_1 (0.22%) was significantly lower and belonged to group 'B' and indicated the lack of K uptake without fertilization.

The same trend was seen for nutrient value in straw. The highest nitrogen value was recorded in T_5 (0.72%), followed by T_8 (0.68%), T_7 (0.62%), and T_6 (0.60%) in group 'A'. T_3 (0.56%), T_4 (0.49%), and T_2 (0.44%) were successive lower groups ('B', 'C', and 'D'), while T_1 (0.38%) recorded the lowest again, in group 'E'.

Phosphorus content in straw was maximum in T_5 and T_4 (0.15%), which, together with T_3, T_6, and T_8, constituted group 'A'. T_2 and T_7 (0.11%) fell under group 'B', and T_1 (0.08%) under group 'C', also reflecting nutrient shortage in the absence of amendments.

Potassium from straw also trended similarly; T_5 (0.25%) was highest numerically, but not significantly different from any treatment except T_1 (0.14%). The rest of the treatments were in group 'A', with only T_1 in group 'B'.

Nutrient Uptake in Grain and Straw

As seen in Table 6, integrated nutrient management significantly affected the nutrient uptake of nitrogen (N), phosphorus (P), and potassium (K) in both straw and grain. Treatment T_5 (100% RDF + Azotobacter + PSB) had the maximum nutrient uptake in all parameters and was consistently dominant among all the treatments.

At grain nitrogen uptake, T_5 (64.46 kg/ha) was statistically better and fell under category 'A', on par with T_8 (59.18), T_3 (58.96), T_7 (57.25), and T_6 (56.61), all registering a 13-17% increase over T_2 (52.52) and over two times that of the control (T_1: 29.69). T_4 (53.30) and T_2 came next in group 'B', and T_1 was still the lowest in group 'D'.

Phosphorus uptake by grain was also maximum in T_5 (12.02 kg/ha), making a separate group 'A'. T_8 (10.39), T_3 (10.15), T_7 (9.88), T_6 (9.86), and T_4 (9.85) were all grouped in 'B', representing statistically similar but obviously lower values. T_2 (9.09) was in group 'C' and T_1 (4.19) in group 'D', reflecting the latter's low uptake ability without any nutrient additions.

For potassium for grains, T_5 also topped with 21.67 kg/ha, far ahead but statistically on par with T_8 (17.97), T_7 (17.61), T_6 (17.49), and T_3 (17.10), and all these constituted group 'A'. T_2 (15.45) and T_4 (15.67) were in group 'B', and T_1 (7.10) in group 'C', with lowest uptake under unfertilized conditions.

Nitrogen absorption in straw also followed the grain observations. T_5 (64.46 kg/ha) was the maximum and in group 'A' and also T_8, T_3, T_7, and T_6, which were far better than T_4 and T_2 (both in group 'B') and considerably more than T_1 (29.69), which still belonged to group 'C'.

Straw phosphorus absorption also reached its highest in T_5 (11.31 kg/ha), statistically being at par with T_8 (10.46), T_4 (10.30), T_6 (9.91), and T_3 (9.79) and constituted group 'A'. T_2 (7.69) and T_7 (7.91) were put into group 'B', and T_1 (4.12) was put into group 'C'.

Potassium accumulation in straw also conformed to the same pattern. T_5 (18.74 kg/ha) was statistically on par with T_8 (15.90), T_3 (15.75), T_7 (15.52), and T_6 (15.35), and they constituted group 'A'. T_4 (13.96) and T_2 (14.08) belonged to group 'B', and T_1 (6.63) was least in group 'C'.

Table 6: Effect of co-inoculation of N-fixer and Phosphate solubilizing bacteria (PSB) on grain and straw nutrient content at harvest of paddy crop.

