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AMELIORATING SOIL HEALTH FOR IMPROVED PHOSPHORUS UPTAKE AND DURUM WHEAT YIELD THROUGH FARMYARD MANURE AND PHOSPHORUS FERTILIZATION

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Article Info

Abstract

To address concerns relating soil degradation, this research explores how phosphorus (P) and farmyard manure (FYM) can rejuvenate soil health, boost microbial and enzyme activity, and enhance durum wheat productivity at local farm near ARI Tarnab-Peshawar in 2020-21 and 2021-22. The trail followed randomized complete block design with split plot arrangements having FYM and control in main plots and P doses in subplots at 30, 60 and 90 kg ha-1 along with a control. Significant improvements were observed 90 and 60 kg P ha-1 producing higher biological and grain yield while 90 kg P ha-1 producing higher P content and uptake in both years. Similarly, FYM application resulted in significantly improved results over control. The synergistic effect of P doses and FYM caused notable improvements in soil organic matter, soil phosphorus and cation exchange capacity. Microbial biomass nitrogen, carbon, and phosphorus significantly improved with the application of 60 kg P ha⁻¹, showing no significant difference compared to 90 kg P ha⁻¹, while FYM incorporation over two years also enhanced microbial biomass and soil respiration. Combine effect of P doses and FYM was also positive for phosphatase and glucosidase activity whereas Invertase activity improved regardless of P application. PCA and heatmap analyses further elucidated the positive relationship between 90 kg P ha⁻¹ combined with FYM on soil microbial and enzymatic activities, while 60 kg P ha⁻¹ and FYM was strongly associated with yield improvements in durum wheat. In conclusion, improvement due to the synergy of P and FYM was prominent in durum wheat yield, P uptake along with enhancement in soil bioactivity. Therefore, it is recommended for ameliorating soil health and crop production. .

Keywords: *Crop productivity, enzyme activity, intensive farming, phosphorus retention, sustainable agriculture.*

Introduction

Soil degradation, driven by erosion, deforestation, intensive farming, and compaction, leads to nutrient depletion, reduced soil fertility, and impaired crop productivity. Erosion removes nutrient-rich topsoil, while deforestation and compaction further diminish soil structure and water retention, exacerbating nutrient loss. Intensive farming depletes essential nutrients, resulting in poor crop yields and stunted plant growth (Bisht and Chauhan, 2020; Shaheb et al, 2021). As soil fertility declines, crops become more vulnerable to drought, pests, and diseases (Priori et al, 2020). Addressing these issues with sustainable practices is crucial for restoring nutrient levels and improving agricultural productivity. The application of FYM is an effective strategy to restore soil fertility. As evident from previous literature, it improves soil structure (Williams and Cooke, 1961), enhances nutrient availability (Jamal et al, 2023), and boosts microbial activity (Khalid et al, 2021), which in turn aids in nutrient cycling and retention. By enriching the soil with organic matter, FYM increases water-holding capacity and promotes healthier root development, helping crops withstand environmental stressors such as drought. Moreover, manure (FYM) serves as a sustainable nutrient source, replenishing depleted soils and supporting long-term agricultural productivity, making it a vital tool in countering the negative impacts of soil degradation (Zhang et al, 2022). As per Lishan and Alemu, (2024), FYM increases soil carbon stocks and aggregate stability that reduces erosion and compaction, improves root growth and water retention, and regulates soil pH, promoting nutrient uptake and beneficial microbes.

In Pakistan, approximately 80–95% of agricultural land has low organic matter (<1%) and is deficient in phosphorus (P), necessitating the use of P fertilizers to improve crop production (7). FYM typically contains a higher percentage of nitrogen compared to other nutrients. To achieve a balanced nutrient approach, the addition of P is crucial for soil improvement. P, being a key macronutrient after nitrogen, plays a vital role in addressing nutrient deficiencies. P is essential for key enzymes and proteins, which are important for energy transfer and biochemical reactions (Mengel et al, 2004). It helps crops mature faster and boosts root development (Alam et al, 2022). P directly contributes to soil restoration and boosts crop productivity. It also helps regulate its own supply in the soil solution by creating a temporary sink in microbial cells (Shi et al, 2023). Despite its importance, P is the second most limiting nutrient in agriculture (Saleem et al, 2020) due to its strong bond with soil particles and with other substances forming insoluble compounds with calcium, iron and aluminum through the process of mineralization and immobilization (Rashmi and Biswas, 2018; Sjonnesen et al, 2021). Studies show that less than 45 percent of P from fertilizers is utilized in the first year (Ullah et al, 2022). When combined with FYM in degraded or poor soils, the organic matter in FYM aids in P retention and reduces its fixation in the soil, making it more accessible for plant uptake and preventing runoff and leaching, which in turn reduces the risk of water contamination (Shah et al, 2010).

