



# Effects of phosphorus sources and application levels on soil properties and phosphorus dynamics under a pearl millet-mustard cropping system in semi-arid slightly alkaline soils

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## Abstract

Phosphorus (P) fertiliser application significantly influences soil quality by modifying key physicochemical attributes and regulating P dynamics, which are essential for sustaining nutrient supply and crop productivity. A field experiment was conducted from July 2021 to November 2021 using a randomised block design (RBD) comprising eleven treatments with three replications to evaluate the impact of different P sources and levels on soil properties and P fractions after pearl millet harvest. Implementation of different nutrient management practices decreased the soil pH ( $p = 0.001$ ) as compared to initial value, while soil electrical conductivity (EC) increased ( $p = 0.069$ ). Integrated application of farmyard manure (FYM) + single super phosphate (SSP) showed the highest increases in available nitrogen (N), P and sulphur (S), as well as significant increases in key inorganic P fractions (sodium-P (Sa-P), aluminum-phosphorus (Al-P), iron-phosphorus (Fe-P), calcium-phosphorus (Ca-P), total inorganic phosphorus (Tpi) and total-P) and biological yield ( $114.36 \text{ q ha}^{-1}$ ) compared to control. However, application of FYM + di-ammonium phosphate (DAP) showed highest increase in available potassium (K) ( $p = 0.001$ ). In control plots, inorganic P fractions followed the order Ca-P (66.5 %) > Fe-P (19.02 %) > Al-P (11.83 %) > Sa-P (2.61 %). Overall integrating  $7.5 \text{ t FYM ha}^{-1}$  along with SSP superiorly modulates P transformation and availability in semi-arid soils compared to chemical fertilisers alone. These findings demonstrate that integrated nutrient management (INM) is vital for optimising P efficiency, restoring soil health and ensuring sustainable agricultural productivity in semi-arid regions.

**Keywords:** farmyard manure; integrated nutrient management; inorganic phosphorus; nutrients status

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## 1. Introduction

Phosphorus (P) is an essential macronutrient involved in energy transfer through ATP synthesis, nucleic acid metabolism, membrane phospholipids formation, root development and overall crop productivity. However, its availability in soils is often limited by strong chemical interactions with soil minerals, resulting in low fertiliser use efficiency (1, 2). Phosphorus is among the most immobile and inaccessible nutrients in soil and its deficiency is a major constraint to crop growth and productivity worldwide. Globally, about 5.7 billion ha of agricultural land are P-deficient (3).

To overcome P deficiency, soluble phosphatic fertilisers are applied; however, a large proportion of applied P rapidly transforms into fixed inorganic P

fractions through adsorption and precipitation reactions with aluminium (Al), iron (Fe) and calcium (Ca), particularly in neutral to alkaline and calcareous soils (4, 5). In addition, organic P fractions are also immobilised by soil microorganisms, further limiting P availability to plants (6). Consequently, only approximately 20 % of applied P is utilised by the first crop, while the remaining 80–90 % may remain unutilised in short-term and contribute to residual P availability for succeeding crops (7). However, these proportions are approximate and can vary considerably with soil type, P source, application method, crop and nutrient management practices.

The transformation and availability of P in soil are influenced by several factors, including soil texture, soil organic carbon (SOC), soil pH, moisture,

temperature, land use, cropping system, P source and plant uptake capacity (8). Among these, P availability is closely related to the amount and form of P added through organic and inorganic sources (9). Soils amended with manures, rock phosphate (RP), bone meal and compost generally show higher P availability and dry matter production than those receiving only inorganic P sources. Organic amendments improve soil organic matter, microbial diversity, P cycling and uptake, physical properties, fertility and crop yield and quality (10). Furthermore, studies have shown that nearly 25 % of N, P and potassium (K) supplied through chemical fertilisers can be substituted with organic sources without yield reduction in pearl millet. However, the limited availability of quality organic manure often restricts its large-scale adoption.

In India, single super phosphate (SSP) and di-ammonium phosphate (DAP) are widely used water-soluble inorganic P fertilisers, but their high cost often limits accessibility for small farmers (11). Therefore, integrated use of organic manures and chemical fertilisers, based on soil and crop requirements, is essential for sustaining productivity and soil health (11–13). Combined application of manures with inorganic P fertilisers significantly improves P availability and inorganic P fractions (9). Although FYM contains low P ( $\approx 0.22\%$ ) and is costlier on a nutrient basis, its beneficial effects on soil properties compensate for the cost. Rock phosphate, containing 27–41 % phosphorus pentoxide ( $P_2O_5$ ), is water-insoluble and effective mainly under acidic conditions; while its immediate availability is low, it has a strong residual effect. Thus, sole RP application is less effective in neutral to alkaline soils, but its combined use with FYM enhances P availability and soil P dynamics (14, 15).

Based on these previous studies, a comprehensive evaluation of the interactive effect of different P fertilisers, including SSP, DAP and RP, applied

at varying P levels with or without FYM, on soil physicochemical properties and P dynamics under the pearl millet–mustard cropping system in the semi-arid alkaline soils of North-western India is scarce. In particular, previous studies have not adequately investigated the combined effects of P source and FYM integration on inorganic P fractions and P availability. Understanding these effects is essential for improving P use efficiency, reducing P fixation and developing sustainable nutrient management strategies for such production systems (16). Therefore, in this study we hypothesised that integrating FYM with chemical P sources would enhance soil P availability, reduce P fixation into less soluble fractions and improve overall soil physico-chemical properties and crop yields more effectively than applying P fertilisers alone. Therefore, the present study was conducted at Hisar, Haryana, to evaluate the combined effects of different P sources and application levels, alone and in combination with FYM, for improving soil physico-chemical properties, available nutrient status and inorganic P fractions following pearl millet under a pearl millet–mustard cropping system in the semi-arid region of north-western India.

## 2. Materials and Methods

### Study location and treatment details

The field experiment was established during the rabi season of 2020 by sowing mustard variety (RH-725) at the Research Farm of Department of Soil Science, CCS HAU, Hisar to initiate the P management treatments ( $T_1$ – $T_{11}$ ) in the pearl millet–mustard cropping system (Table 1). The present study, however, reports the post-harvest data after kharif 2021 pearl millet crop grown under the established experimental treatments (Fig. 1). Data regarding the preceding rabi 2020–21 mustard crop served for system baseline/treatment establishment and are not included in the present scope.

**Table 1.** Treatment details carried out during the experiment

| Treatment | Pearl millet (HHB 299)                                            | Mustard (RH 725)                                                  |
|-----------|-------------------------------------------------------------------|-------------------------------------------------------------------|
| $T_1$     | Control (no phosphorus treatment)                                 | Control (no phosphorus treatment)                                 |
| $T_2$     | 60 kg P ha <sup>-1</sup> through SSP                              | 20 kg P ha <sup>-1</sup> through SSP                              |
| $T_3$     | 60 kg P ha <sup>-1</sup> through DAP                              | 20 kg P ha <sup>-1</sup> through DAP                              |
| $T_4$     | 60 kg P ha <sup>-1</sup> through RP                               | 20 kg P ha <sup>-1</sup> through RP                               |
| $T_5$     | 60 kg P ha <sup>-1</sup> through RP                               | 20 kg P ha <sup>-1</sup> through SSP                              |
| $T_6$     | 60 kg P ha <sup>-1</sup> through RP                               | 20 kg P ha <sup>-1</sup> through DAP                              |
| $T_7$     | 7.5 t FYM ha <sup>-1</sup> + 30 kg P ha <sup>-1</sup> through SSP | 7.5 t FYM ha <sup>-1</sup> + 10 kg P ha <sup>-1</sup> through SSP |
| $T_8$     | 7.5 t FYM ha <sup>-1</sup> + 30 kg P ha <sup>-1</sup> through DAP | 7.5 t FYM ha <sup>-1</sup> + 10 kg P ha <sup>-1</sup> through DAP |
| $T_9$     | 7.5 t FYM ha <sup>-1</sup> + 30 kg P ha <sup>-1</sup> through RP  | 7.5 t FYM ha <sup>-1</sup> + 10 kg P ha <sup>-1</sup> through RP  |
| $T_{10}$  | 7.5 t FYM ha <sup>-1</sup> + 30 kg P ha <sup>-1</sup> through RP  | 7.5 t FYM ha <sup>-1</sup> + 10 kg P ha <sup>-1</sup> through SSP |
| $T_{11}$  | 7.5 t FYM ha <sup>-1</sup> + 30 kg P ha <sup>-1</sup> through RP  | 7.5 t FYM ha <sup>-1</sup> + 10 kg P ha <sup>-1</sup> through DAP |

SSP: single super phosphate; DAP: di-ammonium phosphate; RP: rock phosphate; FYM: farm-yard manure.



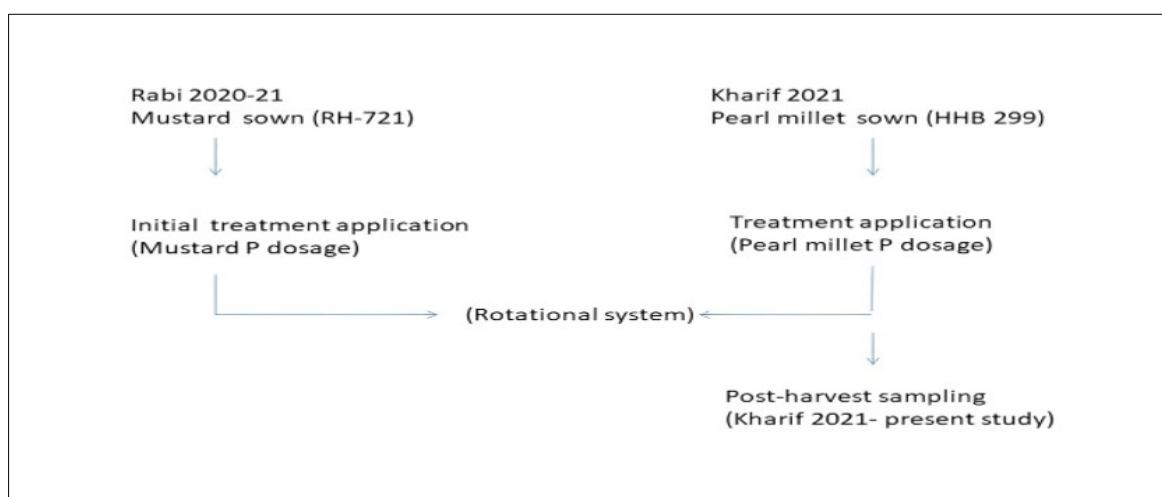


**Fig. 1.** Schematic representation of the experimental timeline, crop rotation (Mustard-pearl millet), treatment application sequence and soil/plant sampling.