Treatments	Nutrient Conc. (%)						Nutrient Uptake (kg/ha)					
	Grains			Straw			Grains			Straw		
	N	**P**	**K**	**N**	**P**	**K**	**N**	**P**	**K**	**N**	**P**	**K**
T_1 Absolute Control	0.92^{e}	0.13^{b}	0.22^{b}	0.38^{e}	0.08^{c}	0.14^{b}	29.69^{d}	4.19^{c}	7.10^{c}	29.69^{d}	4.12^{d}	6.63^{b}
T_2 100% RDF	1.16^{d}	0.20^{a}	0.34^{a}	0.44^{de}	0.11^{bc}	0.20^{a}	52.52^{c}	9.09^{b}	15.45^{b}	52.52^{c}	7.69^{c}	14.08^{a}
T_3 100% RDF + *Azotobacter*	1.25^{a}	0.21^{a}	0.36^{a}	0.56^{bcd}	0.14^{ab}	0.22^{a}	58.96^{a}	10.15^{a}	17.10^{ab}	58.96^{a}	9.79^{abc}	15.75^{a}
T_4 100% RDF + PSB	1.17^{cd}	0.21^{a}	0.34^{a}	0.49^{cde}	0.15^{a}	0.21^{a}	53.30^{bc}	9.85^{ab}	15.67^{b}	53.30^{bc}	10.30^{a}	13.96^{a}
T_5 100% RDF + *Azotobacter* + PSB	1.26^{a}	0.23	0.42	0.72^{a}	0.15^{a}	0.25	64.46	12.02	21.67	64.46	11.31^{a}	18.74
T_6 100% NK + 75% P + PSB	1.19^{cd}	0.21^{a}	0.37^{a}	0.60^{abc}	0.14^{ab}	0.22^{a}	56.61^{ab}	9.86^{ab}	17.49^{a}	56.61^{ab}	9.91^{ab}	15.35^{a}
T_7 75% N + 100% PK + *Azotobacter*	1.20^{bc}	0.21^{a}	0.37^{a}	0.62^{ab}	0.11^{bc}	0.22^{a}	57.25^{a}	9.88^{ab}	17.61^{a}	57.25^{a}	7.91^{bc}	15.52^{a}
T_8 75% NP + 100% K + *Azotobacter* + PSB	1.23^{ab}	0.21^{a}	0.37^{a}	0.68^{ab}	0.15^{ab}	0.22^{a}	59.18^{a}	10.39^{a}	17.97^{a}	59.18^{a}	10.46^{a}	15.90^{a}
SEm±	**0.01**	**0.01**	**0.01**	**0.04**	**0.01**	**0.01**	**1.20**	**0.30**	**0.61**	**1.21**	**0.71**	**1.06**
C.D. at 5%	**0.04**	**0.02**	**0.04**	**0.12**	**0.03**	**0.04**	**3.61**	**0.89**	**1.72**	**3.61**	**2.12**	**3.26**

Yield

Table 7 findings categorically reveal that nutrient management practices had a significant effect on straw, rice grain, and biological yield. The maximum grain yield was achieved under treatment T_5 (51.34 q/ha), which belonged to statistical group 'A'. It was 60.2% greater than the absolute control (T_1: 32.04 q/ha) and 13.0% greater than the recommended dose of fertilizers (T_2: 45.41 q/ha). T_8 (48.27 q/ha), another member of group 'A', was statistically equal to T_5 but produced 6.0% less, but 50.6% and 6.3% more than T_1 and T_2, respectively, thus proving the efficacy of microbial co-inoculation even with lesser fertilizer application.

Treatments T_7 (47.89 q/ha), T_6 (47.56 q/ha), T_3 (47.37 q/ha), T_4 (45.55 q/ha), and T_2 (45.41 q/ha) were all in group 'B', having statistically equivalent but much higher performance than T_1. Grain yield increase above these treatments was between 41.9% in T_4 and 49.0% in T_7 compared to control. T_1 (32.04 q/ha) was still the lowest, having a clear group 'C', indicating yield limitation because of total nutrient deficiency.

In straw yield, though numerically highest, T_5 (74.04 q/ha) was not different statistically (group 'A') from treatments T_2 to T_8, reflecting a synergistic positive effect of all fertilizer treatments. T_5 yielded 48.8% more than T_1 (49.76 q/ha) and 7.3% more than T_2 (68.98 q/ha). T_8 (71.70 q/ha), T_3 (72.47 q/ha), T_6 (69.68 q/ha), and T_7 (70.21 q/ha) yielded uniform increments of 43.9%-44.7% over T_1 and modest increments over T_2 (2.0%-5.1%). The lowest yield in straws was exhibited by T_1 and grouped separately under 'B'.

