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Assessing integrated phosphorus management practices on crop performance and soil–plant phosphorus dynamics under pearl millet–chickpea system in alkaline *Fluvisol*

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Integrated phosphorus (P) management encompassing both conventional and organic sources is a sustainable option to save synthetic fertilizers without compromising crop productivity. Thus, a three 3-year field (2019–2021) experiment has been conducted to assess the impact of six integrated P-management modules on crop productivity and soil–plant P dynamics under pearl millet–chickpea system in the alkaline *Fluvisol* of Kanpur. The results showed productivity of both the crops increased over the years irrespective of treatments and highest chickpea equivalent pearl millet yield was recorded in 100% recommended dose of P (3.90 t ha^{-1}). Nitrate reductase (61 and 26% in pearl millet and chickpea, respectively) and total chlorophyll had significant jump in 60% recommended dose of P + farm yard manure (5 t ha^{-1}) over control. Soluble P fraction surged by 45% (pearl millet) and 18% (chickpea) in 60% recommended dose of P +crop residue (50%)+ P solubilising bacteria over control with efficient utilization of non-labile inorganic P fractions in both the crops. Higher physiological and internal P use efficiency in control plot indicates efficient use of above ground P under deficiency in both the crops. Correlation study showed grain yield was not significantly interlinked with soil inorganic P fractions in both the crops. Improved physio-chemical condition of soil along continual nutrient and labile carbon availability lead to significant leap in dehydrogenase (27% in pearl millet and 17% in chickpea) and alkaline phosphatase (27% in pearl millet and 31% in chickpea) in 60% recommended dose of P +crop residue (50%)+ P solubilising bacteria over completely fertilized plots in the end of 3 years. In nutshell, it can be inferred that application of 60% recommended dose of P +crop residue (50%)+ P solubilising bacteria along could be an excellent alternative to conventional practices (100% recommended dose of P) certifying higher P-availability and P-use efficacy.

KEYWORDS

chickpea, nitrate reductase, poultry manure, physiological efficiency, soil P-fractions, productivity, uptake

1 Introduction

Pearl millet [*Pennisetum glaucum* (L.) R. Br.]–chickpea (*Cicer arietinum* L.) sequence is an important cropping system in the semi-arid tracts of India (Bana et al., 2023). In India, pearl millet grows in an area of ~7 Mha with production of 97.85 lakh tones and peculiar characters like resistance toward biotic stresses, minimum input requirement, early maturity with high yield, and adaptability to climatic anomalies making the same extremely suitable in the IGP [Ministry of Agriculture Farmers Welfare (MoAFW), 2023; Satyavathi et al., 2021]. In addition, nutritional attributes such as gluten free high protein (8–19%), with low fat (3–8%), richness in mineral nutrients (potassium, magnesium, iron and zinc), vitamins (niacin and thiamine), high fiber, essential amino acids, and polyunsaturated fatty acids (74%) rightly categorize pearl millet as '*nutri-cereal*' with countless health benefits (Satyavathi et al., 2021). As per input availability, several crops such as wheat, mustard, and sorghum can perfectly fit with pearl millet in cropping sequences, but combination with legumes such as chickpea might have been the best fit as it thrives perfectly in the residual soil moisture, restores soil fertility, and ensures profitability to the growers (Bana et al., 2023). Chickpea is the most popular pulse crop in India with an area and production of ~11 Mha and 13.75 Million tons, respectively [Ministry of Agriculture Farmers Welfare (MoAFW), 2023]. Like pearl millet, distinctive characters such as low carbon and water footprint with nominal greenhouse gas (GHG) emission, ability to sequester atmospheric nitrogen (N) through biological nitrogen fixation (BNF), adaptability in the problem soils and resilience toward climate change classify chickpea as a climate smart crop (Dutta et al., 2022). Chickpea grains are packed with proteins (18–22%), vitamins (A, B, C, and K), unsaturated fatty acids (omega-6 and omega-9), minerals (calcium, phosphorus, and micronutrients), dietary fiber (7.4–12.2%), and low fat (<4%) with positive pharmacological impacts on human health (Koul et al., 2022). Hence, based on the facts, pearl millet–chickpea system can be a potential alternative against intensive cereal based systems. Even so, the desired results from any system will not be achieved without balanced P-fertilization which was known as the 'king-pin' of Indian agriculture (Dey et al., 2017).

After N, the most important element for plant growth is phosphorus (P), involved in several biochemical activities such as root growth, energy transformation, seed production, synthesis of nucleic acid, translocation of photosynthates, and BNF (Mitran et al., 2018). However, reports suggest a large part (80%) of India is low or medium in available P and unable to cater P-demand to the crops (Dey et al., 2017). Furthermore, the critical limit for pearl millet in alluvial and black soil was 4.8 and 7.7 ppm, respectively, indicating the need of balanced P-fertilization for achieving targeted yield (Dey et al., 2017). In India, the demand for phosphate fertilizer is mostly contended through imported di-ammonium phosphate (DAP) (~53 lakh tons in 2022–23) posing enormous burden on economy (Open Government Data, 2024). So, sustainable efforts must be made to curtail the dependency on DAP and look for eco-friendly alternatives such as P-rich organic amendments for supplying the available P without compromising yield.

Over-reliance on synthetic fertilizers may not be a viable option for long run as it has major loop holes such as (i) exacerbating cost, (ii) environmental pollution due to unsystematic application, (iii) increasing gap between rate of application and anticipated production, (iv) meager domestic supply, (v) multi-nutrient deficiencies and depletion in soil fertility (Mahajan et al., 2008). While, on the other side integrated phosphorus management (IPsM) combining both synthetic and organic sources not only have minimal environmental pay-offs but also improve P-use efficiency (PUE) and system productivity (Mahajan et al., 2008). In soil, P availability strongly determined by soil constituents (sesquioxides, carbonates of Ca and Mg), clay minerology, pH, moisture, management practices and dynamics between soil P-pools (Hazra et al., 2021). Mengel et al. (2001), delineated soil P pools into four main fractions, namely, (1). sparingly soluble, (2). strongly adsorbed, (3). Occluded, and (4). organic. In the alkaline or calcareous soil, Ca-phosphate is the dominant fraction and changes into more non-labile (Ca_8-P or Ca_{10}-P) forms depending on soil Ca concentration and pH (Mengel et al., 2001). Majority of soil P is present as organic form, but underscoring the dynamic changes of inorganic P (Pi) is utmost important as it directly linked with plant availability (McLaughlin et al., 2011). Organic amendments such as poultry manure (PM), farm yard manure (FYM), and crop residue (CR) along phosphorus solubilising bacteria (PSB) have appreciable impact on Pi-fractions as decomposition of the organic amendments releases different acids which improve P-solubilisation, mobilization, and reduce P-fixation eventually improving PUE (Touhami et al., 2020). Inorganic P-fractions also influenced positively under IPsM as findings suggest significant increase in available P pools (soluble-P and Ca_2-P) under integrated practices in rice–wheat system (Dutta et al., 2024). In addition, plants under organically amended plots utilize Ca_{10}-P more efficiently than completely fertilized plots with lower amount of occluded P in the former than the later (Bhattacharyya et al., 2015; Liu et al., 2017). Therefore, it will be really interesting to see the dynamics of Pi-fractions under IPsM particularly in pearl millet–chickpea system. Optimistic impact of IPsM on growth attributes, productivity, available P, and microbial activity in crops such as rice (Ahmed et al., 2018), wheat (Ding et al., 2020), maize (Venkatesh et al., 2019), mustard (Kumawat et al., 2014), and legumes (Dotaniya et al., 2022) has been documented. So, in the present circumstances, it is highly pertinent to take our research studies beyond growth attributes and discover the complex interaction between grain yields with soil Pi-fractions as information about the complex interlink between grain yield and Pi-fractions was absent under pearl millet–chickpea system.

Therefore, a three 3-year field experiment was carried out encompassing different IPsM modules in pearl millet–chickpea system to assess the effect on growth attributes, soil vis-à-vis plant P availability, and interlink with crop productivity. The main hypotheses of this study were (i) integration of synthetics with organic amendment (IPsM) has optimistic impact on growth, productivity, and P availability, (ii) influence of IPsM would be more effective in bioavailable Pi fractions (soluble-P, Ca_2-P) than sole chemical fertilization, and (iii) grain yield do have strong linkage with Pi-fractions along with other growth attributes.

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2 Materials and methods

2.1 Description of the experimental site

A field experiment has been taken up for three 3 years (2019–2022) in the main research block (plot no. 10/5) of ICAR-Indian Institute of Pulses Research, Kanpur. Weather of the experimental site was typically hot summer with cool winters, and weather parameters during the experimental period are presented in Figure 1. Taxonomically, soil of the experimental area belongs to order '*Fluvisol*' (USDA-NRCS, 1999) with sandy loam texture and moderately alkaline pH (8.1). Soil was non-saline (EC: 0.25 ds m^{-1}), low in organic carbon (0.36%) (Walkley and Black, 1934), available K (211 kg ha^{-1}) (Jackson, 1973), and medium in available N (184.5 kg ha^{-1}) (Subbaiah and Asija, 1956) and available P (15.4 kg ha^{-1}) (Olsen, 1954).

