



ISSN Print: 2618-060X
 ISSN Online: 2618-0618
 NAAS Rating (2026): 5.20
 IJRA 2026; 9(10): 409-416
www.agronomyjournals.com
 Received: 13-08-2026
 Accepted: 24-09-2026
 Published: 07-10-2026

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Performance of Indian mustard under different wheat–mustard intercropping systems and microbial phosphorus management

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DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i10f.6814>

ABSTRACT

A field experiment was conducted during 2021–22 and 2022–23 at the Genetics D Block of the Experimental Farm, ICAR–Indian Agricultural Research Institute (IARI), New Delhi, to evaluate the effect of wheat–mustard intercropping systems and microbe-mediated phosphorus management on the growth, yield attributes and productivity of mustard (*Brassica juncea* L.). The experiment was laid out in a factorial randomized block design comprising four cropping systems and six phosphorus management practices. The cropping systems included sole wheat, sole mustard, wheat + mustard in 5:1 row ratio and wheat + mustard in 5:2 row ratio. Phosphorus treatments comprised phosphorus control, recommended dose of phosphorus (RDP), 75% RDP + phosphate-solubilizing bacteria (PSB) @ 0.5 kg ha⁻¹, 75% RDP + phosphate-rich organic manure (PROM) @ 125 kg ha⁻¹, 75% RDP + PROM @ 125 kg ha⁻¹ + PSB @ 0.5 kg ha⁻¹, and P0 + PROM @ 125 kg ha⁻¹ + PSB @ 0.5 kg ha⁻¹. The results revealed that the wheat + mustard 5:1 row ratio consistently recorded superior plant growth, dry matter accumulation, crop growth rate and leaf area index of mustard compared with the other intercropping systems. It also recorded the highest number of siliquae plant⁻¹ and seeds siliqua⁻¹ among the evaluated cropping systems. However, the 5:2 row ratio recorded higher mustard productivity within the intercropping treatments, with seed yield of 9.71 and 9.80 q ha⁻¹ during 2021–22 and 2022–23, respectively. Among phosphorus management practices, the application of 75% RDP + PROM + PSB resulted in the highest plant height, dry matter accumulation, crop growth rate, branching, leaf area index, siliquae plant⁻¹, seeds siliqua⁻¹, seed yield and biological yield in both years. The treatment recorded seed yields of 12.70 and 12.81 q ha⁻¹ and biological yields of 36.48 and 36.81 q ha⁻¹ during 2021–22 and 2022–23, respectively. Test weight and harvest index were comparatively less responsive to cropping system and phosphorus management. Overall, the findings indicate that suitable wheat–mustard row arrangement combined with integrated phosphorus management using reduced mineral phosphorus, PROM and PSB can improve mustard growth, yield attributes and productivity under the Indo-Gangetic Plains.

Keywords: Growth, Yield, Phosphorus nutrition, Productivity, Mustard

Introduction

Indian agriculture is increasingly confronted with the challenges of sustaining crop productivity while improving nutrient-use efficiency, soil health and farm profitability. Wheat (*Triticum aestivum* L.) and Indian mustard (*Brassica juncea* L.) are two important winter-season crops of the Indo-Gangetic Plains and are widely grown under irrigated as well as semi-arid production systems. However, continuous cultivation of individual crops and imbalanced application of chemical fertilizers may reduce resource-use efficiency and contribute to declining soil fertility. Consequently, appropriate combinations of intercropping and integrated nutrient management have gained considerable importance as sustainable approaches for enhancing productivity and resource-use efficiency.

Intercropping of wheat with Indian mustard provides an opportunity to exploit differences in plant architecture, rooting pattern, nutrient acquisition and temporal resource use. Proper row arrangement can minimize interspecific competition while promoting complementary utilization of light, water, nutrients and space. Previous studies have demonstrated that wheat–mustard intercropping can improve yield advantage and economic returns compared with less efficient row arrangements. In particular, the 5:1 row proportion has been reported as a promising configuration because of its favourable competitive interactions and higher land-use efficiency (Srivastava *et al.*, 2007) [1]. Similarly, Singh *et al.* (2012) [2] reported that wheat + mustard intercropping under a 5:1 row proportion responded positively to improved fertility management, resulting in enhanced yield attributes and productivity. More recent studies have also demonstrated that appropriate wheat–mustard row proportions can improve wheat equivalent yield, land equivalent ratio and profitability compared with sole cropping or less efficient planting arrangements.