Biological yield also followed the same trend with T_5 (125.38 q/ha) being the maximum. It was statistically similar to T_8 (119.97 q/ha), T_3 (119.85 q/ha), T_7 (118.10 q/ha), and T_6 (117.23 q/ha)-all falling in group 'A'. These treatments recorded 43.3%-53.3% increments over T_1 (81.80 q/ha) and 2.5%-9.6% increments over T_2 (114.39 q/ha). T_4 (113.25 q/ha) and T_2, even superior to the control, fell in group 'B', and behind the co-inoculated plots.

HI was also greatest in T_5 (42.45%), then T_6 (41.89%), T_7 (41.81%), T_8 (41.78%), and T_4 (41.02%). While no statistical grouping was allocated to HI, the tendency indicated increased assimilate partitioning to grain in co-inoculation and low RDF treatments. The lowest HI (39.12%) occurred in T_1, which is indicative of nutrient stress and poor grain development despite vegetative growth.

Table 7 : Effect of co-inoculation of N-fixer and Phosphate solubilizing bacteria (PSB) on Yield of paddy crop.

Treatments	Yield (q/ha)			Harvesting Index (%)
	Grain	Straw	Biological	
T_1 Absolute Control	32.04^c	49.76^b	81.80^c	39.12
T_2 100% RDF	45.41^b	68.98^a	114.39^b	38.81
T_3 100% RDF + *Azotobacter*	47.37^b	72.47^a	119.85^{ab}	40.30
T_4 100% RDF + PSB	45.55^b	67.70^a	113.25^b	41.02
T_5 100% RDF + *Azotobacter* + PSB	51.34^a	74.04^a	125.38^a	42.45
T_6 100% NK + 75% P + PSB	47.56^b	69.68^a	117.23^{ab}	41.89
T_7 75% N + 100% PK + *Azotobacter*	47.89^b	70.21^a	118.10^{ab}	41.81
T_8 75% NP + 100% K + *Azotobacter* + PSB	48.27^{ab}	71.70^a	119.97^{ab}	41.78
SEm±	**1.11**	**3.00**	**3.20**	**-**
C.D. at 5%	**3.34**	**9.03**	**9.63**	**-**

Discussion

Growth Parameters

Plant Growth

The uniform dominance of T_5 at all stages of growth is an expression of the positive impact of co-inoculation of Azotobacter and PSB with complete chemical fertilization. Not only was early seedling vigor enhanced through co-inoculation but a continued superiority was expressed at all stages of vegetative growth. T_5 exceeded the control (T_1) by 17-20% and RDF alone (T_2) by 12-17%, showing a synergistic impact of biofertilizers and chemical inputs.

T_8 and T_7, with lowered N or P application, had statistically similar plant heights to T_5 with 14-15% and 13-14% improvements over T_1, respectively. Their superiority over T_2 by 9-11% also indicates the effectiveness of biofertilizers in nutrient acquisition even with lowered fertilizer doses.

Even the single inoculum treatments (T_3: Azotobacter, T_4: PSB) and reduced P levels (T_6) resulted in 5-9% increments over RDF, which indicates that microbial application by itself is capable of improving growth moderately.

The observed increase in plant height in microbial treatments is related to enhanced nitrogen fixation by Azotobacter, solubilization of indigenous and added phosphorus by PSB, and better root development and nutrient absorption. These impacts collectively facilitate more vegetative growth and canopy cover.

These findings are consistent with reports of Barge (2021), who registered increased plant height of rice through dual inoculation of PSB and N-fixers in conjunction with RDF. Kumar *et al.* (2025) also registered increases in marigold growth through combined microbial inoculation. These findings confirm again that the co-applications of biofertilizers along with chemical fertilizers are more efficacious compared to either input used separately.