2.2 Crop husbandry practices and treatment details

The experiment consists of a total of six treatments with four replications, and details are presented in Table 1. The experiment was set up in randomized block design, and size of every experimental plot was 8 m × 5.5 m. Pearl millet hybrid "MP 7288" was sown under flat beds with 45 cm (row) × 10 cm (plant) spacing in the first fortnight of July ever year. Similarly, chickpea *cv.* "IPC 11-112" was sown every year in the 3rd week of October in 30 cm × 10 cm spacing. Seed rate of pearl millet and chickpea was 3 and 75 kg ha^{-1}, respectively. After harvesting of pearl millet, plots were plowed, harrowed, and planked before sowing of chickpea. The recommended fertilizer dose of pear millet (N: P_2O_5: K_2O: 60:40:40 in kg ha^{-1}) and chickpea was (N: P_2O_5: K_2O: 20:60:40 in kg ha^{-1}) followed every year (in T_2). In both the crops based on respective treatment, the calculated dose of P (except T_1) and K was applied as basal, while in chickpea 100% of recommended dose of nitrogen (RDN) was applied as a starter dose. In case of pearl millet, the entire RDN was divided in two where 50% of RDN was applied as basal and rest amount was applied 30 days after sowing. Supplementation of N, P, and K in the crops was done through urea (N: 46%), DAP (18% N and 46% P_2O_5), and muriate of potash (MOP: 63% K_2O). In the respective IPsM plots, well-decomposed FYM (N: P: K: 0.55:0.3:0.55) (in T_3 at 5 tons ha^{-1}), PM (N: P: K: 2: 1.8:2.6) (in T_4 at 1 tons ha^{-1}), and CR (N: P: K: 0.50:0.25:1.2) (in T_5 and T_6) were applied 15 days prior to sowing of *kharif* crop (pearl millet) and mixed thoroughly. Wheat residue was collected from an ongoing experiment and applied based on 50% (3 t ha^{-1}) of the stover yield in T_5 and T_6 same as other organic manures in pearl millet. Before sowing, chickpea seeds were treated with *Rhizobium leguminosarum* (20 g Kg^{-1} of seed) and a subsection of chickpea and pearl millet seeds were treated with PSB (*Bacillus polymyxa* sp.) (for T_6) with same dose such as *Rhizobium* sp. Two manual weeding in both the crops were done 30 days and 60 days after sowing. No plant protection measures were taken in any crop, and both the crops were irrigated as per recommended package practices following check basin method.

2.3 Plant and soil sampling

In both the crops, three plants were sampled from two rows in every plots at full vegetative stage just before flowering for the estimation of growth attributes. Plot-wise harvesting of the pearl millet was done when the leaves became yellow and grains became hard. Manually, the cobs were separated from the stalk using a sickle, and yield was recorded on plot basis (tons ha^{-1}) after it attains physiological maturity (<14% moisture content). Chickpea was harvested when leaves started falling, stem became completely brown, and pods produce rattling sound. Similar to pearl millet, plot-wise harvesting was followed and before threshing harvested plants were sundried to achieve 10% moisture content. Chickpea equivalent pearl millet yield was calculated based on procedure by Nath et al. (2023), and minimum support price of the pearl millet and chickpea was obtained from Government of India (GOI, 2025). Plant samples of both the crops (grain and stover) from the respective plots were collected, cleaned, oven-dried (65°C), grinded, and packed in paper bags for determination of nutrient (N, P, and K) concentration.

Post-harvest soil samples from the individual plots (total 18 plots) were collected following standard soil sampling procedure for the analysis of inorganic P (Pi) fractions and microbial parameters. After collecting soil samples, any visible dirt or foreign material was removed. Then, the samples were air-dried, grounded, passed through 1 mm sieve, and packed in clean poly packets. The soil samples were divided into two halves as one section was kept in ambient condition for estimation of different Pi-fractions, while the rest portion was kept at refrigerator (4°C) for determining microbial parameters.

2.4 Estimation of growth attributes, nutrient utilization index, and P-use efficiency

Total along with Chlorophyll A, B, nitrate reductase (NR), and relative leaf water content (RLWC) was recorded in the peak vegetative stage in both the crops in every year. For chlorophyll A and B, 100 mg fresh leaf samples were collected and extracted using dimethyl sulfoxide (DMSO). The leaf samples were incubated in an oven for 2.30 h at 50°C, and the optical density (OD) of the supernatant was measured at 645 and 663 nm (Hiscox and Israelstam, 1979). The final calculation was done based on formula given by Arnon (1949) and expressed as mg per gram of fresh leaf. The formula for calculating chlorophyll A (Formula 1), chlorophyll B (Formula 2), and total content (Formula 3) was given underneath. For NR, 100 mg fresh plant samples were incubated with 3 ml of each phosphate buffer, potassium nitrate, and propanol at 30°C for 60 min. After incubation, 1 ml of each aliquot, sulphanilamide, and 0.025% N-(1-naphthyl)-ethylenediamine dihydrochloride (NEDD) and final OD was measured at 540 nm. The amount of NR can be calculated by multiplying OD with 406.8 and expressed in nano-mole NO_2^- g^{-1} of fresh weight h^{-1} (Cazetta and Villela, 2004).

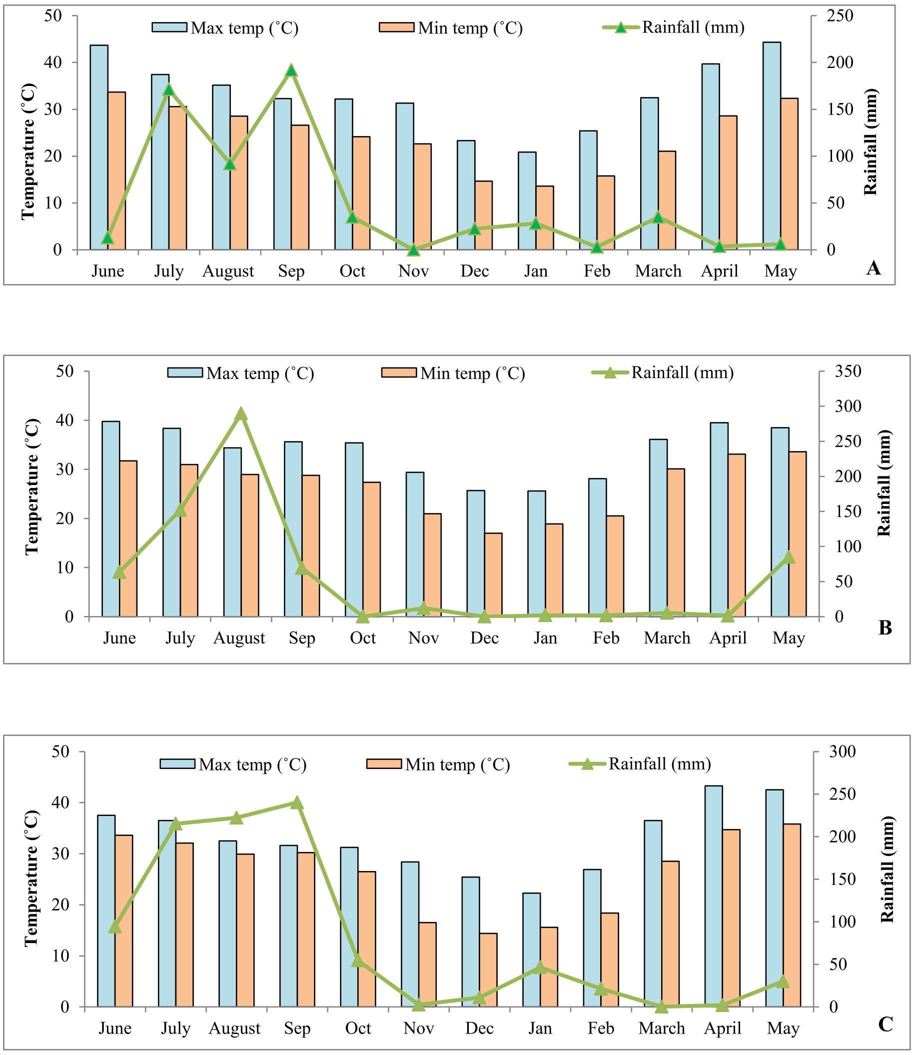

FIGURE 1
Weather events during the experimental period [2019–2020: **(A)**; 2020–21: **(B)**; 2021–22: **(C)**].

