



Enhancing wheat productivity and economics through microbe-mediated phosphorus fertilization in wheat (*Triticum aestivum*) + mustard (*Brassica juncea*) intercropping systems of the semi-arid region of India

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ABSTRACT

The study was carried out during the winter (*rabi*) season of 2021–22 and 2022–23 at ICAR-Indian Agricultural Research Institute, New Delhi to evaluate the impact of microbe-mediated phosphorus fertilization on the growth, yield attributes and yield of wheat (*Triticum aestivum* L.) in intercropping systems. Four cropping systems (CSs), viz. CS₁, Sole wheat (control); CS₂, Sole mustard (*Brassica juncea*); CS₃, Wheat + mustard (5:1); CS₄, Wheat + mustard (5:2) and six P management strategies (PMS) viz. PMS₁, Control; PMS₂, RDF; PMS₃, 75% RDP + PSB (0.5 kg/ha); PMS₄, 75%RDP + PROM (125 kg/ha); PMS₅, 75% RDP + PROM (125 kg/ha) + PSB (0.5 kg/ha); PMS₆, No RDP + PROM (125 kg/ha) + PSB (0.5 kg/ha) in a factorial randomized block design (FRBD) with three replications. Among the PMS; 75% RDP + PROM + PSB (PMS₅) significantly outperformed others. It recorded the highest wheat equivalent yield (56.86 q/ha), which was 34.5% higher than the control (PMS₁). This was accompanied by the highest 1000 grain weight (41.8 g), tillers no. (509.7/m²), harvest index (43.1%) and net return (₹129.3 × 10³/ha), with a benefit-cost ratio of 3.28 (vs. 2.76 in PMS₁). Additionally, PMS₅ improved dry matter accumulation at harvest (1001 g/m², a 23.1% increase over PMS₁), leaf area index (5.73), and crop growth rate (4.57 g/m²/day at 40 DAS, up by 37.3% over PMS₁). In terms of cropping systems, CS₄ (wheat + mustard in 5:2 row ratio) proved superior with the highest wheat equivalent yield (56.16 q/ha), representing a 9.6% increase over sole wheat (CS₁). This system also enhanced dry matter accumulation (1000 g/m²), crop growth rate at 80 DAS (18.9 g/m²/day), and net returns (₹82.2 × 10³/ha), while maintaining a high benefit-cost ratio (2.44). These results underscore the potential of 75% RDP + PROM + PSB and strategic intercropping (wheat + mustard in 5:2 row ratio) with mustard for improving productivity and profitability and support the adoption of biologically enriched P sources to reduce dependency on chemical fertilisers.

Keywords: Growth parameters, Phosphorus nutrition, Productivity, Profitability

Wheat (*Triticum aestivum* L.) is a key global staple food, providing calories and protein to over 35% of the world's population (FAO 2023). In 2022–23, global wheat production reached 781 million tonnes from 218 million ha, with an average yield of 3.58 t/ha (FAOSTAT 2023). Major producers i.e. China, India, Russia, the USA, and France contribute over 60% of output. India, the second-largest producer, harvested 112 million tonnes from 30.5 million ha, mainly in Uttar Pradesh, Punjab, Haryana, Madhya Pradesh, and Rajasthan (MoAFW 2023). With an average yield of 3.6 t/ha, India lags behind countries like France and Germany (>7 t/ha). This yield gap underscores the need for improved agronomic practices, including balanced

nutrient management, resource-efficient cropping systems, and climate-resilient technologies (ICAR-IIWBR 2023).

