



## Synergistic effect of humic acid and phosphate solubilizing bacteria on rhizospheric functions and phosphorous acquisition in direct-seeded rice (*Oryza sativa*)

SK ASRAFUL ALI<sup>1,2</sup>, VIPIN CHANDRA DHYANI<sup>2</sup>, ANJALI KUMARI<sup>2\*</sup> and SUNIL KUMAR PRAJAPATI<sup>1</sup>

Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand 263 145, India

Received: 22 May 2025; Accepted: 03 November 2025

### ABSTRACT

This study was carried out during the rainy (*kharif*) season of 2022 and 2023 at Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand to investigate the synergistic effects of humic acid (HA) and phosphate solubilizing bacteria (PSB) under reduced phosphorus fertilisation on root development, microbial activity, and phosphorus acquisition in direct-seeded rice (DSR) (*Oryza sativa* L.). Experiment was laid out using a factorial randomized block design (FRBD) with 12 treatment combinations. Treatments included three phosphorus levels (control, 50%, and 100%, corresponding to 0, 30, and 60 kg P<sub>2</sub>O<sub>5</sub>/ha) and four phosphate solubilizers (control, HA @10 kg/ha, PSB @10 g/kg seed, and HA @10 kg/ha + PSB @10 g/kg seed). Results showed that 100% phosphorus significantly increased root dry weight density (2922 g/m<sup>3</sup>) and root volume density (6129 cc/m<sup>3</sup>), representing improvements of 18.4% and 37.4% over the control, respectively. The combined HA + PSB treatment at 50% phosphorus achieved root traits comparable to full phosphorus application, indicating improved phosphorus use efficiency (PUE). PSB populations were highest under HA + PSB (22.67 × 10<sup>4</sup> CFU/g soil), while acid and alkaline phosphatase activities increased by 11–19% and 10–11% over sole PSB, respectively. Growth parameters and grain yield were also enhanced, with plant height, tillers, and dry matter accumulation increasing by 8.2–15.2% compared to the control. Overall, integrating HA and PSB with 50% phosphorus effectively sustained root growth, microbial populations, phosphatase activity, and grain yield, demonstrating a viable strategy to optimize PUE, reduce fertiliser costs, and maintain rice productivity under DSR systems.

**Keywords:** Direct-seeded rice, Humic acid, Microbial activities, Phosphate solubilizing bacteria, Phosphorous acquisition

Rice (*Oryza sativa* L.) is a staple food for over half of the world's population and is cultivated across a vast area of 168.36 million ha (Mha) globally during the 2023 season (Srinivasan 2025). India stands out as a major rice producer, growing the crop on 47.6 Mha and yielding approximately 138 million tonnes during the fiscal year (April–March) 2024 (Statista 2025). Phosphorus (P), the 2<sup>nd</sup> most important macronutrient after nitrogen is vital for numerous physiological and biochemical processes in rice. It plays a key role in photosynthesis, energy storage, cell division, signal transduction, and the synthesis of nucleic acids and phospholipids (Khan *et al.* 2023). Despite its importance, phosphorus is often one of the least available nutrients in many soils due to its immobilisation through rapid chemical reactions with cations like Ca<sup>2+</sup> (calcareous

to normal soils), Al<sup>3+</sup> and Fe<sup>3+</sup> (acid soils), forming insoluble compounds. This leads to low phosphorus availability, adversely affecting crop performance. Moreover, the global supply of high-quality rock phosphate, the primary raw material for phosphorus-based fertilisers, faces significant challenges, with estimates suggesting depletion within this century (Baker *et al.* 2024). In light of these challenges both environmental and resource-related, it is crucial to optimize fertiliser usage and improve phosphorus use efficiency (PUE). One promising approach to enhancing PUE is the use of phosphate solubilizers, such as humic acid (HA) and phosphate solubilizing bacteria (PSB) with reduced P fertiliser without jeopardizing crop yield (Ali *et al.* 2024, Ali *et al.* 2025a).

Humic products like humic acid, fulvic acid, and humin enhance P availability by converting insoluble P into plant available forms, rupturing Fe/Al-bonded P in acidic soils and Ca-bonded P in calcareous soils. Humic acid containing 51–57% organic carbon, 4–6% nitrogen, and 0.2–1% phosphorus, improves soil properties and nutrient supply.

