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Levels and Sources of Phosphorus Improve Soil Organic Carbon and Microbiological Properties under Pearl Millet-Mustard Cropping System in Semi–Arid Region

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Abstract

This study aimed to elucidate the impact of varying phosphorus sources and levels on soil organic carbon (SOC), dissolved organic carbon (DOC) and microbiological properties in semi–arid regions of northwest India. Application of P fertilisers (SSP; single super phosphate, DAP; di-ammonium phosphate, RP; rock phosphate) either alone or in combination with farmyard manure (FYM) improved SOC and DOC content in soil, and the highest SOC (0.60%) and DOC (20.30 mg kg^{-1}) was observed with the conjoint application of FYM with SSP. Application of FYM along with P fertilisers significantly increased the alkaline phosphatase and aryl sulphatase activity as compared to sole P fertilisers; however, a non–significant increment was observed for urease activity. Among P fertilisers, higher enzyme activity was observed with DAP (29.25 µg NH^{+} g^{-1} hr^{-1} as urease activity; 321.52 and 260.81 ìg PNPg^{-1} hr^{-1}, as alkaline phosphatase and aryl sulphatase, respectively) as compared to SSP and RP. Conjoint application of P fertilisers and FYM significantly increased microbial biomass in soil and the highest microbial biomass carbon (224.42 mg kg^{-1}), nitrogen (26.38 mg kg^{-1}), phosphorus (17.00 mg kg^{-1}) and sulphur (15.15 mg kg^{-1}) was recorded with application of 7.5 t FYM ha^{-1} along with SSP. The results conclusively indicated that the application of FYM, along with P fertilisers, played a pivotal role in enhancing soil chemical and microbiological properties under the pearl millet–mustard cropping system.

Keywords: Enzymatic activities, Farmyard manure, Microbial biomass, Phosphorus, Soil organic carbon

Introduction

A vital indicator for assessing soil health, fertility and atmospheric CO_2 sequestration is soil organic carbon (SOC) content and storage. The SOC affects physicochemical and microbiological properties of soil especially in arid and semi–arid areas, as SOC controls the soil structure, water and nutrients use efficiency (Kumari *et al.,* 2024; Wei *et al.*, 2025; Kumar *et al.*, 2024). The SOC decomposition *via* microbial activity regulates nutrient cycling and bioavailability in soil (Ankit *et al.,* 2024). Active pools of organic carbon, such as microbial biomass C (MBC) and dissolved organic C (DOC), constitute a very small fraction of SOC (<1%) but play a major role in the mobility of soluble nutrients. Because they are sensitive to management practices, these pools can serve as early indicators of changes in soil quality. Organic and inorganic fertilisation improves the accumulation of SOC and its pools in soil; therefore, they promote sustainable soil health (Sheoran *et al.,* 2024; Basak *et al.*, 2021). Recent studies have highlighted the role of exogenous nutrient applications, such as P, in enhancing SOC mineralisation by competing with SOC for binding sites on the surfaces of Fe/Al oxides (Thaqi *et al.,* 2025). Ultimately, this P-induced SOC desorption increased DOC content; however, the mineralisation rate is controlled by both the quantity and quality of SOC, especially in slightly saline soils of semi–arid regions (Sundha et al. 2017, 2023). Earlier studies also showed that the application of P fertilisers alters the carbon source preferences of soil microorganisms, thereby increasing the concentrations of active organic carbon pools, such as DOC and MBC (Xia *et al.,* 2024). But because P is the most immobile and inaccessible nutrient in the soil, only a small amount is available to plants and microorganisms. So, P deficiency in soil restricts plant growth, crop productivity, and global SOC reservoirs (Du *et al.,* 2020). Single superphosphate (SSP) and diammonium phosphate (DAP) are commonly used inorganic P fertilisers, but the high prices of chemical fertilisers still render them beyond the reach of poor farmers in India (Prakash *et al.,* 2022). The integrated use of manures and chemical fertilisers can not only maximise crop production and improve the quality of agricultural produce but also help maintain soil fertility, productivity, and overall soil health by enhancing soil organic carbon (SOC) content and stimulating microbial activity (Preeti *et al.*, 2025). However, the use of manures and inorganic fertilisers may affect SOC and microbial communities differently due to contrasting nutrient availability and inherent soil quality.

Soil microorganisms directly influence soil durability and functioning, and changes in the composition and activity of the microbial community may affect plant diversity and productivity (Sheoran *et al.,* 2025). They are the key drivers of nutrient transformation in soil and directly control nutrient use efficiency. Conversely, the addition of nutrients, especially N, P and micronutrients, to soil also influences the diversity, population and functioning of microorganisms. The microbial activities are also positively correlated with SOC and P fertilisation (Qaswar *et al.*, 2022). P fertilisation enhances nutrient availability for microbial growth and metabolism, thereby increasing SOM decomposition (Wei *et al.,* 2025). Incorporating SOM into soil improves microbial activity because it serves as a substrate for microbial growth and development. So, the combined use of manures and chemical fertilisers can increase the sustainability of the agricultural system over the long term and directly affect soil quality, productivity, the composition of the microbial community, and functional diversity. Therefore, an experiment was conducted to evaluate the impact of different levels and sources of phosphorus application on SOC, DOC, and microbiological properties in a pearl millet–mustard cropping system in the semi-arid regions of North–west India.

Materials and Methods

Study location, treatment details and replications

The field experiment of the effect of different levels of phosphorus through varying sources in the pearl millet–mustard cropping system was initiated in *Rabi*, 2020, by sowing mustard variety (RH–725) at Research Farm, Department of Soil Science, Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana; however, the present study includes the data of *kharif* 2021 sown pearl millet. The experimental site is located at 29°01′00″ latitude and 75°04′00″ longitude in the north–west part of India. The climate of the study area is semi–arid, with a mean annual temperature of 24.80 °C and a mean annual precipitation of 443 mm, 90% of which is received during June to September. 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%; wind speed averaged 6–10 km h^{-1}; sunshine hours varied from 4–9 h day^{-1}. Soil was sandy loam in texture with 65% sand, 20% silt, and 15% clay. Initial soil $pH_{1:2}$ 7.98, electrical conductivity ($EC_{1:2}$) 0.31 dS m^{-1} and soil organic carbon (SOC) as 0.45%. Soil available nitrogen, phosphorus and potassium were 134.0, 12.24 and 420.0 kg ha^{-1}, respectively. The experiment comprised a total of eleven treatments, including recommended doses of P *via* fertilisers [di–ammonium phosphate (DAP), rock phosphate (RP) and single super phosphate (SSP)] or half of the recommended P fertilisers along with 7.5 Mg FYM ha^{-1} replicated three times on the permanent plots in a randomised block design. The details of treatments are shown in Table 1. The FYM, having $pH_{1:5}$ 7.4, $EC_{1:5}$ 2.1 dS m^{-1}, organic carbon 24.5% with a C: N ratio 21:1,

