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Sustainable phosphorus management in wheat (*Triticum aestivum*): Synergistic effects of humic acid and phosphate solubilising bacteria on yield, uptake and profitability

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ABSTRACT

Phosphorus (P) is an essential macronutrient for wheat (*Triticum aestivum* L.) growth and productivity. However, indiscriminate use of P fertilisers poses environmental and economic challenges. To address this, a field experiment was conducted to evaluate the effectiveness of humic acid (HA) and phosphate solubilising bacteria (PSB) in enhancing phosphorus use efficiency under reduced phosphorus fertilisation. The experiment comprised three phosphorus levels (control, 50%, and 100%, corresponding to 0, 30, and 60 kg of P_2O_5/ha) and four phosphate solubiliser treatments (control, HA @10 kg/ha, PSB biofertiliser @10 g/kg seed, and HA @10 kg/ha + PSB biofertiliser @10 g/kg seed) arranged in a factorial randomised block design (F-RBD) with three replications. Application of 100% phosphorus recorded the highest plant height (98.8 cm), tiller number (390.8/m^2), dry matter accumulation (890.5 g/m^2), spike count (366.7/m^2), grain yield (5.48 t/ha), straw yield (9.15 t/ha), total phosphorus uptake (41.45 kg/ha), gross returns (₹136.71 × 10^3/ha), and net returns (₹97.35 × 10^3/ha). Among phosphate solubiliser treatments, HA + PSB significantly improved plant height (96.3 cm), tiller number (362.4/m^2), dry matter accumulation (879.3 g/m^2), spike count (342.7/m^2), grain yield (5.10 t/ha), straw yield (8.60 t/ha), and total phosphorus uptake (37.22 kg/ha). A significant interaction between phosphorus levels and phosphate solubilisers was observed for spike count, grain yield, and straw yield. Notably, 50% phosphorus combined with HA + PSB produced 331.0 spikes/m^2, 4.97 t/ha grain yield, and 8.47 t/ha straw yield, which were statistically comparable to the sole application of 100% phosphorus (338.0 spikes/m^2, 5.09 t/ha grain yield, and 8.91 t/ha straw yield). The results demonstrate that integration of HA and PSB can reduce phosphorus fertiliser requirements by 50% without significant yield reduction, thereby improving phosphorus use efficiency and supporting economically viable and environmentally sustainable wheat production.

Keywords: Humic acid, Phosphate solubilising bacteria, Phosphorus use efficiency, Sustainable nutrient management

Phosphorus (P) is an essential macronutrient that plays a vital role in the growth and development of plants. It is one of the key nutrients required for photosynthesis, energy transfer, and cell division, making it crucial for achieving high productivity in wheat (*Triticum aestivum* L.), a staple crop of significant economic importance worldwide (Khan *et al.* 2023, Ali *et al.* 2025a, Kumari *et al.* 2026). In many agricultural systems, phosphorus is commonly applied in the form of chemical fertilisers, which provide readily available nutrient forms to crops (Sayed Ahmed *et al.* 2025). While phosphorus is known to dramatically enhance wheat yields, its excessive application can lead to diminishing returns due to factors such as nutrient fixation in soils and inefficient plant uptake (Kaur *et al.* 2024). Moreover, the overuse of phosphorus fertilisers has created economic challenges, including increased input costs for farmers and significant environmental impacts, such as soil degradation and nutrient runoff, which contribute to the eutrophication of water bodies (Liu *et al.* 2021, Prajapati *et al.* 2025). In light of rising phosphorus fertiliser costs, driven by geopolitical factors and market monopolisation, there is an urgent need for a strategic approach to phosphorus management. Such an approach should aim to optimise returns while minimising the negative environmental effects associated

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with phosphorus application (Baker *et al.* 2024). To enhance phosphorus availability in soils and improve economic outcomes, the concept of phosphate solubilisers (humic substances, phosphate solubilising bacteria, phosphate solubilising fungi etc.) has gained traction in modern agricultural practices (Ali *et al.* 2024, Hozayn *et al.* 2025).