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Among the essential plant nutrients, phosphorus (P) plays a critical role in plant growth and development. It is involved in energy transfer, nucleic acid synthesis, membrane formation, root development, flowering, reproductive growth and translocation of photosynthates. Despite its importance, phosphorus availability to plants is frequently limited because a considerable proportion of applied P becomes fixed in soil and is converted into relatively unavailable forms. Thus, merely increasing fertilizer P application may not always provide proportional increases in crop productivity and may reduce fertilizer-use efficiency. Improving the availability of native and applied soil phosphorus through integrated approaches is therefore important for sustainable crop production (Singh *et al.*, 2021) [3].

Phosphate-solubilizing bacteria (PSB) offer an important biological approach for improving phosphorus availability. These microorganisms can solubilize otherwise unavailable forms of soil phosphorus through the production of organic acids, proton release and other biochemical mechanisms, thereby increasing the pool of P accessible to plants. Research in Indian mustard has demonstrated that phosphorus application in combination with PSB can significantly improve yield and nutrient availability compared with the absence of these inputs (Solanki *et al.*, 2019). Studies on mustard rhizosphere microorganisms have further highlighted the potential of phosphate-solubilizing microorganisms for improving P availability and plant growth.

Phosphate-rich organic manure (PROM) represents another promising component of integrated phosphorus management. Its incorporation with reduced rates of mineral phosphorus may provide a gradual supply of phosphorus while contributing to improved nutrient availability and soil biological activity. Combining PROM with PSB may therefore provide complementary benefits: PROM supplies a phosphorus-rich organic source, whereas PSB can enhance the solubilization and mobilization of less-available phosphorus fractions. Such integrated nutrient management has particular relevance under intercropping systems, where two crops simultaneously exploit soil nutrient resources and efficient nutrient cycling becomes essential (Raut *et al.*, 2020) [4].

The interaction between cropping geometry and phosphorus availability can substantially influence crop growth and yield formation. Improved phosphorus nutrition may promote root development, leaf expansion, photosynthetic activity and assimilate production, which subsequently influence plant height, dry matter accumulation, crop growth rate, branching, leaf area development and reproductive growth. In mustard, these processes ultimately determine important yield attributes such as number of siliques plant⁻¹, seeds silique⁻¹ and seed weight, thereby affecting final seed and biological yields. Earlier investigations have confirmed that phosphorus and PSB application can enhance mustard yield and yield components, indicating the importance of integrated phosphorus nutrition for improving crop performance (Rana *et al.*, 2021) [5].

Although considerable research has been conducted on wheat–mustard intercropping and conventional fertilizer management, comparatively less attention has been given to the combined effects of row arrangement and microbe-mediated phosphorus management, particularly through the integration of reduced mineral phosphorus with PROM and PSB. Recent evidence from wheat–mustard systems indicate that 75% recommended phosphorus combined with PROM and PSB can perform favourably compared with conventional phosphorus fertilization, while suitable row arrangements can further enhance system productivity and nutrient-use efficiency. However, crop-specific responses of mustard in terms of growth, physiological development, yield attributes and productivity under these integrated management strategies require further evaluation (Potdar *et al.*, 2021).

Therefore, the present investigation was undertaken to evaluate the effect of wheat–mustard intercropping systems and microbe-mediated phosphorus management on growth, yield attributes and productivity of Indian mustard under the agro-climatic conditions of the Indo-Gangetic Plains. The study specifically compared sole mustard with wheat + mustard intercropping in 5:1 and 5:2 row proportions and

evaluated different combinations of recommended/reduced phosphorus, PROM and PSB. The hypothesis was that an appropriate intercropping geometry combined with integrated phosphorus management, particularly 75% recommended dose of phosphorus + PROM + PSB, would improve phosphorus-use efficiency, crop growth, yield attributes and productivity of mustard while reducing dependence on mineral phosphorus fertilizers.

Materials and Methods

The field experiment was conducted at the Genetics D Block of the Experimental Farm, ICAR–Indian Agricultural Research Institute (IARI), New Delhi, India. Geographically, the experimental site was located at 28°40' N latitude and 77°12' E longitude, at an elevation of approximately 228.6 m above mean sea level (MSL). The experimental farm is situated in the Indo-Gangetic Plain region, which represents an important agricultural production zone of northern India. The soil of the experimental field was sandy clay loam in texture, providing a representative soil environment for evaluating the effects of intercropping systems and phosphorus management practices. The experiment comprised a factorial combination of four intercropping systems (Factor A) and six phosphorus management practices (Factor B). The intercropping systems included C₁: sole wheat (control), C₂: sole mustard, C₃: wheat + mustard in a 5:1 row ratio, and C₄: wheat + mustard in a 5:2 row ratio. The phosphorus management treatments consisted of P₁: phosphorus control (P₀), P₂: recommended dose of phosphorus (RDP), P₃: 75% RDP + phosphate-solubilizing bacteria (PSB) @ 0.5 kg ha⁻¹, P₄: 75% RDP + phosphate-rich organic manure (PROM) @ 125 kg ha⁻¹, P₅: 75% RDP + PROM @ 125 kg ha⁻¹ + PSB @ 0.5 kg ha⁻¹, and P₆: P₀ + PROM @ 125 kg ha⁻¹ + PSB @ 0.5 kg ha⁻¹. Thus, the study involved 24 treatment combinations (4 × 6) to evaluate the interactive effects of intercropping systems and phosphorus management on crop performance and soil-related parameters