The experimental site located at 29°10' N latitude and 75°46' E longitude in North-west part of India (17). The climate of study area is semi-arid, with an average annual temperature of 24.8 °C and mean annual rainfall of 443 mm, ~ 90 % of which occurs during the southwest monsoon (June–September) (17, 18). During crop duration (kharif 2021), mean maximum temperature was about 33–38 °C, mean minimum temperature 24–27 °C, with mean seasonal rainfall 450–500 mm, relative humidity ranged from 45–90 %; sunshine hours varied from 4–9 h day<sup>-1</sup> as shown in Fig. 2 (19). The soil was sandy loam in texture with 65 % sand, 20 % silt and 15 % clay. Initial soil pH<sub>1:2</sub> 7.98, EC<sub>1:2</sub> 0.31 dS m<sup>-1</sup> and soil organic carbon (SOC) as 0.45%. Soil available nutrients

were 134.0, 12.27, 420.0 and 36.10 mg kg<sup>-1</sup> as N, P, K and S, respectively (20).

The experiment comprised a total of 11 treatments, with three replications each, arranged in a randomised block design (RBD). Single superphosphate (SSP), DAP and RP were applied either individually or in combination with FYM. Treatment details for pearl millet-mustard cropping system are summarised in Table 1. Notably, treatments T<sub>4</sub>, T<sub>5</sub>, T<sub>6</sub> and T<sub>9</sub>, T<sub>10</sub>, T<sub>11</sub> receive identical direct P treatment applications during pearl millet phase. These treatments differ solely in the source of P applied during the preceding mustard phase (SSP, DAP and RP). Consequently, any observed differences among T<sub>4</sub>–T<sub>5</sub> and T<sub>9</sub>–T<sub>11</sub> in pearl millet reflect the residual effects of preceding mustard phase P treatment.

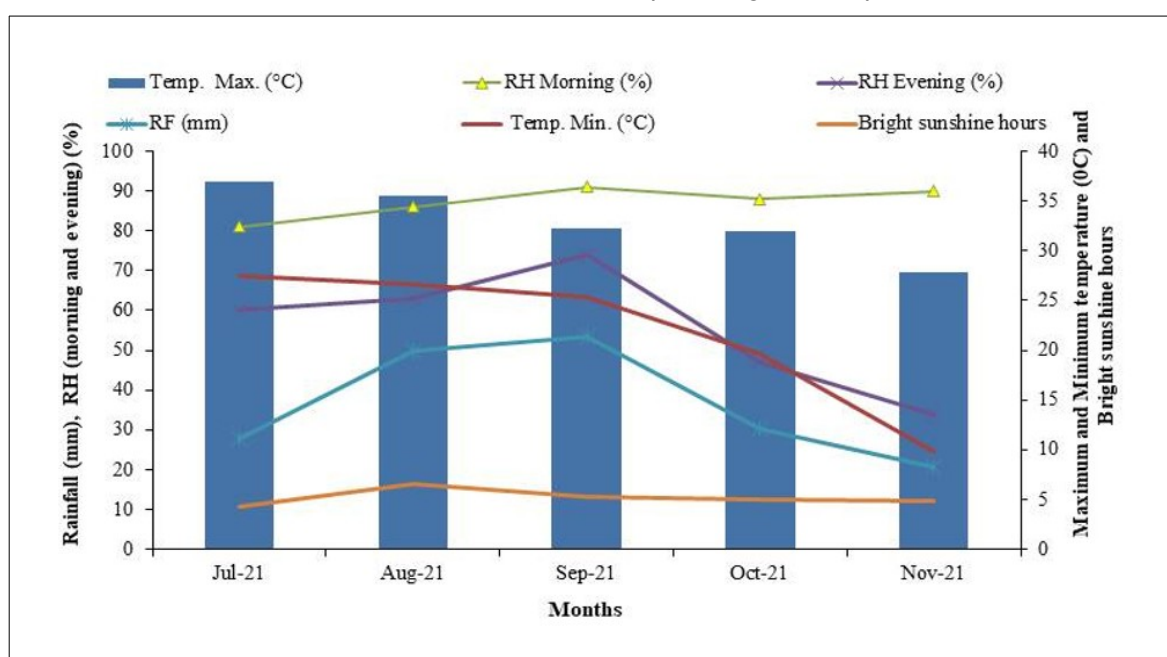


**Fig. 2.** Mean monthly weather data during experimental study (kharif 2021).

After field preparation, pearl millet variety HHB 299 was sown in kharif 2021 at the onset of monsoon during first week of July, using a row spacing of 45 cm and plant-to-plant spacing of 10–15 cm. A seed rate of 4 kg ha<sup>-1</sup> was used and seedlings were thinned at 15–20 days after sowing (DAS) to maintain the desired plant population. The recommended dose of fertilisers (RDF) applied was 60 kg N and 60 kg P ha<sup>-1</sup>. Farmyard manure (dry weight basis) having pH<sub>1:5</sub> 7.4, EC<sub>1:5</sub> 2.1 dS m<sup>-1</sup>, organic carbon 24.5 % with a C : N ratio 21 : 1 was incorporated before sowing pearl millet. The entire dose of P was applied as a basal application at the time of sowing. Nitrogen (N) was applied through urea in two equal splits, with 50 % applied as a basal dose at sowing and the remaining 50 % top-dressed at 25–30 DAS in all the treatments except control. The crop was primarily grown under rainfed conditions; however, two supplemental irrigations were applied during prolonged dry spells, at tillering and flowering to avoid moisture stress. Other intercultural operations including thinning, hand weeding and plant protection measures were also carried out timely. This study showed the data of pearl millet (*Pennisetum glaucum* L.) crop.

The crop was harvested manually at physiological maturity at about 2–3 cm above the ground level in the month of November, 2021. Grain and straw yield of pearl millet were recorded at harvest following the standard procedures. The agronomic yield data have been reported and discussed in detail in companion publication (20). In the present study, biological yield was calculated as the sum of grain and straw yield for each treatment and expressed on hectare basis (q ha<sup>-1</sup>).

Soil samples were collected following the pearl millet crop harvest from the treatment plots (Table 1).

### Sample collection, preparation and analysis

Soil sampling (0–15 cm) was carried out in individual plots using an auger after pearl millet harvest in November 2021. One representative soil sample was collected from each plot across 11 treatments and three replications (a total of 33 samples) to evaluate the effects of different nutrient management practices on soil P dynamics and related soil properties. The collected soil samples were air dried, crushed with a wooden roller and sieved (2 mm sieve) in laboratory for further analysis (21). Potentiometric method proposed by Jackson which was used to determine soil pH (1 : 2 soil : water). Soil EC was determined with glass electrode using conductometric method (22).

Available N content of soil samples was estimated by Kjeldahl-distillation method (23). The soil was treated with 0.32 % potassium permanganate (KMnO<sub>4</sub>) and 2.5 % sodium hydroxide (NaOH) solution. Ammonia liberated on oxidation was absorbed in standard boric acid solution and excess was treated with standard alkali.

The sodium bicarbonate (NaHCO<sub>3</sub>) extraction and colourimetry method was used to determine the available P content in soil sample (24). The soil was extracted with 0.5M NaHCO<sub>3</sub> solution in presence of Darco G-60. After

filtration, the aliquot was treated with 1.5 % ammonium molybdate solution and reducing agent (SnCl<sub>2</sub>). Reduction of heteropoly complexes imparts the blue colour and intensity was measured at 660 nm on spectrophotometer.

Available K content in soil sample was determined by using the method of Jackson (22). The soil was extracted with 1N ammonium acetate (CH<sub>3</sub>COONH<sub>4</sub>) solution for 5 min. Available K in the filtrate was measured using flame photometer.

Available S content in soil was measured following the method outlined by Chesnin and Yien (25). The soil was treated with 0.15 % calcium chloride dihydrate (CaCl<sub>2</sub>·2H<sub>2</sub>O) solution for 30 min. The soluble sulphates get precipitated when mixed with barium chloride (BaCl<sub>2</sub>) in presence of gum acacia. The turbidity produced was measured at 420 nm on visible spectrophotometer.

Inorganic P fractions viz., saloid-P (Sa-p), aluminium-P (Al-P), iron-P (Fe-P), calcium-P (Ca-P) in soil samples were determined by following the method outlined by Chesnin and Yien (26) and modified by Peterson and Corey (27) as give below:

#### Saloid- P

One g of soil and 50 mL 1M NH<sub>4</sub>Cl was shaken in a 100 mL centrifuge tube for 30 min and centrifuged at 2000 rpm for 10 min. The supernatant was filtered and then 5 mL of aliquot was pipetted out into 25 mL volumetric flask and 5 mL of ammonium molybdate was added. Then, 1 mL of chlorostannous reductant (SnCl<sub>2</sub>·2H<sub>2</sub>O) solution was added and final volume was made with distilled water. The intensity of blue colour was measured at 660 nm wavelength using visible spectrophotometer.

#### Aluminium- P

Fifty mL of NH<sub>4</sub>F (pH 8.2) was added to residual soil of saloid P. The suspension was shaken for an hour and centrifuged for 10 min (2000 rpm). The supernatant was decanted in volumetric flask and used for Al-P analysis. Three mL of aliquot was taken into the volumetric flask and chloromolybdic boric acid solution (3 mL) was added to it. Then chlorostannous reductant was added and intensity of blue colour was measured at 660 nm within 15 min of adding chlorostannous reductant.

#### Iron- P

The residual soil from Al-P was washed twice with 25 mL portions of saturated NaCl and centrifuged at 2000 rpm for 10 min. The supernatant solution was discarded and soil residue was shaken for 17 hr after addition of 50 mL 0.1N NaOH and then centrifuged at 2000 rpm for 5 min. The supernatant solution was decanted in 50 mL volumetric flasks. Five to six drops of sulphuric acid were added and flask was swirled so that organic matter flocculates. Then supernatant was discarded in volumetric flask and used for Fe-P analysis. Three mL of aliquot was taken into the volumetric flask and chloromolybdic boric acid solution (3 mL) was added to it. Then chlorostannous reductant was added and intensity

of blue colour was measured at 660 nm within 15 min of adding chlorostannous reductant.