<sup>1</sup>ICAR-Indian Agricultural Research Institute, New Delhi; <sup>2</sup>Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand. \*Corresponding author email: [anjali440@gmail.com](mailto:anjali440@gmail.com)

When co-applied with phosphatic fertilisers, humic acid increases P mobility and availability by promoting ligand exchange and solubilization, and by releasing H<sup>+</sup> ions in the rhizosphere, which acidifies the soil and enhances phosphate uptake. This dual action synergistically improves soil health and crop productivity (Izhar Shafi *et al.* 2020, Gao *et al.* 2023, Ali *et al.* 2025b). Microorganisms are vital to the soil P cycle, transporting P among different soil pools and making it bioavailable to plants. Phosphate Solubilizing Microorganisms (PSM), including bacteria and fungi, transform inorganic and organic soil P into plant-accessible forms through solubilization and mineralization mechanisms. Phosphorus Solubilizing Bacteria (PSB), notably genera *Pseudomonas* and *Bacillus*, secrete organic acids such as formic, acetic, propionic, lactic, gluconic, 2-ketogluconic, fumaric, and succinic acids, which dissolve insoluble phosphates. This acidification process increases soluble P, enhancing plant uptake and supporting sustainable soil fertility and crop productivity (Rawat *et al.* 2021).

Humic acid and PSB in agriculture were shown to increase phosphorus availability and plant growth significantly, as seen in recent studies indicating increased nutrient uptake and microbial diversity of the treated soils (Xiong *et al.* 2023, Bansal *et al.* 2024). The combined use of humic acid and PSB, in addition to promoting phosphorus solubilization, also promotes positive interactions in the soil microbiome, enhance rhizosphere resilience and support plant health in nutrient poor conditions by improving P solubilization, enriching beneficial microbial diversity, and stimulating root growth (Cozzolino *et al.* 2021, Rawat *et al.* 2022, Xiong *et al.* 2023). Together, these amendments also improve soil structure and water retention by boosting aggregate stability, infiltration, and drought tolerance while increasing soil organic matter and microbial biomass for long-term fertility (Joshi and Maiti 2024). In DSR, humic containing enriched biochar-based fertilisers have improved nutrient release profiles and increased apparent nutrient use efficiency relative to conventional fertilisers, underscoring the potential of organic amendments to enhance P availability in DSR systems (Roy *et al.* 2022). Overall, this combined strategy addresses immediate nutrient limitations and advances sustainable, climate resilient. Considering the potential impact of HA and PSB, the present study was carried out to assess the effects of applying 50% of the recommended phosphorus fertiliser rate along with HA and PSB on root development and microbial activity in direct-seeded rice.

## MATERIALS AND METHODS

This study was carried out during the rainy (*kharif*) season of 2022 and 2023 at Govind Ballabh Pant University of Agriculture and Technology, Pantnagar (29°N, 79°E; at an elevation of 243.8 m amsl), Uttarakhand. The soil at the research site was classified as sandy loam and had the following nutrient content: 0.77% organic carbon, 141.3 kg/ha of available nitrogen, 18.1 kg/ha of available phosphorus, and 174.6 kg/ha of available potassium. Additionally, the

soil had a neutral pH of 7.1. The experiment comprised 12 treatment combinations, including 3 phosphorus levels (control, 50%, and 100%, corresponding to 0, 30, and 60 kg of P<sub>2</sub>O<sub>5</sub>/ha) and 4 phosphate solubilizers (control, HA @10 kg/ha, PSB @10 g/kg seed, and HA @10 kg/ha + PSB @10 g/kg seed). This was laid out in a factorial randomized block design (FRBD) with three replications. The recommended fertiliser application rate was 150 kg of N, 60 kg of P<sub>2</sub>O<sub>5</sub>, and 40 kg of K<sub>2</sub>O per hectare. One-third of the nitrogen, along with phosphorus according to the treatments, and the full amount of potassium was applied as a basal dose before sowing followed by soil application of humic acid (10 kg/ha). The remaining nitrogen was applied in two equal splits, with the first application 30 days after sowing (DAS) and the second at 60 DAS as top dressing. Seeds of the rice variety NDR-359, treated with PSB (NE10 strain) and untreated seeds, were manually sown in furrows spaced 20 cm apart. A seed rate of 35 kg/ha was used, and the seeds were immediately covered with soil to enhance seed-soil contact. All recommended agricultural practices, except for the treatments, were adopted throughout the experiment for raising a successful DSR. All obtained data were statistically analysed using OPSTAT software. Treatment means were compared using the least significance difference (LSD) test at  $p=0.05$ .

