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Optimizing phosphorus management in wheat-based intercropping systems for enhanced productivity, profitability, energy efficiency, and soil health in Indian Inceptisols

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Phosphorus deficiency in Indian Inceptisols limits crop production due to high fixation, low availability and poor fertilizer use efficiency. Even with recommended fertilizer dose, much of the applied P becomes unavailable, make strategies that enhance its solubility, recycling and plant uptakes are essential. Wheat-mustard intercropping systems improves P use efficiency through complementary root distribution and enhanced biological activity while phosphorus solubilizing bacteria (PSB), rock phosphate and organic manure further increase P availability and soil health. Therefore, a two-year factorial randomized block design field experiment was conducted with four wheat-based intercropping systems and six phosphorus management practices. The results showed significant improvements in mustard and wheat equivalent yield (MEY/WEY); CS$_3$ and CS$_4$ showed 29.6–34.8% enhancements over CS$_2$, with CS$_4$ slightly superior, while CS$_3$ and CS$_4$ show strong profitability (40–60% higher net returns), with CS$_3$ being slightly superior. Among P management strategies, P$_5$ produced the highest MEY/WEY (34.3–34.6%) and profitability (≈45–48% higher net returns; 18–20% higher B:C), energy output (28–35%) and energy productivity (9.5%) enhancement under P$_5$ over P$_1$. The CS$_4$ system recorded the highest soluble P (7.91 mg kg^{-1}), organic P (358.4 mg kg^{-1}) and total P (790.4 mg kg^{-1}), corresponding to increases of 24.7, 51.4, and 7.2% over CS$_1$. Microbial P treatments (P$_5$/P$_3$) further enhanced P pools, such as soluble P (48.1%), Fe-bound P (29.2%), Ca-bound P (41.1%) and total inorganic P (33.9%) over P$_1$. The CS$_4$ system reduced bulk density (5.2%), increased soil organic carbon (13.9%), available N (10.6%), P (24.1%) and K (6.3%), along with higher microbial activity and micronutrient availability. Thus, integrating Wheat + mustard (5:2) and 75% RDP + PROM + PSB is recommended, as a productive, energy-efficient and soil-enriching strategy for profitable wheat-based system in P-deficient Inceptisols.

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KEYWORDS

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Highlights

- Wheat–mustard intercropping (5:2) boosted system productivity, giving 29–35% higher equivalent yields and 40–60% higher net returns than sole cropping.
- Integrated P management 75% RDF + PROM + PSB delivered the greatest benefits, raising equivalent yields (34–35%), NR (45–48%), B: C ratio (18–20%) and energy output (28–35%) over without P.
- Wheat + mustard (5:2) improved soil health, reducing bulk density and enhancing SOC, available N, P, K, microbial activity, and micronutrient status.
- Wheat + mustard (5:2) with 75% RDF + PROM + PSB significantly increased soil P fractions, including soluble P, organic P, Ca-bound P, and total inorganic P over control.

1 Introduction

Phosphorus is an essential plant macronutrient regulating plant growth, energy transfer, root development, flowering, grain formation and a variety of metabolic processes, making it essential for achieving stable and high agricultural productivity (Divito and Sadras, 2014; He and Dijkstra, 2014; Zhang et al., 2022). In India, phosphorus is widely recognized as the second most limiting nutrient after nitrogen, particularly in Inceptisol-dominated regions of the Indo-Gangetic Plains and Eastern India (Dey et al., 2017). These soils suffer from low natural P availability due to strong fixation by Fe/Al oxides, low organic matter content, and decades of nutrient mining (Gupta et al., 2020). As a result, almost 55–60% of Indian soils exhibit low available P, posing a significant threat to crop production and long-term soil fertility (FAI, 2023). Such deficiencies are particularly concerning in the context of climate change, which is intensifying heat stress, altering rainfall patterns, and reducing nutrient availability through accelerated soil degradation (Aggarwal, 2003; Kumari et al., 2020). Ensuring efficient P management is therefore crucial for enhancing resilience, productivity, and sustainability of cropping systems in changing climatic conditions (Maharajan et al., 2021; Lucas et al., 2023). Climate change also intensifies the global challenge of achieving food and nutrition security, aligned with UN Sustainable Development Goals (SDGs) particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Wheat, being a major staple and nutritional security crop in India, plays a pivotal role in fulfilling national caloric and protein demands (Curtis and Halford, 2014; Ramadas et al., 2019). However, declining soil fertility and unsustainable nutrient management threaten wheat yields, jeopardizing national food security strategies (Ladha et al., 2007; Bhatt et al., 2016). Sustainable phosphorus management, particularly in diversified cropping systems such as intercropping, is thus essential for increasing productivity while minimizing environmental footprints, contributing directly to climate-resilient agriculture and sustainable development pathways.

Wheat-based intercropping systems have emerged as a promising strategy to improve land-use efficiency, enhance soil health, reduce input dependence, and achieve higher system resilience under climate uncertainties (Kumar et al., 2024). Intercropping wheat with legumes or oilseeds—such as chickpea, pea, mustard, and linseed can improve biodiversity, stabilize yields, and enhance nutrient cycling (Aziz et al., 2015; Lopes et al., 2016; Singh B. et al., 2019; Singh M. et al., 2019; Kumar et al., 2022; Gong et al., 2024; Jiang et al., 2024; Lakra et al., 2024; Wang et al., 2023; Wang et al., 2025). Complementary rooting patterns and differential nutrient uptake reduce competition while improving access to soil resources that are poorly utilized in monocropping (Aziz et al., 2015; Wang et al., 2018; Rossi et al., 2025). These advantages make wheat-based intercropping a climate-smart intervention with strong relevance to sustainability and national food security. However, efficient phosphorus management in intercropping systems remains challenging because conventional fertilization guidelines are designed for monocropping and fail to address the combined nutrient demands of intercrops. Therefore, optimizing phosphorus management is central to harnessing the agronomic, environmental and nutritional potential of wheat-based intercropping.

The widespread use of inorganic phosphorus fertilizers often leads to low recovery (15–25%), resulting in economic inefficiencies and environmental concerns such as eutrophication (Ali et al., 2025b). Additionally, the manufacturing of chemical P fertilizers has a high carbon footprint, contradicting global climate mitigation targets (Brentrup et al., 2016). Integrated phosphorus management (IPM) combining inorganic fertilizers with FYM, compost, crop residues, phosphate-solubilizing bacteria (PSB), and mineral sources like rock phosphate offers a sustainable alternative that enhances P availability, strengthens soil microbial communities and reduces environmental impact, improve soil health and ecological sustainability (Devi et al., 2011; Meena et al., 2012; Fazily et al., 2021; Gao et al., 2025; Li H.P. et al., 2023; Liu et al., 2024; Luo et al., 2025; Lv et al., 2024; Ma et al., 2025; Cheng et al., 2023; Dos Reis et al., 2024; Eichler-Löbermann and Weidlich, 2025; Fernandez et al., 2025). Despite these findings, several scientific gaps remain.

1.1 Research gaps

- There is limited holistic research examining productivity, profitability, energy-use efficiency, soil health and P dynamics together in wheat-based intercropping systems.
- Studies on P management under Inceptisols characterized by high P-fixation are sparse; the comparative performance of alternative P sources (FYM, PSB, rock phosphate) in wheat intercropping remains poorly documented.
- The long-term influence of P strategies on P fractions, nutrient pools and soil enzymatic activities is not well understood.
- Energy and economic analyses, crucial for the adoption of sustainable technologies by farmers are often neglected

1.2 Research hypothesis

- Integrated phosphorus management combining inorganic, organic, and biological P sources will improve crop productivity, profitability, energy-use efficiency, soil health and phosphorus dynamics in wheat-based intercropping systems under Inceptisols, compared to reliance on inorganic fertilizers alone.
- Further, it is hypothesized that wheat-based intercropping, when complemented with integrated P sources, will intensify nutrient mobilization, enhance microbial activity, strengthen soil quality, reduce external input dependence, and contribute to climate-resilient, sustainable agriculture.

1.3 Research objectives

- To assess the effects of different phosphorus-management strategies on system productivity, resource-use efficiency, and economic performance of wheat-based intercropping systems under Inceptisols
- To evaluate the impact of integrated phosphorus management on soil health and phosphorus dynamics including SOC, microbial activity, enzymatic functions, and P fractions to identify the most sustainable and climate-smart practice aligned with SDGs for long-term agricultural sustainability.

2 Materials and methods

2.1 Experimental site, soil and climate

A field investigation entitled “Microbe-mediated phosphorus management in the wheat + mustard intercropping system” was executed at the research farm of ICAR–Indian Agricultural Research Institute (IARI), New Delhi, during the *Rabi* seasons of 2021–22 and 2022–23. The experimental field situated at 8°38′23″N latitude, 77°09′27″E longitude, and 228.61 m altitude (Figure 1). Prior to the start of study, baseline soil samples from experimental site were taken from 0–15 cm depth, and they were processed for the analyses. The primary samples of soil were collected from the investigational field and thoroughly analyzed. The experimental site was characterized by a sandy clay loam texture with an initial soil *p*H 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 Subbiah and Asija (1956), Olsen et al. (1954), and Jackson (1973), respectively. The study area experiences extremely hot, dry summers and very cold winters, and has a semi-arid, subtropical climate. In the June, the average temperature peaked for the year, reaching around 39 to 40 °C, while in January; the lowest average temperature was recorded at 7.7 °C. In general, the normal yearly