#### Calcium- P

The Fe-P soil residue was washed twice with 25 mL portion of saturated NaCl and centrifuged. The supernatant solution was discarded and soil residue was shaken for 1 hr after addition of 50 mL 0.5N H<sub>2</sub>SO<sub>4</sub> and then centrifuged at 2000 rpm for 10 min. Then the supernatant liquid was analysed for Ca-P. Three mL of aliquot was taken into the volumetric flask and chloromolybdic boric acid solution (3 mL) was added to it. Then chlorostannous reductant was added and intensity of blue colour was measured at 660 nm within 15 min of adding chlorostannous reductant.

#### Total- P

Total P was determined using the perchloric acid digestion method (22). One gram soil was digested in diacid mixture of nitric acid (HNO<sub>3</sub>) and perchloric acid (HClO<sub>4</sub>) and determined using vanado-molybdo phosphoric yellow colour method (28).

#### Statistical analysis

Experimental data were analysed using the online statistical software OPSTAT (29), with critical difference (CD) values calculated at the 5 % significance level ( $\alpha=0.05$ ). Standard error (Sem  $\pm$ ) was determined by following equation:

$$\text{Sem} \pm = \frac{\text{CD}}{\sqrt{2 \times t_{0.05}}}$$

Graphs and correlation matrices were generated using SRplot (30). Principal component analysis (PCA) was also performed using SRplot to evaluate the relationships among soil properties and treatment differences (30). Although, Kaiser criterion considers component with eigenvalues > 1.0, PC<sub>2</sub> (eigenvalue < 1.0) was retained alongside PC<sub>1</sub> to facilitate 2D biplot visualisation, enable

two-dimensional (2D) graphical representation of treatment separation and account for cumulative variance exceeding 90 %, also reported previously (31, 32).

### 3. Results and Discussion

#### Soil pH and electrical conductivity

Soil pH decreased under all nutrient management practices compared to the initial value (7.98), with values ranging from 7.72–7.95 (Fig. 3), as reported previously (33, 34). This pH decline may result from acidity caused by residual effects of P fertilisers from previous crops (35). The highest pH was observed in the control (T<sub>1</sub>), while the lowest pH was recorded with 7.5 t FYM ha<sup>-1</sup> + half recommended dose of P through SSP (T<sub>7</sub>). Application of full recommended dose of P through SSP, DAP and RP reduced soil pH compared to control; however, the reduction was significant only with SSP and DAP ( $p = 0.001$ ). The full recommended dose of P applied as SSP resulted in lower pH (7.83) than DAP (7.85) and RP (7.91), though differences among P sources were non-significant ( $p > 0.05$ ) (35). The lower pH with SSP is due to H<sup>+</sup> release in soil solution and formation of H<sub>2</sub>PO<sub>4</sub><sup>-</sup>, which acidifies the soil (8). Rock phosphate (RP) application resulted in higher soil pH than DAP or SSP, potentially due to its higher Ca content (35). Integrated application of FYM + half recommended dose of P through SSP, DAP and RP further reduced soil pH to 7.72, 7.76 and 7.77, respectively, compared to their corresponding full recommended dose of P treatments (7.83, 7.85 and 7.91). This reduction was significant with SSP (T<sub>7</sub>) and RP (T<sub>9</sub>) only ( $p = 0.001$ ). Similar to sole P application, SSP combined with FYM produced lower soil pH than DAP and RP. Increased SOM in 7.5 t FYM ha<sup>-1</sup> with P fertilisers plots enhance microbial biomass, promoting SOM decomposition and H<sup>+</sup> release that lowers soil pH, reported previously (10).

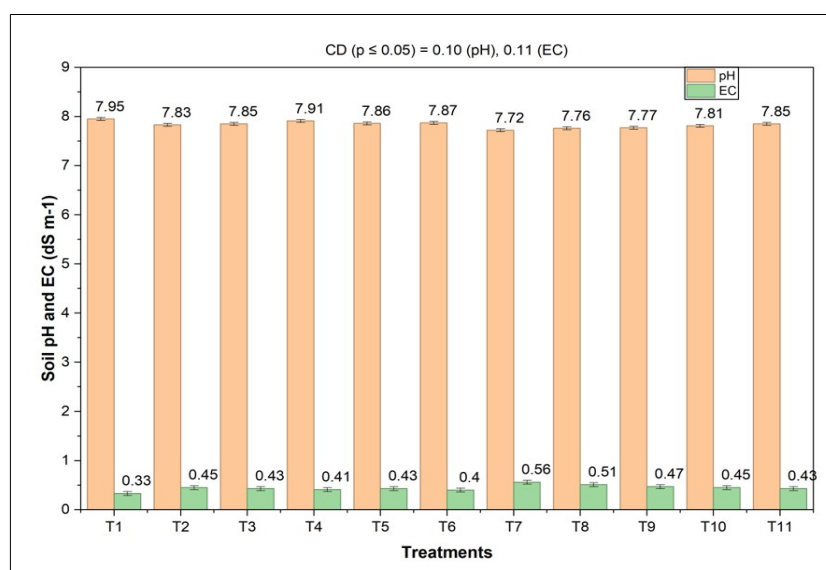


**Fig. 3.** Effect of different levels and sources of phosphorus on soil pH and EC. (Treatments T<sub>1</sub>–T<sub>11</sub> as in Table 1); vertical bars represent standard error of mean (Sem  $\pm$ ); Sem  $\pm$  for soil pH and EC was 0.03 and 0.04, respectively; critical difference (CD) ( $p \leq 0.05$ ) = 0.10 (pH), 0.11 (EC).

A general trend of increasing soil EC was observed due to higher soluble salt concentration as reported previously (34). Soil EC ranged from 0.33–0.56 dS m<sup>-1</sup> (Fig. 3) and increased in all nutrient treatments over the initial value (0.31 dS m<sup>-1</sup>). The highest EC was recorded with FYM + half recommended dose of P through SSP (T<sub>7</sub>: 0.56 dS m<sup>-1</sup>), while the lowest occurred in the control (T<sub>1</sub>: 0.33 dS m<sup>-1</sup>). Increased EC is attributed to salt addition from fertilisers and solubilisation of native minerals due to lower pH. Moreover, decomposition of FYM releases soluble organic compounds and nutrient ions into the soil solution, while organic ligands formed during decomposition enhance mineral weathering and nutrient release, as reported previously (10). These processes increase the concentration of dissolved ions, contributing to higher EC. Application of full recommended dose of P through P fertilisers (0.45, 0.43 and 0.41 dS m<sup>-1</sup> for SSP, DAP and RP, respectively) increased EC over control (0.33 dS m<sup>-1</sup>), but the increase was significant only with SSP (0.45 dS m<sup>-1</sup>) ( $p = 0.069$ ). Full recommended dose of P through SSP resulted in higher EC than DAP and RP, though differences among P sources were non-significant ( $p > 0.05$ ) (33). In contrast to our study, a previous study, reported lower EC with SSP compared to other P fertilisers (36). Application of 7.5 t FYM ha<sup>-1</sup> + half recommended dose of P through SSP, DAP and RP increased EC to 0.56, 0.51 and 0.47 dS m<sup>-1</sup>, respectively, with significant increases over control except T<sub>11</sub> ( $p = 0.069$ ). It may be due to FYM with P fertilisers can accelerate dissolution of sparingly soluble salts, thereby increasing EC (12). Among P sources, FYM + SSP recorded the highest EC, followed by FYM + DAP and FYM + RP. FYM + half recommended dose of P through SSP significantly increased EC over full recommended dose of P through SSP, whereas FYM combined with DAP or RP showed non-significant effects compared to their respective full RDF treatments.

### Available nutrients (N, P, K and S)

Post-harvest available N ranged from 133.11–171.32 kg ha<sup>-1</sup>. All nutrient management treatments improved soil N over the initial value, except control (T<sub>1</sub>) (Fig. 4), similar to previous findings (33, 34, 37–39). The highest N was recorded with 7.5 t FYM ha<sup>-1</sup> + half RDF P through SSP (T<sub>7</sub>: 171.32 kg ha<sup>-1</sup>), while the lowest was in control. Application of the full recommended dose of P through P fertilisers (154.22, 151.21 and 145.80 kg ha<sup>-1</sup> for SSP, DAP and RP, respectively) increased available N over control (133.11 kg ha<sup>-1</sup>). The effect was significant for all treatments except T<sub>4</sub>; however, differences among P sources were non-significant ( $p = 0.082$ ) (40). Rock phosphate resulted in lower available N than DAP and SSP, consistent with earlier findings (36, 41–43). Similarly, application of 7.5 t FYM ha<sup>-1</sup> + half recommended dose of P through SSP, DAP and RP increased available N over control ( $p < 0.001$ ). Available N content in soil was found higher with the application of FYM with SSP (171.32 kg ha<sup>-1</sup>) as compared to application of FYM with DAP (166.11 kg ha<sup>-1</sup>) or RP (163.40 kg ha<sup>-1</sup>), however, the effect was non-significant ( $p = 0.145$ ). The improvement in nutrient availability was mainly due to the release of N during decomposition of organic manures. Integrated FYM + half RDF of P through fertilisers significantly increased available N over recommended dose of P through fertilisers alone ( $p = 0.001$ ) also reported previously (42, 44, 45). Farmyard manure combined with SSP, DAP and RP increased N by 11.08, 9.85 and 12.07 %, respectively, over their corresponding full RDF treatments. Treatments T<sub>10</sub> and T<sub>11</sub> increased available N by 6.56 and 10.79 % over T<sub>5</sub> and T<sub>6</sub>, respectively. Higher available N resulted from mineralisation of native and organic N, supported by increased microbial activity that converts organically bound N into inorganic forms (12).