In the Indian context, especially in eastern and central parts of the Indo-Gangetic Plains (IGP) and other regions dominated by Inceptisols, wheat-based intercropping systems are gaining popularity for enhancing resource-use efficiency and soil health (Singh *et al.* 2022, Jat *et al.* 2023). Phosphorus (P) availability in such soils remains a critical constraint due to its high fixation and low mobility, leading to poor phosphorus-use efficiency (Sharma *et al.* 2020). Strategic P management can play a vital role in enhancing the productivity of wheat in India (Singh and Ahlawat 2006, Jain and Dahama 2007, Sharma *et al.* 2009). P plays a pivotal role in early root development, tillering, and grain formation (Niu *et al.* 2013). Microbial inoculants, particularly phosphate-solubilizing microorganisms (PSMs), such as *Pseudomonas*, *Bacillus*, and arbuscular mycorrhizal fungi (AMF), have emerged as a sustainable solution to enhance phosphorus availability through solubilization and mineralization mechanisms

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(Sahu *et al.* 2021). Microbe-mediated P fertilization has shown promise in improving P uptake, root architecture, and crop productivity in monocropping systems (Banik *et al.* 2022). Yet, their potential role in wheat-based intercropping systems, particularly under low to moderate fertility under semi-arid regions, remains underexplored. Integrating PSMs in intercropping systems involving legumes or oilseeds with wheat could lead to better nutrient cycling, enhanced microbial activity, and improved economic returns (Khan *et al.* 2024). Moreover, microbe-based biofertilisers could potentially reduce chemical P input, aligning with sustainable agriculture and climate-resilient farming practices (Kumar *et al.* 2023). Despite increasing evidence on the role of PSMs in improving phosphorus use efficiency in sole cropping systems, systematic studies evaluating their impact in intercropping contexts, especially wheat-based systems on Inceptisols, are lacking. Key gaps include, limited research on the interactive effects of PSMs and crop combinations on yield and economic performance; lack of region-specific data on crop response to P under acidic and P-fixing Inceptisols; insufficient understanding of how microbial P fertilization influences intercrop complementarity and long-term productivity. So, we hypothesize that the microbe-mediated phosphorus fertilization will enhance phosphorus availability and uptake, leading to improved growth, yield attributes, grain yield, and economic returns in wheat-based intercropping systems under Inceptisols compared to conventional P fertilization. In this background present study was conducted to evaluate the impact of microbe-mediated phosphorus fertilization on growth, yield attributes and yield of wheat in intercropping systems and to examine the economic viability of microbial P application under different intercropping combinations in Inceptisols.

MATERIALS AND METHODS

Experimental site: The study was carried out during the winter (*rabi*) season of 2021–22 and 2022–23 at ICAR-Indian Agricultural Research Institute (8°38'23" N, 77°09'27" E; 228.61 m amsl), New Delhi. The experimental site was characterized by a sandy clay loam texture with an initial soil pH of 7.91, electrical conductivity (EC) of 0.17 dS/m, organic carbon content of 0.46%, and available nitrogen, phosphorus, and potassium contents of 206, 18.67, and 282 kg/ha, determined by Subbaiah and Asija (1956), Olsen *et al.* (1954) and Jackson (1973), respectively.

Experimental details: This experiment was conducted using a factorial randomized block design (FRBD), with two factors: 4 cropping systems, viz. CS₁, Sole wheat (control); CS₂, Sole mustard (*Brassica juncea*); CS₃, Wheat + mustard (5:1 row ratio); CS₄, Wheat + mustard (5:2 row ratio) and 6 phosphorus management practices, viz. PMS₁, Control; PMS₂, Recommended Dose of Phosphorus (RDF); PMS₃, 75% RDP + Phosphate-Solubilizing microorganisms (PSB) (0.5 kg/ha); PMS₄, 75%RDP + Phosphate-Rich Organic Manure (PROM) (125 kg/ha); PMS₅, 75% RDP + PROM (125 kg/ha) + PSB (0.5 kg/ha); PMS₆, No RDP + PROM (125 kg/ha) + PSB (0.5 kg/ha) with three replications.

Crop management: PROM is produced by combining organic materials (such as compost, farmyard manure or press mud) with rock phosphate and PSMs. This process involves microbial decomposition and mineral solubilization, making phosphorus more readily available to plants. PROM was incorporated into the soil during land preparation, while PSB (*Bacillus megaterium*) was applied as a seed treatment @0.5 kg/ha. Crop establishment followed the designated row configurations. Nutrient management was implemented uniformly across treatments with N:P: K applied at 120:26.4:50 kg/ha using urea, SSP and MOP as nutrient sources. Standard crop husbandry practices were followed during the experimentation.