Plant height (cm)

Plant height was recorded at the specified crop growth stages by randomly selecting five representative plants from each plot. The height of each selected plant was measured from the soil surface to the tip of the main shoot using a measuring scale and expressed in centimetres (cm). The mean plant height was calculated for each treatment.

Dry matter accumulation (g m⁻¹ row length)

Dry matter accumulation was determined at 40 and 80 days after sowing (DAS) and at final harvest. Five plants were randomly selected and uprooted from each plot at each sampling stage. The fresh biomass was recorded, and the plant samples were chopped into small pieces. A representative 100 g fresh sample was placed in a labelled paper bag, initially sun-dried, and subsequently oven-dried at 60 °C until a constant weight was obtained. The dry weight was recorded and expressed as grams per metre row length (g m⁻¹).

Number of branches plant⁻¹

The number of primary and secondary branches was recorded at harvest from five randomly selected plants in each plot. The branches were counted manually, and the mean number of primary and secondary branches per plant was calculated for each treatment.

Number of siliques plant⁻¹

At physiological maturity, five randomly selected and tagged plants from each plot were harvested separately. The total number of siliques borne on each plant was counted manually. The average number of siliques plant⁻¹ was calculated from the observations of the five sampled plants.

Number of seeds silique⁻¹

At harvest, ten representative siliques were randomly collected from each of the five tagged plants in every plot. The siliques were opened carefully, and the number of seeds in each silique was counted. The mean number of seeds silique⁻¹ was calculated for each treatment.

1000-seed weight (g)

After threshing and cleaning, a random sample of seeds from each plot was taken. One thousand sound and representative seeds were counted and weighed using a precision electronic balance. The weight was recorded in grams and expressed as 1000-seed weight (g).

Seed yield (kg ha⁻¹)

At maturity, the crop from the net plot area of each treatment was harvested separately. The harvested material was thoroughly dried, threshed, and cleaned to obtain the seed yield. The seed obtained from each net plot was weighed using a precision balance. The recorded yield was converted and expressed as kilograms per hectare (kg ha⁻¹) using the corresponding net plot area.

Stover yield (kg ha⁻¹)

Stover yield was determined after threshing by separating the seed from the remaining above-ground plant biomass. The stover yield was calculated as the difference between total biological yield and seed yield. The values were converted and expressed as kilograms per hectare (kg ha⁻¹).

Biological yield (kg ha⁻¹)

Biological yield was determined by harvesting the entire above-ground biomass from the net plot area of each treatment at crop maturity. The harvested biomass was sun-dried to reduce moisture content and subsequently weighed. Biological yield was calculated as the total dry weight of seed and stover and expressed as kilograms per hectare (kg ha⁻¹).

Statistical analysis

The data were analyzed following the procedures described by Gomez *et al.* (1984) [6] for a Factorial Randomized Block Design (FRBD). Treatment means were compared using the least significant difference (LSD) test at the 5% probability level ($p \leq 0.05$), wherever the analysis of variance indicated significant differences among treatments.

Result and Discussion

Plant height (cm)

Plant height of mustard increased progressively with crop age and was markedly influenced by both cropping system and phosphorus management practices during the two growing seasons (Table 6). Differences among treatments appeared early and became more evident as the crop advanced towards maturity. Mustard grown with wheat in the 5:1 row ratio (C₃) recorded the tallest plants throughout the growth period, attaining 31.30 and 31.40 cm at 30 DAS and 175.2 and 175.9 cm at harvest during 2021–22 and 2022–23, respectively. The 5:2 ratio (C₄) also produced taller plants, while sole mustard (C₂) remained comparatively shorter. The superior growth under C₃ resulted from more efficient light interception, improved spatial arrangement, and favourable microclimatic conditions created by the intercropping pattern. Phosphorus management practices significantly affected mustard growth. The combined application of 75% RDP + PROM + PSB (P₅) resulted in the maximum plant height at all stages, ranging from 31.0–31.1 cm at 30 DAS to 176.0–176.9 cm at harvest. Treatments 75% RDP + PSB (P₃) and RDP alone (P₂) followed closely, while the phosphorus control (P₁) consistently recorded the lowest values.