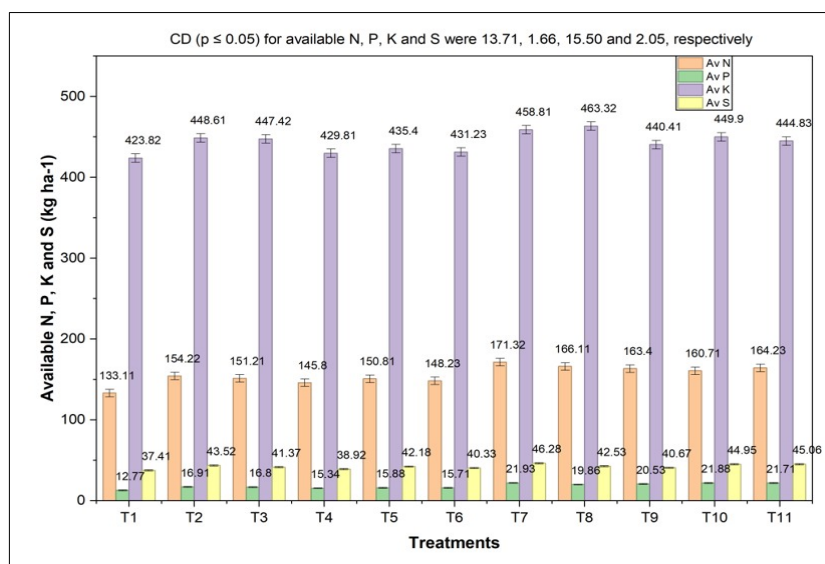


**Fig. 4.** Effect of different levels and sources of phosphorus on soil available nutrients (N, P, K and S) (Treatments T<sub>1</sub>–T<sub>11</sub> as in Table 1); vertical bars represent standard error of mean (SEM  $\pm$ ); SEM  $\pm$  for available N, P, K and S were 4.65, 0.56, 5.25 and 0.70, respectively; critical difference (CD) ( $p \leq 0.05$ ) for available N, P, K and S were 13.71, 1.66, 15.50 and 2.05, respectively. Depictions: Av N (available nitrogen); Av P (available phosphorus); Av K (available potassium); Av S (available sulphur).

Available P content in soil ranged from 12.77–21.93 kg ha<sup>-1</sup>, with all treatments increasing P over the initial value (12.27 kg ha<sup>-1</sup>) (Fig. 4), also reported previously (34, 37–40). The increase in available P was attributed to phosphatic fertiliser application, which enhanced soil acidity and thereby increased solubility and availability of native P (33, 34). The highest available P was recorded with the application of 7.5 t FYM ha<sup>-1</sup> along with half of recommended dose of P through SSP T<sub>7</sub> (21.93 kg ha<sup>-1</sup>) and the lowest in control (T<sub>1</sub>) (12.77 kg ha<sup>-1</sup>). Organic matter influences P sorption-desorption equilibria by blocking adsorption sites and forming complexes with Fe and Al, thereby reducing P fixation and facilitating greater P availability, reported previously (41). Further results showed that, application of recommended P dose through RP resulted in lower available P compared to DAP and SSP, also reported previously (43, 44). Full recommended dose of P through SSP, DAP and RP increased available P by 32.41, 31.55 and 20.10 %, respectively, over control, with non-significant differences among sources ( $p > 0.05$ ) (42). Single super phosphate (SSP) resulted in slightly higher available P (16.91 kg ha<sup>-1</sup>) than DAP (16.80 kg ha<sup>-1</sup>) and RP (15.34 kg ha<sup>-1</sup>) as also reported previously (36, 42–44). Further, application of FYM along with P fertilisers (SSP, DAP and RP) increased available P over control. Incorporation of FYM along with P through SSP showed higher available P content (21.93 kg ha<sup>-1</sup>) as compared to application of FYM along with RP (20.53 kg ha<sup>-1</sup>) or DAP (19.86 kg ha<sup>-1</sup>). This effect was significant for T<sub>7</sub>, T<sub>10</sub> and T<sub>11</sub> over T<sub>8</sub> ( $p < 0.001$ ) and non-significant for T<sub>9</sub> over T<sub>8</sub> treatment ( $p > 0.05$ ). FYM + half recommended dose of P through fertilisers significantly enhanced P over full recommended dose of P through fertilisers also reported earlier (41, 45). Compared to full recommended dose of P through fertilisers, application of FYM + SSP, DAP and RP increased available P by 39.31, 18.21 and 33.83 %, respectively. Treatments T<sub>10</sub> and T<sub>11</sub> increased available P by 37.78 and 38.19 % over T<sub>5</sub> and T<sub>6</sub>, respectively.

Available K in soil varied from 423.82–463.32 kg ha<sup>-1</sup>, with all treatments improving K over the initial value (420 kg ha<sup>-1</sup>) (Fig. 4), consistent with earlier findings (36, 37, 39). The highest available K was recorded with FYM + half recommended dose of P through DAP (T<sub>8</sub>) and the lowest in control (T<sub>1</sub>). Full recommended dose of P through SSP, DAP and RP increased K by 5.84, 5.56 and 1.41 %, respectively, over control, with significant effects in T<sub>2</sub> and T<sub>3</sub> only ( $p = 0.001$ ) (42). Rock phosphate showed lower available K (429.81 kg ha<sup>-1</sup>) than DAP (447.42 kg ha<sup>-1</sup>) and SSP (448.61 kg ha<sup>-1</sup>) which is consistent with previous findings (42, 43). Addition of FYM along with half of recommended dose of P through DAP showed higher available K content (463.32 kg ha<sup>-1</sup>) as compared to application of FYM along with half of recommended dose of P through SSP (458.81 kg ha<sup>-1</sup>) or RP (440.41 kg ha<sup>-1</sup>). The improvement in nutrient availability was mainly due to the release of K during decomposition of organic manures. Farmyard manure (FYM) + half recommended dose of P through DAP significantly increased K over full recommended dose of P through DAP ( $p = 0.001$ ), while effects with

SSP and RP were non-significant ( $p > 0.05$ ), also reported previously (42, 45). Farmyard manure (FYM) + SSP, DAP and RP increased available K by 2.27, 3.55 and 7.79 %, respectively, over their corresponding full recommended P doses in both crops, respectively.

Soil available S ranged from 37.41–46.28 kg ha<sup>-1</sup> (Fig. 4), also reported earlier (39, 40). The highest and the lowest available S content was recorded with application of FYM along with P through SSP (T<sub>7</sub>) and in control plots (T<sub>1</sub>), respectively. Incorporation of full recommended dose of P through SSP, DAP and RP increased available S by 16.33, 10.58 and 4.03 %, respectively, over control; the effect was significant except RP (T<sub>4</sub>) only ( $p > 0.05$ ) (42). Single super phosphate (SSP) resulted in significantly higher available S (43.52 kg ha<sup>-1</sup>) than DAP (41.37 kg ha<sup>-1</sup>) and RP (38.92 kg ha<sup>-1</sup>) ( $p < 0.001$ ), similarly also reported previously (44, 45). Addition of 7.5 t FYM ha<sup>-1</sup> along with half of recommended dose of P through P fertilisers (46.28, 42.53 and 40.67 kg ha<sup>-1</sup> for SSP, DAP and RP, respectively) increased available S content in soil over control ( $p < 0.001$ ). Incorporation of FYM along with SSP showed significantly higher available S content as compared to application of FYM along with DAP or RP ( $p < 0.001$ ). The improvement in nutrient availability was mainly due to the release of S during decomposition of organic manures. Farmyard manure (FYM) + half recommended dose of P through SSP significantly increased available S content over full recommended dose of P through SSP, while increases with DAP and RP were non-significant ( $p > 0.05$ ) also reported previously (42, 44, 45). Application of FYM + SSP, DAP and RP increased available S by 6.34, 2.80 and 4.49 %, respectively, over full recommended dose of P through SSP, DAP and RP treatments. Treatments T<sub>10</sub> and T<sub>11</sub> increased available S by 6.56 and 11.72 % over T<sub>5</sub> and T<sub>6</sub>, respectively. Increased available S content in soil was attributed to improved biomass production and direct S addition through FYM (13).

### Phosphorus fractions (Inorganic)

Inorganic P fractionation is an effective approach to understand inter-conversions among different inorganic P forms in soil systems (16). These fractions differ markedly in bioavailability and chemical behaviour, particularly in sodic soils. Application of P fertilisers increased all inorganic P fractions, also reported previously (2, 36, 37, 46). The lowest inorganic P fractions under control were attributed to continuous cultivation without organic or inorganic P inputs, leading to depletion of soil P reserves. Results showed that, inorganic P fractions under various treatments ranged as; Sa-P (4.79–11.31 ppm), Al-P (21.71–48.12 ppm), Fe-P (34.91–58.21 ppm) and Ca-P (122.11–185.42 ppm) and were highest recorded with 7.5 t FYM ha<sup>-1</sup> along with half of the recommended dose of P through SSP (T<sub>7</sub>), while the lowest was observed in the control (T<sub>1</sub>) (Fig. 5). Among all inorganic P fractions, Sa-P is loosely bound and readily available to plants, contributing directly to plant-available P. Aluminium-bound P (Al-P) is a labile fraction; its availability increases when inorganic P is applied with FYM due to reduced

fixation and chelation effects that keep P in solution and limit its transformation into non-labile forms (45). Similarly, Sa-P and Al-P are key inorganic P forms contributing to biological yield and P uptake (46). Applied soil P often reacts with sesquioxides to form Al-P and Fe-P (45, 47). Addition of full recommended dose of P through SSP, DAP and RP increased Sa-P (8.21, 8.08 and 6.22 ppm), Al-P (33.52, 33.30 and 26.61 ppm), Fe-P (51.41, 49.82 and 38.40 ppm) and Ca-P (148.42, 138.62 and 128.61 ppm) over control; with significant increases observed in all treatments except T<sub>4</sub> for Sa-P ( $p < 0.001$ ). Incorporation of full recommended dose of P through SSP showed higher inorganic P fractions (Sa-P, Al-P, Fe-P and Ca-P) due to its high solubility and rapid phosphate release (45) in soil followed by DAP and RP; although effect varied significantly among the various fertilisers ( $p < 0.001$ ). Higher P levels under nutrient management practices resulted from continuous phosphatic fertiliser application and subsequent transformation into different inorganic forms (Sa-P, Al-P, Fe-P and Ca-P) (48). Integration of 7.5 t FYM ha<sup>-1</sup> with half the recommended P dose further significantly enhanced these fractions: Sa-P (11.31, 8.91 and 9.06 ppm with SSP, DAP and RP, respectively), Al-P (48.12, 33.90 and 34.91 ppm with SSP, DAP and RP, respectively), Fe-P (58.21, 51.62 and 52.02 ppm with SSP, DAP and RP, respectively) and Ca-P (185.42, 150.52 and 153.41 ppm with SSP, DAP and RP, respectively) over control ( $p < 0.001$ ),

corroborating with previous findings (45, 47, 48). This increase was attributed to complex formation, organic acid release during FYM decomposition, enhanced P solubilisation and transformation into Fe- and Ca-bound P forms (41). Farmyard manure combined with half P through SSP produced significantly higher inorganic P fractions than combinations with RP or DAP ( $p < 0.001$ ). Application of FYM with half the recommended P through SSP or RP significantly increased Sa-P and Al-P compared to the full recommended dose of P through SSP or RP, whereas the increase with FYM plus DAP was non-significant over full-dose of P through DAP. Farmyard manure combined with half-dose DAP and RP significantly increased Fe-P compared to their respective full-dose treatments, while the increase with SSP was non-significant ( $p = 0.128$ ). However, all FYM plus half-dose P treatments significantly increased Ca-P compared to their respective full-dose P applications ( $p < 0.001$ ). The soil inorganic P fractions followed the order Ca-P > Fe-P > Al-P > Sa-P. Inorganic P constituted 63 % of the total-P in soil, with Ca-P being the dominant fraction, followed by Fe-P, Al-P and saloid P (2). Calcium-bound P (Ca-P) was the dominant inorganic fraction across all treatments, likely due to the calcareous nature of the soil and transformation of applied P into Ca-P in the presence of amorphous calcium carbonate (CaCO<sub>3</sub>), as reported previously (46).