TABLE 1 **Treatment details followed in pearl millet–chickpea cropping system.**

Treatment	Details	Abbreviation	Pearl millet				Chickpea		
			OA*	N	P_2O_5	K_2O	N	P_2O_5	K_2O
T_1	100% recommended dose of nitrogen (N) and potassium (K) but no phosphorus (P)	$P_{Control}$	-	60	-	40	20	-	40
T_2	100% recommended dose of N, P and K	$P_{100\%}$	-	60	40	40	20	60	40
T_3	60% recommended dose of P with 100% N and K + 5 tons farm yard manure (FYM) ha^{-1}	$P_{60\%}$+FYM	FYM (5 t ha^{-1})	60	24	40	20	36	40
T_4	60% recommended dose of P with 100% N and K + 1 ton poultry (PM) ha^{-1}	$P_{60\%}$+PM	PM (1 t ha^{-1})	60	24	40	20	36	40
T_5	60% recommended dose of P but 100% N and K + 50% crop residue (CR)	$P_{60\%}$+CR	CR (3 t ha^{-1})	60	24	40	20	36	40
T_6	60% recommended dose of P but 100% N and K + 50% CR+ phosphate solubilising bacteria (PSB)	$P_{60\%}$+CR+B	CR (3 t ha^{-1}) + PSB	60	24	40	20	36	40

*OA, Organic amendments were applied in pearl millet only.

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$$\text{Chlorophyll A} = (12.21\ \text{OD}_{663} - 2.81\ \text{OD}_{645}) \times \text{V/W} \times 1{,}000 \quad (1)$$

$$\text{Chlorophyll B} = 20.13\ \text{OD}_{645} - 5.03\ \text{OD}_{663} \times \text{V/W} \times 1{,}000 \quad (2)$$

$$\text{Total chlorophyll} = 20.2\ \text{OD}_{645} + 8.02\ \text{OD}_{663} \times \text{V/W} \times 1{,}000 \quad (3)$$

V = Volume of extract; W = weight of sample

RLWC was calculated based on difference between fresh weight (W_1), turgid weight (W_2), and dry weight (W_3) (Formula 4) (Weatherley and Slatyer, 1957).

$$\text{RLWC}\ (\%) = (W_1 - W_3/W_2 - W_3) \times 100 \quad (4)$$

Total N, P, and K were analyzed in the plant samples (grain and straw) by micro-Kjeldahl, vanado-molybdic yellow color method, and flame photometer, respectively (Jackson, 1973). Nutrient uptake in the grain and straw was calculated by multiplying the content of individual nutrient (%) with respective yield (Singh et al., 2018). Nutrient utilization in both the crops has been expressed by nutrient harvest index (NHI) (Formula 5), physiological P-efficiency (PE_P) (Formula 6), and internal P-utilization efficiency (IUE_P) (Formula 7) (Singh et al., 2018). Agronomic P use efficiency (AgP_e) and agro-physiological P use efficiency ($AgPP_e$) have been calculated as per Formulas 8 and 9, respectively (Babu et al., 2013).

$$\text{NHI}(\%) = \text{Uptake in grain (kg ha}^{-1}\text{)/ Total uptake (kgha}^{-1}\text{)} \times 100 \quad (5)$$

$$PE_P\ (\text{kg kg}^{-1}) = \text{Total dry matter/Total P} - \text{uptake} \quad (6)$$

$$IUE_P\ (\text{kg kg}^{-1}) = \text{Grain yield/Total P} - \text{uptake} \quad (7)$$

$$AgP_e\ (\text{kg kg}^{-1}) = (\text{Grain yield in respective treatment} - \text{Grain Yield in control plots})/\text{Units of P-applied in the respective treatment} \quad (8)$$

$$AgPP_e\ (\text{kg kg}^{-1}) = (\text{Grain yield in respective treatment} - \text{Grain Yield in control plots})/(\text{Total uptake in respective treatment} - \text{Total uptake in control plots}) \quad (9)$$

2.5 Estimation of soil inorganic phosphorus fractions and microbial parameters

The original Pi-fractionation scheme was adapted from Kuo (1996) and further modified to include di and octa-Ca bound P-fractions (Smillie and Syers, 1972). In this scheme, total seven fractions can be extracted. These are 1. soluble-P (Sol-P), 2. di-calcium P (Ca_2-P), 3. octa-calcium P (Ca_8-P), 4. aluminum bound P (Al-P), 5. iron bound P (Fe-P), 6. occluded-P (Occl-P), and 7. deca-calcium P (Ca_{10}-P). In a 50 ml centrifuge tube, 0.5 g soil sample was taken and pre-caution has been taken to avoid soil loss in every step. Irrespective of fraction, in every

TABLE 2 Grain yield of pearl millet, chickpea, and chickpea equivalent yield of pearl millet under phosphorus management practices.

Treatment	Grain yield (t ha^{-1})						Stover yield (t ha^{-1})						Chickpea equivalent yield of pearl millet (CEY) (t ha^{-1})		
	Pearl millet			Chickpea			Pearl millet			Chickpea					
	2019–20	2020–21	2021–22	2019–20	2020–21	2021–22	2019–20	2020–21	2021–22	2019–20	2020–21	2021–22	2019–20	2020–21	2021–22
$P_{Control}$	3.12c[#]	3.50c	3.60b	1.35b	1.42d	1.84b	6.58b	7.23a	7.06a	2.11c	2.23d	2.59b	2.63b	2.90c	3.43c
$P_{100\%}$	3.49a	3.89a	4.09a	1.48b	1.55c	2.14a	6.93a	7.04a	7.34a	2.32b	2.42c	2.88a	2.92a	3.19ab	3.90a
$P_{60\%}$+FYM	3.27b	3.67b	3.88ab	1.59ab	1.69ab	2.00ab	6.78ab	7.09a	7.20a	2.49ab	2.64ab	2.81ab	2.93a	3.23ab	3.66abc
$P_{60\%}$+PM	3.30b	3.61bc	3.71ab	1.52ab	1.77a	2.04ab	6.52b	7.32a	7.68a	2.39ab	2.76a	2.87ab	2.88a	3.29a	3.59bc
$P_{60\%}$+CR	3.37ab	3.66b	3.74ab	1.54ab	1.61bc	2.04ab	7.01a	7.29a	7.38a	2.41ab	2.51bc	2.88a	2.92a	3.15b	3.65bc
$P_{60\%}$+CR+B	3.36ab	3.88a	3.91ab	1.61a	1.68ab	2.05a	6.79ab	7.37a	7.43a	2.53a	2.62ab	2.89a	2.99a	3.32a	3.73ab

[#] Values followed by different upper case letters (a–d) are significantly different between treatments at $p \leq 0.05$.

TABLE 3 Growth attributing properties of pear millet and chickpea as influenced by integrated phosphorus management (IPsM) practices (pooled data of three 3 years).

Crop	Treatment	NR (nM NO_2 $gFW^{-1}h^{-1}$)	Chl-A (mg g^{-1} leaf)	Chl-B (mg g^{-1} leaf)	Total chl (mg g^{-1} leaf)	RLWC (%)
Pearl millet	$P_{Control}$	25.07d[#]	2.28a	0.37d	2.65b	66.27b
	$P_{100\%}$	48.31c	2.56a	0.61b	3.16a	71.87ab
	$P_{60\%}$+FYM	64.58a	2.72a	0.63ab	3.35a	74.18ab
	$P_{60\%}$+PM	55.50bc	2.57a	0.69a	3.26a	77.73a
	$P_{60\%}$+CR	62.55ab	2.60a	0.57b	3.17a	80.36a
	$P_{60\%}$+CR+B	62.71ab	2.66a	0.50c	3.16a	78.47a
Chickpea	$P_{Control}$	53.42d	2.08b	0.40c	2.49b	61.90a
	$P_{100\%}$	61.83c	2.36a	0.49ab	2.85a	70.13a
	$P_{60\%}$+FYM	72.29a	2.36a	0.45bc	2.81a	68.55a
	$P_{60\%}$+PM	71.20ab	2.42a	0.51ab	2.93a	70.40a
	$P_{60\%}$+CR	67.92b	2.50a	0.48ab	2.98a	70.59a
	$P_{60\%}$+CR+B	69.70ab	2.40a	0.53a	2.93a	71.23a

NR, nitrate reductase; Chl, chlorophyll; RLWC, relative leaf water content.
[#]Values followed by different upper case letters (a–d) are significantly different between treatments at $p \leq 0.05$.

step, 25 ml extracting agent was added. Fraction-1 (sol-P) and Fraction-2 (Ca_2-P) were extracted using 1M ammonium chloride (NH_4Cl) and 0.25 M sodium bicarbonate ($NaHCO_3$) (pH 7.5), respectively. However, the respective shaking time for sol-P and Ca_2-P was 30 min and 60 min. Fraction-3 (Ca_8-P) also known as sparingly soluble P was extracted with ammonium acetate ($C_2H_7NO_2$) (shaking time: 60 min and pH 4.2) for 1 h, and further soil samples were washed with 95% methanol (25 ml) for 15 min. Although the fourth and fifth fraction (Al-P and Fe-P) are considered non-available but in extremely depleted conditions plant can use them. Ammonium fluoride (NH_4F-0.5M) (shaking time: 60 min and pH: 8.2) and 0.1 M sodium hydroxide (0.1 M NaOH) (shaking time: 17 h) were taken for extracting Al-P and Fe-P, respectively. Occluded-P (Fraction-6) was basically trapped inside soil constituents or bound on the outer surface of Al hydroxides. Most common method for extracting Occ-P is CDB (sodium citrate [$Na_3C_6H_5O_7.2H_2O$] + sodium dithionate [$Na_2S_2O_4$ + $NaHCO_3$]) method. The last fraction (Ca_{10}-P) which resembles similar chemical structure with as hydroxyl apatite [$Ca_{10}(PO_4)_6.(OH)_2$] was extracted with 0.25 M H_2SO_4 (shaking time: 60 min). After decanting the extracting agent, soil samples from fraction 4 to 7 were washed with 25 ml saturated sodium chloride solution and pooled. The P-concentration was measured by the blue color method (Murphy and Riley, 1962).