Humic products, namely humic acid, fulvic acid, and humin play a crucial role in increasing P availability by transforming insoluble P compounds into forms accessible to plants. They achieve this by breaking Fe/Al-bound P in acidic soils and Ca-bound P in calcareous soils (Yuan *et al.* 2023). Humic acid, which comprises 51–57% organic carbon, 4–6% nitrogen, and 0.2–1% phosphorus, enhances soil structure and nutrient provision. When used together with phosphate fertilisers, humic acid not only boosts the mobility and availability of P through mechanisms such as ligand exchange and solubilisation but also lowers soil *p*H in the rhizosphere by releasing H^+ ions. This acidification further facilitates phosphate uptake. These combined processes support improved soil health and higher crop yields (Izhar Shafi *et al.* 2020). Microorganisms are integral to the soil phosphorus cycle, helping to move P among different soil fractions and making it accessible to plants. Phosphate Solubilising Microorganisms (PSM), like specific bacteria and fungi, convert inorganic and organic phosphorus in soil into forms that plants can easily absorb, using pathways of solubilisation and mineralisation (Aulakh *et al.* 2023, Pan and Cai 2023). Among these, Phosphate Solubilising Bacteria (PSB), notably from the *Pseudomonas* and *Bacillus* genera, produce organic acids such as gluconic and acetic, along with other short-chain acids that contribute to phosphorus solubilisation. These acids help dissolve insoluble phosphate minerals by acidifying the environment, which in turn increases soluble P concentrations and boosts plant uptake, thereby supporting sustainable soil fertility and crop productivity (Karan *et al.* 2026).

Research findings from multiple field studies indicate that combined application of humic acid (HA) and PSB with phosphorus fertilisers can potentially reduce phosphorus fertiliser requirements by up to 50% (Ali *et al.* 2025b and 2025c). These biological approaches align with broader sustainability strategies to improve resource-use efficiency (Prajapati *et al.* 2026a and 2026b). Considering the importance of HA and PSB in improving phosphorus use efficiency within such sustainability frameworks, the present study was conducted to assess the effects of applying 50% of the recommended phosphorus fertiliser rate along with HA and PSB on wheat productivity and profitability.

MATERIALS AND METHODS

Experimental details: The field experiment was conducted during the winter (*rabi*) seasons of 2021–22 and 2022–23 at the N E Borlaug Crop Research Centre, Govind Ballabh Pant University of Agriculture and Technology (29°N and 79.3°E, at an elevation of 243.8 m mean sea level), Pantnagar, Uttarakhand. The experimental soil was sandy loam in texture, with medium organic carbon (0.78%), low available nitrogen (168.5 kg/ha), medium available phosphorus (15.4 kg/ha), and low available potassium (168.4 kg/ha). The soil reaction was neutral, with a *p*H of 7.10. The study comprised three phosphorus levels (control, 50%, and 100%, corresponding to 0, 30, and 60 kg of P_2O_5/ha) and four phosphate solubiliser treatments [control, humic acid (HA) @10 kg/ha, phosphate solubilising bacteria (PSB) biofertiliser @10 g/kg seed, and HA @10 kg/ha + PSB biofertiliser @10 g/kg seed] arranged in a factorial randomised block design (F-RBD) with three replications. The recommended fertiliser dose was 120:60:40 kg N: P_2O_5: K_2O/ha. One-third of the nitrogen and the full dose of potassium, along with phosphorus as per treatment, were applied as basal before sowing. Humic acid (10 kg/ha) was also incorporated at sowing. The remaining two-thirds of nitrogen was top-dressed in two equal splits at 30 and 60 days after sowing (DAS). Wheat variety HD 2967 was sown manually at 100 kg/ha, with PSB-treated and untreated seeds placed in furrows spaced 22.5 cm apart and immediately covered to ensure seed-soil contact. All recommended agronomic practices were followed uniformly, except for treatment-specific variations.

Economics: The cost of cultivation for the various treatments was calculated for each treatment, taking into account expenses related to labour, inputs and various operations including land preparation, sowing, fertiliser application, irrigation, weeding, harvesting and threshing, all based on local market rates. Gross returns were determined using the Minimum Support Price (MSP) for wheat announced by the Government of India for the financial year corresponding to the experimental season 2021–22 (₹1,975/q) and 2022–23 (₹2,015/q) (Department of Food and Public Distribution 2026), along with the local market price of straw (₹2/kg). Net returns for all treatments were calculated by deducting the cost of cultivation from the gross returns.