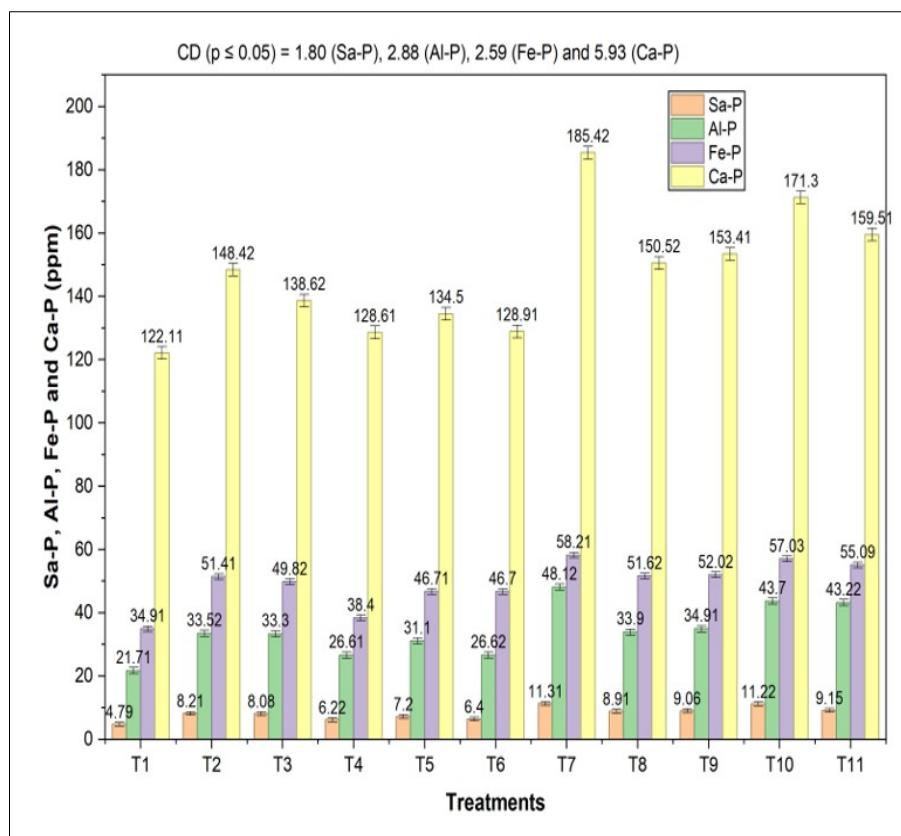


**Fig. 5.** Effect of different levels and sources of phosphorus on soil inorganic P fractions (Sa-P, Al-P, Fe-P and Ca-P) (Treatments T<sub>1</sub>–T<sub>11</sub> as in Table 1); vertical bars represent standard error of mean (SEM ±); SEM ± for Sa-P, Al-P, Fe-P and Ca-P were 0.61, 0.98, 0.88 and 2.01, respectively; critical difference (CD) ( $p \leq 0.05$ ) = 1.80 (Sa-P), 2.88 (Al-P), 2.59 (Fe-P) and 5.93 (Ca-P). Depictions: Sa-P (saloid- phosphorus); Al-P (aluminium- phosphorus); Fe-P (iron- phosphorus); Ca-P (calcium- phosphorus).

Inorganic P pool is the major sink for applied P fertiliser was also reported previously (45). Total inorganic phosphorus (Tpi) content in soil ranged from 183.52–303.06 ppm across treatments (Fig. 6). The highest Tpi was observed with 7.5 t FYM ha<sup>-1</sup> combined with half recommended P through SSP, while the lowest found in the control. Full recommended P application through SSP, DAP and RP significantly increased Tpi to 241.56, 229.82 and 199.84 ppm, respectively, over control (183.52 ppm) ( $p < 0.001$ ). Integration of FYM with half-dose P further increased Tpi to 303.06, 244.95 and 249.40 ppm with SSP, DAP and RP, respectively. Farmyard manure with half-dose SSP resulted in higher Tpi than FYM with RP or DAP. The higher Tpi with SSP may be related to the greater solubility of SSP, which supplies readily available phosphate that can interact with FYM-derived organic ligands, reducing immediate fixation and enhancing P retention in soil. Farmyard manure combined with half-dose of P through SSP, DAP and RP significantly increased Tpi over their respective full-dose treatments ( $p < 0.001$ ). This increase can be attributed to enhanced P retention and transformation processes in soil. Application of FYM stimulates microbial activity and extracellular enzyme production, which promotes mineralisation of organic P compounds and increases the availability of phosphate ions for subsequent transformation into inorganic pools. Overall, full recommended P application through SSP, DAP and RP increased Tpi by 31.62, 25.23 and 8.89 %, respectively, over control. Similarly, half recommended P through SSP, DAP and RP along with 7.5 t FYM ha<sup>-1</sup> increased Tpi by 65.14, 33.47 and 33.90 %, respectively, over control.

## Total phosphorus

Total P content in soil ranged from 242.42–344.52 ppm under different treatments (Fig. 6). All nutrient management practices significantly increased total-P compared to the control, also reported previously (36–38), as phosphatic fertilisers enhance soil acidity, favouring solubility and availability of native P. The highest total-P (344.52 ppm) was recorded with 7.5 t FYM ha<sup>-1</sup> combined with half recommended P dose through SSP, while the lowest was in the control (242.42 ppm). Full recommended P through SSP, DAP and RP increased total-P to 292.52, 286.21 and 259.11 ppm, respectively, with SSP showed significantly higher total-P than DAP and RP ( $p < 0.001$ ), due to high solubility of SSP and immediate phosphate release, although, previous study reported (46) higher total-P in DAP-treated plots compared to SSP and RP. Integration of FYM with half-dose of P further increased total-P to 344.52, 303.71 and 304.91 ppm with SSP, DAP and RP, respectively over control also reported earlier (43, 49, 50), attributed to organic matter decomposition and replacement of phosphate ions by humate ions (40). Farmyard manure (FYM)+half-dose SSP produced significantly higher total-P than FYM+DAP or RP ( $p < 0.001$ ). Application of FYM along with SSP, DAP, or RP significantly increased total-P compared to the respective full recommended P doses ( $p < 0.001$ ). Overall, full recommended P through SSP, DAP and RP increased total-P by 20.66, 18.06 and 6.88 % over control, whereas half recommended P through SSP, DAP and RP combined with 7.5 t FYM ha<sup>-1</sup> increased total-P by 42.11, 25.28 and 25.77 %, respectively, over control.

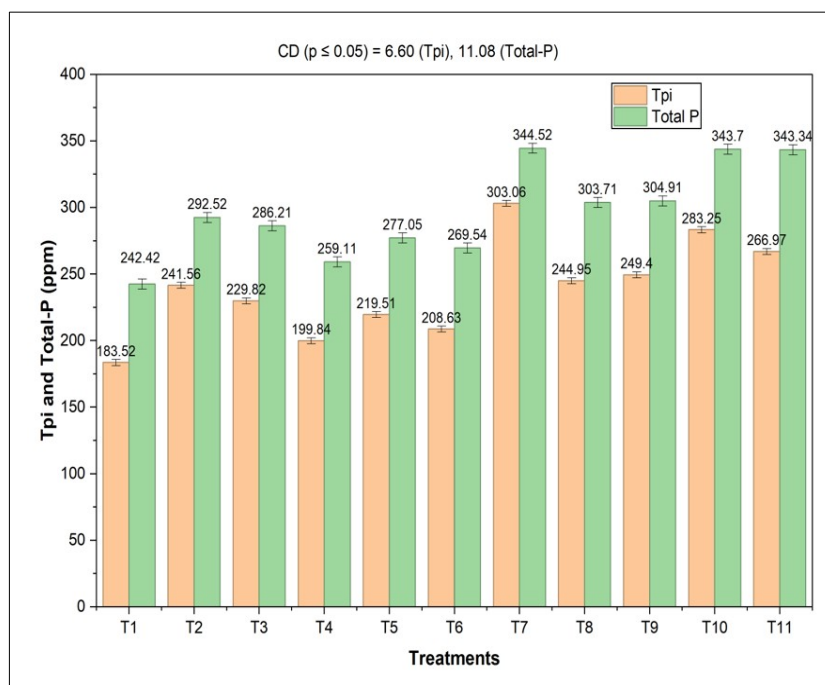


**Fig. 6.** Effect of different levels and sources of phosphorus (P) on total inorganic P (Tpi) and Total-P content in soil (Treatments T<sub>1</sub>–T<sub>11</sub> as in Table 1); vertical bars represent standard error of mean (SEM ±); SEM ± for Tpi and Total-P were 2.24 and 3.76 respectively; critical difference (CD) ( $p \leq 0.05$ ) = 6.60 (Tpi), 11.08 (Total-P). Depictions: Tpi (total inorganic phosphorus); CD (critical difference); SEM ± (standard error of mean).