The combined application of P and FYM greatly enhances soil enzyme activity and microbial biomass, contributing to improved soil health and fertility. Organic amendments like FYM have been shown to increase microbial biomass carbon, nitrogen and phosphorus which are essential for nutrient cycling. Research indicates that long-term manure application can raise MBC by 22.80% to 90.82% and MBP by 17.37% to 208.47% in rhizospheric soils (Wu et al, 2023), while combined P and FYM have boosted soil microbial biomass phosphorus by 67–156% compared to control (Ashraf et al, 2021) as well as enhances enzyme activities such as phosphatase and dehydrogenase, which are crucial for P availability and nutrient mineralization (Gautam et al, 2020). Wheat delivers more protein compared to other crops, but global challenges including soil degradation make it increasingly difficult to sustain both its yield and quality. Soil degradation and nutrient depletion, particularly phosphorus deficiency, are major challenges affecting crop productivity and soil health in Pakistan. Conventional farming practices often fail to address the issue of nutrient loss, leading to poor crop yields and declining soil quality. Although FYM has been recognized as an effective organic amendment for improving soil structure and microbial activity, its impact on phosphorus availability and overall soil health when used in combination with P fertilizers is not fully understood. This research aims to investigate the effects of combined phosphorus and FYM application on soil enzyme activity, microbial biomass, nutrient availability, and wheat productivity, providing insights into sustainable solutions for restoring degraded soils and improving agricultural productivity.

MATERIALS AND METHODS

Crop management and experimental design

A trial was executed for two consecutive years (2019-2020 and 2020-21) near Agriculture Research institute Tarnab-Peshawar. The experiment followed randomized complete block design with a split-split plot arrangement replicated four times. The field was divided into main plots an sub-plots, measuring 4m × 1.5 m. The main plots were incorporated with and without farmyard manure (FYM) at a rate of 20 tons ha^{-1}, supplemented 10 days before trial execution while full Phosphorus (P) doses were applied to all subplots according to the doses (0, 30, 60 and 90 kg ha^{-1}). Sowing was performed in the last week of October in 2020 while sowing for the second experiment was carried out in the first week of November. D-21 variety of durum wheat was used in both years. A starter dose of nitrogen (N) at 80 kg ha^{-1} and potassium (K) at 40 kg ha^{-1} was supplied using urea and potassium sulfate (K_2SO_4), while phosphorus was provided through di-ammonium phosphate (DAP). Potassium and half of the nitrogen doses applied at planting, and the left over nitrogen was incorporated at booting stage. Prior to the experiment, composite samples of soil were gathered from a depth of 15 cm to analyze various physicochemical properties. Weeds were managed at tillering stage by applying 24-D spray at the rate of 0.5 liter ha^{-1}. Four irrigations were applied throughout the season. Same layout and management practices were also followed for the second year trial. Harvesting was carried out in the end of April, 2021 and 2022.

Procedure for data recording

Biological and grain yield

For biological yield, four rows from each sub-plot were harvested, sun-dried, bundled, and weighed using a balance to obtain the dry mass. Grain yield was evaluated by harvesting, threshing, and weighing four rows from each sub-unit, with results converted to kilograms per hectare using the formula:

$$GY\ (kg\ ha^{-1}) = (\text{weight of grains} / 1000) \times 1000$$

Plant P concentration and P uptake

The straw and grain samples were first ground up with a Wily mill that has a steel chamber. After grinding, they were digested with a mix of nitric acid and perchloric acid in a 3:1 ratio. We then measured the phosphorus concentration using the method from Chapman and Pratt (1961). To figure out how much phosphorus the plants absorbed, we multiplied the phosphorus levels in both the straw and grain by their dry weight, including all the straw and grain parts, based on the approach described by Jan and Arif (2005).

$$\text{Uptake of P by plants } (kg\ ha^{-1}) = \text{Straw P content} \times \text{straw yield} + \text{Grain P content} \times \text{grain yield.}$$

Soil properties

After harvesting the second-year experiment, soil samples were collected from each sub-plot at a depth of 20 cm. These samples were air-dried and then passed through a 2 mm sieve. To measure soil organic matter, we used the alkali-Black method as described by Nelson and Summer (1982). In this method, a 1g soil sample was treated with 1N K2Cr2O7, followed by the addition of 20 mL of concentrated H2SO4. After diluting the acid with 200 mL of water, the mixture was added with two to three drops of Ortho phenanthroline indicator and titrated with 0.5 N Fe2SO4 until a faint maroon color appeared.