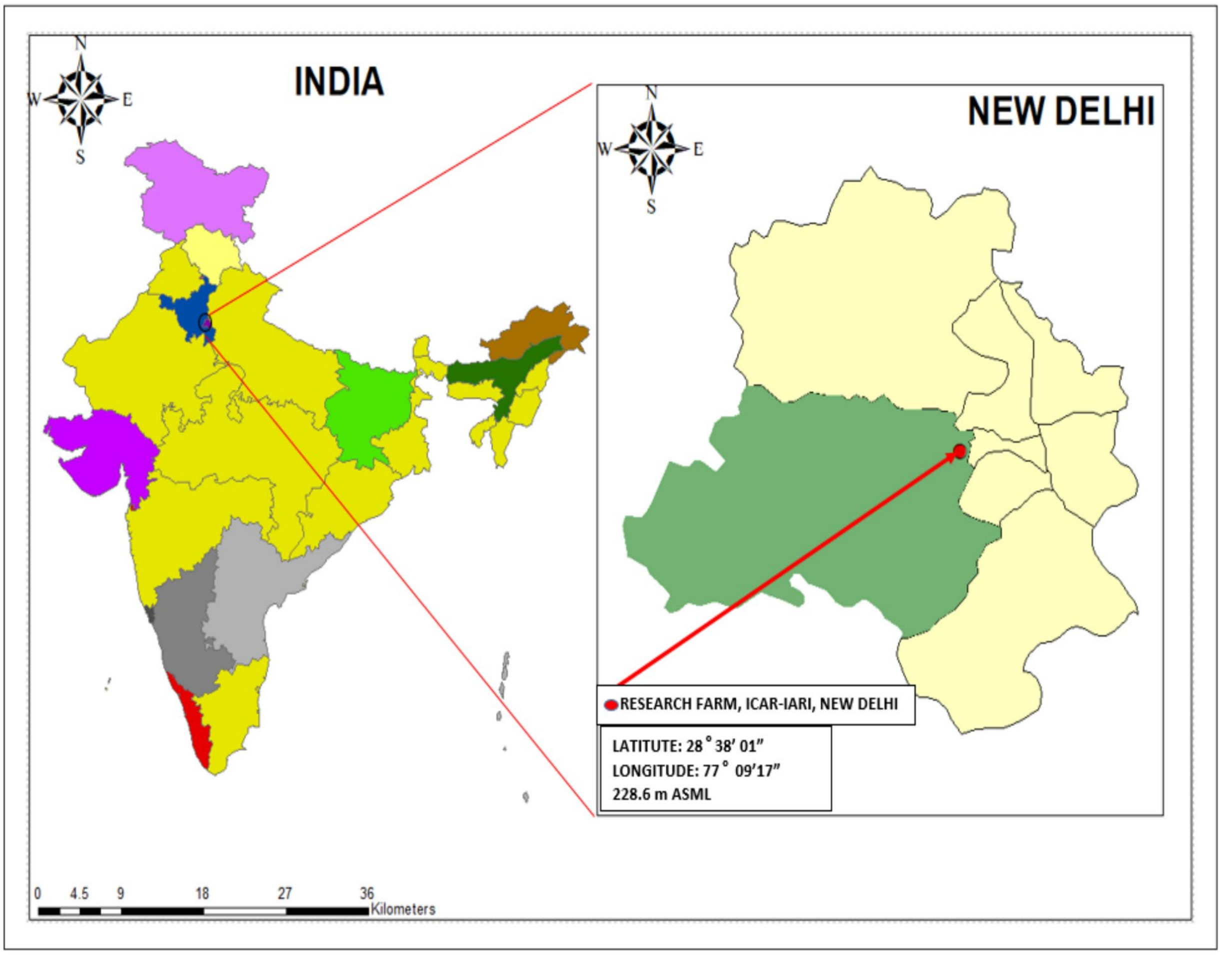

FIGURE 1
Experimental site, Indian Council of Agricultural Research, Indian Agricultural Research Institute, New Delhi.

rainfall is 850 mm, fundamentally concentrated from July to September, which is the rainy season, contributing 80% of the total rainfall, the remaining 20% happens between October to May. The U.S. Weather Bureau's standard daily Class A open evap gauge measurement fluctuates, reaching its peak value around 10.9 mm in the month of June and its lowest value around 1.5 mm in the month of January. The annual average pan evaporation was observed around 850 mm. Weather parameters data throughout the experimental time (2021–22 and 2022–23) was obtained from meteorological observatory of ICAR-IARI, New Delhi are shown in Figures 2a,b.

2.2 Experimental design and treatments

This experiment was conducted using a factorial randomized block design with two factors: four cropping systems and six phosphorus management practices. The cropping system treatments included CS_1: Sole wheat, CS_2: Sole mustard, CS_3: Wheat + mustard in a 5:1 row ratio, and CS_4: Wheat + mustard in a 5:2 row ratio. The phosphorus management treatments consisted of P_1: Control (no phosphorus), P_2: 100% Recommended Dose of Phosphorus (RDP), P_3: 75% RDP + 0.5 kg ha^{-1} phosphate-solubilizing microorganisms (PSM), P_4: 75% RDP + 125 kg ha^{-1} Phosphate-Rich Organic Manure (PROM), P_5: 75% RDP + PROM + PSB, and P_6: 125 kg ha^{-1} PROM + 0.5 kg ha^{-1} PSB with no fertilizer phosphorus. Plot size was 25 m^2. The entire dose of phosphorus was applied at the time of sowing. In the fertilizer-based treatments, phosphorus was supplied through single super phosphate (SSP), and the full amount, as per the treatment, was applied at sowing. In addition to chemical fertilizers, Phosphate-Rich Organic Manure (PROM) was also used as an organic source of phosphorus under P_4 and P_5. PROM is produced by combining organic materials (such as compost, farmyard manure, or press mud) with rock phosphate and phosphorus-solubilizing microorganisms (PSMs). Through microbial decomposition and mineral solubilization, this process makes phosphorus more readily available to plants. The compost inoculant culture used for PROM preparation consisted of *Aspergillus awamori*, *Trichoderma viride*, *Phanerochaete chrysosporium*, and *Aspergillus nidulans*. PROM contained 10.4% phosphorus and 0.4% nitrogen. PROM was incorporated into the soil during land preparation, while the phosphorus-solubilizing bacteria (PSB), *Bacillus megaterium*, were applied as a seed treatment at 0.5 kg ha^{-1}.

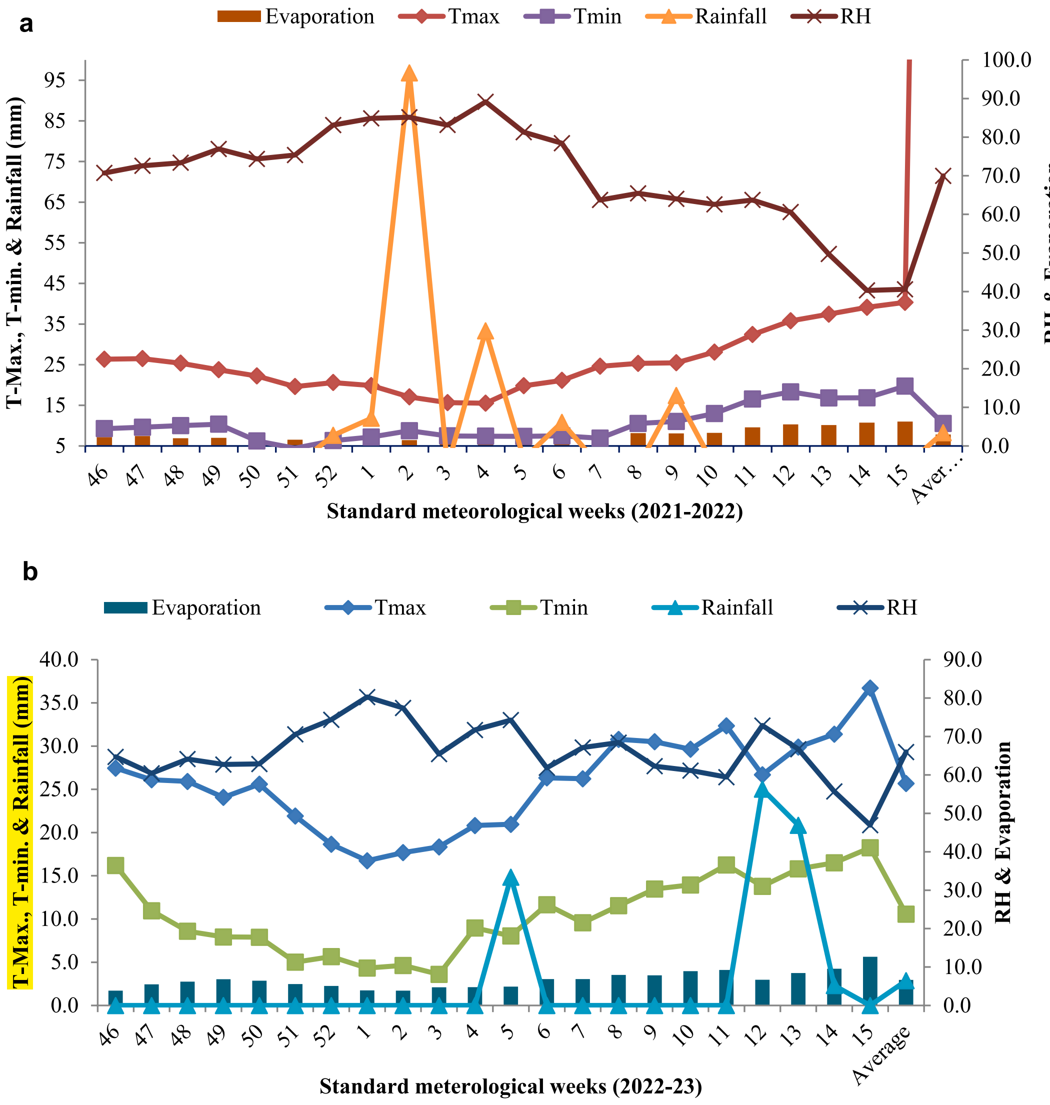

FIGURE 2
(a,b) Weather parameters data throughout the experimental time (2021-22–2022-23).

For seed treatment with phosphorus-solubilizing bacteria (PSB), the seeds were uniformly coated with a *Bacillus megaterium* culture using a jaggery solution as a sticking agent. After coating, the seeds were shade-dried for about 30 min to ensure proper adhesion of the inoculant. The treated seeds were then sown immediately to maintain the viability and effectiveness of the PSB. Both the PSB culture and compost inoculants were provided by the Division of Microbiology, ICAR–Indian Agricultural Research Institute, New Delhi, India.

2.3 Crop management

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. The field was prepared with one harrowing followed by two passes of a cultivator and subsequent planking. Wheat (cv. HD-2967) was manually sown in lines marked with a rope at a row spacing of 22.5 cm, while mustard (cv. PM-28) was sown at a row spacing of 45 cm. A uniform plant-to-plant spacing of 10 cm in both crops was achieved through thinning in densely populated rows and gap filling in sparsely populated areas. The entire dose of potassium (K) was applied at sowing, whereas nitrogen (N) was applied in two splits: 50% at sowing and the remaining 50% two days after the ponded irrigation water had receded in both crops. In intercropping irrigation was applied as per the need of wheat crops, in wheat, six irrigations were applied at critical growth stages: Crown root initiation, tillering, jointing, booting, flowering, and grain filling. In mustard, three irrigations were applied at the key growth stages: branching, flowering, and siliquae formation under sole mustard crop. In both crops, weeds were removed manually at 25 and 45 days after sowing. Mustard aphids were managed by spraying imidacloprid 17.8 SL at 1 mL L^{-1} of water.