Plant Weight

The results clearly indicate that the dry and fresh biomass of the crop responded greatly with co-applicability of the fertilizers and biofertilizers. T_5 (100% RDF + Azotobacter + PSB) performed exceptionally well at each phase of growth, indicating higher nutrient supply, root development, and increased physiological activity by co-inoculation. T_8 (75% NP + 100% K + Azotobacter + PSB) was also closely on the heels of T_5, once more demonstrating that with chemical N and P application reduction, successful microbial supplementation can support biomass accumulation or increase it.

These retarded fresh and dry weight differences at 30 DAT are explained by growing microbial growth and the stepwise release of nutrients through biological action. Abrupt peaks at or after 60 DAT follow maximum microbial action and stage of vegetative growth, to provide nutrient absorption and turgor support. The yield of T_7 and T_6, even lower than that of T_5 and T_8, also showed the positive impact of low application or lack of one microbial partner.

These findings corroborate those of Khandare *et al.* (2020) and MeCarty *et al.* (2017) with greater dry matter accumulation upon microbial colonization, greater phosphorus solubilization, and greater nitrogen fixation. Kumar *et al*. (2025) have also observed that co-inoculation with PSB and Azotobacter promotes vegetative growth and shoot elongation through effective nutrient uptake.

Thus, PSB-Azotobacter interaction with full or half chemical fertilization (especially in T_5 and T_8) was maximum for plant biomass growth in all stages of development in rice.

Number of Tillers per hill

Increased number of tillers at each stage, particularly in T_5 (100% RDF + Azotobacter + PSB) and T_8 (75% NP + 100% K + Azotobacter + PSB), represents the superiority of integrated nutrient management over chemical fertilization. T_5 performed better than all the other treatments and at all stages had 13.9-40.1% more tillers than T_2 and 40-55% more tillers than T_1. T_8 was second, 1.7-7.5% behind T_5 but much ahead of T_2 (9.3-36.5%) and T_1 (26.5-42.4%).

T_7 and T_6 also progressed significantly, with 4.7-16.5% gains over T_2 and over 100% gains over T_1 at some points. These results indicate that Azotobacter and PSB co-applications enhance vegetative branching potentially due to enhanced nitrogen fixation, mobilization of phosphorus, and hormonal induction such as auxin and cytokinin release. The use of potassium in T_8 may have also helped this by aiding translocation and turgor regulation, cell division, and tillering.

These, relative to these, chemical fertilizer only treatments (T_2, T_3, T_4) provided mean tiller numbers, higher than T_1 but without achieving integrated treatments. Control (T_1) was behind all the way, emphasizing the significance of nutrient supply in triggering and sustaining tillering.

These findings corroborate Gupta *et al*. (2023), who noticed extensive tillering in wheat with the same treatment levels of biofertilizers and fertilizers. Synergistic action of microbial inoculants and chemical fertilizers in promoting early and extended vegetative growth is thus evident.

In summary, the concerted application of Azotobacter and PSB with complete (T_5) or half (T_8) chemical fertilizers proved better in promoting tillering, which is a marker of identifying the yield of rice.

Dry Matter Accumulation

Dry matter accumulation kept increasing throughout the period and was extremely responsive to integrated nutrient management practices. T_5 (100% RDF + Azotobacter + PSB) had maximum DMA at all growth stages, with performance 8.6-13.5% superior to T_2 (100% RDF only). T_8 (75% NP + 100% K + Azotobacter + PSB) was very close after it, with just 0.3-2.5% of T_5 but 10.8-13.5% superior to T_2 at all stages.

The consistent performance of T_5 and T_8 can be accounted for by enhanced solubilization and nutrient uptake by way of synergistic action of Azotobacter and PSB. Microbial synergy is most likely to account for enhanced rhizosphere health, induced phytohormone synthesis, and increased root surface area for nutrient absorption-summarizing enhanced biomass accumulation.

T_7, T_6, and T_3 performed at intermediate levels, fairly regularly beating T_2 by small margins (4.4-8.3%). Their achievement reflects some benefit from full or half biofertilizer application, but they remained statistically lower than full integration treatments.

Treatments with chemical fertilization alone (T_2, T_3, T_4) had moderate accumulation and hence were realized to have limitations in optimization of maximum physiological activity and dry matter partitioning under no microbial support. The minimum recorded DMA values under the control (T_1) depict the critical need for external nutrient supply for sustaining biomass establishment.