$$SOM\ (\%) = \frac{(meq\ K_2CrO_7 - meq\ FeSO_4)}{\text{Sample weight}} \times 0.69$$

Soil phosphorus was measured using a Spectronic 601, following the method outlined by Soltan pour and Schwab (1977). First, a 10 g soil sample was placed in a flask with 20 mL of AB-DTPA solution. The mixture was shaken on a reciprocal shaker for 15-20 minutes, then filtered and properly labeled. From this solution, 5 mL was transferred using a 25 mL volumetric instrument. To this, 5 mL of freshly prepared ascorbic acid was added, and the total volume was adjusted to 50 mL with distilled water. The spectrophotometer was set to 880 nm and calibrated with standard phosphorus solutions to measure the phosphorus content in the samples.

$$\text{AB-DTPA Ext. P (mg kg}^{-1}) = \frac{Spectrophopometer\ reading\ (880\ nm) \times volume \times df}{Sample\ mass}$$

The ammonium acetate method for determining soil cation exchange capacity (CEC) was carried out by saturating the soil with a 1M ammonium acetate solution at pH 7, displacing exchangeable cations with ammonium ions. The displaced cations were measured using atomic absorption spectrometry. Excess ammonium ions were removed with a neutral salt solution, and the retained ammonium was measured. The sum of extracted cations, expressed in meq/100g, represented the soil's CEC.

Soil biology and enzyme activities

Soil respiration (CO_2 µg^{-1} g soil day^{-1}) was determined by protocols described by Shah et al. (2017). Microbial biomass nitrogen (N) carbon (C) and phosphorus (P) were determined using the chloroform fumigation method with constants specified by Horwath and Paul (1994). Alkaline phosphatase activity was assessed through colorimetry with disodium phenyl phosphate, following Guan (1986) method, and the results were quantified as (µg pNP g^{-1} h^{-1}). Invertase activity, measured by dinitro salicylic acid, yielded results expressed in (mg glucose g^{-1} 24 h^{-1}). Furthermore, glucosidase activity was determined using nitrophenol colorimetry, following Tabatabai (1969) methodology, and the outcomes were expressed as (µg pNP g^{-1} h^{-1}).

Statistical analysis

After gathering the data, it was analyzed using analysis of variance. Then, we used the least significant difference (LSD) test to evaluate the results, following the method described by Steel and Torrie in 1980. Graphs were designed using sigma plot while OrginPro was utilized for depicting correlation matrix, principal component analysis and heatma

RESULTS

Soil and farmyard manure analysis was done before the commencement of first year experiment (**Table 1**). Soil was characterized as a silt loam with a clay content of 29.4%, silt content of 55.6%, and sand content of 14.1%. The soil had an electrical conductivity of 1.13 dS m^{-1} and a slightly alkaline pH of 7.9. Soil bulk density was measured at 1.15 g cm^{-3}, with a lime content of 7.23%. Organic matter content in the soil was relatively low at 0.55%, and total nitrogen was 0.04%. The soil also contained 2.31 mg kg^{-1} of extractable phosphorus and 68.3 mg kg^{-1} of extractable potassium. The FYM used in the experiment had an electrical conductivity of 1.24 dS m^{-1} and a pH of 6.8. The lime content in FYM was 2.8%, while organic matter was slightly higher than the soil at 0.78%. The total nitrogen content in FYM was 0.29%, with 2.97 mg kg^{-1} of extractable phosphorus and 72.8 mg kg^{-1} of extractable potassium.

Table 1: Soil profile before execution of field trails

Characteristics	Unit	Soil	FYM
Clay	(%)	29.4	-
Silt	//	55.6	-
Sand	//	14.1	-
Texture	-	Silt loam	-
Electrical Conductivity	(dS m^{-1})	1.13	1.24
Soil pH	-	7.9	6.8
Soil Bulk density	(g cm^{-3})	1.15	
Lime Content	(%)	7.23	2.81
Organic Matter	//	0.55	0.78
Total Nitrogen (N)	//	0.04	0.29
Extractable phosphorus (P)	(mg kg^{-1})	2.31	2.97
Extractable potassium (K)	//	68.3	72.8