Plant height increased progressively with crop growth and was highest under wheat + mustard (5:1) (C₃), followed by C₄ and sole mustard. The superior growth under C₃ was associated with improved light interception, spatial resource utilization, and root complementarity. Similar responses were reported by Ghosh *et al.* (2023) and Kumar *et al.* (2021). The integrated phosphorus treatment, 75% RDP + PROM + PSB (P₅), produced the tallest mustard plants, followed by P₃ and P₂, whereas P₁ recorded the lowest values. Improved phosphorus availability, microbial activity, and root proliferation under P₅ enhanced plant growth. Similar effects of integrated phosphorus management were reported by Mahanta *et al.*, (2023).

Table 1. Effect of microbe mediated phosphorus management in wheat + mustard intercropping system on plant height of mustard (cm)

Treatments	30 DAS		60 DAS		90 DAS		Harvest	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
C ₂	30.30	30.40	82.20	82.50	122.30	122.70	169.90	170.40
C ₃	31.30	31.40	85.10	85.40	125.10	125.70	175.20	175.90
C ₄	30.80	30.90	83.80	84.30	123.90	124.50	174.00	174.80
SEm (±)	0.67	0.67	1.36	1.36	1.35	1.35	1.83	1.84
LSD ($P = 0.05$)	2.00	2.01	4.09	4.10	4.06	4.07	5.48	5.50
P ₁	27.60	27.50	81.00	80.70	121.00	120.60	167.60	167.10
P ₂	31.00	31.03	85.30	85.50	125.30	125.50	175.30	175.60
P ₃	30.00	30.10	85.00	85.20	125.00	125.30	175.00	175.50
P ₄	30.60	30.80	85.00	85.30	125.00	125.50	175.00	175.70
P ₅	31.00	31.10	86.00	86.40	126.00	126.60	176.00	176.90
P ₆	29.60	29.60	84.20	84.30	124.50	124.80	173.30	173.70
SEm (±)	0.92	0.92	1.50	1.50	1.50	1.50	2.28	2.29
LSD ($P = 0.05$)	2.75	2.76	4.49	4.50	4.49	4.50	6.83	6.85

Dry matter (g m⁻²)

Dry matter accumulation in mustard plants increased progressively with crop age and was significantly influenced by both cropping systems and phosphorus management strategies during 2021–22 and 2022–23 (Table 7). The variation among treatments became more evident at later growth stages, reflecting the cumulative effect of improved nutrient uptake and biomass production. Mustard grown in association with wheat under the 5:1 ratio (C₃) produced the highest dry matter at all growth stages. The recorded values were 1.30 and 1.40 g/plant at 30 DAS, 8.30 and 8.40 g/plant at 60 DAS, 26.20 and 26.40 g/plant at 90 DAS, and 49.90 and 50.20 g/plant at harvest during

2021–22 and 2022–23, respectively. The 5:2 ratio (C₄) followed closely, while sole mustard (C₂) consistently accumulated less dry matter. The superiority of C₃ likely resulted from better resource sharing, improved canopy structure, and a favorable microenvironment due to intercropping with wheat. Phosphorus management also exerted a significant effect on mustard dry matter accumulation. The treatment 75% RDP + PROM + PSB (P₅) resulted in the maximum biomass production, with values of 1.41 and 1.43 g/plant at 30 DAS and 50.74 and 51.02 g/plant at harvest during the two years. Treatments RDP alone (P₂) and 75% RDP + PSB (P₃) performed comparably, while the phosphorus control (P₁) produced the least dry matter throughout.

Dry matter accumulation increased progressively with crop growth and was highest under wheat + mustard (5:1) (C₃), followed by C₄, while sole mustard recorded the lowest biomass. Greater biomass production under C₃ was attributed to improved radiation interception,

nutrient sharing, canopy efficiency, and root complementarity. Similar findings were reported by Das *et al.*, (2021) [7], and Kumar *et al.*, (2023) [8].

Table 2. Effect of microbe mediated phosphorus management in wheat + mustard intercropping system on dry matter accumulation in mustard (g/plant).

Treatments	30 DAS		60 DAS		90 DAS		Harvest	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
C2	1.20	1.23	7.80	7.82	24.60	24.70	47.20	47.40
C ₃	1.30	1.41	8.30	8.40	26.20	26.40	49.90	50.20
C4	1.30	1.33	8.00	8.10	25.30	25.50	48.90	49.10
SEm (±)	0.05	0.05	0.15	0.15	0.29	0.29	0.53	0.53
LSD (P = 0.05)	0.15	0.15	0.44	0.45	0.86	0.86	1.56	1.57
P1	1.22	1.23	7.65	7.67	24.09	24.15	46.12	46.26
P2	1.41	1.43	8.45	8.50	26.67	26.83	50.70	50.98
P3	1.40	1.42	8.43	8.48	26.56	26.72	50.40	50.68
P4	1.40	1.42	8.44	8.49	26.60	26.76	50.56	50.84
P ₅	1.41	1.43	8.46	8.52	26.69	26.85	50.74	51.02
P6	1.37	1.39	8.33	8.38	26.14	26.30	49.51	49.78
SEm (±)	0.03	0.03	0.09	0.09	0.17	0.17	0.31	0.31
LSD (P = 0.05)	0.09	0.09	0.27	0.27	0.49	0.49	0.91	0.92