Growth parameters and yield attributes: Growth parameters, yield attributes recorded in wheat encompassed effective tillers, spike length, grains/spike, test weight, and grain yield were measured by following the standard procedures.

Wheat equivalent yield (WEY): Wheat equivalent yield was calculated to assess the productivity of intercropping systems by converting the mustard yield into its wheat equivalent based on minimum support price for grain and prevailing market price for straw prices. For intercropping treatments, WEY was derived by combining the actual wheat yield with the equivalent wheat yield of mustard using the following formula:

$$\text{WEY (t/ha)} = \left(\frac{\text{Wheat yield (q/ha)}}{\text{q/ha}} + \frac{[(\text{Seed Yield of mustard (q/ha)} \times \text{Price of mustard (₹/q)})]}{\text{Price of wheat (₹/q)}} \right)$$

Economics: The cost of cultivation was estimated by accounting for inputs, such as farm machinery, seeds, fertilisers, plant protection, wages, and miscellaneous expenses. Input-wise data were recorded, and costs calculated. Gross returns included income from grains and straw sales. Seeds valued at the minimum support price (MSP) and straw at local market rates. Net returns were derived by subtracting total costs from gross returns. The benefit-cost ratio (BCR) was computed by dividing net returns by the respective cost of cultivation for each treatment.

$$\text{Gross return (₹/ha)} = \text{Monetary return of sale of grains} + \text{Sale of straw}$$

$$\text{Net return (₹/ha)} = \text{Gross return (₹/ha)} - \text{Total cost of cultivation (₹/ha)}$$

$$\text{Net B:C ratio} = \frac{\text{Net returns (₹/ha)}}{\text{Cost of cultivation (₹/ha)}}$$

Statistical analysis: The collected data were subjected to statistical analysis using the methods of Gomez and Gomez (1984) appropriate for factorial RBD. Analysis of variance was used to detect significant treatment effects. Treatment means were compared using the least significant difference (LSD) at a 5% level of significance ($p \leq 0.05$). Standard error of the mean (SEM) was also computed and

reported to support the reliability of observed treatment differences.

RESULTS AND DISCUSSION

Growth: Growth parameters of wheat were influenced significantly by microbes mediated phosphorus management practices in different wheat based intercropping system (Table 1). Although plant height in CS₁ was similar to CS₃ and significantly lower than CS₄ at 40 days after sowing (DAS). The differential response of wheat growth parameters under various wheat-based intercropping systems is attributed to improved resource utilization, enhanced soil nutrient dynamics, and microclimate moderation facilitated by the associated crops (Srivastava *et al.* 2008). There was no significant difference among all cropping system treatments at 80 DAS and harvest time, and consistently higher values were recorded in CS₄ (wheat + mustard at a 5:2 row ratio) at 40 DAS, 80 DAS, and harvest time. This indicates a better growth environment in CS₄. This may be due to efficient spatial and temporal resource partitioning in the intercropping system, which minimizes interspecific competition and promotes vertical growth (Li *et al.* 2020). Highest amount of dry matter accumulation (DMA) at 80 DAS and harvest stage was recorded under CS₄ (wheat + mustard at 5:2 row ratio) as compared to the CS₁ and CS₃ (wheat + mustard at 5:1 row ratio). The significantly higher DMA observed under CS₄ at 80 DAS and harvest may be due improved photosynthate production and assimilation due to increased radiation use efficiency (RUE) and better soil nutrient availability (O'Connell *et al.* 2004, Li *et al.* 2014). Intercropping systems have been reported to improve nutrient cycling and organic matter status, thereby enhancing

crop biomass in the later growth stages (Li *et al.* 2014). In case of leaf area index (LAI), maximum LAI was recorded under CS₄ which was statistically at par with CS₃ and significantly higher than other cropping systems. It might be due to improved nitrogen and phosphorus availability facilitated by complementary intercropping partners, higher LAI enhances light interception and photosynthetic efficiency, which are critical for biomass production and grain yield (Zhang *et al.* 2021). Crop growth rate follows the similar trend as DMA.