Total phosphorus uptake: The phosphorus concentration in grain and straw was determined using the Vanado-Molybdo-Phosphoric Acid Yellow Colour method (Jackson 1973). Phosphorus uptake in grain and straw was calculated separately by multiplying phosphorus concentration with their respective yields, and the values were subsequently summed to obtain total phosphorus uptake (kg/ha).

Statistical analysis: Data were subjected to analysis of variance (ANOVA) for statistical interpretation using OPSTAT software, and treatment means were compared using the least significant difference (LSD) test at $p = 0.05$.

RESULTS AND DISCUSSION

Growth parameters: The application of 100% phosphorus markedly enhanced plant height (98.8 cm) compared to 50% phosphorus (89.4 cm) and the control (86.4 cm), which can be attributed to improved root development and more efficient nutrient uptake resulting from higher phosphorus availability (Table 1). A similar trend was observed with bio-stimulant treatments, where the combined application of humic acid (HA) and phosphate

Table 1 Effects of phosphorus levels and phosphate solubilisers on growth, yield attributes, yields, and total P uptake of wheat (Two-year mean)

Treatments	Plant height at harvest (cm)	Tiller counts at harvest (No./m^2)	Dry matter accumulation at harvest (g/m^2)	Spikes (No./m^2)	Grain yield (t/ha)	Straw yield (t/ha)	Total phosphorus uptake (kg/ha)
Phosphorus levels							
Control	86.4	299.4	778.6	281.2	4.41	7.56	26.24
50% phosphorus	89.4	335.7	823.4	321.0	4.75	8.09	32.43
100% phosphorus	98.8	390.8	890.5	366.7	5.48	9.15	41.45
SEM±	0.7	1.2	1.8	2.5	0.03	0.05	0.44
LSD (p=0.05)	1.9	3.5	5.3	7.3	0.10	0.14	1.30
Phosphate solubilisers							
Control	87.7	323.1	791.8	304.6	4.67	7.93	30.25
HA	93.8	346.6	830.3	330.1	4.93	8.35	34.13
PSB	88.6	335.6	821.8	314.3	4.81	8.18	31.90
HA + PSB	96.3	362.4	879.3	342.7	5.10	8.60	37.22
SEM±	0.7	1.4	2.1	2.9	0.04	0.06	0.51
LSD (p=0.05)	2.1	4.1	6.1	8.4	0.12	0.16	1.50

HA, Humic acid; PSB, Phosphate solublising bacteria.

solubilising bacteria (PSB) produced significantly taller plants (96.3 cm) than PSB alone (88.6 cm) and the untreated control (87.7 cm). This superior performance of the HA + PSB combination likely stems from its synergistic role in enhancing phosphorus solubility and providing phytohormones such as indole acetic acid (IAA), gibberellins, and cytokinins, which collectively stimulate root elongation, nutrient absorption, and vegetative growth (Izhar Shafi *et al*. 2020, Karan *et al.* 2026). Phosphorus levels also exerted a notable influence on tiller production, with tiller counts increasing from 299.4/m^2 under control to 335.7/m^2 under 50% phosphorus and 390.8/m^2 under 100% phosphorus. This improvement is indicative of increased root biomass and enhanced physiological activity under adequate phosphorus nutrition. Among bio-stimulants, HA, PSB and HA + PSB recorded tiller counts of 346.6, 335.6 and 362.4/m^2, respectively, with HA + PSB significantly outperforming the control (323.1/m^2), reflecting the complementary roles of HA in rhizosphere acidification and root stimulation and PSB in promoting tillering through IAA-mediated lateral root formation (Rawat *et al*. 2022, Ali *et al*. 2025b). Dry matter accumulation followed parallel trends, with 100% phosphorus producing the highest biomass (890.5 g/m^2), followed by 50% phosphorus (823.4 g/m^2) and the control (778.6 g/m^2). Likewise, HA + PSB resulted in the greatest biomass among bio-stimulants (879.3 g/m^2), followed by HA (830.3 g/m^2), PSB (821.8 g/m^2) and untreated control (791.8 g/m^2). These findings align closely with straw yield responses and collectively highlight that integrating HA and PSB effectively enhances root establishment, nutrient acquisition, vegetative growth and dry matter production, even under reduced phosphorus inputs (Nabi *et al.* 2025, Xu *et al.* 2025). The observed increase in biomass is further supported by improved crop vigour, greater tiller formation, and strengthened root systems facilitated by bio-stimulant and phosphorus interactions.