2.4 Crop productivity

For crop productivity assessment, one border row from each side was removed, and the remaining net plot area was used for recording yield data. The designated net plot areas were manually harvested using a sickle, and the harvested biomass underwent sun drying. Subsequently, a pullman thresher was employed to thresh the dried biomass. The weight of grains was meticulously recorded after thorough cleaning. The resultant grain production per net plot was then quantified and expressed as Mega grams per hectare (Mg ha^{-1}). Furthermore, the wheat and mustard equivalent yields (WEY/MEY) were calculated using the following Equations 1–3.

$$WEY = Wheat\ yield\left(q\,ha^{-1}\right) + \frac{Mustard\ yield\left(q\,ha^{-1}\right) x\ Price\ of\ mustard\left(\$\,ha^{-1}\right)}{Price\ of\ wheat\left(q\,ha^{-1}\right)} \tag{1}$$

$$MEY = Mustard\ yield\left(q\,ha^{-1}\right) + \frac{Wheat\ yield\left(q\,ha^{-1}\right) x\ Price\ of\ wheat\left(\$\,ha^{-1}\right)}{Price\ of\ Mustard\left(\$\,ha^{-1}\right)} \tag{2}$$

2.4.1 Intercropping advantage

Land Equivalent Ratio (LER) is an index used to evaluate the productivity advantage of intercropping compared to sole cropping (Willey, 1979). An LER value greater than 1 indicates that intercropping uses land more efficiently and produces higher combined yield than growing the crops separately.

$$LER = \frac{Yab}{Yaa} + \frac{Yba}{Ybb} \tag{3}$$

Y_{aa} represents the yield of crop *a* (wheat) under sole cropping, while Y_{ab}denotes the yield of crop *a* in the intercropping system. Similarly, $Y_{bb}$is the yield of crop *b* (mustard) under sole cropping, and Y_{ba}refers to the yield of crop *b* in intercropping.

2.5 Profitability

The cost of cultivation was estimated by accounting for inputs such as farm machinery, seeds, fertilizers, plant protection, wages, irrigation, land rent and interest rate and miscellaneous expenses. Input-wise data were recorded, and costs calculated. Gross returns (Equation 4) included income from seed and straw sales—seeds, net returns were derived by subtracting total costs from gross returns (Equation 5). The benefit–cost ratio (BCR) was computed by dividing net returns by the respective cost of cultivation (Equation 6).

$$Gross\ return\left(\$\,ha^{-1}\right) = Sale\ of\ grain + Sale\ of\ straw \tag{4}$$

$$Net\ return = Gross\ return\left(\$\,ha^{-1}\right) - cost\ of\ cultivation\left(\$\,ha^{-1}\right) \tag{5}$$

$$B:C\ ratio = \frac{Net\ return\left(\$\,ha^{-1}\right)}{Cost\ of\ cultivation\left(\$\,ha^{-1}\right)} \tag{6}$$

2.6 Energy footprints

Energy parameters in this study were calculated following the methodology as per Kumar et al. (2025). Energy input was estimated by recording all treatment-wise agricultural inputs—including chemical fertilizers, pesticides, seed, human labour, machinery use, diesel, electricity, and irrigation water—and converting them into energy units using their respective energy equivalents (Table 1). The total energy input was obtained by summing these converted values. Energy output was computed by considering both seed and stover yields (Equation 7), which were multiplied by their corresponding energy equivalents and then summed. Energy balance (Equation 7), energy use efficiency (Equation 9), and specific energy (Equation 10) were subsequently derived using the standard formulas:

$$Energy\ output\left(MJ\,ha^{-1}\right) = Grain\ energy\left(MJ\,ha^{-1}\right) + Straw\ energy\left(MJ\,ha^{-1}\right) \tag{7}$$

TABLE 1 Equivalent of agriculture inputs used in the estimation.

Particular unit	Units	Equivalent energy (MJ)	References
Labour	Hour	1.96	Mohammadi et al. (2008)
N	kg	60.6	Yadav et al. (2017)
P	kg	11.1	Yadav et al. (2017)
K	kg	6.7	Yadav et al. (2017)
S	kg	1.12	Mohammadi et al. (2010)
Pesticide	kg	120	Yadav et al. (2017)
Irrigation	m^3	1.03	Mohammadi et al. (2008)
Electricity consumption	KWh	11.9	Mittal et al. (1985)
Tractor	kg	68.4	Mittal et al. (1985)
Harrow	kg	62.7	Mittal et al. (1985)
Seed drill	kg	62.7	Mittal et al. (1985)
Cultivator	kg	62.7	Mittal et al. (1985)
Threshing	kg	62.7	Mittal et al. (1985)
Diesel	L	56.31	Mittal et al. (1985)
Seed	kg	22.75	Yadav et al. (2017)
Stover	kg	12.5	Yadav et al. (2017)

$$Net\ energy\ balance = Energy\ output - Energy\ input \quad (8)$$

$$Energy\ Use\ Efficiency\left(kg\ MJ^{-1}\right) = \frac{Crop\ yield\left(kg\ ha^{-1}\right)}{Energy\ input\left(MJ\ ha^{-1}\right)} \quad (9)$$

$$Specific\ Energy\left(MJ\ kg^{-1}\right) = \frac{Energy\ input\left(MJ\ ha^{-1}\right)}{Crop\ yield\left(kg\ ha^{-1}\right)} \quad (10)$$

2.7 Soil sampling and analysis

A screw augur was used to take a soil sample from each plot's plough layer (0 to 15 cm deep) after the experiment completed. Each plot included three points where samples were taken, which were then combined to create the composite soil sample. Altogether 45 sets of soil samples were collected and placed in zip-top polypropylene containers and sent to the lab. Samples of soil were dried in air at room temperature and stained with 2 mm sieves after the visible roots and crop residue had been removed. The phosphorus fractionation method, which was developed by Chang and Jackson (1957) and updated by Kuo (1996), was used to determine the phosphate concentration in soil samples. In order to extract the P fractions from the soil, the following extract was used (Figure 3). Soil samples were analyzed for physico-chemical properties using standard procedures. Bulk density was measured by the core sampling method (Chopra and Kanwar, 1991), while soil texture was determined using the USDA soil textural triangle. Soil pH and electrical conductivity were estimated using a glass-electrode pH meter and a conductivity bridge, respectively (Richards, 1954). Organic carbon content was analyzed using the Walkley and Black (1934) wet digestion method. Available nitrogen was determined by the alkaline permanganate method (Subbiah and Asija, 1956), available phosphorus by Olsen's method (Olsen et al., 1954), and available potassium by the flame photometric method (Jackson, 1973). Available sulfur was estimated following Williams and Steinbergs (1959). Micronutrients such as Fe, Mn, and Zn were extracted using DTPA solution and quantified as per the procedure of Lindsay and Norvell (1978). Dehydrogenase activity (DHA) was estimated using the reduction of TTC to TPF as described by Casida et al. (1964). Acid phosphatase activity was determined by measuring p-nitrophenol (PNP) released from p-nitrophenyl phosphate following Tabatabai and Bremner (1969). Soil microbial biomass carbon (SMBC) was measured using the chloroform fumigation–extraction method (CFE) following Vance et al. (1987). Protease activity was estimated by quantifying ammonium released from casein substrate using the method of Ladd and Butler (1972).

2.8 Statistically analysis

In this investigation, data from three independent replicates for each treatment were subjected to standard linear modelling using the SAS 9.3 software package (SAS Institute, Cary, NC). The relevance of the "F" value for the factorial randomized block design was determined through using the technique of ANOVA. For numerous comparisons of treatment means, we used the LSD at a 5% level of probability.

3 Results

3.1 Crop productivity

Across two years, intercropping systems showed a strong yield advantage over sole mustard (CS2) (Table 2). For mustard equivalent yield (MEY), CS3 (Wheat + mustard 5:1) and CS_4 (Wheat + mustard 5:2) recorded 34–35% higher MEY in 2021–22 and 29–31% higher MEY in 2022–23 over CS_2, while CS_1 (sole wheat) produced 25%

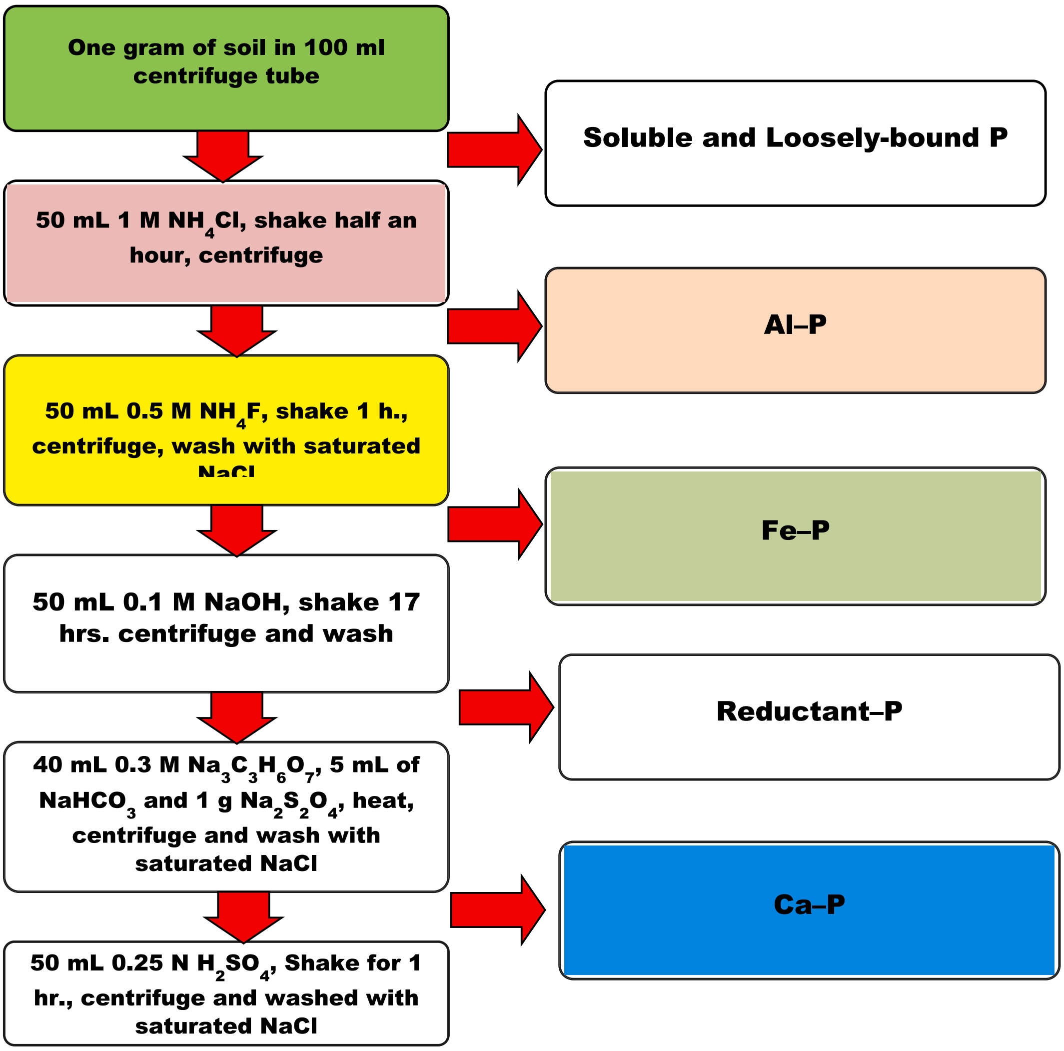

FIGURE 3
Extract used for extraction of P fractions from the soil.