Crop growth rate (g/m²/day)

Crop growth rate (CGR) of mustard was significantly affected by both cropping system and phosphorus management practices during 2021-22 and 2022-23 (Table 8). The CGR increased from 30–60 DAS to 60–90 DAS and slightly declined thereafter, reflecting normal physiological progression and biomass accumulation patterns of the crop. Mustard grown in the wheat + mustard (5:1) system (C₃) consistently exhibited the highest growth rate at every stage. Plants under this arrangement achieved 23.4 and 23.6 g/m²/day during 30–60 DAS, 29.9 and 30.1 g/m²/day during 60–90 DAS, and 27.0 and 27.2 g/m²/day from 90 DAS to harvest in the respective years. The 5:2 ratio (C₄) followed closely, while sole mustard (C₂) maintained lower CGR values throughout. The enhanced growth under C₃ may be attributed to more efficient utilization of light, nutrients, and space within the intercropping setup, leading to better canopy development and photosynthetic activity. Variation due to phosphorus management was equally distinct. The treatment 75% RDP + PROM + PSB (P₅)

recorded the maximum CGR at all stages 23.7 and 23.8 g/m²/day during 30–60 DAS, 30.2 and 30.4 g/m²/day during 60–90 DAS, and 27.4 and 27.6 g/m²/day between 90 DAS and harvest. Treatments RDP alone (P2), 75% RDP + PSB (P3), and 75% RDP + PROM (P4) showed comparable performance, whereas the phosphorus control (P1) consistently registered the lowest values.

Crop growth rate increased from 30–60 to 60–90 DAS and subsequently declined, reflecting rapid vegetative growth followed by re-productive assimilate partitioning. Wheat + mustard (5:1) (C₃) recorded the highest CGR, followed by C₄, whereas sole mustard was lower. Phosphorus management significantly affected CGR, with 75% RDP + PROM + PSB (P₅) recording the highest values across stages. Improved phosphorus solubilization, microbial activity, root proliferation, and nutrient translocation probably enhanced growth kinetics. Similar benefits of bio-organic phosphorus management were reported by Kaur *et al.*, (2022) [9], Mahanta *et al.*, (2023) and Gul *et al.*, (2020) [10].

Table 3. Effect of microbe mediated phosphorus management in wheat + mustard intercropping system on crop growth rate (g/m²/day) of mustard

Treatments	30–60 DAS		60–90 DAS		90 DAS (harvest)	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
C2	22.00	22.10	28.00	28.10	25.10	25.20
C ₃	23.40	23.60	29.90	30.10	27.00	27.20
C4	22.60	22.80	28.80	29.00	26.00	26.10
SEm (±)	0.20	0.20	0.27	0.27	0.32	0.32
LSD (P = 0.05)	0.58	0.58	0.78	0.79	0.93	0.94
P1	21.30	21.40	27.50	27.60	24.60	24.70
P2	23.60	23.80	30.20	30.40	27.30	27.50
P3	23.60	23.70	30.10	30.30	27.20	27.40
P4	23.60	23.70	30.10	30.30	27.30	27.50
P ₅	23.70	23.80	30.20	30.40	27.40	27.60
P6	23.20	23.40	29.80	30.01	26.90	27.10
SEm (±)	0.12	0.12	0.17	0.17	0.19	0.19

(continued on next page)

Treatments	30–60 DAS		60–90 DAS		90 DAS (harvest)	
	2021–22	2022–23	2021–22	2022–23	2021–22	2022–23
LSD ($P = 0.05$)	0.35	0.35	0.50	0.50	0.56	0.57

Number of branches and shoot length

The number of primary and secondary branches as well as the length of the main shoot in mustard were significantly influenced by cropping systems and microbe-mediated phosphorus management treatments during both experimental years (2021–22 and 2022–23). Among the cropping systems, wheat + mustard intercropping significantly affected branching behaviour and shoot length. The wheat + mustard (5:1) row ratio (C_3) recorded higher values of primary branches (5.57 and 5.62 plant⁻¹) and secondary branches (12.07 and 12.18 plant⁻¹) during 2021–22 and 2022–23, respectively. This was followed by the 5:2 row ratio (C_4), while sole mustard (C_2) recorded comparatively lower branching. However, the length of the main shoot was significantly higher under sole mustard (C_2), recording 86.97 and 87.75 cm during 2021–22 and 2022–23, respectively, compared to the intercropping treatments.