## Biological yield

Biological yield of pearl millet varied from 74.6–114.36 q ha<sup>-1</sup> (Fig. 7), as agronomic yield data reported earlier (20). The highest biological yield was recorded with FYM + half recommended dose of P through SSP (T<sub>7</sub>) and the lowest in control (T<sub>1</sub>). Full recommended dose of P through SSP, DAP and RP significantly increased biological yield by 39.44, 32.92 and 23.11 %, respectively, over control, ( $p < 0.001$ ). Rock phosphate showed lower biological yield (91.84 q ha<sup>-1</sup>) than DAP (99.16 q ha<sup>-1</sup>) and SSP (104.02 q ha<sup>-1</sup>) which is consistent with previous findings (18, 20). Addition of FYM along with half of recommended dose of P through SSP showed higher biological yield (114.36 q ha<sup>-1</sup>) followed by application of FYM along with half of recommended dose of P through RP (112.18 q ha<sup>-1</sup>) and DAP (106.92 q ha<sup>-1</sup>). The improvement in biological yield was mainly due to the release of more nutrients during decomposition of organic manures. Farmyard manure (FYM) + recommended dose of P through SSP, DAP and RP significantly increased biological yield by 9.94, 7.83 and 22.15 % over full recommended dose of P through SSP, DAP and RP ( $p < 0.001$ ) also reported previously. However, application of FYM + SSP, DAP and RP increased biological yield by 53.3, 43.32 and 50.38 %, respectively, over control.

## Correlation matrix and principal component analysis

The correlation analysis revealed strong and significant associations among soil pH, nutrient availability, P

fractions and biological yield (Fig. 8; Table 2), also reported previously (50). Soil pH was negatively correlated with EC, available N, P, K and S, as well as with all measured P fractions and biological yield, indicating that increasing soil pH was associated with reduced nutrient availability and P fractions. In contrast, EC showed positive relationships with nutrient availability, P fractions, total P and biological yield. Available N, P, K and S were generally positively associated with the P fractions and biological yield, with available N showing particularly strong relationships with available P ( $r = 0.94$ ), total inorganic P ( $r = 0.91$ ), total P ( $r = 0.89$ ) and biological yield ( $r = 0.96$ ;  $p < 0.001$ ). The P fractions were strongly interrelated, suggesting coordinated changes in soil P pools; notably, Ca-P and TPi showed an exceptionally strong correlation ( $r = 0.99$ ,  $p < 0.001$ ). Overall, biological yield was positively associated with nutrient availability and P fractions, whereas soil pH exhibited a strong negative relationship with biological yield ( $r = -0.92$ ). The complete correlation matrix and significance levels are presented in Table 2. The strong responsiveness of inorganic P fractions to total P that observed during study, underscores their key role in regulating P availability. In this study, soil organic matter decomposition with the application of P fertilisers (both organic and inorganic sources) was the major factor that influenced the SOC and labile P that increased overall available P and its fractions (41). Further, the well-correlated attributes were used to generate a minimum data set (MDS) using PCA for soil quality assessment (Fig. 9, Table 3).

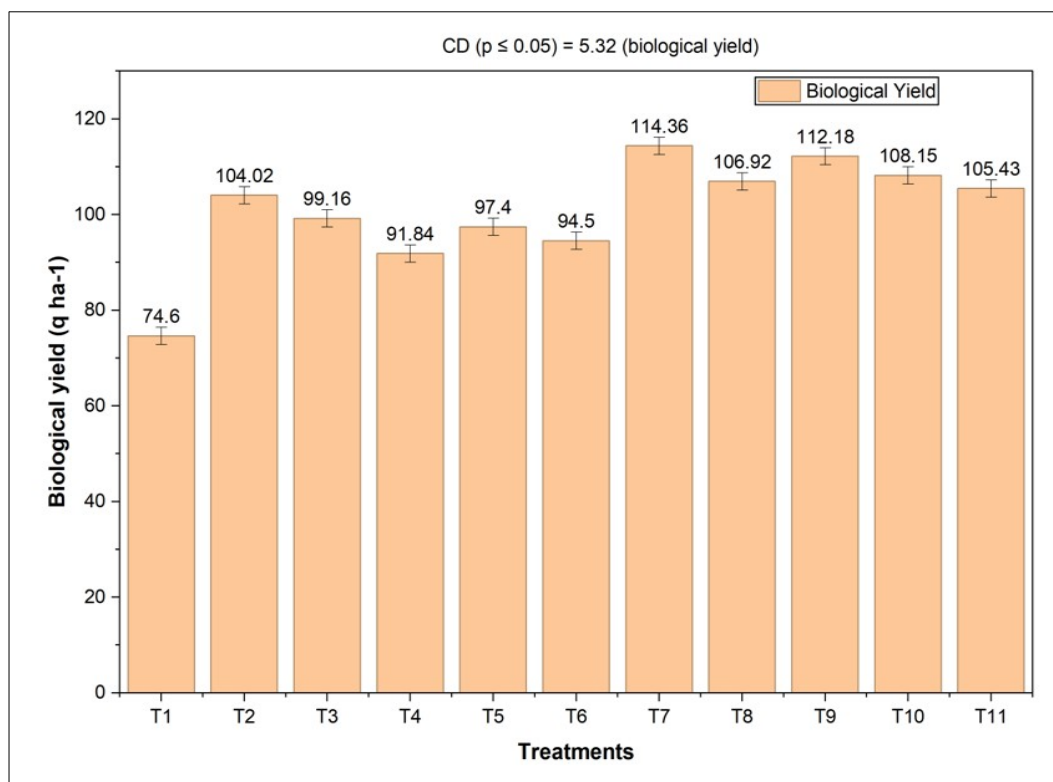


**Fig. 7.** Effect of different levels and sources of phosphorus on biological yield (Treatments T<sub>1</sub>–T<sub>11</sub> as in Table 1); vertical bars represent standard error of mean (SEM ±); SEM ± = 1.80 and critical difference (CD) ( $p \leq 0.05$ ) = 5.32 for biological yield.

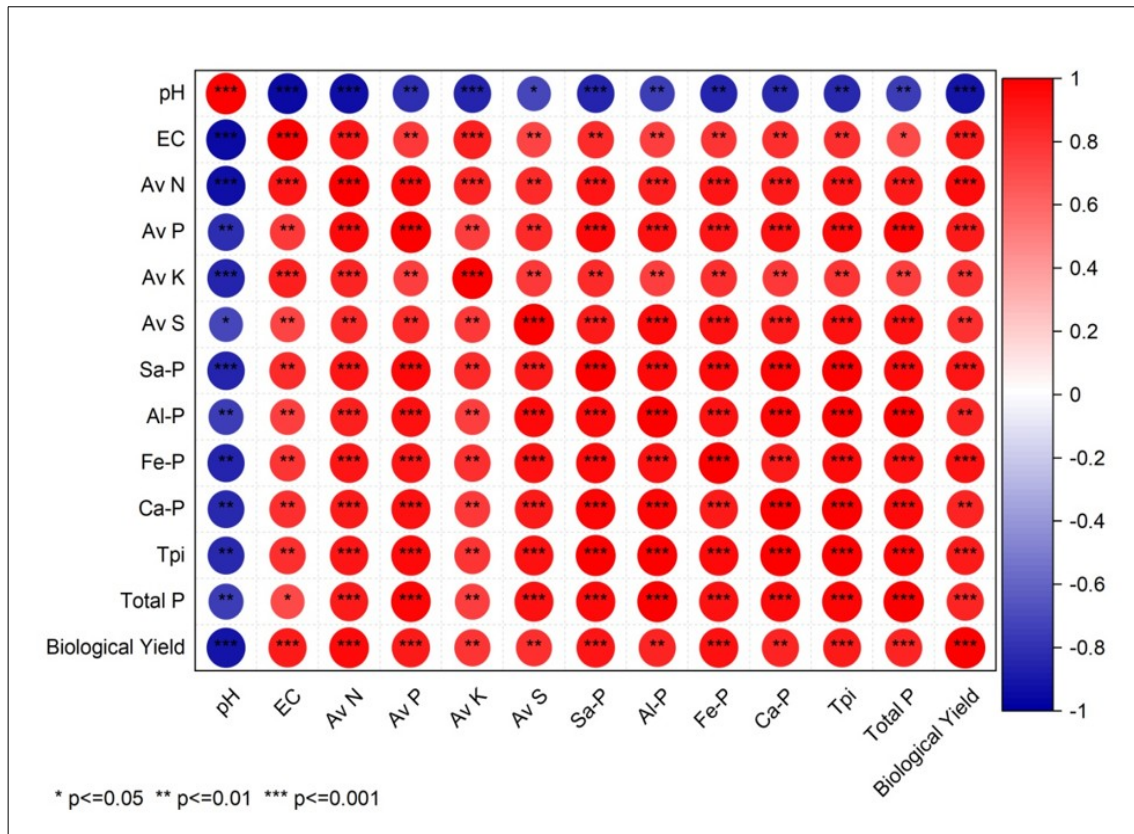


**Fig. 8.** Correlation matrix depicting relationship among soil physico-chemical properties and P fractions. Depictions: Av N (available nitrogen); Av P (available phosphorus); Av K (available potassium); Av S (available sulphur); Sa-P (saloid- phosphorus); Al-P (aluminium- phosphorus); Fe-P (iron- phosphorus); Ca-P (calcium- phosphorus); Tpi (total inorganic phosphorus).

**Table 2.** Correlation matrix depicting relationship among soil physico-chemical properties and phosphorus fractions

|                  | pH      | EC     | Avl N  | Avl P  | Avl K | Avl S  | Sa-P   | Al-P   | Fe-P   | Ca-P   | TPi    | Tot-P | Biological yield |
|------------------|---------|--------|--------|--------|-------|--------|--------|--------|--------|--------|--------|-------|------------------|
| pH               | 1       |        |        |        |       |        |        |        |        |        |        |       |                  |
| EC               | -0.96** | 1      |        |        |       |        |        |        |        |        |        |       |                  |
| Avl N            | -0.93** | 0.91** | 1      |        |       |        |        |        |        |        |        |       |                  |
| Avl P            | -0.82*  | 0.77*  | 0.94** | 1      |       |        |        |        |        |        |        |       |                  |
| Avl K            | -0.86** | 0.87** | 0.85** | 0.75*  | 1     |        |        |        |        |        |        |       |                  |
| Avl S            | -0.71*  | 0.74*  | 0.83*  | 0.83*  | 0.78* | 1      |        |        |        |        |        |       |                  |
| Sa-P             | -0.86** | 0.82*  | 0.90** | 0.94** | 0.82* | 0.89** | 1      |        |        |        |        |       |                  |
| Al-P             | -0.76*  | 0.76*  | 0.88** | 0.93** | 0.75* | 0.94** | 0.96** | 1      |        |        |        |       |                  |
| Fe-P             | -0.84** | 0.78*  | 0.91** | 0.91** | 0.81* | 0.90** | 0.94** | 0.92** | 1      |        |        |       |                  |
| Ca-P             | -0.82*  | 0.80*  | 0.87** | 0.92** | 0.77* | 0.85** | 0.97** | 0.97** | 0.89** | 1      |        |       |                  |
| TPi              | -0.84** | 0.81*  | 0.91** | 0.94** | 0.83* | 0.85** | 0.98** | 0.98** | 0.94** | 0.99** | 1      |       |                  |
| Tot-P            | -0.74*  | 0.71*  | 0.89** | 0.97** | 0.74* | 0.91** | 0.95** | 0.98** | 0.94** | 0.95** | 0.97** | 1     |                  |
| Biological yield | -0.92*  | 0.89*  | 0.96*  | 0.90*  | 0.80* | 0.80*  | 0.91*  | 0.84*  | 0.93*  | 0.84*  | 0.88*  | 0.84* | 1                |

Avl N: available nitrogen; Avl P: available phosphorus; Avl K: available potassium; Avl S: available sulphur; Sa-P: Saloid phosphorus; Al-P: Aluminium phosphorus; Fe-P: Iron-phosphorus; Ca-P: Calcium-phosphorus; TPi: Total inorganic phosphorus; Tot-P: Total-phosphorus.\*\*Correlation is significant at  $p < 0.01$  level; \* Correlation is significant at  $p < 0.05$  level.