Table 1. Treatment details carried out during the experiment

Treatment	Pearl millet (HHB 299)	Mustard (RH 725)
T1	Control (no phosphorus treatment)	Control (no phosphorus treatment)
T2	60 kg P through SSP	20 kg P through SSP
T3	60 kg P through DAP	20 kg P through DAP
T4	60 kg P through RP	20 kg P through RP
T5	60 kg P through RP	20 kg P through SSP
T6	60 kg P through RP	20 kg P through DAP
T7	FYM @ 7.5 Mg ha^{-1} + 30 kg P through SSP	FYM @ 7.5 Mg ha^{-1} + 10 kg P through SSP
T8	FYM @ 7.5 Mg ha^{-1} + 30 kg P through DAP	FYM @ 7.5 Mg ha^{-1} + 10 kg P through DAP
T9	FYM @ 7.5 Mg ha^{-1} + 30 kg P through RP	FYM @ 7.5 Mg ha^{-1} + 10 kg P through RP
T10	FYM @ 7.5 Mg ha^{-1} + 30 kg P through RP	FYM @ 7.5 Mg ha^{-1} + 10 kg P through SSP
T11	FYM @ 7.5 Mg ha^{-1} + 30 kg P through RP	FYM @ 7.5 Mg ha^{-1} + 10 kg P through DAP

SSP- single super phosphate, DAP- di-ammonium phosphate, RP- rock phosphate, P- phosphorus and FYM- farmyard manure

was applied on a dried weight basis before sowing of pearl millet. The total nutrient contents in FYM were 0.68% N, 0.32% P, 0.58% K, 1.12% Ca, 0.36% Mg, and 0.18% S. The FYM also contained appreciable amounts of micronutrients, namely Fe (4850 mg kg^{-1}), Mn (320 mg kg^{-1}), Zn (95 mg kg^{-1}), and Cu (28 mg kg^{-1}). The entire dose of phosphorus was applied as a basal application at the time of sowing. Nitrogen 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 days after sowing (DAS) in all treatments except the control. 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^{-1} was used, and seedlings were thinned at 15–20 DAS to maintain the desired plant population. The recommended dose of fertilisers (RDF) applied was 60 kg N and 30 kg P_2O_5 ha^{-1}. 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 in a timely manner. This study presented data on the pearl millet (*Pennisetum glaucum* L.) crop.

Sample collection, preparation and analysis

Composite soil samples from individual plots were collected using an auger at a depth of 0–15 cm after harvest of the pearl millet crop in November 2021 and stored in polythene bags. For analysis of chemical properties, soil samples were air dried, crushed with a wooden roller and sieved (2 mm sieve) in the laboratory for further analysis. The microbiological parameters were analysed from moist, freshly collected samples and expressed on an oven-dry weight basis. The SOC content was determined using the Walkey and Black (1934) wet-digestion method, and the DOC content was estimated following the method of Ciavitta *et al.* (1989). Microbial biomass carbon (MBC) (Vance *et al.,* 1987), microbial biomass nitrogen (MBN) (Brookes *et al.,* 1985), microbial biomass phosphorus (MBP) (Jenkinson, 1966), and microbial biomass sulphur (MBS) (Jenkinson, 1966) were estimated using the fumigation extraction method. Urease activity was measured according to the method of Tabatabai and Bremner (1972). Alkaline phosphatase activity (APA) was measured by using the method described by Tabatabai and Bremner (1969). Activity of aryl sulfatase enzyme was determined by using the method proposed by Tabatabai and Bremner (1970).

The experimental results were analysed using an online statistical analysis tool (OPSTAT: Sheoran *et al.,* 1998). The critical difference (CD) value was calculated using a 5% significance level (α = 0.05). Correlation matrix and PCA of data analysed through SRplot (Tang *et al.,* 2023).

Results and Discussion

Soil organic carbon (SOC)

Application of P fertilisers either alone or in combination with FYM improved soil organic carbon (SOC) content over initial values (0.45%), and this observation is in line with Grant *et al.* (2022); Qin *et al.* (2024); Thaqi *et al.* (2025) and Wei *et al.* (2025). SOC content in soil after pearl millet harvest varied from 0.44 to 0.60% under different treatments (Fig. 1). The highest and lowest SOC content were observed with the application of 7.5 Mg FYM ha^{-1} along with P dose through SSP (T_7) and control plots (T_1), respectively. Application of the full recommended dose of P through various P fertilisers increased SOC content compared with the control, but the effect was significant only in treatments T2, T3, and T5. The effect of various P fertilizers on SOC accrual in soil was apparent. Application of the full recommended dose of P through RP resulted in a lower SOC content (0.47%) compared with DAP (0.51%) or SSP (0.53%), consistent with the observations of Meena *et al.* (2023). It may be due to RP having poor solubility and low P availability, especially under alkaline soil conditions, resulting in lower biomass production and organic matter addition. However, the higher SOC under DAP and SSP was due to greater phosphorus availability, which promoted crop growth and the incorporation of residues into the soil. Like the sole application of P fertilisers, incorporating half the recommended dose of P through chemical fertilisers, along with 7.5 Mg FYM ha^{-1}, significantly increased soil SOC compared with the control. The SOC content was not significantly higher with the application of FYM along with SSP (0.60%) compared with the addition of FYM along with DAP (0.57%) or RP (0.55%). Application of FYM along with SSP, DAP, or RP increased SOC content compared with the sole application of P fertilisers; however, the effect was significant only in treatments T7, T9, and T10. SOC content in soil increased by 20.45, 15.90 and