In case of phosphorus management practice, significantly higher plant height was observed under PMS₅ (75% RDP + PROM + PSB) at 80 DAS followed by PMS₄ (75% RDP + PROM) and PMS₂ (100% RDP), as compared to the other treatments. At harvest stage, higher plant height was noticed under PMS₄ which was statistically at par with PMS₅ and PMS₂ and significantly higher than remaining treatments. It might be attributed to enhanced P availability and uptake at critical growth stages. Treatments like PMS₅ and PMS₄, likely involving microbial consortia or integrated P sources (e.g. chemical + organic or biofertilisers), improve soil phosphorus solubilization and stimulate early and sustained vegetative growth. Phosphate-solubilizing microorganisms enhance phosphorus use efficiency, promote phytohormone (e.g. auxin) production, and improve shoot elongation (Kumar *et al.* 2021, Meena *et al.* 2022). Significantly higher dry matter accumulation was found under PMS₆ (PROM + PSB only) followed by PMS₄ and PMS₅ at 40 DAS, 80DAS and harvest stage, as compared to the other treatments. This reflects efficient photosynthate production and partitioning. PMS₆ likely combines organic and biological P sources

Table 1 Effect of microbes mediated P management practices on performance of wheat in intercropping systems (2 years mean data)

Treatment	Plant height (cm)			Dry matter accumulation (g/m ²)			Leaf area index		Crop growth rate (g/m ² /day)	
	40 DAS	80 DAS	Harvest	40 DAS	80 DAS	Harvest	40 DAS	80 DAS	40 DAS	80 DAS
Intercropping systems										
CS ₁	56.0	92.3	99.0	141	608	848	3.37	5.01	3.77	15.7
CS ₃	58.0	95.0	102.4	153	661	915	3.53	5.41	4.07	17.1
CS ₄	59.2	96.1	102.6	168	730	1000	3.38	5.58	4.49	18.9
SEM±	0.96	1.58	1.69	2.57	11.1	15.3	0.06	0.09	0.05	0.29
LSD ($p \leq 0.05$)	2.86	4.71	5.07	7.7	33.3	46	0.18	0.27	0.21	0.86
Phosphorus management practices										
PMS ₁	53.6	90.4	95.8	128	567	813	3.13	4.81	3.33	15.2
PMS ₂	60.4	96.9	104.5	132	586	821	3.32	5.52	3.47	15.3
PMS ₃	55.8	92.8	99.2	145	638	877	3.36	5.27	3.82	16.6
PMS ₄	60.1	96.9	105.7	169	724	1002	3.52	5.63	4.56	18.7
PMS ₅	61.4	97.4	104.5	169	723	1001	3.46	5.73	4.57	18.6
PMS ₆	55.2	92.4	98.4	170	733	1014	3.69	5.08	4.58	18.9
SEM±	0.96	1.58	1.69	2.54	11.0	15.3	0.06	0.09	0.07	0.29
LSD ($p \leq 0.05$)	2.83	4.73	5.07	7.61	31.0	46.0	0.17	0.27	0.20	0.83

DAS, Days after sowing. Treatment details are given under Materials and Methods.