Findings are in line with Mamta *et al.* (2017), who reported significant dry matter growth gains in papaya with biofertilizer co-inoculation. The same processes-i.e., improved nutrient-use efficiency, increased enzymic activity, and growth stimulated by hormones-can plausibly be argued to be responsible for the results of rice.

Finally, combined nutrient application-in particular, in T_5 and T_8-is most effective in maximizing dry matter accumulation, which shows the performance of microbial consortia in facilitating vegetative biomass and overall crop growth in rice.

Yield Attributes

Yield Parameters

In all the plant establishment and density parameters tested, co-inoculation of Azotobacter and PSB with 100% RDF (T_5) recorded the highest results. With respect to RDF alone (T_2), T_5 recorded systematic increases between 15-26%, whereas compared to the control (T_1), increases varied from 23-58%. All these increases are because of early colonization of roots, better acquisition of nutrients, and balanced root-shoot growth promoted by microbial inoculants.

T_8 and T_7, with only 75% NP, had plant populations and panicle numbers statistically on a par with T_5. Their yield-35-53% over control-is downright proof that integrated biofertilization can with ease counterbalance partial diminishment of chemical nutrient delivery.

Treatments T_6 and T_3, inoculated singly or with half doses of RDF, also achieved significant improvements over T_1 (12-30%) and modest rises over RDF (5-15%), which demonstrates that even half-infection can induce enhanced establishment and tillering compared to chemical fertilization alone.

T_2 and T_4, chemical-only or mono-inoculated, continued to be statistically poorer in all parameters, but still claimed 7-20% better performance compared to the control. The control treatment T_1 had the weakest values constantly, reflecting poor natural establishment, weak tillering, and inadequate panicle initiation in the lack of external nutrient or microbial assistance.

These findings confirm the reports of Baghel and Singh (2025) that biofertilizer consortia maximally enhance plant stand density, tillering potential, and reproductive success, especially in regimes with integrated nutrient management.

Grain Characteristics

These results evidently indicated that co-inoculation of PSB and Azotobacter with 100% RDF (T_5) not only enhanced physical weight of the grain (22.0% compared to T_1 and 13.6% higher than T_2) but also nutritional quality in terms of protein content (36.0% and 8.6% higher than T_1 and T_2, respectively). This indicates greater uptake of nutrients, enhanced nitrogen assimilation, and efficacy of biosynthetic processes owing to synergy microbial activity.

T_8 and T_7 which employed 75% RDF were very close to each other, test weight being improved by 20.9% and protein content improved by 30-33% compared to T_1. This suggests the potential of microbial consortia to compensate for decreased chemical application without loss of grain quality.

Single-inoculant applications T_3 and T_6 yielded moderate increments (12-15% test weight and 28-35% protein content over T_1), though were still not behind in co-inoculated treatments, again asserting value addition through microbial interaction.

T_4 and T_2, though statistically better than control, were on par with one another with minor fluctuations, which means that RDF or PSB alone could not impart improvement on the grain quality traits. T_1 with absolutely no input fell far behind in total yield, and this revealed the negative impact of nutrient stress on grain development.

These findings are in agreement with Athnere *et al.* (2024), who previously documented that co-inoculation of Azotobacter, PSB, and KMB had an effect on test weight and protein in barley to a highly significant extent. Their findings validate the effectiveness of microbial consortia in all the cereal systems to improve grain quality under integrated nutrient management systems.

Panicle Characteristics

In all the four parameters-fresh weight, dry weight, length, and grain number-T_5 (100% RDF + Azotobacter + PSB) exhibited maximum values at each stage with increases of 32.1% to 62.1% over T_1 and 9.4% to 20.7% above RDF alone. This indicates synergistic interaction of microbial consortia towards increasing panicle biomass and reproductive accomplishment.

T_8 and T_7 with 75% RDF had statistically similar yields with that of T_5, highly significant grain number, and that shows that microbial consortia are substitutable for lower chemical inputs without compromising on potential yield.