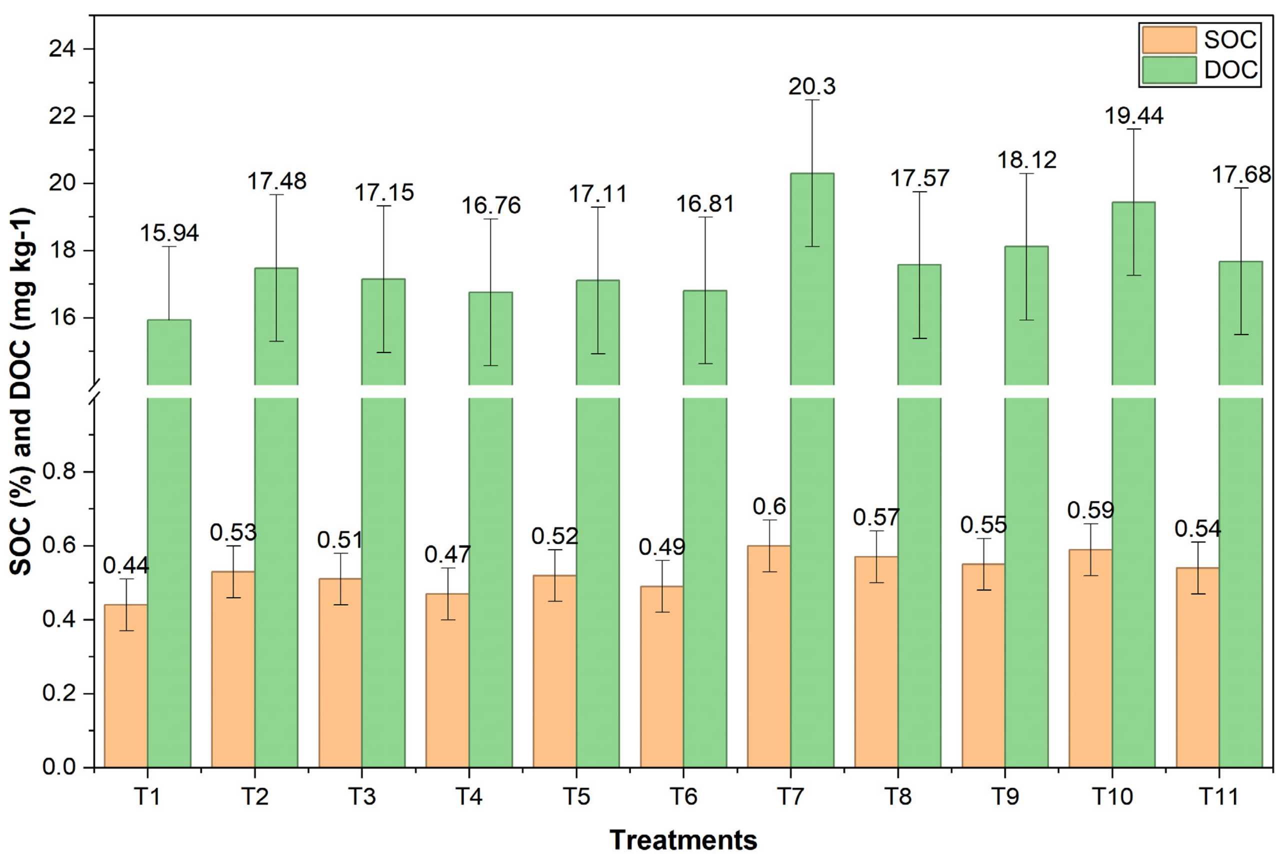

Fig. 1 Effect of different levels and sources of phosphorus on soil organic carbon (SOC) and dissolved organic carbon (DOC) content in soil. (Treatments T1 to T11 as in Table 1).

6.82%, respectively, over control plots with the addition of full recommended dose of P through SSP, DAP and RP. However, incorporation of half the recommended dose of P through SSP, DAP, and RP, along with 7.5 Mg FYM ha^{-1}, increased the SOC content in soil by 13.21, 11.76, and 14.89%, over the application of the full recommended dose of P *via.* SSP, DAP and RP in both crops, respectively, like the findings of Govednik *et al.* (2023). The increase in SOC may be attributed to the direct addition of organic carbon through FYM, improvement in soil physical environment, enhanced microbial proliferation and activity, and greater stabilisation of organic matter within soil aggregates. Furthermore, the combined application of FYM and phosphorus fertilisers promoted root growth and biomass production, resulting in higher root exudation and greater return of crop residues to the soil, thereby contributing to increased SOC accumulation (Sheoran *et al.,* 2024).

Dissolved organic carbon

Dissolved organic carbon (DOC) constitutes a very small fraction of SOC (<1%) but plays a major role in the mobility and bioavailability of soluble nutrients (Silveira *et al*., 2005). The DOC content in soil ranged from 15.94 to 20.30 mg kg^{-1} across various treatment combinations (Fig. 1). Application of P fertilisers increased the DOC content in soil relative to the control (Wei *et al.,* 2024), thereby making more C available to soil microbes. Application of the full recommended dose of P through various fertilisers increased the DOC content in soil over the control; however, the effect was apparent. The full recommended dose of P applied through RP showed a lower DOC content (16.76 mg kg^{-1}) than DAP (17.15 mg kg^{-1}) and SSP (17.48 mg kg^{-1}). The addition of 7.5 Mg FYM ha^{-1}, in combination with half the recommended dose of P through fertilisers, increased the DOC content over the control, but the effect was significant only in T_7, T_9 and T_{10}. Application of FYM along with SSP (20.30 mg kg^{-1}) resulted in higher DOC content than FYM with RP (18.12 mg kg^{-1}) or DAP (17.57 mg kg^{-1}). The integrated application of FYM along with SSP significantly increased DOC content compared with the sole application of P through SSP. However, the effect of FYM along with DAP or RP was non–significant to full recommended dose of respective fertilizers P. Application of FYM increased C content in soil, which liberated more DOC, due to the rapid mineralization of labile organic compounds present in FYM, leading to greater microbial activity and improved carbon turnover in the soil (Ankit *et al.,* 2024; Sheoran *et al.,* 2025).

Microbial biomass carbon, nitrogen, phosphorus and sulphur

The microbial biomass carbon (MBC) content of soil after pearl millet cultivation ranged between 137.41 to 224.42 mg kg^{-1} under various treatments (Fig. 2). The increase in MBC content of soil with the application of P fertilisers over control showed that exogenous P application enhanced microbial activity and SOC mineralisation (Qin *et al.,* 2024; Thaqi *et al*., 2025; Wei *et al.,* 2025). The highest MBC content was observed with the incorporation of 7.5 t FYM ha^{-1}, along with half the recommended dose of P through SSP (224.42 mg kg^{-1}). Treatment with the full recommended dose of P through SSP, DAP, and RP (182.22, 176.51, and 157.61 mg kg^{-1}, respectively) significantly increased the MBC content in soil compared with the control (137.41 mg kg^{-1}). Results showed that adding the full recommended dose of P through SSP significantly increased MBC content in soil compared with DAP and RP, consistent with the observations of Meena *et al.* (2023). Similarly, application of 7.5 t FYM ha^{-1} in combination with half of the recommended dose of P through SSP, DAP and RP (224.42, 217.91 and 192.81 mg kg^{-1}, respectively) increased the MBC content over control ($P < 0.05$). In comparison to the full recommended dose of P applied through SSP, DAP and RP, application of half of the recommended dose of P through SSP, DAP and RP, along with FYM, recorded significantly higher MBC content in soil after pearl millet harvest. The higher MBC under INM treatments might be attributed to increased root exudates, more SOC, and available N content, in addition to SOM added through organic manures. Incorporation of half of the recommended dose of P through SSP, DAP and RP, along with 7.5 Mg FYM ha^{-1}, increased the MBC content of soil by 23.15, 23.45

and 22.33%, over application of the full recommended dose of P through SSP, DAP and RP.

The data related to MBN content in soil showed in Fig. 2 ranged between 11.67 and 26.38 mg kg^{-1} under various treatments and application of various P fertilisers increased the MBN content over control, similar to the earlier observations (Qin *et al.,* 2024; Thaqi *et al.*, 2025; Wei *et al.,* 2025). Use of various P fertilisers, *viz*. SSP, DAP, and RP (18.11, 17.75, and 15.53 mg kg^{-1}, respectively) significantly increased the MBN content over the control (11.67 mg kg^{-1}). The addition of the full recommended dose of P through SSP resulted in higher MBN content in the soil, followed by DAP and RP. Incorporation of 7.5 Mg FYM ha^{-1} along with half of the recommended dose of P through SSP showed higher MBN content (26.38 mg kg^{-1}), followed by FYM along with DAP (25.50 mg kg^{-1}) or RP (21.62 mg kg^{-1}). Supply of FYM along with half of the recommended dose of P through SSP, DAP and RP showed a higher MBN content as compared to the full recommended dose of P through SSP, DAP and RP ($p < 0.05$). The addition of higher SOC content results in more root proliferation, and additional N supply through organic manures increased the level of MBN in organically amended plots (Sheoran *et al.,* 2024). Incorporation of half of the recommended dose of P through SSP, DAP, and RP, along with 7.5 Mg FYM ha^{-1} in both the crops, increased the MBN content of soil by 45.66, 43.66 and 39.21%, over application of the full recommended dose of P through SSP, DAP and RP in both crops.