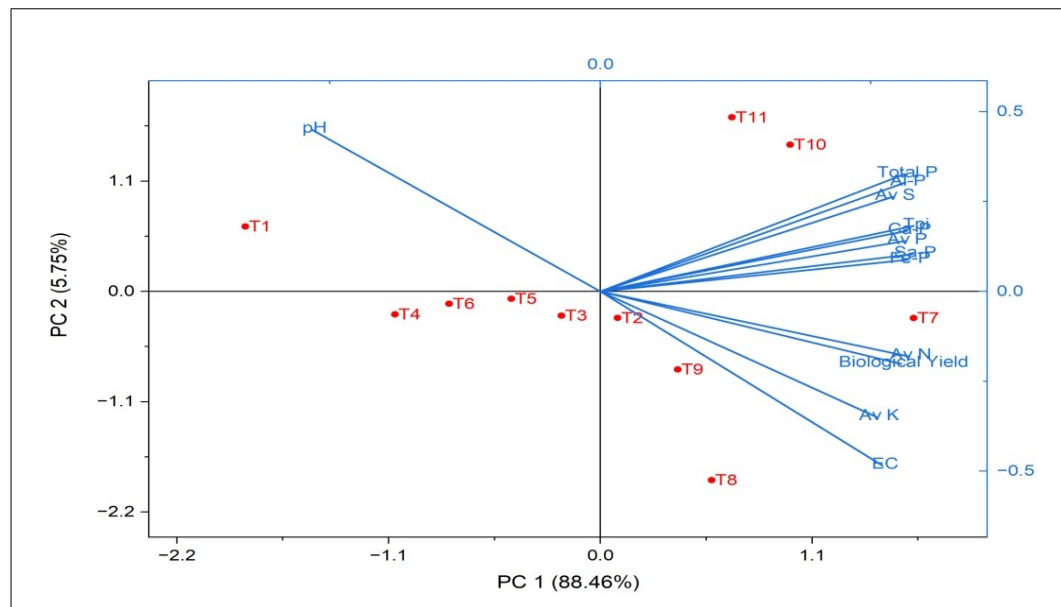


**Fig. 9.** Biplot of soil physico-chemical properties and phosphorus fractions.

**Table 3.** Principal component analysis of soil physico-chemical properties and phosphorus fractions; bold and underline values indicated high loading in principal component

| Statistics       | PC1    | PC2    |
|------------------|--------|--------|
| Total            | 11.50  | 0.75   |
| % of variance    | 88.46  | 5.75   |
| Cumulative %     | 88.46  | 94.21  |
| Eigenvector      |        |        |
| pH               | -0.267 | 0.450  |
| EC               | 0.261  | -0.485 |
| Avl N            | 0.284  | -0.180 |
| Avl P            | 0.281  | 0.140  |
| Avl K            | 0.255  | -0.349 |
| Avl S            | 0.270  | 0.263  |
| Sa-P             | 0.288  | 0.103  |
| Al-P             | 0.282  | 0.303  |
| Fe-P             | 0.284  | 0.088  |
| Ca-P             | 0.283  | 0.168  |
| Tpi              | 0.289  | 0.182  |
| Tot-P            | 0.281  | 0.326  |
| Biological yield | 0.278  | -0.202 |

Avl N: available nitrogen; Avl P: available phosphorus; Avl K: available potassium; Avl S: available sulphur; EC: electrical conductivity; Sa-P: Saloid phosphorus; Al-P: Aluminium phosphorus; Fe-P: Iron-phosphorus; Ca-P: Calcium-phosphorus; Tpi: Total inorganic phosphorus; Tot-P: Total-phosphorus.

For pearl millet, PCA extracted two principal components (PCs) that together explained 94.21 % of the total variance. Although, only PC<sub>1</sub> met the strict Kaiser criterion of eigenvalues > 1.0 (eigenvalue = 11.5, explaining 88.46 % of variance), PC<sub>2</sub> (eigenvalue = 0.75, explaining 5.75 % of variance) was retained to construct a 2D biplot. Retaining PC<sub>2</sub> provided essential visual

separation among experimental treatments and allowed total cumulative explained variance to reach 94.21 %. Principal component 1 (PC<sub>1</sub>) was mainly associated with P dynamics and nutrient availability, as indicated by high loadings of Tpi, Sa-P, available N, Fe-P, Ca-P and Al-P, reflecting the influence of nutrient management practices on soil P transformations and fertility status. Principal component 2 (PC<sub>2</sub>) was primarily represented by EC, indicating variation in soil salinity associated with the treatments. To minimise redundancy, Sa-P was retained from the highly correlated variables in PC<sub>1</sub> because it effectively represented the inorganic P pool, which is closely linked to plant-available P and nutrient cycling, while EC was retained from PC<sub>2</sub> as an indicator of changes in the soil chemical environment. Consequently, the MDS comprised Tpi, Sa-P, available N, Fe-P, Ca-P, Al-P and EC, providing a simplified yet comprehensive set of indicators that captured the major variations in soil fertility and P dynamics for soil quality assessment.

## 4. Conclusion

Integrated nutrient management practices effectively improved soil available nutrients (nitrogen (N), phosphorus (P), potassium (K) and sulphur (S)), P fractions and pearl millet biological yield, with maximum enhancements observed when farmyard manure (FYM) was combined with P fertilisers. Inorganic P fractions followed the dominance order of Ca-P > Fe-P > Al-P > Sa-P. Overall, integrating FYM with P fertilisers improves soil health and crop productivity, though large-scale adoption requires policy support for decentralised organic manure production. Where FYM availability is limited, alternative organic inputs like vermicompost or green manures should be promoted for sustainable P management.

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## Authors' contributions

P<sup>1</sup> contributed to data processing and preparation of the original draft manuscript. SS and DP contributed to the conceptualisation, supervision and formal analysis. RS, RSC, RKS, RY contributed to the formal analysis. P<sup>2</sup> contributed to data arrangement. All authors read and approved the final manuscript. P<sup>1</sup> stands for Preeti and P<sup>2</sup> stands for Priyanka.

## Compliance with ethical standards

### Conflict of interest

Authors do not have any conflict of interests to declare.

### Ethical issues

None

### Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly and the QuillBot Grammar Checker to improve the language, grammar and readability of the manuscript. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

## References

- Raniro HR, Papera J, José LU, Valença RM, Pavinato PS, Hermann L, et al. New investments in phosphorus research and training are paramount for Brazilian long-term environmental and food security. *Environ Syst Decis.* 2023;43(3):504–08. <https://doi.org/10.1007/s10669-023-09903-4>
- Singh P, Dheri GS, Nazir G, Singh S. Impact of long-term use of fertilizers on soil phosphorus fractions and its uptake. *Geoderma Reg.* 2025;43:e01021. <https://doi.org/10.1016/j.geodrs.2025.e01021>
- Dhillon J, Torres G, Driver E, Figueiredo B, Raun WR. World phosphorus use efficiency in cereal crops. *Agron J.* 2017;109:1670–77. <https://doi.org/10.2134/agronj2016.08.0483>
- Prakash D, Benbi DK, Saroa GS. Land-use effects on phosphorus fractions in Indo-Gangetic alluvial soils. *Agrofor Syst.* 2018;92:437–48. <https://doi.org/10.1007/s10457-016-0061-6>
- Turrión MB, Bueis T, Lafuente F, López O, San José E, Eleftheriadis A, et al. Effects on soil phosphorus dynamics of municipal solid waste compost addition to a burnt and unburnt forest soil. *Sci Total Environ.* 2018;642:374–82. <https://doi.org/10.1016/j.scitotenv.2018.06.051>
- Ducoussou-Détrez A, Fontaine J, Lounès-Hadj Sahraoui A, Hijri M. Diversity of phosphate chemical forms in soils and their contributions on soil microbial community structure changes. *Microorganisms.* 2022;10(3):609. <https://doi.org/10.3390/microorganisms10030609>
- Solangi F, Zhu X, Khan S, Rais N, Majeed A, Sabir MA, et al. The global dilemma of soil legacy phosphorus and its improvement strategies under recent changes in agro-ecosystem sustainability. *ACS Omega.* 2023;8(26):23271–82. <https://doi.org/10.1021/acsomega.3c00823>
- Prakash D, Benbi DK, Saroa GS. Clay, organic carbon, available P and calcium carbonate effects on phosphorus release and sorption-desorption kinetics in alluvial soils. *Commun Soil Sci Plant Anal.* 2017;48(1):92–106. <https://doi.org/10.1080/00103624.2016.1253724>
- Sun F, Sun N, Ma X, Zhou B, Zhu P, Gao H, et al. The application of fertilizer phosphorus affected Olsen P and the phosphorus fractions of Hedley method in black soil. *Agronomy.* 2022;12(12):3146. <https://doi.org/10.3390/agronomy12123146>
- Sheoran S, Prakash D, Raj D, Yadav PK, Singh R, Gupta RK, et al. Organic manure and fertilizer N management strategies improve soil health at different growth stages of pearl millet under pearl millet-wheat sequence. *BMC Plant Biol.* 2025;25:117. <https://doi.org/10.1186/s12870-025-06128-2>
- Sharma P, Sheoran S, Prakash D, Priyanka. Levels and sources of phosphorus improve soil organic carbon and microbiological properties under pearl millet-mustard cropping system in semi-arid region. *J Soil Salin Water Qual.* 2026;18:101–12. <https://doi.org/10.56093/jsswq.v18i1.177037>
- Kumari M, Prakash D, Sheoran S, Yadav PK, Ankit, Yadav HK, et al. Long-Term Manuring and Fertilization Influence on Soil Properties and Wheat Productivity in Semi-Arid Regions. *Agron J.* 2024;14:2383. <https://doi.org/10.3390/agronomy14102383>
- Sheoran S, Prakash D, Raj D, Mor VS, Yadav PK, Gupta RK, et al. Long-term organic and N fertilization influence the quality and productivity of pearl millet under PW sequence in north India. *Sci Rep.* 2024;14:19503. <https://doi.org/10.1038/s41598-024-70009-1>
- Deshpande AN, Dalavi SS, Pandey SH, Bhaleraol VP, Gosavi AB. Effect of rock phosphate along with organic manures on soil properties, yield and nutrient uptake by wheat and chickpea. *J Indian Soc Soil Sci.* 2015;63:93–9. <https://doi.org/10.5958/0974-0228.2015.00013.4>
- Dhaliwal SS, Naresh RK, Mandal A, Singh R, Dhaliwal MK. Dynamics and transformations of micronutrients in agricultural soils as influenced by organic matter build-up: A review. *Environ Sust Indic.* 2019;1–2:100007. <https://doi.org/10.1016/j.indic.2019.100007>
- Mussarat M, Ali H, Muhammad D, Mian I, Khan S, Adnan M, et al. Comparing the phosphorus use efficiency of pre-treated (organically) rock phosphate with soluble P fertilizers in maize under calcareous soils distributed. *PeerJ.* 2021;9:e11452. <https://doi.org/10.7717/peerj.11452>
- Anurag, Kumar A, Singh R, Singh D, Kumar M. Long term trends in weather parameters at Hisar (Haryana): A location in semi arid region of North West India. *Int J Recent Sci Res.* 2017;8(7):18087–90. <https://doi.org/10.24327/ijrsr.2017.0807.0449>