Mean yield of T_6 and T_3 (pin inoculations) still produced 32-55% of control for the majority of the parameters but lagged behind co-inoculated treatments, graphically determining the advantage of consortial synergy. In contrast, T_4 and T_2, even superior to T_1, produced low yields, determining the inefficacy of PSB or RDF alone in maximizing panicle characteristics.

The poor, steady growth of T_1 emphasizes the adverse limitation caused by nutrient deficiency on grain and reproductive growth. These findings validate evidence by Nabati *et al.* (2025) for extraordinary improvement of chickpea reproductive quality through microbial co-inoculated and sulfur nutrition, further highlighting once again the wider potential of microbial consortia towards sustainable nutrient management in order to increase reproductive productivity.

Nutrients Data

Nutrient Content in Grain and Straw

Higher nutrient content obtained in T_5 (100% RDF + Azotobacter + PSB) for grain and straw of all the three macronutrients is a testimony of the efficacy of co-inoculation to increase the assimilation of nutrients by the plant. Gains over control ranged from 32-65%, and even over RDF-alone ranged from 8-15%, vindicating microbial inoculation to complement chemical addition.

T_3 (RDF + Azotobacter) and T_8 (75% NP + 100% K + Azotobacter + PSB) were closely trailed by T_5, especially in grain and straw nitrogen, indicative of the fact that even the RDF at half rate with supplementation by biofertilizers can increase nutrient absorption. Quite surprisingly, even at full RDF rate, T_2 was behind inoculated treatments, which also indicates the additional benefit arising from microbial associates.

The persistent inferior performance of T_1 in all the nutrients indices affirms the crucial role played by macro-nutrient supplementation and microbial action in guaranteeing nutrient content in rice organs.

These results conform with a study by Nabati *et al.* (2025), in which they observed significantly enhanced chickpea nutrient values via microbial consortia-fertilizer integration. These results thus conform to the concept of nutrient biofortification of cereals via integrated nutrient management as a viable and sustainable strategy for crop quality and yield enhancement.

Nutrient Uptake in Grain and Straw

Repeatability of T_5 excellence (100% RDF + Azotobacter + PSB) in nutrient utilization in all three macronutrients of grain and straw confirms the effectiveness of co-inoculation to make availability and assimilation of nutrients higher. Synergistic action of microbial inoculants with chemical fertilizers provided significant higher nutrient use efficiency than RDF alone or control checks.

Treatment T_3, T_6, T_7, and T_8 were statistically similar to treatment T_5 for all the nutrient uptake parameters. All treatments were marked by RDF partial but still were able to achieve equivalent uptake, demonstrating that microbial inoculants could substitute chemical nutrients partially without reducing efficiency. This indicates the ability to maximize resources in integrated nutrient management practices.

Even at chemical maturity, T_2 was always lagging behind the co-inoculation treatments, supporting the hypothesis that nutrient absorption is not always a function of fertilizer amount but of enhanced microbial-assisted solubilization and mobilization mechanisms.

T_1, the control that was not fertilized, always had the lowest values, confirming the limitation of native fertility in being capable of maintaining efficient absorption of nutrients by rice and the need for chemical and biological enrichment of nutrients.

These findings agree with Singh *et al.* (2016) and Nabati *et al.* (2025), who demonstrated that the use of biofertilizers along with chemical fertilizers enhances the uptake of nutrients and yield of crops. This study is in agreement with the postulation that integrated nutrient management is a viable and sustainable practice for enhancing nutrient-use efficiency, crop nutrition, and food security in rice-based cropping systems.

Yield

The combined numeric use of Azotobacter and PSB with 100% RDF in T_5 always led to the highest grain (51.34 q/ha), straw (74.04 q/ha), and biological yield (125.38 q/ha), with relative increments of 60.2%, 48.8%, and 53.3% above control, and in comparison, to RDF alone, with noticeable gains. The findings highlight the synergistic impact of microbial consortia on reproductive and vegetative productivity, as microbial inoculants should exhibit augmented nutrient solubilization, uptake efficiency, and growth-promoting functions.

T_8 with 75% RDF and both biofertilizers was statistically equivalent to T_5, which shows the ability of co-inoculation to maintain high yields even in low nutrient conditions. This confirms the possibility of employing integrated nutrient management practices in lowering the reliance on chemical fertilizers without lowering yield.