higher MEY in 2021–22 and 18% higher in 2022–23. For wheat equivalent yield (WEY), CS_3 and CS_4 increased WEY by 34–35% in 2021–22 and 30–31% in 2022–23 compared with CS_2, whereas CS_1 recorded 25 and 18% higher WEY in the respective years. The yields under CS_1, CS_3 and CS_4 were statistically at par (non-significant with each other), but all three treatments recorded significantly higher yields compared to CS_2. For phosphorus management, all treatments except P_1 (No RDP) and P_6 (No RDP + PROM+PSB) significantly improved equivalent yields over P_1. The highest response was with P_5 (75% RDP + PROM + PSB) which enhanced MEY and WEY by 34–35%, followed by P_2; 100% RDP through fertilizers (28–30%), P_4; 75% RDP + PROM (30–31%), and P_3; 75% RDP + PSB (23–24%). P_6 reduced MEY and WEY by 9–10% relative to P_1. The treatments P_2, P_3, P_4 and P_5 were statistically at par with each other (non-significant), indicating that their effects on equivalent yield did not differ significantly. Except for P_5, P_6 did not differ significantly from the other phosphorus-management treatments.

3.2 Profitability analysis

Across two years, intercropping systems recorded higher profitability than sole mustard (CS_2) (Table 3). Gross returns under CS_3 (Wheat + mustard 5:1) and CS_4 (Wheat + mustard 5:2) were 41–42% higher in 2021–22 and 39–40% higher in 2022–23 over CS_2, while CS_1 showed 34 and 29% higher returns, respectively. Net returns followed a similar trend, with CS_3 and CS_4 outperforming CS_2 by 37–38% in 2021–22 and 35–36% in 2022–23, whereas sole wheat (CS_1) produced 35 and 30% higher net returns, respectively. The B:C ratio was also higher in CS_3, CS_4 and CS_1 (2.38–2.44) compared to CS_2 (2.06–2.13). Differences among CS_1, CS_3 and CS_4 were statistically non-significant, but all three provided significantly higher gross and net returns, and B:C ratio than CS_2. For phosphorus management, profitability increased markedly with improved P-application strategies. Compared with P_1 (control; no RDP), the treatments P_2 (100% RDP), P_3 (75% RDP + PSB), P_4 (75% RDP + PROM) and P_5 (75% RDP + PROM + PSB) increased gross returns by 28–30% and net returns by 32–33%, with the highest gains obtained under P_2 and P_5, reflecting their superior profitability. The B:C ratio was also highest under P_2 (3.31–3.37) and P_5 (3.25–3.31). Treatment P_6 improved returns over P_1 by 12–13%, but remained lower than other improved P strategies. Treatments P_2, P_3, P_4 and P_5 were statistically at par for gross return, net return and B:C ratio, indicating similar profitability. Except for P_2 and P_5, P6 was statistically non-significant with the other treatments. Across phosphorus-management treatments, both intercropping systems (CS_3 and

TABLE 2 Effect of microbe mediated phosphorus management in wheat + mustard intercropping system on crop equivalent yield.

Treatment	Mustard equivalent yield (q ha^{-1})		Wheat equivalent yield (q ha^{-1})	
	2021–22	2022–23	2021–22	2022–23
Cropping systems				
CS1	21.66	20.55	50.99	51.49
CS2	17.37	17.37	40.89	43.52
CS3	23.31	22.51	54.89	56.42
CS4	23.42	22.82	55.14	57.18
SEm (±)	0.72	0.67	1.70	1.68
LSD (P = 0.05)	2.16	2.01	5.09	5.03
Microbe mediated phosphorus management				
P_1	17.67	17.12	41.61	42.92
P_2	23.06	22.31	54.12	55.92
P_3	21.78	21.15	51.28	53.00
P_4	22.99	22.38	54.28	56.09
P_5	23.75	23.07	55.91	57.81
P_6	19.40	18.83	45.67	47.20
SEm (±)	1.49	1.30	3.50	3.25
LSD (P = 0.05)	4.47	3.89	10.51	9.74

Where, CS1: Sole wheat (control); CS2: Sole mustard; CS3: Wheat + mustard (5:1); CS4: Wheat + mustard (5:2); P1: Control; P2: RDF; P3: 75% RDP+ PSB; P4: 75%RDP+PROM; P5: 75% RDP + PROM + PSB; P6: No RDP+ PROM+PSB.

TABLE 3 Effect of microbe mediated phosphorus management in wheat + mustard intercropping system on profitability.

Treatments	Cost of cultivation ($ ha^{-1})		Gross return ($ ha^{-1})		Net return ($ ha^{-1})		B:C ratio	
	2021–22	2022–23	2021–22	2022–23	2021–22	2022–23	2021–22	2022–23
Cropping systems								
CS1	626.5	645.3	1512.5	1551.7	886.0	906.4	2.41	2.40
CS2	548.2	564.7	1129.9	1202.2	581.6	637.5	2.06	2.13
CS3	662.6	682.5	1595.3	1668.5	932.7	986.0	2.41	2.44
CS4	666.5	686.5	1587.3	1665.3	920.7	978.8	2.38	2.43
SEm (±)	-	-	32.4	33.8	18.5	19.5	0.05	0.05
LSD (P = 0.05)	-	-	97.1	101.5	55.4	58.5	0.15	0.16
Microbe-mediated phosphorus management								
P1	583.6	601.2	1609.8	1657.1	1026.1	1055.9	2.76	2.76
P2	626.4	645.2	2073.8	2174.3	1447.4	1529.1	3.31	3.37
P3	621.7	640.3	2077.0	2170.2	1360.0	1437.8	3.19	3.24
P4	648.4	667.9	2077.4	2188.3	1428.9	1520.4	3.21	3.28
P5	657.0	676.7	2136.0	2239.8	1479.0	1563.2	3.25	3.31
P6	618.6	637.2	1767.4	1900.8	1148.7	1263.6	2.86	2.91
SEm (±)	-	-	44.2	46.4	30.1	31.9	0.07	0.07
LSD (P = 0.05)	-	-	132.7	139.3	90.3	95.6	0.21	0.21

Where, CS1: Sole wheat (control); CS2: Sole mustard; CS3: Wheat + mustard (5:1); CS4: Wheat + mustard (5:2); P1: Control; P2: RDF; P3: 75% RDP+ PSB; P4: 75%RDP+PROM; P5: 75% RDP + PROM + PSB; P6: No RDP+ PROM+PSB.

CS$_4$) achieved a Land Equivalent Ratio (LER) greater than 1.0 under all treatments except CS$_3$. P$_6$ (LER = 0.95), indicating that intercropping was generally advantageous (Figure 4). In CS$_3$, the highest LER was recorded under P$_5$ (1.20) followed closely by P$_2$ (1.20) and P$_4$ (1.20). In CS4, LER values were consistently higher than in CS$_3$, with the maximum under P$_5$ (1.21), followed by P$_4$ (1.20) and P$_2$ (1.19)

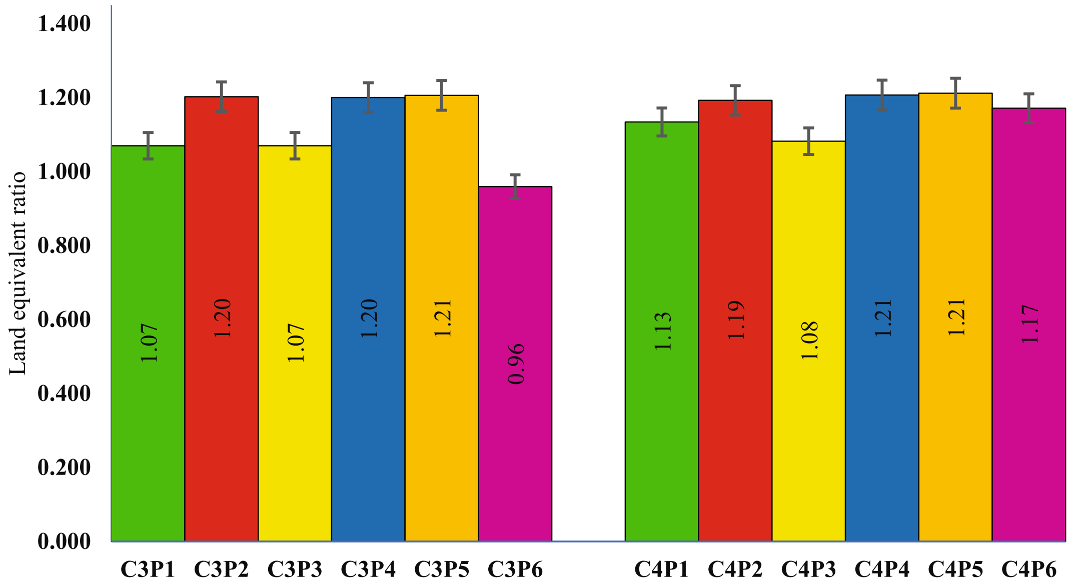

FIGURE 4
Effect of microbe mediated phosphorus management in wheat + mustard intercropping system on total phosphorus uptake (02 year mean).

TABLE 4 Effect of microbe mediated phosphorus management in wheat + mustard intercropping system on energy use indices.