Yield and yield contributing characters: Phosphorus levels exerted a significant influence on spike counts, with the highest number of spikes being recorded under 100% phosphorus (366.7/m^2), followed by 50% phosphorus (321.0/m^2) and the control (281.2/m^2) (Table 1). The increase in spike counts under higher phosphorus application may be attributed to enhanced tillering, improved root growth, and greater nutrient availability during the reproductive stage. Among phosphate solubiliser treatments, the combined application of HA + PSB produced the maximum number of spikes (342.7/m^2), followed by HA (330.1/m^2), PSB (314.3/m^2), and the untreated control (304.6/m^2). The superior performance of HA + PSB highlights the synergistic effect of humic acid and phosphate solubilising bacteria in improving phosphorus availability and promoting reproductive growth, resulting in a greater number of productive tillers and spikes (Ali *et al*. 2025b and 2025c).

Grain yield responded positively to increasing phosphorus levels, with 100% phosphorus producing the highest grain yield (5.48 t/ha), followed by 50% phosphorus (4.75 t/ha) and the control (4.41 t/ha). The yield improvement under adequate phosphorus nutrition can be attributed to enhanced photosynthetic activity, efficient translocation of assimilates, and better grain filling. A similar trend was observed among phosphate solubiliser treatments, where HA + PSB registered the highest grain yield (5.10 t/ha),

followed by HA (4.93 t/ha), PSB (4.81 t/ha), and the untreated control (4.67 t/ha). The combined application of HA and PSB likely improved phosphorus uptake and nutrient use efficiency, thereby enhancing crop productivity through better growth and yield formation (Muhammad *et al*. 2023, Bajya and Sharma 2024).

Straw yield also increased significantly with phosphorus application, reaching a maximum of 9.15 t/ha under 100% phosphorus, compared with 8.09 t/ha under 50% phosphorus and 7.56 t/ha in the control. This increase in straw yield reflects the positive impact of phosphorus on vegetative growth, biomass accumulation, and overall crop vigour. Among phosphate solubiliser treatments, HA + PSB recorded the highest straw yield (8.60 t/ha), followed by HA (8.35 t/ha), PSB (8.18 t/ha), and untreated control (7.93 t/ha). The enhanced straw production under HA + PSB treatment further demonstrates the beneficial role of these bio-stimulants in improving nutrient availability, root activity, and biomass accumulation, contributing to greater overall productivity of wheat (Izhar Shafi *et al.* 2020, Karan *et al.* 2026).

Total phosphorus uptake: Phosphorus application significantly influenced total phosphorus uptake by wheat, with the highest uptake being recorded under 100% phosphorus (41.45 kg/ha), followed by 50% phosphorus (32.43 kg/ha) and the control (26.24 kg/ha) (Table 1). The enhanced phosphorus uptake under higher phosphorus levels may be attributed to greater phosphorus availability in the soil, improved root proliferation, and increased biomass production, which collectively enhanced nutrient acquisition by the crop. Among phosphate solubiliser treatments, the combined application of HA + PSB resulted in the maximum total phosphorus uptake (37.22 kg/ha), followed by HA (34.13 kg/ha), PSB (31.90 kg/ha), and the untreated control (30.25 kg/ha). The superior performance of HA + PSB can be attributed to the synergistic action of humic acid and phosphate solubilising bacteria, wherein HA improves root growth, nutrient absorption efficiency, and soil physicochemical properties, while PSB enhances phosphorus availability through the solubilisation of insoluble phosphate compounds. Consequently, the integrated use of HA and PSB improved phosphorus acquisition and utilisation by wheat, highlighting their potential as effective components of sustainable phosphorus management strategies (Ali *et al*. 2025a and 2025b, Prajapati *et al*. 2026a and 2026b).