that enhance microbial activity and soil health, leading to greater nutrient mobilization and root biomass, which ultimately boosts above-ground dry matter accumulation. Increased P availability accelerates cell division and leaf area expansion, contributing to higher biomass (Zhou *et al.* 2023). At 40 DAS, the LAI was observed to be statistically non-significant among the different treatments, indicating that there was no considerable variation in leaf development at this stage due to the applied treatments. While at 80 DAS, significant maximum LAI was recorded under PMS₅ which was statistically at par with PMS₃ and PMS₂ and significantly higher than other treatments. At 40 DAS, the non-significant differences in LAI suggested uniform early-stage leaf development across treatments, as initial leaf expansion is often more influenced by seed reserves and early soil conditions. However by 80 DAS, significantly higher LAI under PMS₅ (statistically at par with PMS₂ and PMS₃) indicated that enhanced mid-season P availability supports increased leaf expansion and canopy development, improving light interception and photosynthetic efficiency (Zhang *et al.* 2021). In terms of CGR at 40 and 80 DAS, significantly maximum value was observed under PMS₆ followed PMS₅ and PMS₄ while, lowest was noticed under PMS₁. The significantly higher CGR at both 40 and 80 DAS under PMS₆ followed by PMS₅ and PMS₄, suggests more efficient conversion of assimilates into biomass under treatments that enhance P use efficiency and nutrient synchrony. CGR improvements under these treatments were consistent with better nutrient availability, increased LAI, and stronger physiological activity. The lowest CGR under PMS₁ (likely control or sole inorganic P) indicates suboptimal nutrient uptake and limited biomass production (Karak *et al.* 2018).

Yield attributes and yield: The yield attributes did not exhibit any statistically significant differences across the various intercropping systems, except for the number of tillers per square meter, which showed a significant response, indicating that this particular parameter was influenced by the intercropping arrangements (Table 2). The maximum number of tillers/m² was recorded under CS₄ (wheat + mustard at 5:2 row ratio); which was statistically at par with CS₃ (wheat + mustard at 5:1 row ratio), and significantly higher than CS₁. It might be due to reduced interspecific competition for below-ground resources, improved root zone environment, and complementary use of nutrients, particularly nitrogen and phosphorus, by the component crops. In case of interaction effect seed yield was maximum found under wheat + mustard at 5:2 row ratio intercropping with 75% RDP + phosphate-rich organic manure (Fig. 1). In the present study, highest grain yield under CS₄ suggested that the sole cropping or simpler intercropping in CS₄ might have allowed for optimal resource capture especially light, space, and nutrients without the stress of interspecies competition. In some cases, more complex intercropping arrangements can lead to competition for resources, reducing final yields despite higher early growth or tillering (Zhou *et al.* 2023). CS₄ higher yields may also reflect better crop management compatibility, planting geometry or less interference between crops. While intercropping can improve resource use efficiency and system resilience, the final productivity is a function of the degree of complementarity versus competition between component crops (Raza *et al.* 2021). Thus, CS₄ improved vegetative traits like tillering due to facilitative interactions, but CS₁ achieved superior reproductive output due to lower competitive stress and better resource allocation to the main crop.