Treatments	Energy input (MJ ha^{-1})		Energy output (MJ ha^{-1})		Energy productivity (kg MJ^{-1})		Specific energy (MJ kg^{-1})	
	2021–22	2022–23	2021–22	2022–23	2021–22	2022–23	2021–22	2022–23
Cropping systems								
CS1	23,251	23,251	206,514	208,572	0.219	0.221	4.56	4.51
CS2	16,601	16,601	109,055	110,076	0.105	0.106	9.56	9.47
CS3	26,322	26,322	200,589	202,460	0.176	0.177	5.70	5.64
CS4	26,656	26,656	190,830	192,582	0.158	0.159	6.35	6.29
SEm (±)	-	-	5,965	5,965	0.007	0.007	0.17	0.18
LSD (P = 0.05)	-	-	15,754	15,754	0.02	0.02	0.52	0.52
Microbe-mediated phosphorus management								
P1	19,610	19,610	199,146	197,483	0.224	0.222	4.46	4.50
P2	23,245	23,245	249,581	251,777	0.241	0.243	4.15	4.12
P3	22,843	22,843	243,366	245,309	0.231	0.233	4.33	4.29
P4	25,118	25,118	250,506	253,440	0.223	0.226	4.48	4.42
P5	25,843	25,843	254,366	265,681	0.222	0.234	4.50	4.46
P6	22,585	22,585	212,757	217,579	0.211	0.216	4.73	4.66
SEm (±)	-	-	7,322	7,441	0.02	0.02	0.18	0.18
LSD (P = 0.05)	-	-	20,232	21,131	0.02	0.02	0.52	0.52

Where, CS1: Sole wheat (control); CS2: Sole mustard; CS3: Wheat + mustard (5:1); CS4: Wheat + mustard (5:2); P1: Control; P2: RDF; P3: 75% RDP+ PSB; P4: 75%RDP+PROM; P5: 75% RDP + PROM + PSB; P6: No RDP+ PROM+PSB.

3.3 Energy use indices

Across two years, intercropping systems showed clear improvements in total energy output compared with sole mustard (CS_2) (Table 4). Energy output under CS_3 (wheat + mustard 5:1) and CS_4 (5:2) was 84–85% higher than CS_2, while CS_1 (sole wheat) produced 89–90% higher energy output. Energy productivity followed a similar trend, where CS_1 recorded the highest values (0.219–0.221 kg MJ^{-1}), significantly superior to CS_2 (0.105–0.106). Intercropping systems CS_3 and CS_4 improved energy productivity by 67–69% and 50–51%, respectively, over CS_2. Specific energy was lowest under CS_1 (4.51–4.56 MJ kg^{-1}), followed by CS_3 and CS_4, all significantly lower than CS_2 (9.47–9.56 MJ kg^{-1}). Differences among CS_1, CS_3 and CS_4 were statistically non-significant, but all three were significantly superior to CS2 for energy output, energy productivity and specific energy. For phosphorus management, all improved strategies enhanced energy performance over P_1 (control; no RDP). Compared with P_1, P_2 (100% RDP), P_3 (75% RDP + PSB), P_4 (75% RDP + PROM) and P_5 (75% RDP + PROM + PSB) increased energy output by 22–28%, with the highest under P_5, followed by P_2 and P_4. Energy productivity was also higher under P_2 and P_3 (0.231–0.243 kg MJ^{-1}), while specific energy was lowest under P_2 (4.12–4.15 MJ kg^{-1}). Treatment P_6 improved energy output by 7–10% over P_1, but remained lower than the other improved P treatments. Treatments P_2, P_3, P_4 and P_5 were statistically at par for energy output, energy productivity and specific energy. Except for P_2 and P_5, P_6 was statistically non-significant with other treatments, indicating a comparable energy response.

3.4 Soil phosphorus fractions

The data presented in Table 5 illustrate that both intercropping systems and microbe-mediated phosphorus management practices markedly influenced the distribution of different soil phosphorus (P) fractions under the wheat + mustard intercropping system. However, the interaction effect between intercropping systems and P management was found to be non-significant for all phosphorus forms. Significant differences were observed among the intercropping systems for most phosphorus fractions. The soluble and loosely bound P, which represents the most labile and plant-available form, varied from 6.34 to 7.91 mg kg^{-1}. The highest concentration was recorded under CS_4 (7.91 mg kg^{-1}), followed closely by CS_3 (7.88 mg kg^{-1}), while the lowest was observed in CS_1 (6.34 mg kg^{-1}). This indicates enhanced P mineralization and turnover in diversified intercropping arrangements, possibly due to greater rhizosphere activity and microbial interactions. The Al-bound P fraction ranged between 27.0 and 30.9 mg kg^{-1}, with CS_1 (30.9 mg kg^{-1}) recording the highest and CS_3 (27.0 mg kg^{-1}) the lowest value. The Fe-bound P, which contributes to the moderately labile pool, decreased from 44.9 mg kg^{-1} in CS_1 to 31.5 mg kg^{-1} in CS_4, indicating greater microbial solubilization and transformation into more available forms in C_3 and C_4 systems. The Ca-bound P, representing the non-labile pool, ranged from 260.8 to 302.6 mg kg^{-1}, with the highest in C_1, while CS_4 (260.8 mg kg^{-1}) exhibited the lowest, showing a decline of 13.8% over the control system. A similar trend was observed for reductant soluble P, which decreased from 115.7 mg kg^{-1} in CS_1 to 102.1 mg kg^{-1} in CS_4, a 11.7% reduction, suggesting improved biological mobilization of occluded P under more diversified intercropping. The total inorganic P ranged from 432.0 to 500.6 mg kg^{-1}, while organic P increased steadily from 236.6 mg kg^{-1} in CS_1 to 358.4 mg kg^{-1} in CS_4, showing an increase of 51.4%. Consequently, the total P content was maximum in CS_4 (790.4 mg kg^{-1}) and minimum in CS_1 (737.3 mg kg^{-1}), marking a 7.2% overall enhancement in total soil P under CS_4, likely due to greater biological P cycling through litter deposition and root exudation. Microbe-mediated phosphorus management significantly affected all measured P fractions. The soluble and loosely bound P increased substantially from 5.59 mg kg^{-1} in P_1 (control) to 8.28 mg kg^{-1} in P_5, representing an increase of 48.1%, indicating enhanced P solubilization by microbial inoculants and organic amendments. The Al-bound P ranged

TABLE 5 Effect of microbe mediated phosphorus management in wheat + mustard intercropping system on phosphorus fraction after completion of 2 years cropping cycle.

Treatment	Soluble and loosely bound P (mg kg^{-1})	Al-bound P (mg kg^{-1})	Fe-bound P (mg kg^{-1})	Ca-bound P (mg kg^{-1})	Reductant soluble P (mg kg^{-1})	Total inorganic P (mg kg^{-1})	Organic P (mg kg^{-1})	Total P (mg kg^{-1})
Cropping systems								
CS1	6.34	30.9	44.9	302.6	115.7	500.6	236.6	737.3
CS2	7.51	28.1	37.1	274.3	109.2	456.4	287.6	744.0
CS3	7.88	27.0	33.7	263.0	104.5	436.2	323.6	759.9
CS4	7.91	29.7	31.5	260.8	102.1	432.0	358.4	790.4
SEm±	0.18	0.69	0.91	7.12	2.03	9.52	6.10	3.50
LSD (P = 0.05)	0.68	2.65	3.60	28.0	7.93	37.1	24.8	13.2
Microbe-mediated phosphorus management								
P1	5.59	24.2	33.9	235.1	106.6	405.5	245.5	651.0
P2	6.26	29.7	39.7	290.6	119.6	486.0	288.8	774.9
P3	7.89	33.8	43.8	331.7	125.5	542.9	325.3	868.3
P4	8.21	28.3	38.3	275.9	99.8	450.6	278.0	728.8
P5	8.28	27.3	37.1	286.6	110.5	469.7	275.3	745.3
P6	6.23	30.4	32.8	280.3	103.7	503.4	269.7	773.1
SEm±	0.22	0.66	0.85	6.70	1.71	8.42	5.78	7.33
LSD (P = 0.05)	0.58	1.95	2.53	18.7	5.10	24.2	16.1	21.9

Where, CS1: Sole wheat (control); CS2: Sole mustard; CS3: Wheat + mustard (5:1); CS4: Wheat + mustard (5:2); P1: Control; P2: RDF; P3: 75% RDP+ PSB; P4: 75%RDP+PROM; P5: 75% RDP + PROM + PSB; P6: No RDP+ PROM+PSB.

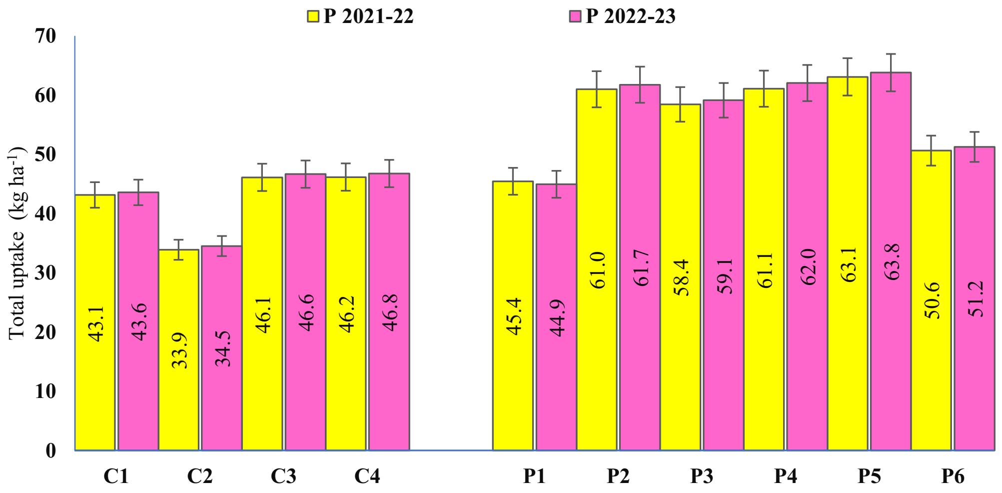

FIGURE 5
Effect of microbe-mediated phosphorus management in the wheat + mustard intercropping system on total phosphorus uptake.

from 24.2 to 33.8 mg kg^{-1}, with the highest under P$_3$ (33.8 mg kg^{-1}), which was 39.7% higher than the control. Similarly, the Fe-bound P improved from 33.9 mg kg^{-1} (P$_1$) to 43.8 mg kg^{-1} (P$_3$), marking a 29.2% increase due to microbial oxidation–reduction reactions facilitating P desorption from Fe oxides. The Ca-bound P fraction varied significantly, ranging between 235.1 and 331.7 mg kg^{-1}, with P$_3$ (331.7 mg kg^{-1}) recording the maximum (41.1% higher than P$_1$), indicating a cumulative buildup of sparingly soluble phosphates due to enhanced P mobilization and fixation balance. The reductant soluble P ranged from 99.8 mg kg^{-1} (P$_4$) to 125.5 mg kg^{-1} (P$_3$), where P$_3$ showed a 17.7% improvement over P$_1$, reflecting efficient microbial redox activity in the rhizosphere. The total inorganic P and organic P were significantly higher under bio-based treatments. The P$_3$ treatment recorded the highest total inorganic P (542.9 mg kg^{-1}), which was 33.9% higher than P$_1$ (405.5 mg kg^{-1}). Similarly, the organic P increased from 245.5 mg kg^{-1} (P$_1$) to 325.3 mg kg^{-1} (P$_3$), showing a 32.5% improvement. The total soil P was also maximum under P$_3$ (868.3 mg kg^{-1}), which was 33.4% higher than the control (P$_1$: 651.0 mg kg^{-1}). Treatments P$_3$ and P$_5$ were statistically at par, reflecting the synergistic impact of microbial inoculants and organic P sources in improving overall P transformation and accumulation in soil.