Economics: Phosphorus application had a marked effect on the economics of wheat cultivation (Table 2). The cost of cultivation increased with increasing phosphorus levels, ranging from ₹36.04 × 10^3/ha in the control to ₹37.70 × 10^3/ha under 50% phosphorus and ₹39.36 × 10^3/ha under 100% phosphorus. The higher cultivation cost under 100% phosphorus was mainly due to the additional expenditure incurred on phosphatic fertilisers. Despite the increased production cost, phosphorus application substantially improved economic returns. The highest gross returns (₹136.71 × 10^3/ha) and net returns (₹97.35 × 10^3/ha) were obtained with 100% phosphorus, followed by 50% phosphorus (₹118.88 × 10^3 and ₹81.18 × 10^3/ha, respectively) and the control (₹110.58 × 10^3 and ₹74.54 × 10^3/ha, respectively). The higher profitability associated with 100% phosphorus can be attributed to the corresponding increase in grain and straw yields, which translates into greater market returns.

Table 2 Effects of phosphorus levels and phosphate solubilisers on economics (Two-year mean)

Treatments	Cost of cultivation (₹/ha) (× 10^3)	Gross returns (₹/ha) (× 10^3)	Net returns (₹/ha) (× 10^3)
Phosphorus levels			
Control	36.04	110.58	74.54
50% phosphorus	37.70	118.88	81.18
100% phosphorus	39.36	136.71	97.35
SEM±	-	0.68	0.68
LSD (*p*=0.05)	-	2.01	2.01
Phosphate solubilisers			
Control	36.60	116.80	80.20
HA	38.60	123.35	84.75
PSB	36.80	120.48	83.68
HA + PSB	38.80	127.60	88.80
SEM±	-	0.78	0.78
LSD (*p*=0.05)	-	2.32	2.32

HA, Humic acid; PSB, Phosphate solublising bacteria.

Among phosphate-solubiliser treatments, the combined application of HA + PSB recorded the highest cost of cultivation (₹38.80 × 10^3/ha), followed by HA (₹38.60 × 10^3/ha), PSB (₹36.80 × 10^3/ha), and the untreated control (₹36.60 × 10^3/ha). The increased cultivation cost in treatments receiving HA was mainly due to the additional input cost of the bio-stimulant. However, these treatments also resulted in higher economic returns. The maximum gross returns (₹127.60 × 10^3/ha) and net returns (₹88.80 × 10^3/ha) were recorded under HA + PSB, followed by HA (₹123.35 × 10^3 and ₹84.75 × 10^3/ha, respectively), PSB (₹120.48 × 10^3 and ₹83.68 × 10^3/ha, respectively), and the untreated control (₹116.80 × 10^3 and ₹80.20 × 10^3/ha, respectively). The superior economic performance of the HA + PSB treatment may be attributed to its positive influence on crop growth, yield attributes, grain yield, and nutrient uptake, which ultimately enhanced overall productivity and profitability. These findings indicate that the integrated use of humic acid and PSB can improve the economic returns of wheat cultivation while supporting efficient phosphorus management and sustainable crop production.

Interaction effect (Phosphorus levels × Phosphate solubilisers): A significant interaction between phosphorus levels and phosphate solubilising treatments was observed for spike counts, grain yield, and straw yield (Table 3), indicating that the response of wheat to phosphorus

Table 3 Interaction effect of phosphorus levels and phosphate solubilisers on spike counts, grain yield and straw yield of wheat (Two-year mean)