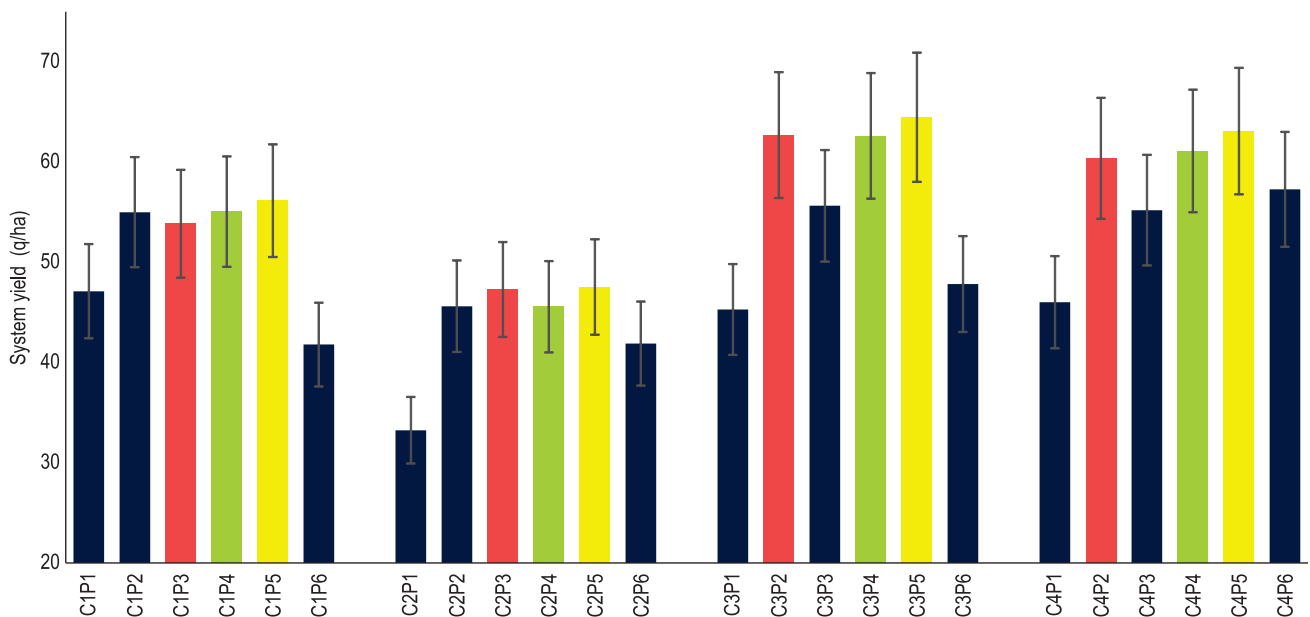


Fig. 1 Interactive effect of microbes mediated P management practices on yield attributes and yield of wheat in intercropping systems (2 years mean data).

Treatment details are given under Materials and Methods.

The yield attributes did not showed any statistically significant differences across the various P management practices, except for the number of tillers/m², which exhibited a significant variation, indicating that this particular trait was influenced by the applied P treatments. Among the P management practices, significantly higher number of tillers/m² was noticed under PMS₅ followed by PMS₄ and PMS₂ because improved reproductive performance and better nutrient partitioning towards grain formation. Phosphorus plays a key role in promoting flowering, grain filling, and assimilate translocation. Treatments like PMS₅, which likely involved integrated P sources (e.g. chemical P + biofertiliser or organic P), ensure sustained nutrient availability, thereby supporting better panicle development and seed weight (Meena *et al.* 2022). The maximum value of ear length, number of grains/ear, 1000-grain weight and harvest index were recorded under PMS₅ while lowest was noticed under PMS₁. A significantly higher grain yield was recorded under treatment PMS₅, followed by PMS₄, PMS₂, indicating the superior performance of PMS₅ in terms of grain production. PMS₅ had better yield components may be due to greater synchronization between P supply and crop demand during critical growth stages, boost microbial activity and enzymatic mineralization of P, leading to better nutrient acquisition and dry matter accumulation (Karak *et al.* 2018, Li *et al.* 2018, Zhou *et al.* 2023).

Economics: The economic performance of different cropping systems, particularly in terms of gross and net returns, largely influenced by yield levels, input efficiency, and cost of cultivation results, have been presented in

Table 2. In terms of economics, the higher gross return was obtained under CS₄, which was statistically at par with CS₃ and significantly higher than CS₁. This may be explained by synergistic effects in intercropping (e.g. better resource use efficiency and reduced pest pressure), all of which contribute to increased system productivity and profitability (Ghaley *et al.* 2018, Li *et al.* 2020). Similar trend was also seen for net return and B:C ratio, CS₄ recorded higher net return followed by CS₃ and lower in CS₁. However, CS₃ had higher cost of cultivation compared to CS₄ and CS₁. This indicates that the input costs under CS₃ were higher, possibly due to increased labour requirements, costlier intercrop or additional nutrient and crop management needs to support the more intensive or diversified system. CS₄ appears to have maintained a better balance between cost and return, leading to more cost-efficient resource utilization, and hence a higher B: C ratio (Zhang *et al.* 2021).