**Root dry weight density:** Root samples were collected at 90 DAS using a core (diameter: 13 cm, height 10 cm). The collected samples were placed in a nylon net bag and thoroughly rinsed with tap water to eliminate any soil attached to the root surfaces. After washing, the samples were dried to eliminate excess soil moisture. The dried root samples were subsequently placed in a hot air oven maintained at 70°C for further drying.

$$\text{Root dry weight density (g/m}^3\text{)} = \frac{\text{Root dry weight}}{\text{Volume of core}}$$

**Root volume density:** The root volume density was measured using the displacement method. To measure the root volume density, the dried root samples were immersed in water within a graduated tube of suitable dimensions, and the volume of water displaced by the immersed root samples was recorded. This provided a direct measurement of the root volume.

$$\text{Root volume density (cc/m}^3\text{)} = \frac{\text{Volume displaced}}{\text{Volume of core}}$$

**PSB counts:** The methodology for counting PSB followed Pikovskaya's technique as outlined in 1948. Initially, a 1 g sample of rhizospheric soil was collected at 90 and 120 DAS and placed into a sterile test tube. To this soil sample, 10 mL of sterile distilled water was added, and the mixture was shaken vigorously to create a 10<sup>-1</sup> dilution. Subsequently, 1 mL of this suspension was transferred to a different test tube containing 9 mL of distilled water, resulting in a 10<sup>-2</sup> dilution. This dilution process continued sequentially, extending to 10<sup>-6</sup> (including dilutions of 10<sup>-3</sup>, 10<sup>-4</sup>, 10<sup>-5</sup>, and 10<sup>-6</sup>). After obtaining the necessary dilutions,

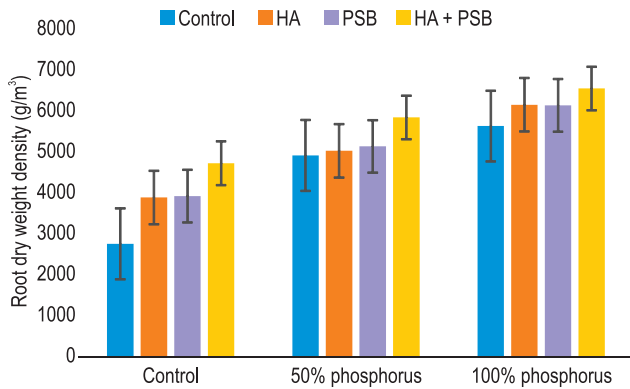


Fig. 1 Interactive effect of phosphorus levels and phosphate solubilizers on root dry weight density (Pooled mean). HA, Humic acid; PSB, Phosphorus solubilising bacteria.

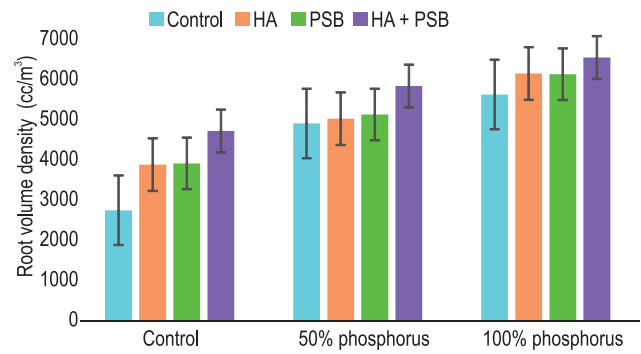


Fig. 2 Interactive effect of phosphorus levels and phosphate solubilizers on root volume density (Pooled mean). HA, Humic acid; PSB, Phosphorus solubilising bacteria.

the Total Plate Count (TPC) method was implemented using Pikovskaya's selective media, which is specifically designed to encourage the growth of PSB. The pour plate technique was utilized by combining the appropriate dilutions (typically  $10^{-4}$  and  $10^{-5}$ ) with molten Pikovskaya agar at approximately  $45^{\circ}\text{C}$ , which was then poured into sterile petri plates. After permitting the agar to solidify, the plates were incubated at  $28^{\circ}\text{C}$  for a duration of 3–5 days to facilitate colony growth. Once the incubation period was complete, the colonies on each plate were counted, and the PSB count was calculated as Colony Forming Units (CFU) per gram of soil using the specified formula.