Chloroform fumigation followed by extraction using 0.5 M potassium sulfate (K_2SO_4) was followed for determination of soil microbial biomass C (SMBC) (Jenkinson and Powlson, 1976). Standard protocol by Eivazi and Tabatabai (1977) has been followed for quantifying alkaline phosphatase using p-nitrophenyl phosphate as a substrate. Klein et al. (1971) method was followed for the estimation of dehydrogenase activity in the samples using 2,3,5-tri-phenyl tetrazolium chloride (TTC) as a substrate.

2.6 Statistical analysis

Experimental datasets were subjected to Duncan's multiple range test (DMRT) (significance level: $p \leq 0.05$) to test the significant difference between the treatments using SPSS (version: 20) software (Gomez and Gomez, 1984). Pearson's correlation coefficient (r) was carried out using Microsoft Excel^{TM} 2010 with the Data Analysis Tool pack.

3 Results

3.1 Impact of IPsM on crop productivity and growth attributes

Irrespective of years, the pearl millet productivity was recorded significantly higher in plots under 100% recommended dose of P ($P_{100\%}$). In all the three 3 years (from 2019 to 2022), the productivity of pearl millet was >10% in $P_{100\%}$ over P $_{control}$, whereas integrated plots were all statistically at par specifically in the third year of experimentation. In case of chickpea, the results were more variable, and in general, the performance of $P_{60\%}$+CR+B was considerably better over others irrespective of years. In 2021–22, the productivity of chickpea was statistically at par in $P_{60\%}$+CR+B with $P_{100\%}$, and yield gain was ∼10% in $P_{60\%}$+CR+B over P-devoid plots ($P_{control}$) (Table 2). The significant difference in stover yield between the P-management practices was only recorded in the first year (2019–20) under pearl millet with highest recorded stover yield in $P_{60\%}$+CR (7.01 t ha^{-1}). In case of chickpea, stover yield increased over the year's and varies between 2.59 and 2.89 t ha^{-1} in the final year (2021–22). Highest stover yield in chickpea was recorded in $P_{60\%}$+CR+B in first (2.53 t ha^{-1}) and third year (2.89 t ha^{-1}), while plots under

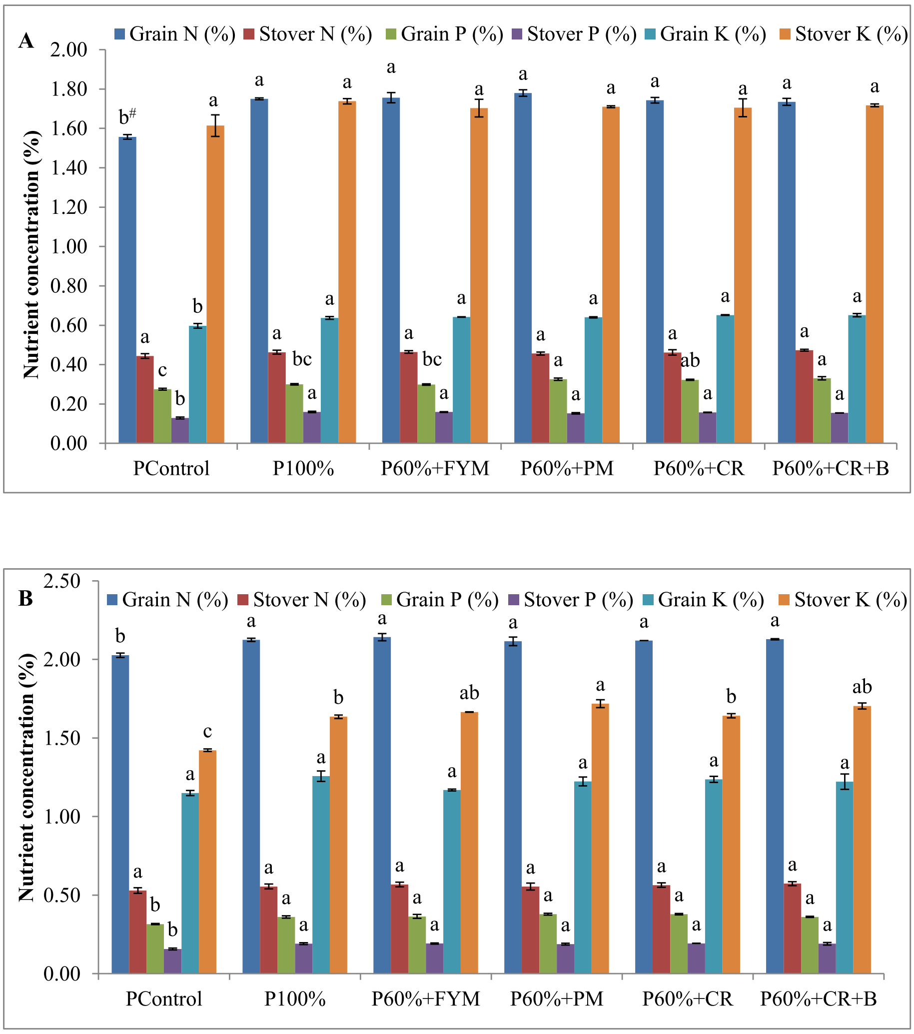

FIGURE 2
Nutrient concentration in grain and stover in pearl millet **(A)** and chickpea **(B)** (pooled data of three 3 years) under integrated nutrient management practices. #Values followed by different upper case letters (a–c) are significantly different between treatments at $p \leq 0.05$.

$P_{60\%}$+PM have registered maximum stover yield in 2020–21 (2.76 t ha^{-1}) (Table 2). In terms of chickpea equivalent yield of pearl millet (CEY), there was no surprising variation in the first year (2019–20), but in second (2020–21) and third year (2021–22), maximum value was recorded in $P_{60\%}$+CR+B (3.32 t ha^{-1}) and $P_{100\%}$ (3.90 t ha^{-1}), respectively The trend of CEY in 2021–22 was as follows: $P_{100\%} >$ $P_{60\%}$+CR+B > $P_{60\%}$+FYM > $P_{60\%}$+CR= $P_{60\%}$+PM> $P_{Control}$ ($p < 0.05$) (Table 2). Nitrate reductase (NR) content varies from 25.07 to 64.58 nM NO_2 gFW^{-1}h^{-1} in pearl millet and 53.42 to 72.29 nM NO_2 gFW^{-1}h^{-1} in chickpea, and in both the crop, crops under $P_{60\%}$+FYM recorded significantly higher NR over others. There was no significant variation of chlorophyll A content in pearl millet, but highest chlorophyll B (0.69 mg g^{-1} leaf) and total chlorophyll (3.35 mg g^{-1} leaf) content was found in $P_{60\%}$+PM and $P_{60\%}$+FYM, respectively. In chickpea, highest total chlorophyll was found in $P_{60\%}$+CR (2.98 mg g^{-1} leaf), although it was statistically with par with rest of treatment except $P_{Control}$. Values of RLWC vary from 66.27 to 80.36% in pearl millet and 61.92 to 71.23% in chickpea (Table 3).

3.2 Impact of IPsM on nutrient concentration, uptake, nutrient harvest index, and P-use efficiency

Pooled values of grain N-concentration vary between 1.56–1.78% and 2.05–2.17% in pearl millet and chickpea, respectively. There was no significant difference in stover N-concentration in any crop. In pearl millet, grain P content was 9% and 17% higher in $P_{60\%}$+CR+B (0.33%) as compared to $P_{100\%}$ and $P_{Control}$, respectively. Irrespective of year, grain P and stover P content ranged from 0.316% to 0.379% and 0.157% to 0.193% in chickpea, respectively. Grain-K in pearl millet and stover-K in chickpea was highest in $P_{60\%}$ + CR (0.651%) and $P_{60\%}$ + PM (1.72%), respectively (Figure 2). Over the years, the uptake of N, P, and K increased in both the crops. Highest N-uptake in pearl millet was recorded in $P_{100\%}$ in all the three 3 years (69.98 and 74.92 kg ha^{-1} in 2020–21 and 2021–22, respectively), but there was no statistical difference in stover N-uptake in any year. Nitrogen harvest index (NHI) did not differ markedly over the years, and

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TABLE 4 Nitrogen (N) uptake (kg ha^{-1}) and N-harvest index (NHI) (%) of pearl millet and chickpea under integrated phosphorus management practices.