3.5 Phosphorus uptake

Across cropping systems, phosphorus uptake was consistently higher in intercropping than in sole mustard (CS$_1$). In both years, CS$_3$ (wheat + mustard 5:1) and CS$_4$ (5:2) increased P uptake by 7–7.3% over CS$_1$, while CS$_2$ showed a 21–20% (Figure 5) reduction. Among P-management treatments, all improved phosphorus strategies markedly enhanced P uptake over P$_1$. In 2021–22, P$_2$ (100% RDP), P$_3$ (75% RDP + PSB), P$_4$ (75% RDP + PROM) and P$_5$ (75% RDP + PROM + PSB) increased P uptake by 28–39%, with the highest increase under P$_5$ (+38.8%), followed closely by P$_4$ and P$_2$ (~34%). A similar trend was observed in 2022–23, where P$_5$ again recorded the maximum gain (+41.9%), followed by P4 (+38%) and P2 (+37%). P$_6$ showed only modest improvement (11–14% over P$_1$), remaining distinctly lower than the other improved P treatments (see Figures 6–8).

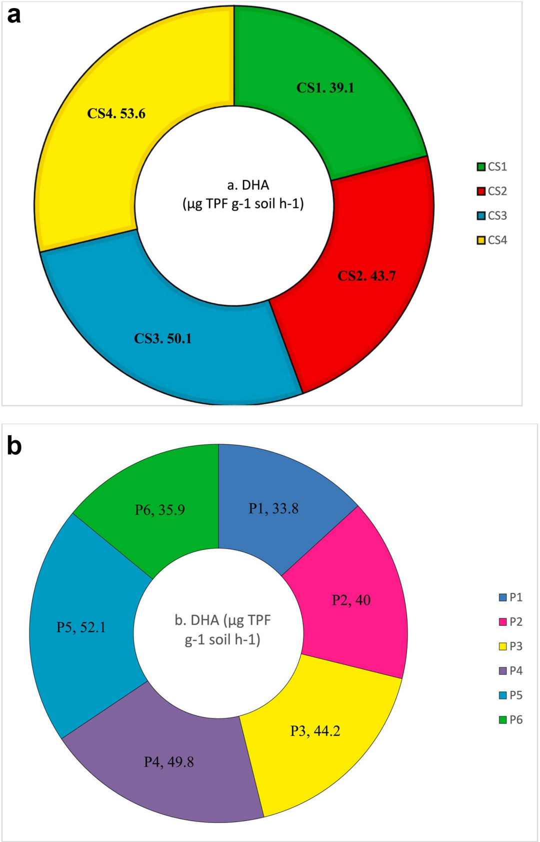

FIGURE 6
(a,b) Effect of cropping systems and microbe-mediated phosphorus management in the wheat + mustard intercropping system on DHA (02-year mean).

3.6 Soil physico-chemical and biological properties

The data presented in Table 6 demonstrate that both intercropping systems and microbe-mediated phosphorus management practices significantly influenced the soil's physico-chemical characteristics,

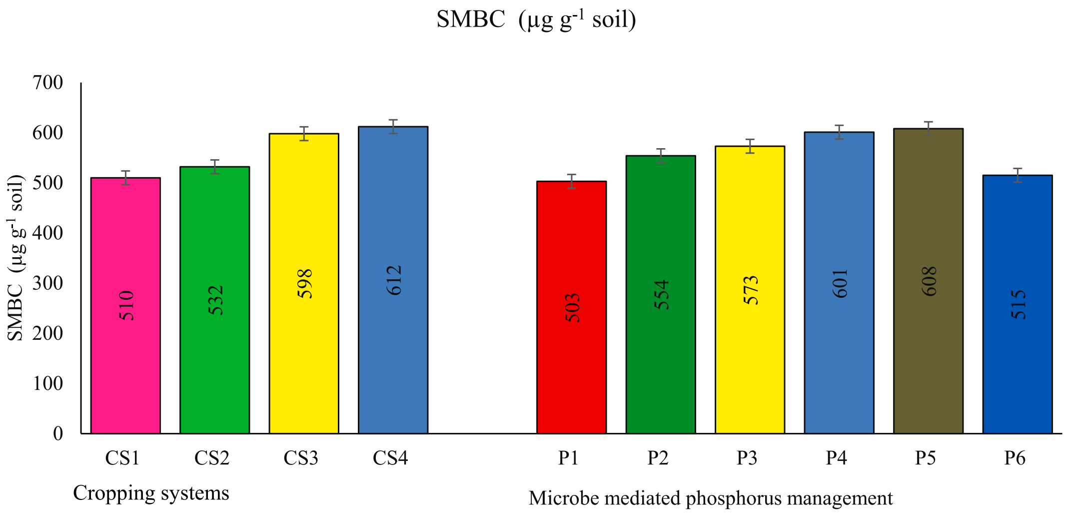

FIGURE 7
Effect of cropping systems and microbe mediated phosphorus management in wheat + mustard intercropping system on SMBC (02-year mean).

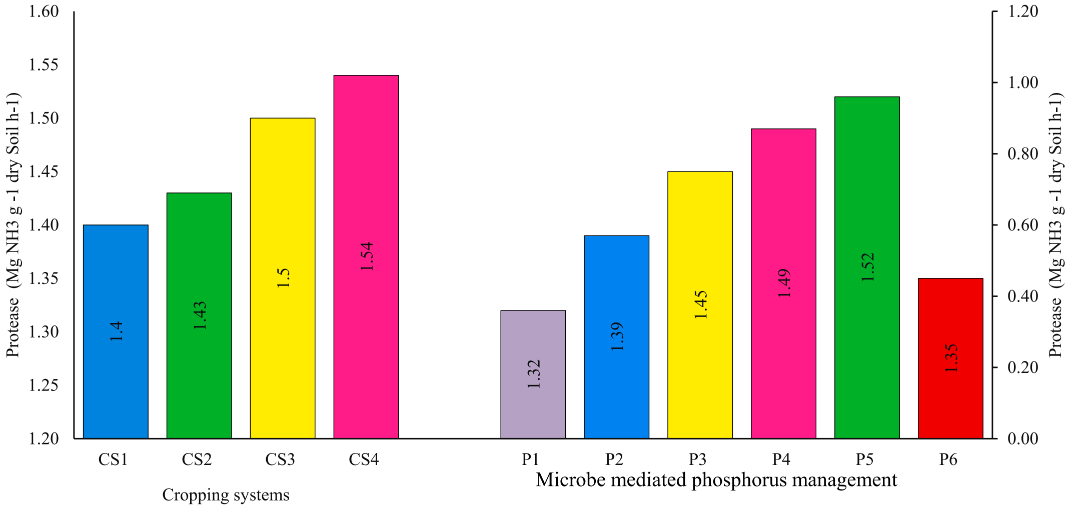

FIGURE 8
Effect of cropping systems and microbe mediated phosphorus management in wheat + mustard intercropping system on protease (02-year mean).

nutrient availability, and biological activity under the wheat + mustard intercropping system. However, the interaction effect between intercropping systems and phosphorus management was found to be non-significant for all parameters. The intercropping systems exerted a significant influence on soil bulk density, organic carbon content, and nutrient availability. The bulk density (BD) decreased significantly from 1.53 g cm^{-3} in CS_1 to 1.45 g cm^{-3} in CS_4, representing a 5.2% reduction, while organic carbon (OC) increased from 0.43% in CS_1 to 0.49% in CS_4, an improvement of 13.9%. The soil pH ranged from 8.08 to 8.30, with a slight but non-significant decline under CS_4, indicating minor acidification due to enhanced microbial and root activity. The available macronutrient contents showed consistent improvement under diversified systems, with CS_4 recording the highest available N (215.3 kg ha^{-1}), P (17.5 kg ha^{-1}), and K (227.7 kg ha^{-1}), which were 10.6, 24.1, and 6.3% higher, respectively, compared to CS_1. Similarly, the availability of micronutrients (Fe, Mn, Zn, and Cu) increased under CS_4, with Fe improving from 4.31 to 4.88 mg kg^{-1}, Mn from 1.90 to 2.05 mg kg^{-1}, Zn from 1.46 to 1.57 mg kg^{-1}, and Cu from 1.50 to 1.64 mg kg^{-1}. Soil biological properties also improved markedly under diversified intercropping. The dehydrogenase activity (DHA) increased from 39.1 to 53.6 µg TPF g^{-1} soil h^{-1}, while alkaline phosphatase activity increased from 243 to 265 µg PNP g^{-1} soil h^{-1}. Similarly, soil microbial biomass carbon (SMBC) and protease activity increased from 135.9 to 177.5 µg g^{-1} soil and 1.40 to 1.54 mg NH_3 g^{-1} dry soil h^{-1}, respectively. The CS_4 intercropping system thus demonstrated a marked improvement in soil biological activity, nutrient cycling, and organic matter buildup compared to CS_1. Microbe-mediated phosphorus management significantly influenced soil fertility and biological indices. The bulk density decreased from 1.54 g cm^{-3} (P_1) to 1.45 g cm^{-3} (P_5), while organic carbon content increased from 0.41% (P_1) to 0.50% (P_5). A gradual reduction in soil pH from 8.30 (P_1) to 7.75 (P_5) was observed, indicating slight acidification due to the release of organic and microbial acids under biologically enriched treatments. The available macronutrients increased significantly with microbial and organic phosphorus sources. The P_5 treatment (PSB + Rock phosphate + PROM) recorded the highest available N

TABLE 6 Physico-chemical properties of soil influenced by intercropping and phosphorus management practices after completion of 2 years cropping cycle.