The microbial biomass P (MBP) content is a potential biological index for P availability in soil. The results of the present study revealed that MBP content in soil ranged between 6.71 to 17.00 mg kg^{-1} under various treatment combinations (Fig. 2). Incorporation of various P fertilisers (13.04, 11.83 and 7.75 mg kg^{-1} for SSP, DAP and RP, respectively) significantly increased the MBP

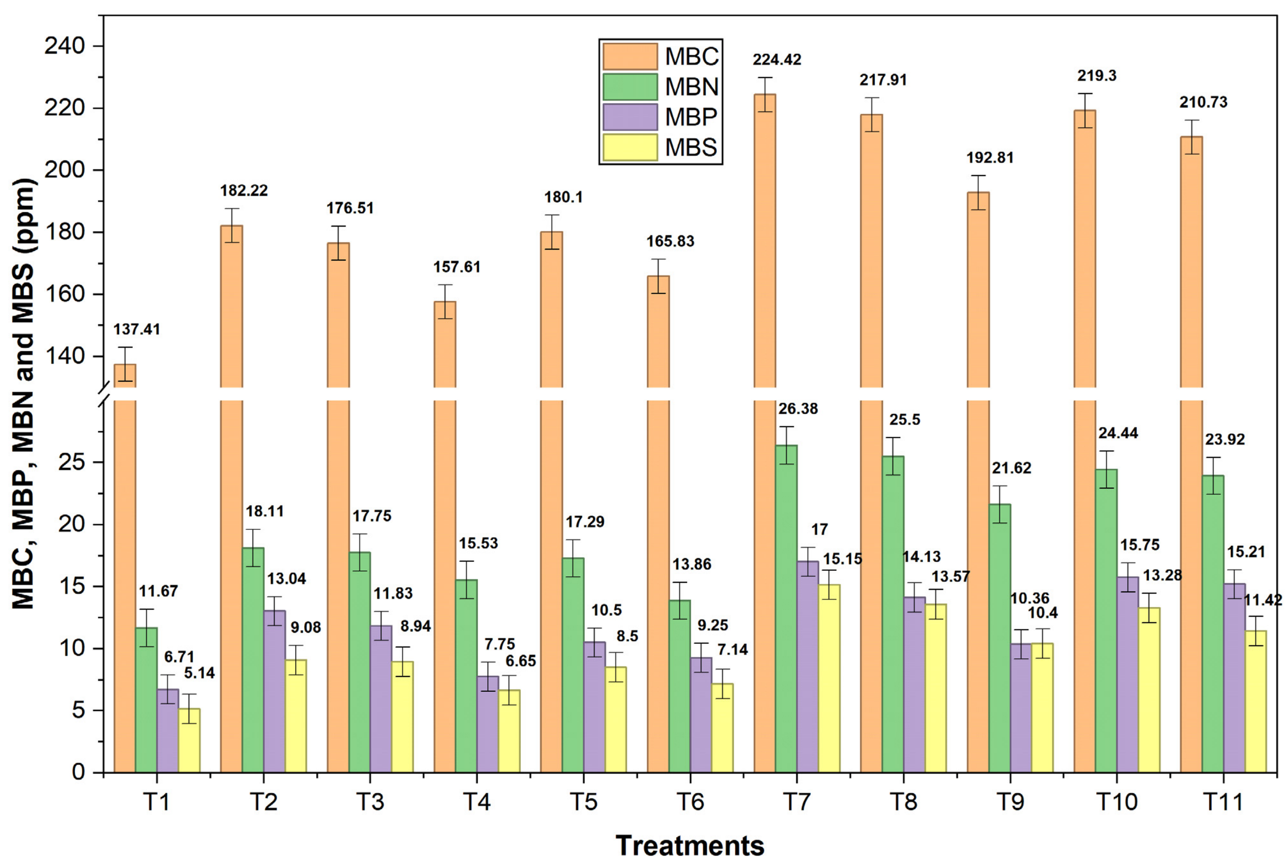

Fig. 2 Effect of different levels and sources of phosphorus on MBC, MBN, MBP and MBS content in soil (Treatments as in Table 1) Depictions: MBC-microbial biomass carbon, MBN-microbial biomass nitrogen, MBp- microbial biomass phosphorus, MBS-microbial biomass sulphur

content over the control (6.71 mg kg^{-1}) except T_4. Increased MBP in soil with P fertilisation has also been reported by Chen *et al.* (2023) and Solangi *et al.* (2024). The supply of the full recommended dose of P through SSP resulted in significantly higher MBP content in soil (13.04 mg kg^{-1}) than DAP (11.83 mg kg^{-1}) and RP (7.75 mg kg^{-1}), consistent with the findings of Touhami *et al.* (2022). Similarly, incorporation of FYM along with half of the recommended dose of P through SSP (17.00 mg kg^{-1}) showed a higher MBP in soil as compared to FYM added with half the dose of P through DAP (14.13 mg kg^{-1}) or RP (10.36 mg kg^{-1}; $P < 0.05$). MBP content of soil increased by 94.33, 76.30 and 15.49%, respectively, over control with the application of full recommended dose of P through SSP, DAP and RP. Application of half the recommended dose of P through SSP, DAP, RP, along with 7.5 t FYM ha^{-1} in both the crops, increased the MBP content of soil by 30.36, 19.44 and 33.67%, over application of the full recommended dose of respective P fertilisers in both crops, respectively. Co–utilisation of organic manures and chemical fertilisers significantly regulates P availability in soil for better crop production, a finding supported by earlier studies (Wei *et al.,* 2025).

The microbial biomass S (MBS) fraction of total organic S in soil is relatively labile, and the most active pool for S turnover in soil. The MBS content in soil fluctuated between 5.14 and 15.15 mg kg^{-1} across various treatment combinations (Fig. 2) and adopting different nutrient management practices increased the MBS content in soil relative to the control. The full recommended dose of P applied through SSP, DAP and RP (9.08, 8.94 and 6.65 mg kg^{-1}, respectively) increased the MBS content compared with the control (5.14 mg kg^{-1}; $p > 0.05$). Use of FYM, along with half the recommended dose of P through SSP, resulted in higher MBS content than the application of FYM with DAP or RP ($p > 0.05$). Application of the full recommended dose of P through SSP, DAP, and RP in both crops increased the soil MBS content by 76.65%, 73.92%, and 29.37%, respectively, over the control treatment. Combined application of half recommended dose of P through SSP, DAP, RP, along with 7.5 t FYM ha^{-1} increased the MBS content of soil by 66.85, 51.78 and 56.39%, over application of full recommended dose of P through SSP, DAP and RP, respectively, that may be due to more substrate availability in confirmation to the reporting of Grant *et al.* (2022).