Phosphorus levels × Phosphate solubilisers	Spikes (Nos./m^2)				Grain yield (t/ha)				Straw yield (t/ha)			
	Control	HA	PSB	HA + PSB	Control	HA	PSB	HA + PSB	Control	HA	PSB	HA + PSB
Control	264.7	282.8	275.2	301.8	4.32	4.48	4.37	4.49	7.05	7.72	7.70	7.74
50% phosphorus	311.0	322.7	319.2	331.0	4.59	4.80	4.62	4.97	7.83	8.22	7.86	8.67
100% phosphorus	338.0	384.8	348.7	395.3	5.09	5.50	5.45	5.88	8.91	9.10	8.95	9.62
SEM ±	5.0				0.07				0.10			
LSD (p=0.05)	14.5				0.10				0.27			

HA, Humic acid; PSB, Phosphate solublising bacteria.

fertilisation was strongly influenced by the application of HA and PSB. The combined use of HA and PSB substantially improved crop performance under reduced phosphorus fertilisation and helped maintain productivity at levels comparable to those achieved with the full recommended phosphorus dose. For spike count, the highest value (395.3 spikes/m^2) was recorded under 100% phosphorus + HA + PSB, followed by 100% phosphorus + HA (384.8 spikes/m^2). Under reduced phosphorus fertilisation, the treatment 50% phosphorus + HA + PSB produced 331.0 spikes/m^2, which was statistically at par with the sole application of 100% phosphorus (338.0 spikes/m^2). The enhanced spike production under HA + PSB may be attributed to improved phosphorus solubilisation, greater nutrient availability, enhanced root development, and increased survival of productive tillers, resulting in a higher number of spikes per unit area (Kumari *et al.* 2026). A similar trend was observed for grain yield. The maximum grain yield (5.88 t/ha) was obtained with 100% phosphorus + HA + PSB, whereas the sole application of 100% phosphorus produced 5.09 t/ha. Importantly, the treatment 50% phosphorus + HA + PSB recorded a grain yield of 4.97 t/ha, which was statistically comparable to that obtained with 100% phosphorus alone, with a marginal difference of only 0.12 t/ha. This finding clearly demonstrates that the combined use of HA and PSB was able to compensate for a 50% reduction in phosphorus fertiliser by enhancing phosphorus availability and uptake, thereby sustaining grain production (Ali *et al.* 2025b and 2025c). Straw yield also responded significantly to the interaction between phosphorus levels and phosphate solubilisers. The highest straw yield (9.62 t/ha) was recorded under 100% phosphorus + HA + PSB, followed by 100% phosphorus + HA (9.10 t/ha) and 100% phosphorus + PSB (8.95 t/ha). The application of 50% phosphorus + HA + PSB produced 8.67 t/ha straw yield, which remained statistically comparable to the sole 100% phosphorus treatment (8.91 t/ha). The increased straw yield under integrated treatments may be attributed to greater dry matter accumulation resulting from improved nutrient acquisition, enhanced photosynthetic activity, and better crop vigour throughout the growing season (Izhar Shafi *et al.* 2020, Karan *et al.* 2026).

The present study demonstrated that the combined application of humic acid (HA) and phosphate solubilising bacteria (PSB) significantly enhanced wheat growth, yield attributes, productivity, phosphorus uptake, and economic returns under different phosphorus levels. While the full recommended phosphorus dose produced the highest overall performance, the integrated application of HA and PSB consistently improved crop growth and nutrient acquisition compared with the untreated control and individual bio-stimulant applications. A significant interaction between phosphorus levels and phosphate solubilisers revealed that the application of 50% recommended phosphorus along with HA + PSB produced 331.0 spikes/m^2, 4.97 t/ha grain yield, and 8.47 t/ha straw yield, which were statistically comparable to the sole application of 100% phosphorus (338.0 spikes/m^2, 5.09 t/ha grain yield, and 8.91 t/ha straw yield). These findings indicate that the combined use of HA and PSB can effectively compensate for a 50% reduction in phosphorus fertiliser without causing a significant decline in wheat productivity. Therefore, the integration of HA @10 kg/ha and PSB @10 g/kg seed with 50% of the recommended phosphorus dose (30 kg P_2O_5/ha) represents an efficient nutrient-management strategy for wheat, enabling substantial fertiliser savings while maintaining yield, phosphorus uptake, and economic returns. This approach offers a practical means of enhancing phosphorus use efficiency and reducing dependence on chemical phosphorus fertilisers in wheat cultivation.

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