Treatment	BD (g cm^{-3})	pH	OC (%)	Available nutrients (kg ha^{-1})			Available nutrients (mg kg^{-1})		
				N	P	K	Fe	Mn	Zn
Cropping systems									
CS1	1.53	8.30	0.43	194.6	14.1	214.1	43.1	17.0	1.46
CS2	1.49	8.25	0.45	198.3	15.4	216.6	45.0	19.4	1.49
CS3	1.47	8.18	0.47	204.0	16.7	219.1	48.3	20.1	1.54
CS4	1.45	8.08	0.49	215.3	17.5	227.7	48.8	20.5	1.57
SEm±	0.01	0.10	0.01	1.87	0.40	1.40	1.03	0.33	0.02
LSD (P = 0.05)	0.03	NS	0.03	5.18	1.60	4.32	3.10	1.04	0.07
Microbe-mediated phosphorus management									
P1	1.54	8.30	0.41	198.0	12.4	212.4	38.3	18.0	1.39
P2	1.52	8.25	0.45	200.9	13.9	216.2	47.3	19.1	1.44
P3	1.48	8.10	0.47	203.9	18.1	219.9	47.6	19.5	1.48
P4	1.49	7.82	0.48	209.7	17.6	222.8	48.1	19.8	1.50
P5	1.45	7.75	0.50	214.1	18.4	229.1	48.6	20.3	1.53
P6	1.53	8.11	0.43	199.6	12.8	214.3	45.7	18.2	140
SEm±	0.02	0.03	0.01	1.83	0.41	1.35	1.12	0.31	0.03
LSD (P = 0.05)	0.06	0.09	0.02	5.11	1.32	4.12	3.99	0.99	0.08

Where, CS1: Sole wheat (control); CS2: Sole mustard; CS3: Wheat + mustard (5:1); CS4: Wheat + mustard (5:2); P1: Control; P2: RDF; P3: 75% RDP+ PSB; P4: 75%RDP+PROM; P5: 75% RDP + PROM + PSB; P6: No RDP+ PROM+PSB.

(214.1 kg ha^{-1}), P (18.4 kg ha^{-1}), and K (229.1 kg ha^{-1}), showing respective increases of 8.1, 48.4, and 7.9% over the control (P_1). Micronutrient availability also improved, with Fe, Mn, Zn, and Cu contents increasing by 7.3, 12.8, 10.1, and 11.5%, respectively, under P_5 compared to P_1. Soil enzymatic and microbial parameters were considerably enhanced under biologically mediated phosphorus management. The DHA increased from 33.8 µg TPF g^{-1} soil h^{-1} (P_1) to 52.1 µg TPF g^{-1} soil h^{-1} (P_5), representing a 54.1% increase, while alkaline phosphatase activity improved from 221 to 262 µg PNP g^{-1} soil h^{-1}. Similarly, SMBC increased from 219.1 to 262 µg g^{-1} soil, and protease activity from 1.32 to 1.52 mg NH_3 g^{-1} dry soil h^{-1}, reflecting enhanced microbial biomass and enzymatic functioning in biologically enriched treatments.

4 Discussion

4.1 Equivalent yield of cropping system

Both intercropping systems and microbe-mediated phosphorus management significantly influenced mustard equivalent yield (MEY) and wheat equivalent yield (WEY) of the wheat + mustard intercropping system during 2021–22 and 2022–23. Among the systems, C_4; Wheat + mustard (5:2) consistently achieved the highest intercropping system yield, closely followed by C_3 Wheat + mustard (5:1), while C_2 (sole wheat) produced the lowest values. The superior performance of C_4 may be attributed to its favorable spatial configuration, which enhanced light interception, nutrient sharing and complementary root activity between the component crops. Similar yield improvements in optimized intercropping arrangements have been reported by Sisodia (2025), Picone et al. (2025), and Stubbs et al. (2025); Begam et al., 2024; Ahmad et al., 2025; Solanki and Sharma, 2018; Wu et al., 2025 who noted that diversified planting geometry increases resource-use efficiency and system productivity. Microbe-mediated phosphorus management also exerted a strong effect on both equivalent yields. The P_5 (75% RDP + PROM + PSB) consistently recorded the highest intercropping system yield, followed by P_2 (100% RDF) and P_4 (75%RDP + PROM) while the control (P_1) remained lowest. The yield advantage under P_5 reflects improved soil P solubilization, microbial activity, and nutrient uptake efficiency. PSB-based inoculation enhances rhizosphere enzyme activity and synergistic nutrient mobilization, as observed by Babar et al. (2024) and Damathia et al. (2025); Chaurasiya et al., 2024. The integration of intercropping (C_4) with bio-phosphorus management (P_5) thus provided the most productive and nutrient-efficient combination, supporting earlier evidence that combining biological inputs with spatial diversification promotes higher yield equivalence and sustainability (Dakshyani et al., 2024; Deeksha Gupta et al., 2024; Ughamba et al., 2025; Bhardwaj et al., 2022; Beltran-Medina et al., 2023; Chauhan et al., 2024).

4.2 Profitability analysis

Among the intercropping systems, CS4 Wheat + mustard (5:2) recorded the highest gross return and net return along with the highest B: C ratio (2.41 and 2.44) during 2021–22 and 2022–23, respectively. This might be due to improved resource utilization, superior light interception, and enhanced yield synergy between component crops. These findings align with those of Sisodia (2025) and Stubbs et al. (2025), Meena S.L. et al., 2025, who emphasized that balanced crop geometry in intercropping increases land-use efficiency, reduces input wastage, and stabilizes farm income. Similar intercropping-based profitability improvements have been documented by Picone et al. (2025), who reported that efficient legume–cereal, intercropping increases system output value through better resource partitioning and nutrient recycling. Microbe-mediated phosphorus management further enhanced profitability by significantly increasing returns and benefit–cost ratios. The P_5 (75% RDP + PROM + PSB) treatment recorded the maximum gross and net returns. The higher economic gains under P_5 resulted from improved soil phosphorus availability, higher yields, and reduced dependence on costly chemical fertilizers. Phosphate-solubilizing bacteria and organic amendments improve nutrient-use efficiency and energy balance, resulting in higher profitability per unit cost. These findings are consistent with Babar et al. (2024) and Damathia et al. (2025), who observed that microbial consortia improve P mobilization and crop productivity, directly enhancing net economic returns. The higher B: C ratio under P_5 (3.25 and 3.31) demonstrates that biological nutrient management is not only agronomically effective but also economically viable. This supports earlier reports by Dakshyani et al. (2024) and Deeksha Gupta et al. (2024), who found that PSB application with organic P sources reduces production costs while increasing profitability in oilseed-based systems.

4.3 Energy use indices

Among intercropping systems, the total energy input ranged from 16,601 to 26,656 MJ ha^{-1}, with the lowest input in CS_2 and the highest in CS_4 Wheat + mustard (5:2) primarily due to differences in input requirements and component crop combinations. The CS_1 (sole mustard) system consistently recorded the maximum energy output (206,514 and 208,572 MJ ha^{-1}) and the highest energy productivity (0.219 and 0.221 kg MJ^{-1}), which were more than 108% higher than those under C_2 (0.105 and 0.106 kg MJ^{-1}). Conversely, specific energy the energy required to produce one kilogram of output was the lowest in C_1 (4.56 and 4.51 MJ kg^{-1}), indicating superior energy-use efficiency and a more favorable input–output energy balance (Hasanain et al., 2025; Saikia et al., 2026). These observations are consistent with the findings of Zheng et al. (2025), who demonstrated through a meta-analysis that intercropping systems are generally more productive and energy-efficient than monocultures due to enhanced resource capture and energy conversion efficiency. Similarly, Toker et al. (2024) reported that the inclusion of compatible crop species in intercropping leads to better energy efficiency by improving the photosynthetic use of light and minimizing resource competition. Li G. et al. (2024) and Li X. et al. (2024) further noted that optimized plant density and row geometry in intercropping reduce energy waste by balancing input use and maximizing output yield per unit energy consumed. The significantly lower specific energy in C_1 compared to C_2 highlights the importance of interspecific cooperation in minimizing energy loss pathways. Microbe-mediated phosphorus management also had a notable impact on the energy dynamics of the system. Although energy input increased marginally with the application of bio-inoculants and organic amendments ranging from 19,610 to 25,843 MJ ha^{-1} this additional energy investment was more than offset by substantial gains in energy output and productivity. The P_5, produced the highest energy output and treatments P_2 and P_4 were statistically comparable but slightly lower in magnitude, demonstrating that combinations involving bio-inoculants and organic P sources considerably enhanced system energy efficiency. The higher energy productivity and lower specific energy under biologically enriched treatments (P_5 and P_2) reflect the effectiveness of microbial inoculants in improving nutrient transformation efficiency and yield energy conversion. Lei et al. (2025a, 2025b) reported that microbial phosphorus solubilization significantly contributes to soil health restoration and energy balance in agroecosystems by enhancing nutrient turnover and reducing fertilizer energy dependency. Similarly, Pradhan et al. (2025) emphasized that microbe–mineral interactions improve nutrient mobility and soil biochemical activity, thereby enhancing the bioenergetic efficiency of crop production systems. The relatively higher energy output under P_5 indicates that biologically mediated nutrient cycling can effectively replace part of the energy-intensive synthetic fertilizer inputs without compromising productivity. Moreover, the enhanced energy productivity (0.241–0.243 kg MJ^{-1}) observed under bio inoculated treatments aligns with findings by Saikia et al., 2026, Zheng et al. (2025), and Toker et al. (2024), who found that microbial symbioses enhance energy returns by increasing yield efficiency and nutrient recovery. From an environmental perspective, the reduction in specific energy values under bio-based phosphorus management indicates a lower energy cost per unit of yield, supporting the transition toward climate-smart, low-carbon agricultural systems. These results are consistent with the growing body of evidence emphasizing that integrated biological management in intercropping systems not only enhances yields but also minimizes energy intensity, thereby improving the ecological and economic sustainability of agricultural production (Li G. et al., 2024; Li X. et al., 2024; Zheng et al., 2025; Lei et al., 2025a, 2025b).