Soil enzymes activities

Urease is mainly produced by plants and microorganisms and regulates N availability in soil by catalysing urea hydrolysis. Under various treatments, urease enzyme activity in soil exhibited a range of 20.80 to 29.25 µg NH_4^+ g^{-1} hr^{-1} (Fig. 3). Use of various P fertilizers (24.97, 27.12 and 25.75 µg NH4$^+$ g^{-1} hr^{-1} for SSP, DAP and RP, respectively) significantly increased the urease activity over control (20.80 µg NH_4^+ g^{-1} hr^{-1}) also reported by Wei *et al.* (2024). Application of the full recommended dose of P through DAP showed higher urease activity in soil, followed by P through RP and SSP. It might be due to the additional N supply from DAP, which increased substrate availability; ultimately, the higher microbial population produced more extracellular enzymes. Urease activity was found higher with the incorporation of 7.5 Mg FYM ha^{-1} along with half of the recommended dose of P through DAP (29.25 µg NH_4^+ g^{-1} hr^{-1}) as compared to FYM along with SSP (27.03µg NH_4^+ g^{-1} hr^{-1}) or RP (25.69 µg NH_4^+ g^{-1} hr^{-1}). Integrated use of FYM along with half dose of P through SSP and DAP non–significantly increased urease activity as compared to full recommended dose of P through SSP and DAP, like the observations of Govednik *et al.* (2023); Yaganoglu *et al.* (2024), Ankit *et al.* (2024); and Kumari *et al.* (2024). However, the application of FYM along with half the recommended dose of P through RP did not decrease urease activity compared with the full recommended dose of RP ($p < 0.05$). Application of half of the recommended dose of P through SSP and DAP, along with 7.5 Mg FYM ha^{-1} in both the crops, increased the urease activity by 8.2 and 7.85%, over application of the full recommended dose of P through SSP and DAP in both crops.

The results showed that alkaline phosphatase activity in soil varied between 154.40 to 335.95 µg PNP g^{-1} hr^{-1} under various treatments (Fig. 3).

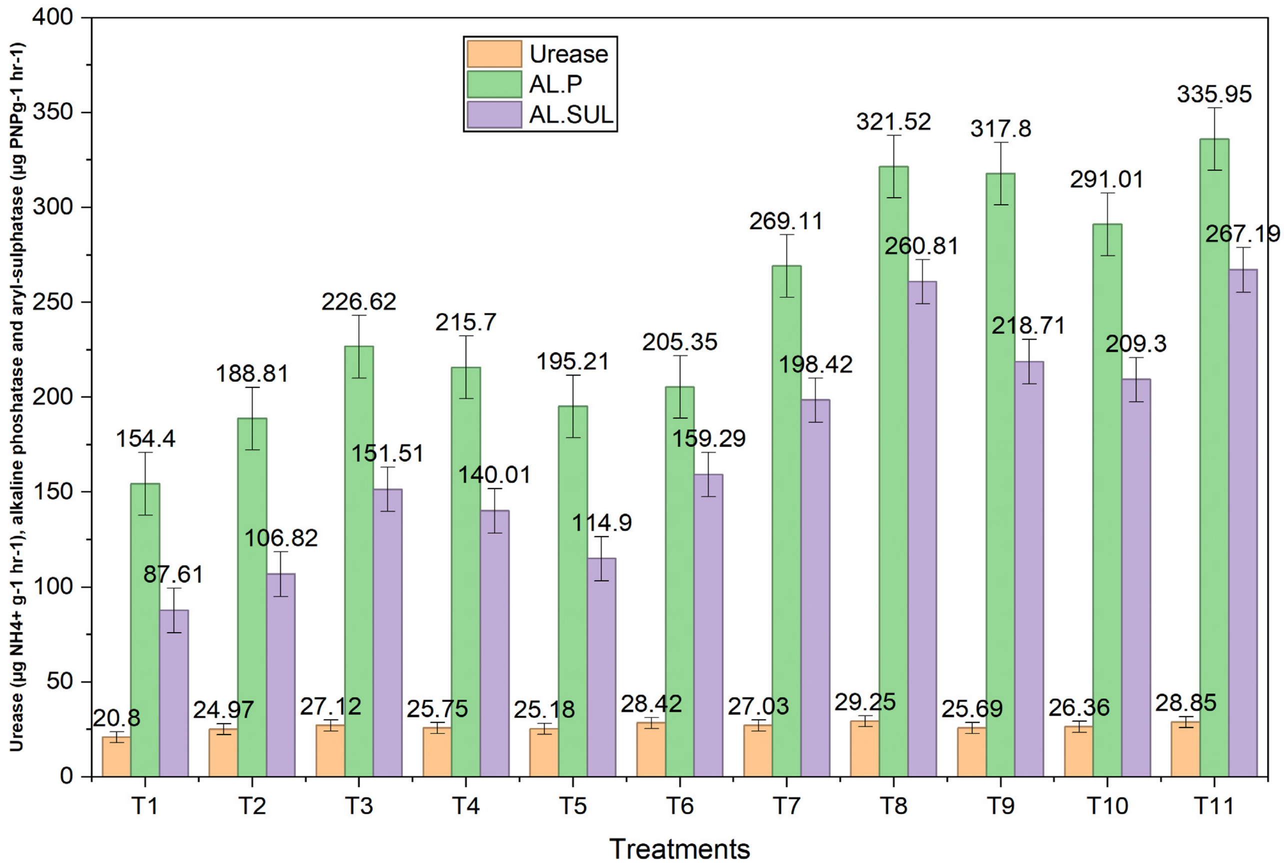

Fig. 3 Effect of different levels and sources of phosphorus on soil enzyme activities. ALP-alkaline phosphatase; AL SUL- aryl sulphatase (Treatments as in Table 1)

Input of full recommended dose of P through various fertilizers (188.81, 226.62 and 215.70 µg PNP g^{-1} soil hr^{-1} for SSP, DAP and RP) increased the alkaline phosphatase activity over control (154.40 µg PNP g^{-1} soil hr^{-1}; $p < 0.05$). Higher alkaline phosphatase activity in soil with P fertiliser application has also been reported in several studies (Touhami *et al.*, 2022; Solangi *et al.,* 2024; Thaqi *et al.,* 2025; Wei *et al.,* 2025). The supply of P through DAP resulted in higher alkaline phosphatase activity in soil, followed by RP and SSP. However, Meena *et al.* (2023) reported higher alkaline phosphatase activity with SSP over DAP or RP. Integrated use of FYM along with half of recommended dose of P through DAP showed higher alkaline phosphatase activity (321.52 µg PNP g^{-1} soil hr^{-1}) followed by FYM along with RP (317.80 µg PNP g^{-1} soil hr^{-1}) and SSP (269.11 µg PNP g^{-1} soil hr^{-1}). Integrated application of FYM along with SSP, DAP and RP significantly increased alkaline phosphatase activity as compared to the full recommended dose of respective P fertilisers (Grant *et al.,* 2022; Rocabruna *et al.,* 2024; Yaganoglu *et al.,* 2024; Kumari *et al.*, 2024). Application of half of the recommended dose of P through SSP, DAP, and RP, along with 7.5 Mg FYM ha^{-1} in both the crops, increased the enzyme activity by 42.52, 41.87 and 47.33%, over application of the full recommended dose of P through SSP, DAP and RP in both crops.