$$\text{CFU/g of soil} = \frac{\text{Total number of CPU} \times \text{Dilution factor}}{\text{Volume of sample plated}}$$

**Acid phosphatase and alkaline phosphatase:** The procedure for evaluating the activity of acid phosphatase and alkaline phosphatase followed the method established by Tabatabai and Bremner (1969), which involved measuring the release of *p*-nitrophenol from 4-nitrophenyl phosphate, the substrate for these enzymes. A 1 g soil sample was collected at 90 and 120 DAS and mixed with toluene and a modified universal buffer. The buffer pH was adjusted to 6.5 for acid phosphatase or to 11.0 for alkaline phosphatase. Following the addition of the substrate, the mixture underwent incubation at  $37^{\circ}\text{C}$  for a duration of one hour. To halt the reaction, calcium chloride and sodium hydroxide were added, which also aided in extracting the produced *p*-nitrophenol. The resulting solution was then filtered, and the absorbance of the yellow-coloured *p*-nitrophenol was assessed at a wavelength of 420 nm. Control samples were prepared to account for background absorbance, enabling precise calculation of enzyme activity, which was reported as micrograms of *p*-nitrophenol released per gram of soil per hour.

## RESULTS AND DISCUSSION

**Root dry weight density and root volume density:** The study demonstrated that reducing the rate of phosphatic fertiliser application led to a clear decline in both root

dry weight density and root volume density in rice. When 100% of the recommended phosphorus rate was applied ( $60 \text{ kg P}_2\text{O}_5/\text{ha}$ ), root dry weight density reached  $2922 \text{ g/m}^3$  and root volume density was  $6129 \text{ cc/m}^3$ . These values were significantly higher than those observed with 50% phosphorus application and control treatment. Specifically, full phosphorus application resulted in an 18.4% increase in root dry weight density and a 37.4% increase in root volume density compared to the control (Fig. 1 and 2). This improvement is attributed to enhanced phosphate availability, which stimulates microbial activity and auxin production, ultimately enhancing root biomass (Jing *et al.* 2022).

The use of phosphate solubilisers also had a notable effect on root development (Table 1). The combined application of humic acid and PSB produced the highest root volume density ( $5716 \text{ cc/m}^3$ ), representing increase of 11.2%, 11.9%, and 22.2% compared to sole PSB, sole HA, and control, respectively. This synergistic effect is likely due to the complementary roles of HA and PSB. Humic acid is known to stimulate auxin transporters, which enhances cell division and increases root dry weight density (Nardi *et al.* 2021). Meanwhile, PSB produces indole-3-acetic acid (IAA), a plant hormone that further encourages root biomass accumulation (Elhaissofi *et al.* 2022). Interestingly, while the combined HA and PSB treatment significantly improved root volume density, its effect on root dry weight density was statistically similar to the sole applications of HA or PSB.

Furthermore, a significant interaction was observed between root dry weight density and root volume density across various phosphorus levels and phosphate solubilizers. The treatment with 50% phosphorus combined with HA and PSB resulted in root dry weight and volume densities that were statistically similar to those obtained with 100% phosphorus alone. This suggests that the combined use of HA and PSB can effectively offset reduced phosphorus fertilisation, sustaining comparable root growth characteristics. Slight increase in root growth under combined PSB and humic acid application might be attributed to increased root system resilience against

Table 1 Effects of phosphorus levels and phosphate solubilizers on root development, PSB counts and phosphatase activity (Pooled mean)