Crop	Treatment	N uptake in grain (kg ha^{-1})			N uptake in stover (kg ha^{-1})			N-harvest index (NHI) (%)		
		2019–20	2020–21	2021–22	2019–20	2020–21	2021–22	2019–20	2020–21	2021–22
Pearl millet	$P_{Control}$	42.68b#	56.43b	59.56c	27.61a	32.49a	32.58a	60.72b	63.45b	64.62a
	$P_{100\%}$	55.53a	69.98a	74.92a	30.63a	32.74a	35.36a	64.45a	68.16a	67.94a
	$P_{60\%}$+FYM	54.87a	64.40ab	69.74b	28.68a	34.03a	35.19a	65.66a	65.39ab	66.46a
	$P_{60\%}$+PM	57.25a	64.21ab	67.57b	27.38a	34.46a	36.77a	67.67a	65.06b	64.79a
	$P_{60\%}$+CR	56.32a	64.78ab	68.58b	30.16a	34.28a	35.84a	65.17a	65.39ab	65.68a
	$P_{60\%}$+CR+B	55.90a	67.80a	69.56b	29.82a	35.62a	36.85a	65.22a	65.55ab	65.38a
Chickpea	$P_{Control}$	27.17b	29.12c	37.16b	6.48b	7.55a	10.60b	80.78a	79.43a	77.81a
	$P_{100\%}$	31.31a	32.85b	45.83a	7.65ab	8.54a	12.79a	80.39a	79.40a	78.15a
	$P_{60\%}$+FYM	33.05a	36.22a	43.93a	8.30ab	9.54a	12.31a	79.95a	79.17a	78.11a
	$P_{60\%}$+PM	32.18a	37.63a	42.90a	7.71ab	9.63a	12.49a	80.72a	79.65a	77.46a
	$P_{60\%}$+CR	32.24a	33.08b	44.93a	7.74ab	9.24a	12.46a	80.63a	78.17a	78.29a
	$P_{60\%}$+CR+B	34.07a	35.47ab	44.33a	8.73a	9.65a	12.39a	79.64a	78.62a	78.15a

#Values followed by different upper case letters (a–c) are significantly different between treatments at $p \leq 0.05$.

TABLE 5 Phosphorus (P) uptake (kg ha^{-1}) and P-harvest index (PHI) (%) of pearl millet and chickpea under integrated phosphorus management practices.

Crop	Treatment	P uptake in grain (kg ha^{-1})			P uptake in stover (kg ha^{-1})			P-harvest index (PHI) (%)		
		2019–20	2020–21	2021–22	2019–20	2020–21	2021–22	2019–20	2020–21	2021–22
Pearl millet	$P_{Control}$	8.19b#	9.43c	10.55c	8.03b	9.40b	9.50b	50.51ab	50.07a	52.65a
	$P_{100\%}$	10.02a	11.51ab	12.98ab	10.73a	11.32a	11.95a	48.25ab	50.48a	52.06a
	$P_{60\%}$+FYM	9.55ab	10.85bc	11.97b	10.65a	11.37a	11.52a	47.26b	48.85a	50.99a
	$P_{60\%}$+PM	10.22a	11.54ab	12.95ab	9.50a	11.10ab	12.38a	51.86a	51.00a	51.18a
	$P_{60\%}$+CR	10.35a	11.74ab	12.75ab	10.69a	11.26a	12.26a	49.20ab	51.04a	50.99a
	$P_{60\%}$+CR+B	10.76a	12.57a	13.55a	10.25a	11.39a	11.76a	51.17a	52.46a	53.53a
Chickpea	$P_{Control}$	4.21b	4.35c	6.06b	3.17b	2.23b	3.04b	57.05a	66.13a	66.64a
	$P_{100\%}$	5.14a	5.68b	7.86a	4.28a	2.96a	4.18a	54.58a	65.78a	65.31a
	$P_{60\%}$+FYM	5.48a	6.15ab	7.66a	4.41a	3.22a	4.14a	55.38a	65.67a	64.87a
	$P_{60\%}$+PM	5.33a	6.76a	8.25a	4.26a	3.25a	4.10a	55.66a	67.54a	66.80a
	$P_{60\%}$+CR	5.42a	6.13ab	8.17a	4.25a	3.13a	4.22a	56.06a	66.18a	65.97a
	$P_{60\%}$+CR+B	5.52a	6.13ab	7.71a	4.56a	3.19a	4.11a	54.84a	65.86a	65.24a

#Values followed by different upper case letters (a–c) are significantly different between treatments at $p \leq 0.05$.

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TABLE 6 Potassium (K) uptake (kg ha^{-1}) and K-harvest index (KHI) (%) of pearl millet and chickpea under phosphorus management practices.

Crop	Treatment	K uptake in grain (kg ha^{-1})			K uptake in stover (kg ha^{-1})			K-harvest index (KHI) (%)		
		2019–20	2020–21	2021–22	2019–20	2020–21	2021–22	2019–20	2020–21	2021–22
Pearl millet	$P_{Control}$	17.94b[#]	20.99c	25.93a	104.30a	117.74a	115.02a	14.68a	15.13a	16.17a
	$P_{100\%}$	21.22a	24.50ab	26.69a	115.75a	122.93a	131.83a	15.49a	16.62a	17.34a
	$P_{60\%}$+FYM	19.59a	22.98bc	26.45a	107.11a	125.61a	126.29a	15.48a	15.46a	17.68a
	$P_{60\%}$+PM	20.08a	22.52bc	26.24a	107.68a	125.03a	135.92a	15.75a	15.26a	15.82a
	$P_{60\%}$+CR	20.65a	23.80ab	26.58a	117.04a	123.69a	129.06a	15.01a	16.15a	16.74a
	$P_{60\%}$+CR+B	20.41a	25.16a	27.26a	110.42a	128.07a	132.97a	15.63a	16.46a	17.08a
Chickpea	$P_{Control}$	14.97b	15.80b	22.65b	28.63d	32.41c	37.71b	34.34a	32.80a	37.50a
	$P_{100\%}$	17.59ab	19.63a	28.15a	36.14c	40.04b	48.97a	32.73a	32.89a	36.51a
	$P_{60\%}$+FYM	17.48ab	19.59a	24.83ab	40.33ab	43.96ab	48.13a	30.22a	30.82a	34.05a
	$P_{60\%}$+PM	17.55ab	21.73a	26.31ab	39.14abc	47.40a	51.77a	30.93a	31.44a	33.72a
	$P_{60\%}$+CR	17.64ab	19.77a	27.19a	37.66bc	42.11ab	48.49a	31.93a	31.94a	35.90a
	$P_{60\%}$+CR+B	18.99a	20.55a	25.92ab	41.84a	44.07ab	51.32a	31.20a	31.81a	33.55a

[#] Values followed by different upper case letters (a–d) are significantly different between treatments at $p \leq 0.05$.

plots under 100% RDP were statistically at par with $P_{60\%}$+CR+B in every year ($p < 0.05$) in pearl millet (Table 4). N-uptake in chickpea grain and stover varies from 27.17 to 45.83 kg ha^{-1} and 6.48 to 12.79 kg ha^{-1} over the years, but NHI became non-significant irrespective of year ($p < 0.05$) (Table 4). In all the years, maximum P-uptake was recorded in $P_{60\%}$+CR+B with 4–8% elevation over conventional practice ($P_{100\%}$) in pearl millet. In chickpea, P-uptake varies from 4.21 to 8.25 kg ha^{-1} and plots under $P_{60\%}$+PM recorded 4% and 25% higher grain P-uptake over $P_{100\%}$ and $P_{Control}$, respectively. Phosphorus harvest index (PHI) did not differ between the treatments irrespective of year except in 2019–20 under pear millet where PHI increased significantly in $P_{60\%}$+CR+B (51.17%) over $P_{60\%}$+FYM (47.26%) and $P_{100\%}$ (48.25%) ($p < 0.05$) (Table 5). Similar to NHI, potassium harvest index (KHI) did not differ significantly between the treatments, while K-uptake in grain varies from 17.94 to 21.22 kg ha^{-1} and 20.99 to 25.16 kg ha^{-1} in 2019–20 and 2020–21, respectively. Grain K-uptake in chickpea was recorded highest in $P_{60\%}$+CR+B in 2019–20 (18.99 kg ha^{-1}) and 2020–21 (20.55 kg ha^{-1}) but not in 2021–22 ($P_{100\%}$ with 28.15 kg ha^{-1}) (Table 6). Irrespective of year and crop, highest physiological P-use efficiency (PE_P) was found in plots without P ($P_{control}$) (Table 7). As compared to $P_{100\%}$ and $P_{60\%}$+CR+B, respective increment in PEp values under control was 13–16% and 16–19% in pearl millet and chickpea, respectively. Internal P-utilization efficiency (IUE_P) was also following similar pattern like PEp (Table 7). Maximum noted agronomic P-use efficiency (AgPe) was 24.37 kg kg^{-1} in 2020–21 under $P_{60\%+CR+B}$ which was +39% over $P_{100\%}$, but in the next year both became statistically at par in pearl millet (Table 7). In chickpea, impact of organic amendments on AgPe was more prominent and it was surged by 16–70% in $P_{60\%}$+CR+B over $P_{100\%}$ within the period of study (2019–22) (Table 7). Agro-physiological P-use efficiency (AgPPe) was highest under conventional practice ($P_{100\%}$) in each year, and over the years (2019 to 2022), it has increased by 18.6% in pearl millet. In case of chickpea, AgPPe varies from 66.38 to 98.83 kg kg^{-1}, 62.54 to 100.34 kg kg^{-1}, and 57.56 to 96.68 kg kg^{-1} in 2019–20, 2020–21, and 2021–22, respectively (Table 7).