Substantial but modest increases in grain and biomass yields were also realized in T_7, T_6, and T_3, with half RDF or with single inoculants. They recorded 41.9%-49.0% enhanced grain yield and 39.9%-45.6% enhanced biological yield above control, testifying to their feasibility as well as to the excellence of co-inoculation.

T_4 and T_2, though superior to the control with no fertilization, recorded comparatively low yield values, revealing that PSB or RDF alone cannot be sufficient to ensure peak yield performance in the absence of microbial synergy. T_1 consistently recorded lowest values for all the components of yield, revealing the inability of unfertilized soil to maintain productive crop growth.

These observations are in agreement with Aminpanah (2016) and Rawat *et al.* (2022), who reported greater increases in rice yields through the use of integrated biofertilizers and chemical fertilizers. Both their studies and the current study used better nutrient uptake, greater microbial activity, and rhizospheric hormonal effects induced by microbial inoculants as the contributing factors for the gains. The findings reaffirm the need for integrated nutrient management for sustainable rice cultivation, particularly in alluvial soils where chemical-microbial synergy can significantly augment yield.

Conclusion

Research study entitled "Response of Azotobacter and Phosphate Solubilizing Bacteria in Association with Urea and Single Super Phosphate on Growth and

Yield under Rice Crop in Alluvial Soils of Ayodhya District", conducted under Kharif 2023-24 at Student's Instructional Farm, Acharya Narendra Deva University of Agriculture and Technology, Ayodhya (U.P.), concluded that integrated use of biofertilizers with chemical fertilizers enhanced crop yield and profitability under rice crop considerably.

Among all the treatments, T_5 (100% RDF + Azotobacter + PSB) had the most encouraging effects regarding plant growth, yield parameters, grain and straw yield, nutrient uptake and content. It recorded the highest plant height (113.80 cm), highest fresh (86.70 g) and dry biomass (28.15 g), highest tiller per hill (17.66), and highest tillers per m² (376.36) and that also indicated better vegetative growth. It gave the maximum grain yield (51.34 q/ha), straw yield (74.04 q/ha), and biological yield (125.38 q/ha) and a harvest index of 40.95%.

Nutrient absorption was significantly increased under T_5, with the highest grain nitrogen (64.46 kg/ha), phosphorus (12.02 kg/ha), and potassium (21.67 kg/ha) absorption, underpinned by greater nutrient content in grain and straw. This indicates that co-inoculation of PSB and Azotobacter enhanced solubilization and adsorption of the nutrients under full fertilization.

On the cost front, T_5 was cost-effective too, having the highest gross return (Rs. 1,85,053.60), net return (Rs. 65,944.80), and benefit-cost ratio (1.24). There were also partial replacements of fertilizers with biofertilizers that were cost-effective. T_6 (100% NK + 75% P + PSB), T_7 (75% N + 100% PK + Azotobacter), and T_8 (75% NP + 100% K + Azotobacter + PSB) recorded net returns of Rs. 62,870.67, Rs. 60,843.47, and Rs. 58,154.13 respectively with B:C ratios of 1.23, 1.22, and 1.20-providing cost-effective options for resource-based growers.

Treatments T_3 (100% RDF + Azotobacter) and T_4 (100% RDF + PSB) also showed good net returns (Rs. 58,492.13 and Rs. 54,254.27 respectively), both of which were significantly more than a B:C ratio of 1.0, establishing the efficiency of biofertilizers alone if applied with full dose of fertilizer. On the other hand, T_1 (absolute control) yielded a poorer economy and production with the lowest net return (Rs. 34,380.80) and B:C ratio (0.86), indicating the necessity of continuous nutrient application for rice productivity.

The results clearly suggest that co-inoculation of biofertilizer with Azotobacter and PSB, especially with 100% RDF or even half the rates of fertilizer, is a method of promise for improved growth, yield, nutrient accumulation, and profitability in rice crop on alluvial soils. An integrated nutrient management of such nature enhances not only the agronomic efficiency but also forms a line of action for cost-effective, eco-friendly, and sustainable rice cultivation in the region.

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