The variation in shoot length may be attributed to reduced interspecific competition and better availability of space and light under sole cropping conditions. Microbe-mediated phosphorus management treatments also exerted a significant effect on branching and shoot

length. Among the treatments, integrated application of phosphorus sources resulted in superior performance over the control. Treatment P_5 (75% RDP + PROM + PSB) recorded the highest number of secondary branches (13.63 and 14.66 plant⁻¹) and maximum length of main shoot (87.00 and 87.78 cm) during both years. Higher primary branching was also observed under P_4 (75% RDP + PROM) and P_2 (RDP alone), which remained statistically at par with P_5 . The lowest values for branching and shoot length were recorded under the phosphorus control (P_1). Enhanced growth parameters under integrated phosphorus management may be attributed to improved phosphorus availability, enhanced microbial activity, and better nutrient uptake throughout the crop growth period.

Phosphorus management significantly influenced branching, with 75% RDP + PROM + PSB (P_5) producing maximum branches. The combined application improved phosphorus availability and root activity, thereby supporting shoot development. Similar effects of PSB, PROM, and integrated nutrient management on phosphorus solubilization, leaf development, and biomass accumulation were reported by Raut *et al.*, (2020) [4], Gupta *et al.*, (2021) [11], and Meena *et al.*, (2024) [12].

Table 4. Effect of microbe mediated phosphorus management in wheat + mustard intercropping system on number of branches and length of main shoot (cm) in mustard

Treatments	Primary branches (No/plant)		Secondary branches (No/plant)		Length of main shoot (cm)	
	2021–22	2022–23	2021–22	2022–23	2021–22	2022–23
Cropping system						
C_2	5.33	5.38	11.90	10.80	86.97	87.75
C_3	5.57	5.62	12.07	12.18	83.57	84.32
C_4	5.43	5.48	11.93	12.04	82.10	82.84
SEm ($\pm$)	0.13	0.14	0.29	0.29	2.11	2.12
LSD ($P = 0.05$)	0.40	0.41	0.87	0.88	6.32	6.37
Microbe mediated phosphorus management						
P_1	6.03	6.01	12.90	12.85	81.83	81.17
P_2	6.47	6.53	13.33	13.45	86.00	86.77
P_3	6.14	6.05	13.00	13.12	84.00	84.76
P_4	6.63	6.71	13.33	13.45	86.00	86.77
P_5	6.47	6.53	13.63	14.66	87.00	87.78
P_6	6.06	6.11	12.97	12.95	83.93	84.69
SEm ($\pm$)	0.16	0.16	0.31	0.32	2.09	2.11
LSD ($P = 0.05$)	0.47	0.48	0.94	0.95	6.26	6.32

Leaf area index

The leaf area index (LAI) of mustard was significantly influenced by cropping systems and microbe-mediated phosphorus management practices at 30, 60 and 90 DAS during both experimental years (2021–22 and 2022–23) (Table 10). The LAI increased progressively from 30 to 90 DAS in both seasons, reflecting continuous canopy development during the crop growth period. Among the cropping systems, wheat + mustard intercropping in a 5:1 row ratio (C_3) recorded significantly higher LAI values at all growth stages. The LAI under C_3 was 0.92 and 0.92 at 30 DAS, 2.77 and 2.79 at 60 DAS, and 4.30 and 4.34 at 90 DAS during 2021–22 and 2022–23, respectively. This was closely followed by the 5:2 row ratio (C_4), whereas sole mustard (C_2) recorded the lowest LAI values at all stages. The higher LAI observed under C_3 may be attributed to better light interception, efficient utilization of growth resources, and favorable micro-environmental conditions created by the intercropping system. Microbe-mediated phosphorus management practices also exerted a significant effect on LAI throughout the crop growth stages. Among

the treatments, 75% RDP + PROM + PSB (P_5) recorded the highest LAI values at 30 DAS (0.83 and 0.83), 60 DAS (2.70 and 2.72), and 90 DAS (4.23 and 4.27) during 2021–22 and 2022–23, respectively. Treatments 75% RDP + PSB (P_3), 75% RDP + PROM (P_4), and RDP alone (P_2) were statistically at par with P_5 and significantly superior to the phosphorus control (P_1), which consistently recorded the lowest LAI values. Improved LAI under integrated phosphorus treatments may be attributed to enhanced phosphorus availability and improved microbial activity, leading to better leaf development and canopy expansion.