Treatments	Root dry weight density (g/m <sup>3</sup> )	Root volume density (cc/m <sup>3</sup> )	PSB counts (CFU/g soil) ( $\times 10^4$ )		Acid phosphatase ( $\mu\text{g } p\text{-nitrophenol/g soil/h}$ )		Alkaline phosphatase ( $\mu\text{g } p\text{-nitrophenol/g soil/h}$ )	
			90 DAS	120 DAS	90 DAS	120 DAS	90 DAS	120 DAS
Phosphorus levels								
Control	2382	3831	9.25	9.83	34.37	36.78	50.7	52.92
50% phosphorus	2729	5241	16.5	17	41.93	45.17	66.07	68.54
100% phosphorus	2922	6129	20.33	21.5	55.35	60.38	80.44	83.52
SEM $\pm$	40	44	0.3	0.33	0.87	1.13	0.89	1.28
LSD ( $p=0.05$ )	117	129	0.89	0.97	2.56	2.64	2.64	3.76
Phosphate solubilizers								
Control	2373	4443	12.78	13.44	36.4	41.43	53.78	57.54
HA	2729	5033	14.22	15.11	41.27	44.63	64.38	66.14
PSB	2776	5075	15.67	16.22	46.48	47.44	68.85	70.93
HA + PSB	2833	5716	18.78	19.67	51.38	56.27	75.94	78.71
SEM $\pm$	46	50	0.35	0.38	1.01	1.30	1.03	1.48
LSD ( $p=0.05$ )	135	149	1.03	1.12	2.96	3.83	3.04	4.34

HA, Humic acid; PSB, Phosphorus solubilising bacteria.

environmental stressors and improved overall nutrient uptake efficiency, leading to healthier plant growth.

**PSB counts:** The application of 100% phosphorus resulted in significantly higher PSB counts compared to 50% phosphorus and the control at both 90 and 120 DAS, with counts varying from  $9.25 \times 10^4$ – $21.5 \times 10^4$  CFU/g soil (Table 1). The combined application of humic acid and PSB resulted in the highest PSB populations, with counts of  $18.78 \times 10^4$  and  $19.67 \times 10^4$  CFU/g soil at 90 and 120 days after sowing (DAS), respectively. A significant interaction was also observed between phosphorus levels and phosphate solubilisers on PSB counts. The combined application of 50% phosphorus with HA and PSB resulted in notably higher PSB counts ( $22.67 \times 10^4$  CFU/g soil) compared to 100% phosphorus alone ( $18 \times 10^4$  CFU/g soil). This finding highlights the superior effectiveness of integrating HA and PSB with reduced phosphorus rates in promoting beneficial microbial populations.

Higher concentrations of inorganic phosphate reduce competition among microorganisms for this essential nutrient, allowing PSB to proliferate and effectively solubilise phosphorus from both organic and inorganic sources. Additionally, the greater root biomass associated with higher phosphorus levels provides a more favourable rhizospheric environment for microbial proliferation (Bilal *et al.* 2021). These values surpassed those recorded with sole HA or PSB applications, though HA and PSB alone produced statistically similar results. Across all phosphate solubiliser treatments, PSB counts increased from 90–120 DAS, reflecting favourable conditions for microbial proliferation. The synergistic effect of HA and PSB is attributed to HA serving as a readily available organic matter source, which enhances microbial respiration and activity (Hasan *et al.* 2024).

**Acid phosphatase and alkaline phosphatase:** The treatment with 100% phosphorus application resulted in the highest levels of both phosphatase enzymes activity, followed by 50% phosphorus and the control. Specifically, from 90–120 DAS, the 100% phosphorus application led to a 37.9–39% increase in acid phosphatase and a 36.6–36.9% increase in alkaline phosphatase compared to control (Table 1). A similar result related to phosphatase was also reported by Bhatt *et al.* (2016). Higher PSB counts in optimum phosphorus levels led to higher phosphatase release.

The application of humic acid combined with PSB led to significantly higher alkaline phosphatase compared to the individual application of PSB or HA, and the control treatment. The combination of humic acid and PSB increased acid phosphatase by 11–19% and alkaline phosphatase by 10–11% over PSB alone from 90 DAS to 120 DAS. This may be attributed to the substantial increase in PSB populations in the HA + PSB treatment. Humic acid serves as an organic nutrient source that promotes microbial proliferation, which directly increases phosphatase activity (Ampong *et al.* 2022). Concurrently, as PSB counts increased, phosphatase activity also increased simultaneously in the soil due to the application of PSB (Aslam *et al.* 2022).

Furthermore, application of 50% phosphorus with HA + PSB recorded significantly higher alkaline phosphatase compared to the 100% phosphorus application under control of phosphate solubilisers while application of 50% phosphorus with HA + PSB had statistically similar acid phosphatase with 100% phosphorus under control of phosphate solubilizers.