Organic sulphate esters are hydrolysed by aryl sulphatase enzyme that mineralises the organic S to SO_4^{2-} and plays a pertinent role in S cycling in soils. The aryl sulphatase enzyme activity in soil ranged between 87.61 to 267.19 µg PNP g^{-1} hr^{-1} under various treatments (Fig. 3) and application of recommended dose of P through SSP, DAP and RP (106.82, 151.51 and 140.01 µg PNP g^{-1} soil hr^{-1}, respectively) increased aryl sulphatase activity over control (87.61 µg PNP g^{-1} hr^{-1}; $P < 0.05$). Among various chemical fertilizers, fertilization of P with DAP showed higher aryl sulphatase activity in soil followed by RP and SSP.

Similarly, addition of FYM along with half of the recommended dose of P through DAP showed higher aryl sulphatase activity (260.81 µg PNPg^{-1} hr^{-1}) as compared to FYM along with RP (218.71 µg PNP g^{-1} hr^{-1}) and SSP (198.42 µg PNPg^{-1} hr^{-1}). Combined application of FYM along with SSP, DAP and RP increased aryl sulphatase activity as compared to the full recommended dose of P through respective fertilisers ($p > 0.05$). Incorporation of half of the recommended dose of P through SSP, DAP, and RP, along with FYM in both the crops, increased the aryl sulphatase activity by 85.75, 72.14 and 56.21%, over the sole application of the full recommended dose of P through SSP, DAP and RP. The higher aryl sulphatase activity with combined application of FYM and P fertilisers as compared to chemical fertilizers alone may be attributed to the protection of the extracellular enzyme because SOM acts as heat insulator and protects the enzyme from denaturation by high soil temperatures and large diurnal fluctuations in semi–arid tropics (Ankit *et al.,* 2024; Kumari *et al.,* 2024; Sheoran *et al.,* 2025).

Correlation matrix and Principal component analysis (PCA)

The SOC content of soil showed positive correlation with almost all microbiological parameters, and it was also significant except for enzymes (Fig. 4). A positive and highly significant correlation of DOC was observed with SOC, and microbial biomass; however, it was positively but non–significantly correlated with enzyme activities of soil. We use principal component analysis (PCA) to represent multivariate data sets for easy interpretation (Table 2; Fig. 5). Under pearl millet cultivation, the first two PCs with eigenvalue> 1.0, which represent at least 5% of the variation in the data, were considered as the outcome of PCA analysis. The highly weighted