The 75% RDP + PROM + PSB (P_5) treatment produced the highest LAI across growth stages. Integrated phosphorus management improved P availability, microbial activity, root development, and chlorophyll formation, thereby supporting leaf expansion. Tripathy *et al.*, (2023) [13], and Meena *et al.*, (2024) [12] similarly reported improved canopy development and nutrient uptake with balanced phosphorus management.

Table 5. Effect of microbe mediated phosphorus management in wheat + mustard intercropping system on leaf area index (LAI) of mustard.

Treatments	30 DAS		60 DAS		90 DAS	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
C2	0.78	0.79	2.43	2.46	4.02	4.05
C ₃	0.92	0.92	2.77	2.79	4.30	4.34
C4	0.88	0.89	2.70	2.72	4.23	4.27
SEm (±)	0.03	0.03	0.09	0.09	0.14	0.14
LSD (<i>P</i> = 0.05)	0.09	0.09	0.26	0.27	0.42	0.42
P1	0.70	0.69	2.23	2.21	3.80	3.77
P2	0.82	0.82	2.67	2.69	4.20	4.24
P3	0.75	0.76	2.57	2.59	4.10	4.14
P4	0.81	0.81	2.63	2.66	4.20	4.24
P ₅	0.83	0.83	2.70	2.72	4.23	4.27
P6	0.73	0.73	2.30	2.32	3.87	3.90
SEm (±)	0.03	0.03	0.08	0.08	0.14	0.14
LSD (<i>P</i> = 0.05)	0.08	0.08	0.25	0.25	0.41	0.41

Yield attributes of mustard

The yield attributes of mustard, namely number of siliquae per plant, number of seeds per silique, and test weight, were significantly influenced by cropping systems and microbe-mediated phosphorus management practices during both experimental years (2021–22 and 2022–23), except for test weight, which remained non-significant. Among the cropping systems, wheat + mustard intercropping in a 5:1 row ratio (C₃) recorded the highest number of siliquae per plant (401.67 and 405.28) and seeds per silique (13.67 and 13.69) during 2021–22 and 2022–23, respectively. This was followed by the 5:2 row ratio (C₄), while sole mustard (C₂) recorded comparatively lower values for these yield attributes. However, test weight was not significantly affected by cropping systems and remained statistically at par across all treatments during both years.

Microbe-mediated phosphorus management practices also exerted a significant influence on yield attributes of mustard. The integrated

phosphorus treatment 75% RDP + PROM + PSB (P₅) recorded the maximum number of siliquae per plant (423.00 and 425.96) and seeds per silique (13.91 and 14.04) during both years. Treatments P4 (75% RDP + PROM), P2 (RDP alone), and P3 (75% RDP + PSB) remained statistically at par with P₅ and were significantly superior to the phosphorus control (P1). Test weight did not differ significantly among phosphorus treatments, indicating that seed size remained largely unaffected by variations in phosphorus management. The improvement in yield attributes under integrated phosphorus treatments may be attributed to enhanced nutrient availability and improved translocation of assimilates towards reproductive structures.

Wheat + mustard (5:1) (C₃) produced the highest siliquae per plant and seeds per silique, followed by C₄, whereas sole mustard recorded lower values. Improved reproductive growth under C₃ was associated with efficient light interception, nutrient utilization, favorable microclimate, and reduced competition. Similar findings were reported by Lal *et al.* (2019) [14].

Table 6. Effect of microbe mediated phosphorus management in wheat + mustard intercropping system on yield attributes of mustard.

Treatments	Siliquae/ plant		Seeds/ silique		Test weight (g)	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
C2	391.67	395.19	13.33	13.45	5.18	5.18
C ₃	401.67	405.28	13.67	13.69	5.19	5.19
C4	395.00	396.56	13.45	13.47	5.18	5.19
SEm (±)	9.90	9.99	0.34	0.34	0.13	0.13
LSD (<i>P</i> = 0.05)	29.71	29.98	1.01	1.02	NS	NS
P1	395.00	391.48	13.03	12.92	5.19	5.19
P2	420.00	423.87	13.64	13.76	5.21	5.22
P3	416.67	420.42	13.50	13.62	5.20	5.20
P4	418.00	419.87	13.69	13.81	5.22	5.23
P ₅	423.00	425.96	13.91	14.04	5.23	5.23
P6	405.00	408.65	13.33	13.45	5.20	5.20
SEm (±)	10.49	10.58	0.34	0.34	0.13	0.13
LSD (<i>P</i> = 0.05)	31.46	31.74	1.01	1.02	NS	NS