**Growth parameters and grain yield:** Application of 100% phosphorus at harvest resulted in significantly taller rice plants (100 cm), which was a 5.2% increase compared to

50% phosphorus (95.1 cm) and an 18.1% increase compared to the control (84.7 cm). Similarly, the HA + PSB treatment (97.1 cm) outperformed HA alone (93.7 cm), PSB alone (92.6 cm), and the control (89.7 cm). The increase was 3.6% over HA alone, 4.9% over PSB alone, and 8.2% over the control. In terms of tiller counts, applying 100% phosphorus at harvest significantly increased tiller counts to 338, a 11.5% increase over 50% phosphorus (303) and a 23.8% increase over the control (273). The HA + PSB treatment (321) and HA alone (310) showed statistically similar tiller counts, outperforming PSB alone (297) and the control (291), with increase of 7.5% and 10.3%, respectively compared to the control. At harvest, applying 100% phosphorus significantly increased dry matter accumulation to 1489 g/m<sup>2</sup>, a 15.2% increase over 50% phosphorus (1260 g/m<sup>2</sup>) and a 29.1% increase over the control (1052 g/m<sup>2</sup>). The HA + PSB treatment (1395 g/m<sup>2</sup>) resulted in significantly higher dry matter, outperforming HA alone (1296 g/m<sup>2</sup>), PSB alone (1268 g/m<sup>2</sup>), and the control (1108 g/m<sup>2</sup>) (Table 2). A significant interaction between phosphorus levels and phosphate solubilizers was observed for panicle counts and grain yield. Applying 50% phosphorus with HA alone (292), PSB alone (289), and HA + PSB (307) produced panicle numbers statistically similar to 100% phosphorus without solubilisers (308), indicating that solubilizer integration can compensate for reduced phosphorus input. Grain yield followed a similar trend, with 50% phosphorus combined with HA + PSB (4.7 t/ha), HA alone (4.6 t/ha), and PSB alone (4.4 t/ha) matching the yield of 100% phosphorus without solubilisers (4.6 t/ha). Notably, the HA + PSB with 50% phosphorus treatment slightly exceeded the grain yield of the full phosphorus application, with a 2.2% increase (Fig. 3).

The study highlights the critical role of phosphorus, humic acid and PSB on phosphorus supply that strongly

influences root system development and rhizosphere activities in direct-seeded rice. Across the treatments, higher P rates substantially influenced root dry weight density, root volume density, and PSB counts. Notably, the combined application of HA and PSB demonstrated synergistic effects, leading to improved root characteristics and microbial activity compared to individual treatments. Moreover, applying just 50% of the recommended phosphorus fertiliser rate, in combination with HA and PSB delivered significant improvement in root traits, microbial population, and phosphatase activity relative to the corresponding sole or lower-input treatments, indicating a synergistic effect that improved phosphorus use efficiency. Under *Tarai* belt conditions, combining humic acid and PSB can partially offset reduced mineral phosphorus inputs without impairing key belowground indicators, potentially lowering fertiliser costs and environmental impacts while sustaining soil biological function. The extent of responses might be dependent on varying with HA source and dose,

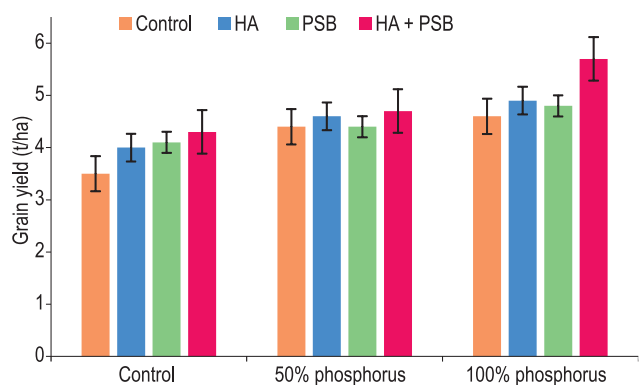


Fig. 3 Interactive effect of phosphorus levels and phosphate solubilisers on grain yield (Pooled mean). HA, Humic acid; PSB, Phosphorus solubilising bacteria.