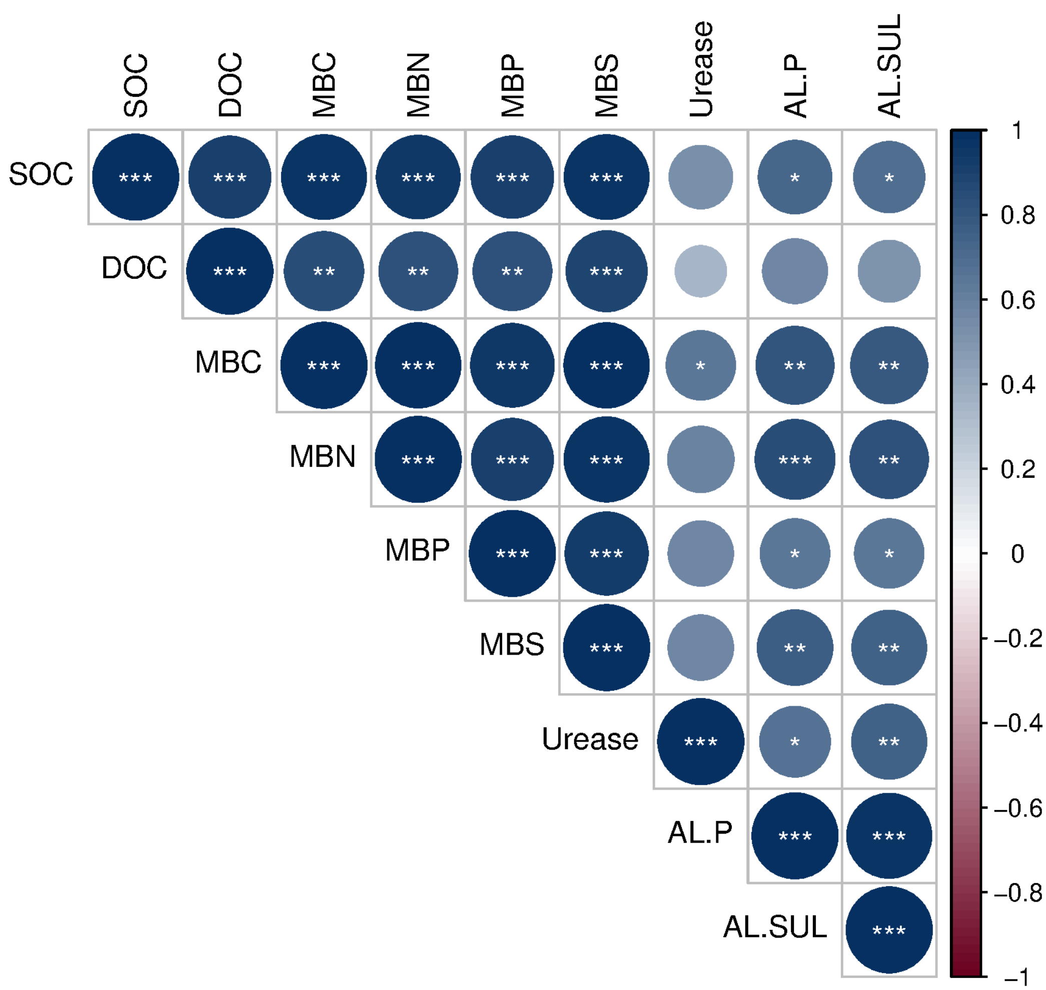

Fig. 4 Correlation matrix between SOC, DOC and micro-biological properties

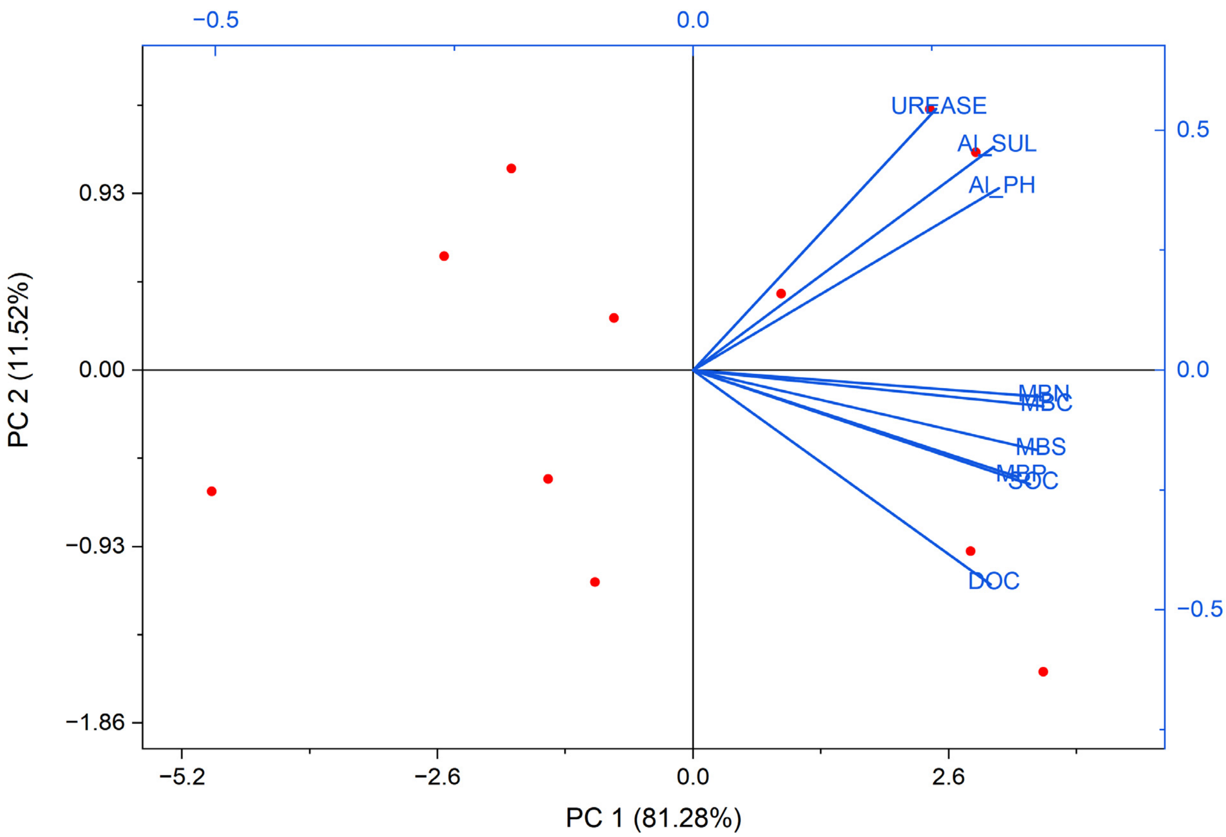

Fig. 5 Biplot of SOC, DOC and microbiological properties

Table 2. Principal component analysis of soil SOC, DOC and microbiological properties; bold and underline values indicated high loading in principal component

Statistics	PC1	PC2
Total	7.3	1.0
% of Variance	81.3	11.5
Cumulative %	81.3	92.8
Eigen vector		
UREASE	0.688	**0.555**
Al_SUL	0.852	0.474
Al_PH	0.865	0.386
MBN	0.984	-0.056
MBC	0.991	-0.076
MBS	0.976	-0.170
MBP	0.920	-0.227
SOC	**0.954**	-0.242
DOC	0.842	-0.455

Depictions: PC1-principal component 1, PC2-principal component 2; others depicted in above figures

variables under PC_1 were SOC, MBC, MBN, MBS and MBP. Then, a simple correlation analysis was performed to assess whether there was any correlation among the selected variables within PC_1. MBC, with a high factor weight, was selected among the multivariate correlated variables to remove redundant variables in the intercorrelation study ($p > 0.05$), and under PC_2, the Urease enzyme was retained. From PC_1 to PC_2, the master indicators, viz., SOC, MBC, MBN, MBS, MBP and Urease enzyme, were retained.

Conclusions

The findings of this study demonstrate that the application of organic manure plays a pertinent role in improving SOC and biological properties. Among the different P sources evaluated, the combined application of 7.5 Mg farmyard manure (FYM) ha^{-1} and single super phosphate (SSP) was proved beneficial for most of the studied parameters in slightly saline soils of semi–arid areas compared to di–ammonium phosphate (DAP) and rock phosphate (RP). The study further reported that the application of FYM along with P fertilisers improved organic and dissolved C and microbiological properties under the pearl millet–mustard cropping system compared with the sole application of P fertilisers. These results highlight the importance of integrating organic and inorganic nutrient sources to sustain soil health, enhance biological activity, and improve soil fertility in semi–arid agroecosystems.

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References

Ankit, Prakash D, Sheoran S, Yadav PK, Raj D, Rachna, Gupta RK, El-Hendawy S and Mattar MA (2024) Sustainable Cropping Sequences to Improve Soil Fertility and Microbiological Properties. *Sustainability* **16**:9821. https://doi.org/10.3390/su16229821.

Basak N, Sheoran P, Sharma R, Yadav RK, Singh RK, Kumar S, Krishnamurthy T and Sharma PC (2021) Gypsum and pressmud amelioration improve soil organic carbon storage and stability in sodic agroecosystems. *Land Degradation and Development* **32**: 4430–4444. https://doi.org/10.1002/ldr.4047

Brookes PC, Landman A, Pruden G and Jenkinson DS (1985) Chloroform fumigation and the release of soil nitrogen: A rapid direct extraction method to measure microbial biomass nitrogen in soil. *Soil Biology and Biochemistry* **17**: 837-842. doi:10.1016/0038-0717(85)90140-3.

Chen C and Xiao W (2023). The global positive effect of phosphorus addition on soil microbial biomass. *Soil Biology and Biochemistry* **176**: 108882. 10.1016/j.soilbio.2022.108882.

Ciavitta C, Antisari LE and Sequi P (1989) Determination of organic carbon in soils and fertilizers. *Communications in Soil Science and Plant Analysis* **20(7-8)**: 759-773. 10.1080/00103628909368115.

Du E, Terrer C, Pellegrini AFA, Ahlstrom A, Lissa CJ, Zhao X, Xia N, Wu X and Jackson RB (2020) Global patterns of terrestrial nitrogen and phosphorus limitation. *Natural Geosciences* **13**: 221–226. 10.1038/s41561-019-0511-1.

Govednik A, Potoènik Z, Eler K, Mihelic R and Suhadolc, M (2023) Combined effects of long-term tillage and fertilisation regimes on soil organic carbon, microbial biomass, and abundance of the total microbial communities and N-functional guilds. *Applied Soil Ecology* **10**.1016/j.apsoil.2023.104876.

Grant PP, Cartes P, Pontigo S, Biron MDL and Rumpel C (2022) Phosphorus fertilizer source determines the allocation of root-derived organic carbon to soil organic matter fractions. *Soil Biology and Biochemistry* **167**: 108614. 10.1016/j.soilbio.2022.108614.

Jenkinson DS (1966) Studies on the decomposition of plant material in soil. II. Partial sterilization of soil and the soil microbial biomass. *Journal of Soil Science* **17**: 280–302. 10.1111/j.1365-2389.1966.tb01474.x.

Kumar P, Sundha P, Basak N, Chandra P, Bedwal S, Rai AK (2024) Predominant cropping systems affect soil organic carbon content in the soil profile of North–West India. *Journal of Soil Salinity and Water Quality* **16**: 280–288. https://doi.org/10.56093/jsswq.v16i2.156658

Kumari M, Prakash D, Sheoran S, Yadav PK, Ankit, Yadav HK, Apurva, Gupta RK, El-Hendaway S and Mattar MA (2024) Long-Term Manuring and Fertilization Influence on Soil Properties and Wheat Productivity in Semi-Arid Regions. *Agronomy* **14**: 2383. https://doi.org/10.3390/agronomy14102383.