4.4 Soil phosphorus fractions

The results presented in Table 5 reveal that both intercropping systems and microbe-mediated phosphorus management significantly affected the distribution of different soil phosphorus fractions under the wheat + mustard intercropping system. Although the interaction effect between the two factors was statistically non-significant, both independently exerted a strong influence on P transformations and buildup of labile and non-labile pools, demonstrating their distinct roles in soil nutrient cycling and phosphorus bioavailability. Among the intercropping systems, significant variation was recorded in all major P fractions, reflecting the combined effects of plant–soil–microbe interactions and the extent of biological turnover. The soluble and loosely bound P, representing the most readily available fraction of phosphorus, varied from 6.34 to 7.91 mg kg^{-1}. The CS_4 system exhibited the highest value (7.91 mg kg^{-1}), closely followed by CS_3 (7.88 mg kg^{-1}), while the lowest was in CS_1 (6.34 mg kg^{-1}). The higher labile P under CS_4 and CS_3 indicates that diversified intercropping systems enhance root exudation and microbial activity, promoting P mineralization and solubilization. These findings align with the observations of Zheng et al. (2025), Toker et al. (2024), and Bai et al. (2024), who reported that legume or oilseed-based intercropping systems improve soil P availability by stimulating root–microbe interactions and rhizosphere enzyme secretion. The Al-bound P and Fe-bound P fractions, which form part of the moderately labile pool, also showed marked differences among intercropping systems. The Al-bound P ranged from 27.0 to 30.9 mg kg^{-1}, being highest under CS_1 and lowest under CS_3, suggesting that enhanced microbial solubilization under CS_3 might have transformed Al-bound P into more labile forms. Similarly, Fe-bound P declined from 44.9 mg kg^{-1} in CS_1 to 31.5 mg kg^{-1} in CS_4, reflecting greater microbial activity and rhizosphere redox reactions that facilitate P desorption from Fe oxides. This observation is consistent with Lei et al. (2025a, 2025b), who reported that microbial oxidation–reduction reactions enhance P release from Fe–P complexes through enzymatic and proton-mediated mechanisms in bioactive soils. The Ca-bound P, representing the stable or non-labile fraction, varied from 260.8 to 302.6 mg kg^{-1}, with CS_4 recording the lowest values. The decline of 13.8% in Ca-bound P under CS_4 compared with CS_1 suggests reduced P fixation and improved P availability due to increased organic acid production and root-induced chelation processes in diversified cropping arrangements. The reduction in reductant-soluble P (from 115.7 mg kg^{-1} in CS_1 to 102.1 mg kg^{-1} in CS_4) further indicates enhanced biological mobilization of occluded P under CS_4. Diversified intercropping, through increased root turnover and litter deposition, likely sustained microbial P cycling and minimized immobilization. Picone et al. (2025), Li G. et al. (2024), and Li X. et al. (2024) similarly emphasized that intercropping improves soil enzymatic activity, particularly phosphatase-mediated mineralization, thereby maintaining higher labile P pools. Importantly, organic P accumulation increased markedly under diversified systems, from 236.6 mg kg^{-1} in C_1 to 358.4 mg kg^{-1} in C_4, indicating a 51.4% enhancement. This rise may be attributed to greater microbial biomass turnover and organic matter incorporation via root residues and rhizodeposits. Microbe-mediated phosphorus management practices exerted a stronger influence on all measured P fractions, highlighting the efficiency of microbial inoculants and organic P amendments in reshaping soil P dynamics. The soluble and loosely bound P increased from 5.59 mg kg^{-1} in P_1 (control) to 8.28 mg kg^{-1} in P_5, representing a 48.1% rise, underscoring the superior solubilization capacity of phosphate-solubilizing bacteria (PSB) and organic amendments. The Al-bound P and Fe-bound P also increased significantly under biologically enriched treatments, reflecting improved transformation of insoluble P forms through organic acid production and enzymatic activity. The Fe-bound P increment from 33.9 mg kg^{-1} (P_1) to 43.8 mg kg^{-1} (P_3) indicates the role of microbial redox processes in liberating P from Fe–P complexes, corroborating the findings of Pradhan et al. (2025) and Lei et al. (2025a, 2025b). The Ca-bound P fraction, which reflects the residual and sparingly soluble pool, also increased under bio-based treatments (235.1 to 331.7 mg kg^{-1}), suggesting that long-term microbial activity and organic inputs facilitated a balanced P transformation cycle between labile and non-labile pools. This supports Babar et al. (2024), who noted that microbial exudates enhance P stabilization in both available and reserve pools, contributing to long-term fertility maintenance. Significant improvement in total inorganic P (542.9 mg kg^{-1}) and organic P (325.3 mg kg^{-1}) under P_3 and P_5 indicates the synergistic role of PSB, rock phosphate, and organic manures in P cycling. The increased organic P fraction signifies greater biological immobilization and slower mineralization, ensuring sustained P availability over time. This pattern corresponds with findings of Damathia et al. (2025) and Deeksha Gupta et al. (2024), who demonstrated that microbial inoculants enhance P turnover and facilitate its gradual conversion to plant-available forms.

4.5 Soil physico-chemical and biological properties

The results from the present study clearly demonstrated that both intercropping systems and microbe-mediated phosphorus management significantly influenced the soil's physico-chemical characteristics, nutrient availability, and biological activity under the *wheat + mustard* intercropping system. However, their interaction effect remained non-significant, suggesting that both factors independently contributed to soil quality improvement rather than synergistically. The significant reduction in soil bulk density (BD) from 1.53 g cm^{-3} in CS_1 to 1.45 g cm^{-3} in CS_4 highlights the beneficial role of diversified intercropping in enhancing soil aggregation and porosity. Such improvements are often attributed to increased root proliferation, greater organic residue input, and enhanced microbial activity (Bhattacharyya et al., 2015; Lal, 2020). Root exudates and microbial polysaccharides act as binding agents, reducing soil compaction and improving structure (Six et al., 2004). The observed 13.9% increase in organic carbon (OC) under CS_4 further substantiates this, reflecting enhanced carbon inputs through root biomass and residue incorporation. Similar observations were made by Saikia et al. (2026), who reported improved soil OC under cereal–legume intercropping due to higher biomass return and rhizodeposition. The minor decline in soil pH under CS_4 (from 8.30 to 8.08) may be attributed to increased microbial respiration and organic acid production, which tend to slightly acidify the rhizosphere (Zhao et al., 2022). Although the change was statistically non-significant, this trend aligns with reports indicating that diversified cropping systems can moderate alkaline soil reactions through organic matter decomposition (Singh et al., 2020). Improvement in macronutrient availability (N, P, and K) under the CS_4 system than C_1 indicates enhanced nutrient cycling efficiency under intercropping. Enhanced biological nitrogen fixation, greater rhizosphere microbial activity, and efficient nutrient uptake by component crops likely contributed to these gains (Lithourgidis et al., 2011; Wang et al., 2020). Similarly, higher micronutrient availability (Fe, Mn, Zn) under CS_4 may be associated with root-induced changes in soil redox conditions and organic acid secretion, which increase metal solubility (Timsina and Connor, 2021). Soil biological properties also exhibited pronounced improvement under the diversified system. The increase in dehydrogenase activity (DHA) from 39.1 to 53.6 µg TPF g^{-1} soil h^{-1} and alkaline phosphatase from 243 to 265 µg PNP g^{-1} soil h^{-1} demonstrates greater microbial metabolic activity and phosphorus turnover (Bandick and Dick, 1999). Likewise, increases in soil microbial biomass carbon (SMBC) and protease activity indicate enhanced microbial proliferation and organic N mineralization potential. These results corroborate earlier findings by Singh B. et al. (2019), Singh M. et al. (2019), and Ali et al. (2025a), who noted that intercropping fosters microbial diversity and enzyme activity due to diverse root exudates and niche complementarity. Parallel trends were observed under microbe-mediated phosphorus management. The significant reduction in bulk density (1.54 to 1.45 g cm^{-3}) and the 22% rise in organic carbon content (0.41 to 0.50%) under biologically enriched treatments such as P_5 reflect improved soil aggregation and organic matter buildup, driven by enhanced microbial colonization and root–microbe interactions (Singh et al., 2023; Ali et al., 2025b). The decline in soil pH (from 8.30 to 7.75) can be ascribed to organic and microbial acid production during rock phosphate solubilization and organic matter decomposition, which are known to increase phosphorus availability in calcareous soils (Rashid et al., 2016). The substantial improvement in available N (8.1%), P (48.4%), and K (7.9%) under P_5 indicates that the integration of phosphate-solubilizing bacteria (PSB) with organic phosphorus sources effectively enhanced nutrient mobilization and mineralization. PSB release organic acids, phosphatases, and chelating compounds that convert insoluble phosphates into plant-available forms (Rodríguez and Fraga, 1999; Khan et al., 2022). This microbial synergy not only enhances phosphorus solubility but also supports better nitrogen and potassium dynamics through increased microbial turnover. Similarly, the increases in micronutrient availability (Fe, Mn, Zn) under P_5 could be due to enhanced chelation and solubilization of these elements by organic acids and microbial metabolites (Kumar et al., 2021). The marked rise in DHA (54.1%), alkaline phosphatase (18.6%), SMBC, and protease activity clearly indicates that biologically enriched treatments stimulate microbial growth and enzymatic functions, which are central to nutrient cycling and soil fertility (Bünemann et al., 2018). The broader understanding that biologically intensive and integrated soil fertility management practices promote long-term soil health, resource-use efficiency, and agroecosystem sustainability (Tittonell, 2020).

5 Conclusion

The results of the study clearly demonstrate that both intercropping systems and microbe-mediated phosphorus management practices played a pivotal role in enhancing productivity, profitability, energy efficiency, and soil health in the wheat + mustard intercropping system under Inceptisols. Among intercropping arrangements, the CS_4 (wheat + mustard; 5:2) system consistently outperformed others by recording the highest mustard equivalent yield (MEY), wheat equivalent yield (WEY), economic returns, and soil biological activity, indicating superior resource-use efficiency and enhanced rhizosphere functioning. Similarly, microbe-mediated phosphorus treatments, particularly P_5 (75% RDP + PROM + PSB), significantly improved crop productivity, profitability, and energy output while reducing specific energy requirements, demonstrating the advantage of integrating organic and biological P sources with mineral fertilizers. The substantial improvements in soil phosphorus fractions, organic carbon, enzymatic activity, and microbial biomass under biologically enriched treatments highlight enhanced nutrient cycling and soil fertility buildup. Overall, the combined use of diversified intercropping systems and biologically mediated phosphorus management proved to be a sustainable strategy for improving crop performance, economic viability, and soil health while aligning with climate-smart agriculture and long-term sustainability goals. The findings suggest that CS_4 intercropping and P_5 nutrient management offer a robust pathway for resilient and efficient agricultural production in phosphorus-deficient Inceptisols.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

ShK: Data curation, Methodology, Validation, Writing – original draft, Writing – review & editing. YS: Conceptualization, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing. AD: Conceptualization, Methodology, Project administration, Resources, Supervision, Writing – review & editing. AmK: Data curation, Formal analysis, Writing – original draft, Writing – review & editing. SP: Investigation, Writing – original draft, Writing – review & editing. AvK: Formal analysis, Investigation, Methodology, Visualization, Writing – review & editing. DK: Formal analysis, Software, Visualization, Writing – review & editing. PD: Data curation, Methodology, Writing – original draft. SA: Formal analysis, Visualization, Writing – review & editing. PC: Investigation, Methodology, Writing – review & editing. AY: Visualization, Writing – review & editing. RD: Methodology, Writing – review & editing. SaK: Methodology, Visualization, Writing – original draft, Writing – review & editing. MH: Visualization, Writing – original draft, Writing – review & editing.

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