3.3 Impact of IPsM on Inorganic P (Pi) fractions and microbial parameters

Labile P pools consisting of soluble-P and Ca_2-P were recorded highest in $P_{60\%}$+CR (13.13 ppm) and $P_{60\%}$+PM (13 ppm), respectively, in pearl millet. Substantial impact of integrated dose with $P_{60\%}$+PM can be seen in labile P pools as sol-P (38%) and Ca_2-P (47%) increased significantly as compared to 100% RDP. Influence of IPsM was not really marked on non-labile P fractions such as Ca_8-P and occluded-P (Occ-P). Application of CR+ PSB with 60% RDP led to highest Fe-P (15.75 ppm) and Al-P (26.22 ppm) over control in pearl millet. A significant surge can be apprehended in $P_{60\%}$+CR+B over $P_{100\%}$ by 12% for Al-P and 32% for Fe-P, respectively. The most stable Pi-fraction, i.e., deca-calcium P (Ca_{10}-P), is as follows: $P_{Control}$ > $P_{100\%}$ > $P_{60\%}$+CR= $P_{60\%}$+PM> $P_{60\%}$+FYM > $P_{60\%}$+CR+B (Table 8). Microbial activity had a significant boost in integrated P-managed plots which can be visible from the experimental

TABLE 7 Physiological P-efficiency (PE_P) (kg kg^{-1}) and internal P-utilization efficiency (IUE_P) (kg kg^{-1}), agronomic P-use efficiency, and agro-physiological P-use efficiency of pearl millet and chickpea under phosphorus management practices.

Crop	Treatment	PE_P (kg kg^{-1})			IUE_P (kg kg^{-1})			Agronomic P-use efficiency (kg kg^{-1})			Agro-physiological P-use efficiency (kg kg^{-1})		
		2019–20	2020–21	2021–22	2019–20	2020–21	2021–22	2019–20	2020–21	2021–22	2019–20	2020–21	2021–22
Pearl millet	$P_{Control}$	599.02a[#]	571.06a	532.30a	192.41a	186.29a	179.61a	-	-	-	-	-	-
	$P_{100\%}$	502.99b	478.76b	458.80b	168.53b	170.43b	164.20b	14.55ab	14.79b	19.11a	82.95a	95.72a	102.73a
	$P_{60\%}$+FYM	497.55b	483.95b	471.44b	161.71b	165.07b	165.00b	9.61c	10.46c	17.88a	39.07c	51.72c	80.26b
	$P_{60\%}$+PM	498.71b	483.28b	450.28b	167.62b	159.50b	146.93c	11.82bc	6.50d	7.46b	52.29b	26.65e	21.74d
	$P_{60\%}$+CR	494.00b	476.07b	444.69b	160.37b	159.22b	149.51c	16.40a	10.06cd	8.99b	52.43b	38.99d	27.15d
	$P_{60\%}$+CR+B	483.16b	469.60b	447.81b	159.83b	162.14b	154.41bc	15.45ab	24.37a	19.94a	50.09b	74.86b	58.15c
Chickpea	$P_{Control}$	470.06a	555.00a	488.50a	183.13a	216.45a	202.73a	-	-	-	-	-	-
	$P_{100\%}$	404.63b	461.58b	416.76b	157.65b	180.02b	177.34b	5.24c	4.87d	11.35ab	66.38c	62.54d	96.68a
	$P_{60\%}$+FYM	412.91b	464.11b	408.24b	160.87b	181.00b	169.42b	15.44a	16.93b	9.97b	96.51a	99.22a	57.56c
	$P_{60\%}$+PM	409.30b	452.88b	398.22b	159.46b	176.62b	165.26b	11.31b	21.89a	12.60ab	80.45b	100.34a	60.29c
	$P_{60\%}$+CR	407.76b	444.78b	397.03b	158.86b	173.46b	164.77b	12.02b	11.71c	12.96ab	80.23b	68.16c	60.13c
	$P_{60\%}$+CR+B	411.78b	462.28b	418.21b	160.43b	180.29b	173.56b	17.07a	16.24b	13.56a	98.83a	94.26b	74.36b

[#] Values followed by different upper case letters (a–e) are significantly different between treatments at $p \leq 0.05$.

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findings in pearl millet. The maximum activity of soil microbial biomass carbon (SMBC) and dehydrogenase (DHA) could be recorded in $P_{60\%}$+CR+B with 15% and 28% surge over $P_{100\%}$. Alkaline phosphatase is a key enzyme which solubilise non-labile P decreased by 31% and 43% in $P_{100\%}$ and $P_{Control}$, respectively, over $P_{60\%}$+CR+B under pearl millet (Figure 3A).

There was no significant variation among the treatments in soluble P content. The range of Ca_2-P varied from 17.95 ppm ($P_{60\%}$+CR) to 33.83 ppm ($P_{60\%}$+PM) in chickpea. In addition, irrespective of integrated management strategies, all treatments except $P_{Control}$ became non-significant with respect to Ca_8-P content ($p < 0.05$). A slight variation can be observed as Al-P content was maximum in $P_{100\%}$ by 27% over $P_{60\%}$+CR (16.44 ppm), but a complete opposite pattern can be found in Fe-P where both the $P_{60\%}$+PM (18.25 ppm) and $P_{60\%}$+CR (17.6 ppm) were statistically at par and Fe-P was recorded 24 and 27% higher over $P_{100\%}$ in chickpea. Occluded-P content ranged from 15.50 to 23.94 ppm, and plots under PM, CR, and CR + PSB were statistically at par. Similar to pearl millet, control plots ($P_{Control}$) had the highest Ca_{10}-P and amount decreased in the integrated P-managed plots in chickpea (Table 8). Plots under $P_{60\%}$+PM quantified highest SMBC (180.35 μg g^{-1} of soil) but at par with $P_{60\%}$+FYM and significantly higher over $P_{100\%}$ (+26%) and $P_{Control}$ (+55%) in chickpea ($p <$ 0.05). Both the enzymes viz. DHA and alkaline phosphatase were highest in $P_{60\%}$+CR+B but at par with $P_{60\%}$+CR. As compared to conventional practices ($P_{100\%}$), the surge in DHA and alkaline phosphatase activity in $P_{60\%}$+CR+B was 16 and 27%, respectively, under chickpea (Figure 3B).

3.4 Correlation of grain yield with Pi fractions

In pearl millet, there was no significant relationship between grain yield and inorganic (Pi) fractions but in chickpea grain yield was negatively correlated with Ca_8-P (−0.899 at $p < 0.05$) and Ca_{10}-P (−0.827 at $p < 0.05$) (Tables 9, 10). In pearl millet, soluble P was strongly interrelated with Ca_2-P (0.864 at $p < 0.05$) and Ca_8-P (0.953 at $p < 0.01$) and negatively with Ca_{10}-P (−0.904 at $p < 0.05$) (Table 9). The negative correlation between soluble P and Occluded-P (−0.919 at p < 0.01) and Ca_{10}-P (−0.852 at $p < 0.05$) could be visible in chickpea (Table 10).

4 Discussion

4.1 Impact of IPsM on growth attributes, nutrient concentration, and yield

The positive sides of IPsM can be reflected in different growth attributes such as pigment (chlorophyll A, B, and total) level and NR activity in both the crops. Applications of organic amendments such as FYM, PM, and CR had positively modified the physio-chemical parameters in soil and improved the availability of nutrients resulting better plant growth similar to conventional practices (Thumar et al., 2016). Synchronized nutrient availability in the integrated plots promoted higher cellular activity such as cell division and expansion ensuing better plant growth (Hashim

TABLE 8 Dynamics of soil P-fraction (in ppm) in pearl millet and chickpea under phosphorus management practices in 0–15 cm.