Table 2 Effects of phosphorus levels and phosphate solubilizers on growth parameters and grain yield (Pooled mean)

Treatments	Plant height At harvest	Tillers/m <sup>2</sup> At harvest	Dry matter (g/m <sup>2</sup> ) At harvest	Panicles/m <sup>2</sup>	Grain yield (t/ha)
Phosphorus levels					
Control	84.7	273	1052	253	3.9
50% phosphorus	95.1	303	1260	292	4.5
100% phosphorus	100	338	1489	335	5.0
SEM±	0.7	3.8	20.12	3.3	0.06
LSD ( <i>p</i> =0.05)	2.1	11.2	59.38	9.6	0.19
Phosphate solubilisers					
Control	89.7	291	1108	273	4.2
HA	93.7	310	1296	296	4.5
PSB	92.6	297	1268	293	4.5
HA + PSB	97.1	321	1395	312	4.9
SEM±	0.8	4.4	23.23	3.8	0.07
LSD ( <i>p</i> =0.05)	2.4	12.9	68.56	11.1	0.22

HA, Humic acid; PSB, Phosphorus solubilising bacteria.

PSB strains, soil P status and pH, irrigation, and seasonal weather. Hence, long term assessment of economic benefits, productivity and phosphorus acquisition, soil phosphorus pools and microbiome alterations might be further explored.