The significantly higher gross and net return were recorded under treatment PMS₅, followed by treatments PMS₂ and PMS₄ for gross returns and PMS₄ and PMS₂, respectively for net returns. Indicating its superior economic performance compared to all other phosphorus management treatments, highlighting the economic advantage of these treatments in terms of profitability. This could be due to PMS₅ involving an integrated or bio-enhanced phosphorus source (e.g. inorganic P + phosphate-solubilizing microorganisms or organic P amendments), which likely improved P availability and uptake throughout the crop growth stages, leading to superior biomass and grain yield (Meena *et al.* 2022). Furthermore, PMS₅ likely

Table 2 Effect of microbes mediated P management practices on yield attributes and yield of wheat in intercropping systems (2 years mean data)

Treatment	Tillers/ m ²	Ear length (cm)	Grains/ ear	Test weight (g)	Harvest index	Wheat equivalent yield (q/ha)	Cost of cultivation (×1000 ₹/ha)	Gross return (×1000 ₹/ ha)	Net return (×1000 ₹/ ha)	B:C Ratio
Intercropping systems										
CS ₁	452.5	10.1	48.5	40.3	42.2	51.24	54.0	130.2	76.2	2.41
CS ₂	-	-	-	-	-	42.21	47.3	99.1	51.8	2.10
CS ₃	480.9	10.6	49.5	40.8	42.3	55.66	57.1	138.7	81.5	2.43
CS ₄	501.3	10.9	49.7	40.9	42.3	56.16	57.0	139.2	82.2	2.44
SEM±	7.29	0.21	0.89	0.37	0.36	1.68	-	2.9	1.7	0.05
LSD (<i>p</i> ≤0.05)	21.0	0.63	2.70	1.11	1.08	5.03	-	8.6	5.0	0.16
Phosphorus management practices										
PMS ₁	431.4	9.60	48.7	40.3	41.8	42.27	50.8	138.8	88.0	2.76
PMS ₂	494.0	10.8	49.3	40.8	42.9	55.02	54.5	180.5	126.0	3.34
PMS ₃	474.4	10.6	49.4	40.8	41.2	52.14	53.6	172.5	118.9	3.22
PMS ₄	503.0	10.9	49.3	40.8	42.9	55.19	55.9	181.4	125.4	3.25
PMS ₅	509.7	11.0	49.9	41.8	43.1	56.86	56.6	186.0	129.3	3.28
PMS ₆	457.0	10.2	49.3	40.8	41.5	46.44	53.7	153.9	100.6	2.89
SEM±	8.89	0.14	0.63	0.34	0.31	3.25	-	3.9	2.7	0.07
LSD (<i>p</i> ≤0.05)	25.5	0.41	1.83	1.01	0.92	9.74	-	11.8	8.1	0.21

Treatment details are given under Materials and Methods.

improved root development, photosynthetic efficiency, and reproductive success, thereby enhancing yield components like number of grains/spike and test weight. These yield advantages translate directly into higher economic returns, especially when market prices are favourable for the primary product (grain) and by-products (straw) (Zhou *et al.* 2023). In contrast, the highest benefit-cost (B: C) ratio was recorded under PMS₂, which was statistically at par with treatments PMS₃, PMS₄, and PMS₅, and significantly higher than the remaining treatments. This suggests that although PMS₅ provided the highest absolute returns, PMS₂ demonstrated greater cost-efficiency in relation to the inputs invested. However, despite higher absolute returns in PMS₅, PMS₂ recorded the highest B:C ratio, suggesting that PMS₂ was more cost-effective. This implies that PMS₂ might have involved lower input costs involve with organic compost. Hence, although PMS₅ had greater total returns, PMS₂ achieved better economic efficiency per unit investment, a key factor in sustainable and low-input farming systems (Bunemann *et al.* 2011, Kumar *et al.* 2021).

The study demonstrated that intercropping of wheat with mustard in a 5:2 ratio (CS₄) significantly enhanced growth parameters, yield attributes and economic returns compared to sole cropping systems. Among phosphorus management practices, PMS₅ (75% RDP + PROM + PSB) showed superior performance in terms of yield, gross and net returns. While C₁ recorded the highest grain yield, CS₃ and CS₄ proved more profitable. In PMS, PMS₅ resulted better crop growth and productivity than conventional phosphorus use and while highest B:C ratio was observed under PMS₂, indicating economic efficiency. Overall, the CS₄ + PMS₅ combination emerged as a cost-effective and sustainable option for wheat production under Inceptisols region of IGPs.

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