Productivity of mustard

The productivity parameters of mustard, including biological yield, seed yield, stover yield, and harvest index, were influenced by both cropping systems and phosphorus management practices during 2021–22 and 2022–23 (Table 12). Mustard grown under the wheat + mustard (5:2) intercropping system (C₄) recorded the highest biological

yield of 28.3 and 28.5 t ha⁻¹, followed by wheat + mustard (5:1) (C₃), which produced 18.7 and 18.9 t ha⁻¹ in the respective years. The sole mustard crop (C₂) registered the highest absolute productivity with a biological yield of 51.2 and 51.6 t ha⁻¹; however, within the intercropping systems, C₄ proved more efficient than C₃. A similar trend was observed for seed and stover yields, where C₄ (9.7–9.8 and 18.6–18.7 t ha⁻¹, respectively) outperformed C₃ (6.4–6.4 and 12.3–

12.4 t ha⁻¹). The harvest index remained statistically unaffected by cropping systems and hovered around 34%. Phosphorus management also had a marked effect on mustard productivity. The integrated treatment 75% RDP + PROM + PSB (P₅) resulted in the highest seed yield (12.7 and 12.8 t ha⁻¹) and biological yield (36.4 and 36.8 t ha⁻¹) during 2021–22 and 2022–23, respectively. Treatments RDP alone (P₂), 75% RDP + PSB (P₃), and 75% RDP + PROM (P₄) performed comparably, while the phosphorus control (P₁) produced the lowest

yield values. The harvest index was not significantly affected by the phosphorus treatments, remaining within a narrow range of 33–35%. Integrated organic and inorganic phosphorus management can improve nutrient cycling, soil biological activity, and crop productivity. PSB and PROM enhance phosphorus availability and support chlorophyll formation, biomass production, and nutrient uptake. Similar benefits were reported by Tripathy *et al.*, (2023) [13], Bhattacharyya *et al.*, (2020) [15], and Verma *et al.*, (2022) [16].

Table 7. Effect of microbe mediated phosphorus management in wheat + mustard intercropping system on productivity of mustard.

Treatments	Biological yield (q/ha)		Seed yield(q/ha)		Stover yield(q/ha)		Harvest index (%)	
	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23	2021-22	2022-23
C2	51.20	51.68	17.37	17.53	33.83	34.15	33.85	33.92
C ₃	18.78	18.94	6.41	6.46	12.37	12.48	34.10	34.12
C4	28.33	28.59	9.71	9.80	18.61	18.78	34.26	34.29
SEm (±)	-	-	-	-	-	-	0.17	0.18
LSD	-	-	-	-	-	-	NS	NS
(P = 0.05)								
P1	25.73	25.51	8.52	8.45	17.21	17.06	33.46	33.11
P2	35.06	35.38	11.96	12.07	23.10	23.30	34.13	34.12
P3	33.91	34.19	11.52	11.62	22.39	22.57	33.96	33.98
P4	35.16	35.59	11.99	12.14	23.17	23.45	34.10	34.10
P ₅	36.48	36.81	12.70	12.81	23.78	24.00	34.81	34.81
P6	30.26	30.56	10.28	10.38	19.98	20.18	33.98	33.97
SEm (±)	-	-	-	-	-	-	0.59	0.53
LSD (P = 0.05)	-	-	-	-	-	-	NS	NS

Conclusion

The present investigation demonstrated that both wheat–mustard intercropping geometry and integrated phosphorus management play an important role in improving the growth, yield attributes and productivity of Indian mustard. The results indicated that appropriate row arrangement reduced interspecific competition and facilitated more efficient utilization of available light, water, nutrients and space. Among the tested arrangements, the 5:1 row proportion of wheat and mustard showed better performance and appeared to be a suitable configuration for mustard production under the prevailing conditions. Phosphorus management also significantly affected crop performance. The integration of 75% recommended dose of phosphorus (RDP) with phosphate-rich organic manure (PROM) and phosphate-solubilizing bacteria (PSB) provided a favourable nutrient environment and supported improved plant growth and yield formation. This treatment combination demonstrated the potential to maintain high productivity while reducing dependence on mineral phosphorus fertilizer. Overall, the study suggests that combining suitable intercropping geometry with integrated, microbe-mediated phosphorus management can enhance mustard productivity and improve phosphorus-use efficiency. The approach may also contribute to sustainable nutrient management and better resource utilization in wheat–mustard production systems. Further studies across different locations and seasons are recommended to validate these findings and assess their long-term effects on soil fertility, profitability and system productivity.

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How to cite this article: Karan S, Dass A, Kumar S, Kumar D, Prajapati SK, Dayal P, et al. Performance of Indian mustard under different wheat–mustard intercropping systems and microbial phosphorus management. *International Journal of Research in Agronomy*. 2026;9(10):409–416. doi: <https://www.doi.org/10.33545/2618060X.2026.v9.i10f.6814>

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