## REFERENCES

- Ali S A, Dhyani V C, Kumari A, Chaturvedi S, Borate R B, Prajapati S K and Babu S. 2025a. Enhancing wheat photosynthetic efficiency and productivity via co-application of humic acid and phosphate solubilizing bacteria under varying phosphorus levels. *Edelweiss Applied Science and Technology* **9**(7): 2056–62.
- Ali S A, Kaur R, Dhyani V C, Kumari M, Ezing U M and Jha R. 2024. Unlocking soil phosphorus: The importance of phosphate solubilizers for crop growth. *Chronicle of Bioresource Management* **8**(3): 77–81.
- Ali S A, Kumari A, Dhyani V C and Chaturvedi S. 2025b. Humic acid and phosphate solubilizing bacteria led phosphorous bioavailability for enhancing photosynthetic efficiency and productivity of direct-seeded rice. *Soil and Environment* **44**(1): 86–91. <https://doi.org/10.25252/SE/2025/253726>
- Ampong K, Thilakarathna M S and Gorim L Y. 2022. Understanding the role of humic acids on crop performance and soil health. *Frontiers in Agronomy* **4**: 848621.
- Aslam M M, Pueyo J J, Pang J, Yang J, Chen W, Chen H, Waseem M, Li Y, Zhang J and Xu W. 2022. Root acid phosphatases and rhizobacteria synergistically enhance white lupin and rice phosphorus acquisition. *Plant Physiology* **190**(4): 2449–65.
- Baker J, Schunk N, Scholz M, Merck A, Muenich R L, Westerhoff P, Elser J J, Duckworth O W, Gatiboni L, Islam M and Marshall A M. 2024. Global-to-local dependencies in phosphorus mass flows and markets: Pathways to improving system resiliency in response to exogenous shocks. *Environmental Science and Technology Letters* **11**(6): 493–502.
- Bansal K K, Sharma A K, Sharma A, Bharti V, Sharma V, Sharma M K and Dey T. 2024. Residual effect of humic acid, PSB and phosphorus nutrition on soil chemical properties after harvest of rice crop under the subtropical condition of Jammu. *International Journal of Plant and Soil Science* **36**(3): 59–68. <https://doi.org/10.9734/ijpss/2024/v36i34398>
- Bhatt B, Chandra R, Ram S and Pareek N. 2016. Long-term effects of fertilization and manuring on productivity and soil biological properties under rice (*Oryza sativa*)-wheat (*Triticum aestivum*) sequence in Mollisols. *Archives of Agronomy and Soil Science* **62**(8): 1109–22.
- Bilal S, Hazafa A, Ashraf I, Alamri S, Siddiqui M H, Ramzan A, Qamar N, Sher F and Naeem M. 2021. Comparative effect of inoculation of phosphorus-solubilizing bacteria and phosphorus as sustainable fertiliser on yield and quality of mung bean (*Vigna radiata* L.). *Plants* **10**(10): 2079.
- Cozzolino V, Monda H, Savy D, Meo V D, Vinci G and Smalla K. 2021. Cooperation among phosphate-solubilizing bacteria, humic acids and arbuscular mycorrhizal fungi induces soil microbiome shifts and enhances plant nutrient uptake. *Chemical and Biological Technologies in Agriculture* **8**: 1–18.
- Elhaissofi W, Ghoulam C, Barakat A, Zeroual Y and Bargaz A. 2022. Phosphate bacterial solubilization: A key rhizosphere driving force enabling higher P use efficiency and crop productivity. *Journal of Advanced Research* **38**: 13–28.
- Gao S, Zhang S, Yuan L, Li Y, Zhao L, Wen Y, Xu J, Hu S and Zhao B. 2023. Effects of humic acid-enhanced phosphate fertiliser on wheat yield, phosphorus uptake, and soil available phosphorus content. *Crop Science* **63**: 956–66.
- Hasan A, Tabassum B, Hashim M and Khan N. 2024. Role of plant growth promoting rhizobacteria (PGPR) as a plant growth enhancer for sustainable agriculture: A review. *Bacteria* **3**(2): 59–75.
- Izhar Shafi M, Adnan M, Fahad S, Wahid F, Khan A, Yue Z and Datta R. 2020. Application of single superphosphate with humic acid improves the growth, yield and phosphorus uptake of wheat (*Triticum aestivum* L.) in calcareous soil. *Agronomy* **10**(9): 1224.
- Jing J, Zhang S, Yuan L, Li Y, Zhang Y and Zhao B. 2022. Synergistic effects of humic acid and phosphate fertiliser facilitate root proliferation and phosphorus uptake in low-fertility soil. *Plant and Soil* **478**(1): 491–503.
- Joshi A and Maiti J. 2024. Trait-based approaches to improve nutrient uptake efficiency in crops. (In) *Plant Functional Traits for Improving Productivity*, pp. 149–68. Kumar N and Singh H (Eds). Springer, Singapore.
- Khan F, Siddique A B, Shabala S, Zhou M and Zhao C. 2023. Phosphorus plays key roles in regulating plants' physiological responses to abiotic stresses. *Plants* **12**(15): 2861.
- Nardi S, Schiavon M and Francioso O. 2021. Chemical structure and biological activity of humic substances define their role as plant growth promoters. *Molecules* **26**(8): 2256.
- Pikovskaya R I. 1948. Mobilization of phosphorus in soil connection with the vital activity of some microbial species. *Microbiology* **17**: 362–70.
- Srinivasan R. 2025. Diversification of rice-based cropping systems with vegetables and legumes in Asia and Africa. *Crops* **5**(4): 43.
- Rawat P, Das S, Shankhdhar D and Shankhdhar S C. 2021. Phosphate-solubilizing microorganisms: Mechanism and their role in phosphate solubilization and uptake. *Journal of Soil Science and Plant Nutrition* **21**(1): 49–68.
- Rawat P, Sharma A, Shankhdhar D and Shankhdhar S C. 2022. Improvement of phosphorus uptake, phosphorus use efficiency, and grain yield of upland rice (*Oryza sativa* L.) in response to phosphate-solubilizing bacteria blended with phosphorus fertiliser. *Pedosphere* **32**(5): 752–63.
- Roy A, Chaturvedi S, Singh S V, Kasivelu G, Dhyani V C and Pyne S. 2022. Preparation and evaluation of two enriched biochar-based fertilisers for nutrient release kinetics and agronomic effectiveness in direct-seeded rice. *Biomass Conversion and Biorefinery* **14**: 2007–18. <https://doi.org/10.1007/s13399-022-02488-z>
- Statista. 2025. Total area of cultivation for rice across India from financial year 2014–2023, with an estimate for 2024 (in million hectares). Accessed August 10, 2025. <https://www.statista.com/statistics/765691/india-area-of-cultivation-for-rice/#:~:text=In%20fiscal%20year%202024%2C%20India,globally%2C%20and%20the%20largest%20exporter>
- Tabatabai M A and Bremner J M. 1969. Use of *p*-nitrophenyl phosphate for assay of soil phosphatase activity. *Soil Biology and Biochemistry* **1**(4): 301–07.
- Xiong Q, Wang S, Lu X, Chen X, Tian D, Zhang L, Jing J and Ye X. 2023. The effective combination of humic acid phosphate fertiliser regulating the form transformation of phosphorus and the chemical and microbial mechanism of its phosphorus availability. *Agronomy* **13**(6): 1581.