Meena D, Meena RH, Jain D, Kumar T, Meena AK, Khardia N and Chundawat DS (2023) Effect of different phosphorus sources on soil physico-chemical property dynamics under chickpea crop. *International Journal of Plant and Soil Science* **35(19)**: 240-249. 10.9734/ijpss/2023/v35i193549.

Prakash D, Benbi DK and Saroa GS (2022) Distribution of phosphorus fractions in soil experienced levels and sources of P application under rice-wheat cropping system. *Frontiers in Crop Improvement* **10**:1394-1401.

Preeti, Sheoran S, Prakash D, Singh R, Sharma RK, Chauhan RS, Priyanka, Yadav R and Choudhary N (2025) Impact of different levels and sources of P on grain quality and crop productivity of pearl millet in semi–arid region of Northwest India. *International Journal of Plant & Soil Science* **37(12)**: 391-401. https://doi.org/10.9734/ijpss/2025/v37i125901.

Qaswar M, Ahmed W, Huang J, Liu K, Zhang L, Han T, Du J, Ali S, Ur-Rahim H, Huang Q and Zhang H (2022) Interaction of soil microbial communities and phosphorus fractions under long-term fertilization in paddy soil. *Journal of Integrative Agriculture* **21(7)**: 2134-2144. https://doi.org/10.1016/S2095-3119(21)63733-4.

Qin W, Feng J and Zhang Q *et al.* (2024) Different responses of priming effects in long-term nitrogen- and phosphorus-fertilized soils to exogenous carbon inputs. *Plant Soil* **500**: 647–663. 10.1007/s11104-024-06510-3.

Rocabruna PC, Domene X, Matteazzi A, Figl U, Fundneider H, Fernández-Martínez M, Venir E, Robatscher P, Preece C, Peñuelas J and Peratoner G (2024) Effect of organic fertilisation on soil phosphatase activity, phosphorus availability and forage yield in mountain permanent meadows. *Agricultural, Ecosystem & Environment* **368**: 109006. https://doi.org/10.1016/j.agee.2024.109006.

Sheoran OP, Tonk DS, Kaushik LS, Hasija RC and Pannu RS (1998) Statistical software package for agricultural research workers. *Recent Advances in Information Theory, Statistics and Computer Applications* by DS Hooda and RC Hasija, Department of Mathematics Statistics, CCS HAU, Hisar (139-143).

Sheoran S, Prakash D, Raj D, Mor VS, Yadav PK, Gupta RK, Alamri S and Siddiqui MH (2024) Long-term organic and N fertilization influence the quality and productivity of pearl millet under PW sequence in north India. *Scientific Reports* **14**: 19503. https://doi.org/10.1038/s41598-024-70009-1

Sheoran S, Prakash D, Raj D, Yadav PK, Singh R, Gupta RK, Alamri S, Siddiqui MH and Khan S (2025) Organic manure and fertilizer N management strategies improve soil health at different growth stages of pearl millet under pearl millet-wheat sequence. *BMC Plant Biology* **25**: 117. https://doi.org/10.1186/s12870-025-06128-2.

Silveira M (2005) Dissolved organic carbon and bioavailability of N and P as indicators of soil quality. *Scientia Agricola* **62**: 502-508. 10.1590/S0103-90162005000500017.

Solangi F, Zhu X and Solangi KA *et al.* (2024) Responses of soil enzymatic activities and microbial biomass phosphorus to improve nutrient accumulation abilities in leguminous species. *Scientific Reports* **14**: 11139. 10.1038/s41598-024-61446-z.

Sundha P, Basak N, Rai A, Yadav R, Sharma D and Sharma P (2017) N and P release pattern in saline-sodic soil amended with gypsum and municipal solid waste compost. *Journal of Soil Salinity and Water Quality* **9**: 145–155.

Sundha P, Basak N, Rai AK, Yadav RK and Sharma PC (2023) Irrigation water quality, gypsum, and city waste compost addition affect P dynamics in saline-sodic soils. *Environmental Research* **216**: 114559. https://doi.org/10.1016/j.envres.2022.114559

Tabatabai MA and Bremner JM (1970) Aryl sulphatase activity of Soils. *Soil Science Society of America Journal* **3(2)**: 225-229.

Tabatabai MA and Bremner JM (1972) Assay of urease activity in soils. *Soil Biology and Biochemistry* **4**: 479-487.

Tabatabai MA and Bremner JM (1969) Use of p-nitrophenyl phosphatase for assay of soil phosphatase activity. *Soil Biology and Biochemistry* **1**: 301-307.

Tang D, Chen M, Huang X, Zhang G, Zeng L, Zhang G, Wu S and Wang Y (2023) SRplot: A free online platform for data visualization and graphing. *PLoS One* **18(11)**: e0294236. doi: 10.1371/journal.pone.0294236.

Thaqi ST, Siani R, Chiba A, Vitow N, Baum C, Leinweber P, Panten K, Schloter M and Schulz S (2025). Effects of novel P fertilizers on microbial abundance related to N and P cycling in two on-farm systems. *Agricultural, Ecosystem & Environment* **385**: 109565. https://doi.org/10.1016/j.agee.2025.109565.

Touhami D, Condron LM, McDowell RW and Moss R (2022). Effects of long-term phosphorus fertilizer inputs and seasonal conditions on organic soil phosphorus cycling under grazed pasture. *Soil Use Management* **39**: 385–401. https://doi.org/10.1111/sum.12830.

Vance EC, Brooks PC and Jenkinson PS (1987). An extraction method for measuring soil microbial biomass carbon. *Soil Biology and Biochemistry* **19(6)**: 703-707. DOI:10.1016/0038-0717(87)90052-6.

Walkley A and Black IA (1934) Estimation of soil organic carbon by chromic acid titration method. *Soil Science* **37**: 29-38. https://doi.org/10.1097/00010694-193401000-00003.

Wei K, Sun Y, Cartmill AD, López IF, Ma C and Zhang Q (2025) Long-term effects of nitrogen and phosphorus fertilizers on rhizosphere physicochemical characteristics and microbial composition in alfalfa. *Industrial Crops Production* **227**: 120776. https://doi.org/10.1016/j.indcrop.2025.120776.

Xia Y, Peñuelas J, Sardans J, Zhong X, Xu L, Yang Z, Yang Y, Yang L, Yue K and Fan Y (2024) Phosphorus addition accelerates soil organic carbon mineralization by desorbing organic carbon and increasing microbial activity in subtropical forest soils. *Applied Soil Ecology* **193**: 105166. https://doi.org/10.1016/j.apsoil.2023.105166.

Yagangolu E and Aydin A (2024) The effect of organic and chemical fertilizers on the activity of soil enzymes in soils of different compositions. *Turkish Journal of Agriculture and Forestry* **48**: 116-128. 10.55730/1300-011x.3167.

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