18. Prakash D, Sheoran S, Ankit. Effect of different levels of phosphorus through varying sources on productivity and oil content of mustard. *J Plant Dev Sci.* 2021;13(8):603–8.
19. Department of Agricultural Meteorology, CCS Haryana Agricultural University, Hisar. Daily meteorological data of Hisar, 2021. Hisar (India): CCS Haryana Agricultural University; 2021.
20. Preeti, Sheoran S, Prakash D, Singh R, Sharma RK, Chauhan RS, et al. Impact of different levels and sources of P on grain quality and crop productivity of pearl millet in semi-arid region of northwest India. *Intern J Plant Soil Sci.* 2025;37(12):391–401. <https://doi.org/10.9734/ijpss/2025/v37i125901>
21. Page AL, editor. Methods of soil analysis. Part 2: chemical and microbiological properties. 2nd ed. Madison (WI): American Society of Agronomy, Soil Science Society of America; 1982. 1159 p. (Agronomy monograph; no. 9).
22. Jackson ML. Soil chemical analysis. Englewood Cliffs (NJ): Prentice Hall; 1973. 498p.
23. Subbiah BV, Asija CL. A rapid procedure for the estimation of available nitrogen in soil. *Curr Sci.* 1956;25:259–60.
24. Olsen SR, Cole CV, Watanabe FS, Dean LA. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Circular from US Department of Agriculture 939. Washington (DC): USDA; 1954.
25. Chesnin L, Yien CH. Turbidimetric determination of available sulphur. *Soil Sci Soc Am Proc.* 1950;15:149–51. <https://doi.org/10.2136/sssaj1951.036159950015000C0032x>
26. Chang SC, Jackson ML. Fractionation of soil phosphorus. *Soil Sci.* 1957;84:133–44.
27. Peterson GW, Corey RB. A modification of the Chang and Jackson procedure for routine fractionation of inorganic soil phosphates. *Soil Sci Soc Am Proc.* 1966;30:563–65. <https://doi.org/10.2136/sssaj1966.03615995003000050012x>
28. Koenig RA, Johnson CR. Colorimetric determination of phosphorus in biological materials. *Ind Eng Chem Anal Ed.* 1942;14:155–56. <https://doi.org/10.1021/i560102a026>
29. Sheoran OP, Tonk DS, Kaushik LS, Hasija RC, Pannu RS. Statistical software package for agricultural research workers. In: Hooda DS, Hasija RC, editors. Recent advances in information theory, statistics and computer applications. Hisar: Department of Mathematics Statistics, CCS HAU; 1998. p. 139–43.
30. Jolliffe IT. Principal component analysis. 2nd ed. New York: Springer-Verlag; 2002. <https://doi.org/10.1007/b98835>
31. Hair JF, Black WC, Babin BJ, Anderson RE. Multivariate data analysis. 7th ed. Upper Saddle River (NJ): Pearson Prentice Hall; 2010.
32. Tang D, Chen M, Huang X, Zhang G, Zeng L, Zhang G, et al. SRplot: A free online platform for data visualization and graphing. *PLoS One.* 2023;18(11):e0294236. <https://doi.org/10.1371/journal.pone.0294236>
33. Navghare NR, Age AB, Jadhao SD, Rakhonde OS, Pandao MR. The impact of different phosphorus levels on soil fertility, yield, phosphorus dynamics and use efficiency after cotton harvest. *Pharma Innov J.* 2023;12(6):4168–71.
34. Cade-Menun BJ, Bainard LD. Effects of long-term nitrogen and phosphorus fertilization on soil phosphorus forms and dynamics under continuous wheat production in Saskatchewan, Canada. *Can J Chem.* 2024;103(6):351–65. <https://doi.org/10.1139/cjc-2024-0079>
35. Rawal N, Pande KR, Shrestha R, Vista SP. Phosphorus and potassium mineralization as affected by phosphorus levels and soil types under laboratory condition. *Agrosyst Geosci Environ.* 2022;5(1):e20229. <https://doi.org/10.1002/agg2.20229>
36. Hou J, Yi G, Hao Y, Li L, Shen L, Zhang Q. The effect of combined application of biochar and phosphate fertilizers on phosphorus transformation in saline-alkali soil and its microbiological mechanism. *Sci Total Environ.* 2024;951:175610. <https://doi.org/10.1016/j.scitotenv.2024.175610>
37. Li S, Chen X, Wang Z, Wu D, Wang M, Müller T, et al. Phosphorus fertilizer management for high yields in intensive winter wheat-summer maize rotation system: Integrating phosphorus budget and soil available phosphorus. *Field Crops Res.* 2024;313:109410. <https://doi.org/10.1016/j.fcr.2024.109410>
38. Iwasaki S, Ikazaki K, Somda BB, Bandaogo A, Bougma A, Koide J, et al. Soil-crop phosphorus interactions in sub-Saharan Africa and feasibility of local fertilizers produced from low-grade phosphate rock. *Field Crops Res.* 2026;336:110158. <https://doi.org/10.1016/j.fcr.2025.110158>
39. Luo L, Li N, Sha W, Li Z, Chai R, Zhang L, et al. Novel phosphorus fertilizers enhance rice yield, efficiency and environmental sustainability by optimizing soil phosphorus pools in paddy fields. *Soil Tillage Res.* 2026;255:106833. <https://doi.org/10.1016/j.still.2025.106833>
40. Liang Y, Liu J, Jin J, Han Y, Wei Z. Effects of low-molecular-weight organic acids on the transformation and phosphate retention of iron (hydr)oxides. *Sci Total Environ.* 2024;940:173667. <https://doi.org/10.1016/j.scitotenv.2024.173667>
41. Meshram P, Patil A, Jadhav A, Gosavi A, Bagade P. Influence of different sources and levels of phosphorus on nutrient use efficiency (NUE) and properties of low calcareous soil. *Int J Basic Appl Res.* 2024;30(6):36–44. <https://doi.org/10.56557/jobari/2024/v30i68937>
42. Wang Y, Zhang W, Müller T. Soil phosphorus availability and fractionation in response to different phosphorus sources in alkaline and acid soils: a short-term incubation study. *Sci Rep.* 2023;13:5677. <https://doi.org/10.1038/s41598-023-31908-x>
43. More G, Sawant PS, Khobragade NH, Meshram NA, Rajamahadik VA, Pawar SV. Effect of different sources of phosphorus on soil properties, growth, yield, quality and nutrient content in green gram (*Vigna radiata* L.). *Int J Res Agron.* 2024;7(1):320–24. <https://doi.org/10.33545/2618060X.2024.v7.i1e.233>
44. Qiong W, Qin ZH, Zhang WW, Chen Y, Zhu P, Chang P, et al. Effect of long-term fertilization on phosphorus fractions in different soil layers and their quantitative relationships with soil properties. *J Integr Agric.* 2022;21(9):2720–33. <https://doi.org/10.1016/j.jia.2022.07.018>
45. Meena MD, Biswas DR. Effect of rock phosphate enriched compost and chemical fertilizers on microbial biomass phosphorus and phosphorus fractions. *Afr J Microbiol Res.* 2018;9:1519–26. <https://doi.org/10.5897/AJMR2014.6957>
46. Saha BN, Saha S, Podder P, Chand T. Phosphate fractions as influenced by long term phosphorus fertilization. *Indian J Agric Res.* 2013;47(1):59–65.
47. Biassoni MM, Vivas H, Gutiérrez-Boem FH, Salvaggiotti F. Changes in soil phosphorus (P) fractions and P bioavailability after 10 years of continuous P fertilization. *Soil Tillage Res.* 2023;232:105777. <https://doi.org/10.1016/j.still.2023.105777>

48. Khan A, Guo S, Wang R, Zhang S, He B, Li T. An assessment of various pools of organic phosphorus distributed in soil aggregates as affected by long-term P fertilization regimes. *Soil Use Manage.* 2023;39(2):833–48. <https://doi.org/10.1111/sum.12901>
49. Hussain A, Muhammad AJ, Abid K, Chen L, Khan L, Duan W, et al. Variations in soil phosphorus fractionations in different water-stable aggregates under litter and inorganic fertilizer treatment in Korean pine plantation and its natural forest. *Heliyon.* 2023;9(6):e17261. <https://doi.org/10.1016/j.heliyon.2023.e17261>
50. Filho JFL, Rodrigues RS, Melo LCA, Figueiredo CC. Changes in phosphorus due to pyrolysis and in the soil-plant system amended with sewage sludge biochar compared to conventional P fertilizers: A global meta-analysis. *Chemosphere.* 2025;371:144055. <https://doi.org/10.1016/j.chemosphere.2024.144055>

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