Treatment	Sol-P		Ca_2-P		Ca_8-P		Al-P		Fe-P		Occ-P		Ca_{10}-P	
	PMi*	C**	PMi	C	PMi	C	PMi	C	PMi	C	PMi	C	PMi	C
$P_{Control}$	7.13c#	11.63a	6.90c	21.24d	29.88b	48.93a	23.13ab	19.51abc	10.70cd	15.08ab	26.25ab	19.50b	53.25a	52.08a
$P_{100\%}$	9.63b	14.38a	9.00bc	20.76cd	34.90ab	39.13b	22.37ab	22.46a	13.20abc	13.29b	25.625b	15.50c	50.92ab	44.50b
$P_{60\%}$ + FYM	11.75ab	11.15a	10.13abc	25.54bc	37.50a	40.18b	25.92ab	21.06ab	9.91d	16.57ab	29.625ab	23.94a	46.25bc	48.44ab
$P_{60\%}$ + PM	11.50ab	14.31a	13.00a	30.83a	35.00ab	33.97b	22.25b	16.80bc	12.42bcd	18.25a	29.05ab	16.90bc	47.37abc	45.63ab
$P_{60\%}$ + CR	13.13a	13.90a	11.25ab	17.95e	40.90a	36.22b	22.56ab	16.44c	13.52ab	17.6a	29.915a	17.30bc	47.5abc	46.53ab
$P_{60\%}$+CR + B	13.00a	14.24a	12.90ab	26.19b	41.25a	38.43b	26.22a	19.51abc	15.75a	16.27ab	28ab	16.82bc	43.25c	44.44b

Values followed by different upper case letters (a–e) are significantly different between treatments at $p \leq 0.05$.
*PMi—pearl millet.
**C—chickpea.

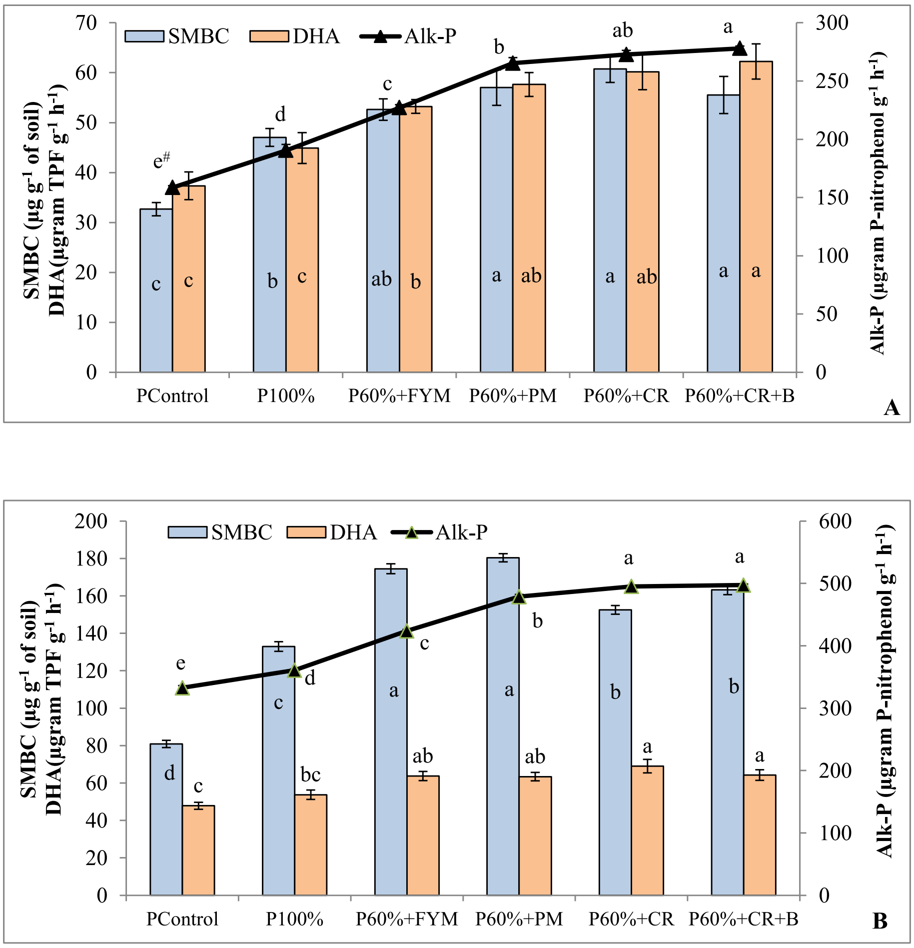

FIGURE 3
Dynamics of microbial parameters in pearl millet **(A)** and chickpea **(B)** under integrated phosphorus management system. SMBC, soil microbial biomass carbon; DHA, dehydrogenase; Alk-P, alkaline phosphatase. #Values followed by different upper case letters (a–e) are significantly different between treatments at $p \leq 0.05$.

et al., 2015). Nitrate reductase (NR) is a crucial enzyme for BNF particularly in the peak vegetative stage of legumes (chickpea) and the activity reduces with time (Banerjee et al., 2024). Higher NR activity in the integrated plots was due to balanced supply of N and molybdenum (Mo) from the organic sources fostering physiological activities and production of amino compounds with efficient N-assimilation (Márquez-Quiroz et al., 2014). As noted in result, the impact of IPsM on chlorophyll content (A, B, and total) was really apparent, and previous study by Ansari and Mahmood (2017) also cited similar findings in pigeonpea. Apart from major nutrients, especially steady K availability under IPsM upscaled photosynthetic activity, root growth and stomatal regulation resulting in higher chlorophyll content over sole chemically fertilized plots (Dodd, 2003). Favorable soil microenvironment with pronounced microbial activity, water availability, and continuous access of essential nutrients uplifted the growth attributes in both the crops under integrated plots over control or conventional practices (Varatharajan et al., 2022). Although the impact of IPsM on RLWC was not significant in chickpea but, in pearl millet application of organic amendments improves the water holding capacity of the soil ensuring optimum water availability as opposed to control plots (Saha and Ghosh, 2013). In addition, under integrated plots, availability of P along with better soil physical health accentuates root growth leading to greater water availability from the subsurface depths in pearl millet (Kumar et al., 2006). In pearl millet, discernible result regarding N content under grain and stover was missing; however, a slight edge in grain N-content can be detected in 100% RDP as deciphered in earlier studies by Hassan et al. (2018) and Sheoran et al. (2024). Combining application of synthetic fertilizers (DAP and MOP) along with organic amendments not only saves fertilizers from leaching and fixation but also maintains an equilibrium in the soil solution which can be reflected in higher grain P (in chickpea) and stover K (in pearl millet) (Murphy, 2015). In addition, formation of proliferated dense roots, better soil health, and physiological activity in plants under IPsM enhanced the nutrient uptake (Dhaliwal et al., 2023). In case of chickpea, previous results from Dewangan et al. (2017) and Dotaniya et al. (2022) logged beneficial impact of integrated P-management on nutrient concentration in above ground plant parts. Both grain and stover yield has been recorded maximum in conventional practice (100% RDP) as pearl millet is an input dependent fertilizer

TABLE 9 Correlation analysis of grain yield of pearl millet with soil inorganic phosphorus (Pi)-fractions under integrated phosphorus management system.

	Grain yield	Soil inorganic P-fractions						
		Soluble P	Ca_2-P	Ca_8-P	Al-P	Fe-P	Occ-P	Ca_{10}-P
Soluble P	0.364	1						
Ca_2-P	0.272	0.864*	1					
Ca_8-P	0.482	0.953**	0.728	1				
Al-P	0.150	0.363	0.221	0.441	1			
Fe-P	0.577	0.527	0.594	0.628	0.077	1		
Occ-P	−0.232	0.772	0.628	0.621	0.247	−0.048	1	
Ca_{10}-P	−0.336	−0.904*	−0.862*	−0.862*	−0.659	−0.508	−0.652	1

Ca_2-P, Di-calcium P; Ca_8-P, Octa-calcium P; Al-P, Aluminum bound P; Fe-P, Iron bound P; Occ-P, Occluded P; Ca_{10}-P, Deca-calcium P.
*Correlation is significant at the 0.05 level (two-tailed).
**Correlation is significant at the 0.01 level (two-tailed).

responsive crop (Sher et al., 2023). Slower nutrient release from the organic amendments along with sub-optimal P-dose under IPsM plots might have hampered pearl millet growth in the early stage which could be reflected in productivity (Rani et al., 2022). However, the yield benefits of IPsM could be apparent under $P_{60\%}$ + CR + PSB in chickpea as stated by Tanwar et al. (2010) in Rajasthan and Thakur et al. (2023) in Madhya Pradesh, India. Multiple advantages of crop residue on soil chemical properties (high CEC, optimum pH, essential nutrients), physical properties (high water holding capacity, low bulk density), and biological properties benefited overall crop performance as presented in the experimental findings (Jat et al., 2018). Development of new tissue, positive sides on morphological and physiological traits, and better crop health led to higher chickpea productivity in integrated plots over control or farmers practices (Thakur et al., 2023). In addition, the positive impact on grain yield particularly in chickpea has also been justified by higher P concentration and leaf chlorophyll content under IPsM (Li et al., 2019; Paramesh et al., 2020).

4.2 Impact of IPsM on nutrient utilization, uptake, and P-use efficiency

As presented in the experimental datasets, IPsM had non-significant impact on NHI as mentioned in previous research studies by Varatharajan et al. (2019) in pigeonpea and Gupta et al. (2020) in wheat. Higher N and P uptake in grain as opposed to total uptake caused non-significant change in NHI which could be further explained by law of diminishing return (Gupta et al., 2020). Fulfillment of nutrient demand without manure addition in both the crops might have caused higher PE_P in plots with no-P, as opposed to P-added plots (Kumar et al., 2017). Earlier study in pigeonpea and sunflower by Babu et al. (2013) and wheat by Randhawa et al. (2021) matches with present finding as increasing nutrient dose had inversely proportional relation with PE_P. Similar to PE_P, the results suggest decreasing IUE_P with increasing P-dose was due to trivial impact on crop biomass even on change in P-uptake leading to P-build up in tissue (Venkatesh et al., 2019). Moreover, higher PE_P in control plots against P-fertilized plots also indicates inherent ability of crops to utilize P-present in above ground parts more economically under P-deficient conditions (Venkatesh et al., 2019). As discussed in the earlier section, concentration of different nutrients in grain and stover has been tuned up positively under integrated plots which were reflected in uptake also. However, in pearl millet, the striking difference between IPsM plots (T_3-T_6) and conventional practice (T_2) on nutrient uptake was missing due to significant jump in productivity in the former plots than the later. The influence of organic amendments PM, FYM, or CR was more apparent in post-rainy season crop (chickpea). Irrespective of crop, higher nutrient uptake were due to: (i). supply of micronutrients from decomposing organic amendments (ii). organic acid mediated solubilisation of native/locked nutrients (iii). averting nutrient loss by chelation (iv). altered root CEC and rhizospheric modifications (Jakhar et al., 2018; Kumar et al., 2021). Agro-physiological P-use efficiency ($AgPP_e$) decreased with increasing synthetic fertilizer supplementation, but agronomic P-use efficiency (AgP_e) followed completely opposite trend. Similar to PE_p, integrated P-application was able to meet the crop demand with lower $AgPP_e$ over 100% RDP (Kumar et al., 2017). Interestingly, application of crop residue ($P_{60\%}$+CR) alone immobilizes bio-available P for the crops resulting significantly lower $AgPP_e$, but the negative impact gets canceled with co-application with PSB, i.e., T_6 (60% RDP+CR+PSB). Continuous P supply in the integrated plots by synthetic fertilizers in the early stage and later on by the decomposing crop residue improved growth, yield attributes, and productivity leading to higher AgPe as compared to fully fertilized plots as noted in other crops such as wheat (Randhawa et al., 2021), rice (Kaur et al., 2023), and lentil (Kumar et al., 2022).

4.3 Impact of IPsM on soil inorganic P (Pi) fractions, microbial activity, and correlation of Pi-fractions with grain yield

Application of organic amendments has consequential impact on labile P-pools (sol-P and Ca_2-P). Crop residues upon

TABLE 10 Correlation analysis of grain yield of chickpea with soil inorganic phosphorus (Pi)-fractions under integrated phosphorus management system.

	Grain yield	Soil inorganic P-fractions						
		Soluble P	Ca_2-P	Ca_8-P	Al-P	Fe-P	Occ-P	Ca_{10}-P
Soluble P	0.504	1						
Ca_2-P	0.491	0.091	1					
Ca_8-P	−0.899*	−0.692	−0.369	1				
Al-P	−0.021	−0.227	−0.107	0.314	1			
Fe-P	0.136	−0.272	0.581	−0.211	−0.688	1		
Occ-P	−0.126	−0.919**	0.109	0.369	0.198	0.413	1	
Ca_{10}-P	−0.827*	−0.852*	−0.234	0.821*	−0.088	0.307	0.616	1

Ca_2-P, Di-calcium P; Ca_8-P, Octa-calcium P; Al-P, Aluminum bound P; Fe-P, Iron bound P; Occ-P, Occluded P; Ca_{10}-P, Deca-calcium P.
*Correlation is significant at the 0.05 level (two-tailed).
**Correlation is significant at the 0.01 level (two-tailed).

decomposition produce different organic acids (humic acid and fulvic acid) which compete for the same sorption site such as P, making it available for the crops (Mitran et al., 2016). Furthermore, the decomposition and solubilisation of P enhanced significantly upon PSB application. Literature did highlight the direct and indirect impact of organic manures and compost on transforming non-labile Pi into labile Pi. These present experimental records were in line with meta-analysis study by Wei et al. (2022) which showed performance of poultry manure was highly efficient in promoting Pi-fractions among others. Blocking the adsorption sites, acid dissolution of complex non-labile fraction, promoting microbial activity, organic C mediated organic P (Po) transformation, and rhizospheric P-transformation are some of the important mechanism behind organic amendment mediated Pi-transformation (Qin et al., 2020). As pearl millet is an input-intensive crop, therefore, continuous cropping lead to depletion of Ca_8-P in the control plots which could be evident from the experimental findings, while recorded spike in Ca_8-P content in the control plot under chickpea was due to low enzymatic activity under the same which was evident in this experimental result too. Apart from organic acid-mediated P-transformation, productions of carbon-di-oxide (CO_2) during decomposition of residue or manures augment the levels of Fe-P and Al-P in soil facilitating higher P-availability to the standing crop (Bhattacharyya et al., 2005). Similarly, decomposed products of manures such as organic acids prevent re-precipitation of soluble P fractions onto amorphous sesquioxides contributing higher plant available P (Ghosh et al., 2021). Similar to earlier study by Bhattacharyya et al. (2015) and Dutta et al. (2024), the improvement in occluded-P in the integrated plots ($P_{60\%}$+CR: pearl millet and in $P_{60\%}$+FYM: chickpea) was resultant of dissolution of trapped P via acidifying agents or protecting solubilised from further entrapment. Low biomass development in the plants under control plots leads to low P-uptake causing build-up of Ca_{10}-P was recorded in control plots under both the crops.

Affirmative impact of organic amendments on microbial parameters (SMBC, DHA, and alkaline phosphatase) was quite evident in this study peculiarly in IPsM plots. SMBC is considered to be an active pool of SOC largely affected by the management-induced changes. Addition of manures (PM) and crop residue increased labile C and nutrient level in the soil resulting exponential increase in SMBC (Rajput et al., 2019; Padbhushan et al., 2021). In addition, application of manures in company with synthetics improves the overall soil quality revamping overall microbial growth and biomass (Dutta et al., 2024). In line with SMBC, rapid availability of mineralisable materials from the decaying residues, intra- and extracellular enzyme content, and metabolic growth could have resulted in remarkable surge in DHA content over conventional plots in both the crops (Nath et al., 2015; Patra et al., 2020). The significant jump in alkaline phosphatase activity in the under integrated plots (T_5 and T_6 majorly) was caused due to the following reasons: 1. adequate availability of food (labile C) from the decaying residues promoted hydrolysis of organic P moieties (esters of phosphoric acid) leads to higher phosphatase activity and 2. continuous availability of P from the amendments fuel up microbial activity conjointly higher phosphatase activity in soil (Kharche et al., 2013; Li et al., 2021; Kumari et al., 2024).

Strong interlinkage among sol-P, Ca_2-P, and Ca_8-P indicates dynamic inter-conversion between the fractions particularly under cereal–legume system (Shen et al., 2004). Ghosh et al. (2021) through long-term study showed strong correlation between soil Pi fractions (saloid bound P, Al-P, occ-P) with maize grain yield but absent in this short time scale of experiment. The results showed significant negative interaction with grain yield with Ca_{10}-P which was quite obvious as the former constitute the most stable and unavailable form of inorganic P.

5 Conclusion

Inclusion of organic amendments such as PM, FYM, and CR along with sub-optimal synthetic fertilizer (DAP) has influential impact on growth attributes, nutrient utilization, P-use efficiency, Pi-fractions, and lastly on yield under pearl millet–chickpea system. Round the season nutrient availability, positive regulation in soil health under integrated condition with boost in microbial activity improved NR, chlorophyll content, and eventually nutrient uptake in both crops. Chickpea equivalent yield of pearl millet was highest in 100% RDP (3.90 t ha^{-1}) which was almost at par with $P_{60\%}$+CR+B (3.73 t ha^{-1}). Similarly, $P_{60\%}$+CR+B resulted ∼50% higher agronomic P-use efficiency over conventional practices (100% RDP), but the results were less evident in input-intensive pearl millet. Higher values of NHI, PE_p, and IUE_p in control plot suggest invariable nutrient uptake with biomass gain in both the crops. In addition, the presence of more soluble-P and Ca_2-P in the integrated plots ensures higher bio-available P than conventional practices with more efficacious use of sesquioxides bound P fractions. However, the strong inter-linkage between grain yields with P-fractions was missing in both crops which further indicate the need of long run studies. Finally, progressive shift in grain yield especially in chickpea confirmed the 60% recommended P-dose + CR (50%) + PSB was better over conventional practices with higher P-use efficacy and P-availability.

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 author.

Author contributions

AD: Conceptualization, Data curation, Formal analysis, Investigation, Supervision, Writing – original draft. KKH: Conceptualization, Investigation, Writing – original draft. CN: Conceptualization, Investigation, Supervision, Writing – review & editing. NK: Supervision, Writing – review & editing. RS: Writing – review & editing. CP: Supervision, Writing – review & editing. AP: Formal analysis, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

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