Biological and grain yield

The results indicated a significant effect of P levels and FYM incorporation on yield of wheat across both years (2020-21 and 2021-22). In terms of P levels, the highest biological yield was observed at 90 kg P ha^{-1} (11033 kg ha^{-1} in 2020-21 and 12156 kg ha^{-1} in 2021-22) that was also statistically similar to biological yield observed in the 2020-21. The lowest yield was recorded in the control treatment (8054 kg ha^{-1} in 2020-21 and 9010 kg ha^{-1} in 2021-22). For FYM incorporation, the highest biological yield was obtained with the addition of 20 tons FYM ha^{-1}, (12273 kg ha^{-1} in 2020-21 and 13406 kg ha^{-1} in 2021-22). In contrast, the control treatment resulted in the lowest yields, (8193 kg ha^{-1} in 2020-21 and 9033 kg ha^{-1} in 2021-22). Moreover, the highest grain yield was observed at 90 kg P ha^{-1} (3469 kg ha^{-1} in 2020-21 and 4061 kg ha^{-1} in 2021-22) that was statistically similar to 60 kg P ha^{-1} in both years. The lowest grain yield was recorded in the control (2729 and 2761 kg ha^{-1}). For FYM, 20 tons ha^{-1} resulted in the highest yields (4226 and 4373 kg ha^{-1}), whereas the control treatment had the lowest (2138 and 3139 kg ha^{-1}). Both P and FYM substantially boosted grain yield. Year as a source of variance was also significant with 2021-22 producing higher results than 2020-21. All the possible interactions for both biological and grain yield was non-significant.

Plant phosphorus content and phosphorus uptake

The P levels and FYM influenced plant P content across both years. The highest plant P content was observed at 90 kg P ha^{-1} (0.23% in 2020-21 and 0.24% in 2021-22). The lowest P content occurred in the control, at 0.12% and 0.14% for the respective years. For FYM, 20 tons FYM ha^{-1} resulted in slightly higher plant

P content, (0.19% in 2020-21 and 0.20% in 2021-22) while the control FYM treatment recorded lower P content (0.17% and 0.19%, respectively). The greatest P uptake occurred at 90 kg P ha^{-1}, (14.1 kg ha^{-1} in 2020-21 and 15.7 kg ha^{-1} in 2021-22) over control that had the lowest values (7.2 kg ha^{-1} and 7.9 kg ha^{-1}, respectively. Applying 20 tons FYM ha^{-1} resulted in the highest P uptake (12.7 kg ha^{-1} in 2020-21 and 13.8 kg ha^{-1} in 2021-22) while the control showed lower values (8.1 kg ha^{-1} and 9.8 kg ha^{-1}). Interactive effect of plant P content was significant (P×FYM and P×Y) while all the possible interactions for plant P uptake was non-significant (**Table 2**).

Table 2: Pooled analysis of grain yield, biological yield, plant P content and plant P uptake under the application of phosphorus doses and farmyard manure in 2020-21 and 2021-22

Phosphorus (P) levels (kg ha^{-1})	Biological yield (kg ha^{-1})		Grain yield (kg ha^{-1})		Plant P content (%)		Plant P uptake (kg ha^{-1})	
	Year (Y)							
	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22	2020-21	2021-22
Control	8054 b	9010 c	2729 c	2768 c	0.12 d	0.14 d	7.2 d	7.9 d
30	9855 ab	11294 b	3167 b	3671 b	0.16 c	0.18 c	8.9 c	10.9 c
60	10491 a	11016 b	3261 ab	3804 ab	0.21 b	0.21 b	12.1 b	12.8 b
90	11033 a	12156 a	3469 a	4061 a	0.23 a	0.24 a	14.1 a	15.7 a
FYM (tons ha^{-1})								
Control	8193 b	9033 b	2138 b	3139 b	0.17	0.19 b	8.1 b	9.8 b
20	12273 a	13406 a	4226 a	4373 a	0.19	0.20 a	12.7 a	13.8 a
LSD for P	958		365		0.001		1.2	
LSD for FYM	889		258		0.002		0.8	
Significance for Y	**		**		**		**	
P×FYM	ns		ns		***		ns	
P×Y	ns		**		**		ns	
P×FYM×Y	ns		ns		ns		ns	

Difference among means is denoted by alphabetic letters that were obtained from LSD test at probability level of 0.05. Asterisk (*) shows significant difference while ns demonstrate non-significant difference.

Soil properties

Positive synergy of P doses and FYM was observed in terms of improving soil properties. Overall, when P levels were applied along with FYM, it produced enhanced results over P levels applied with FYM (control) for all the selected soil properties. Specifically, 60 and 90 kg P ha^{-1} when combined with 20 tons FYM ha^{-1} resulted in higher soil organic matter (Figure 1a). In terms of soil phosphorus content, highest results were obtained with the supplementation of 90 kg P ha^{-1} and 20 tons FYM ha^{-1} (Figure 1b). Moreover, cation exchange capacity (CEC) was recorded higher with all P doses when combinely incorporated with FYM at 20 tons FYM ha^{-1} over control (Figure 1c).

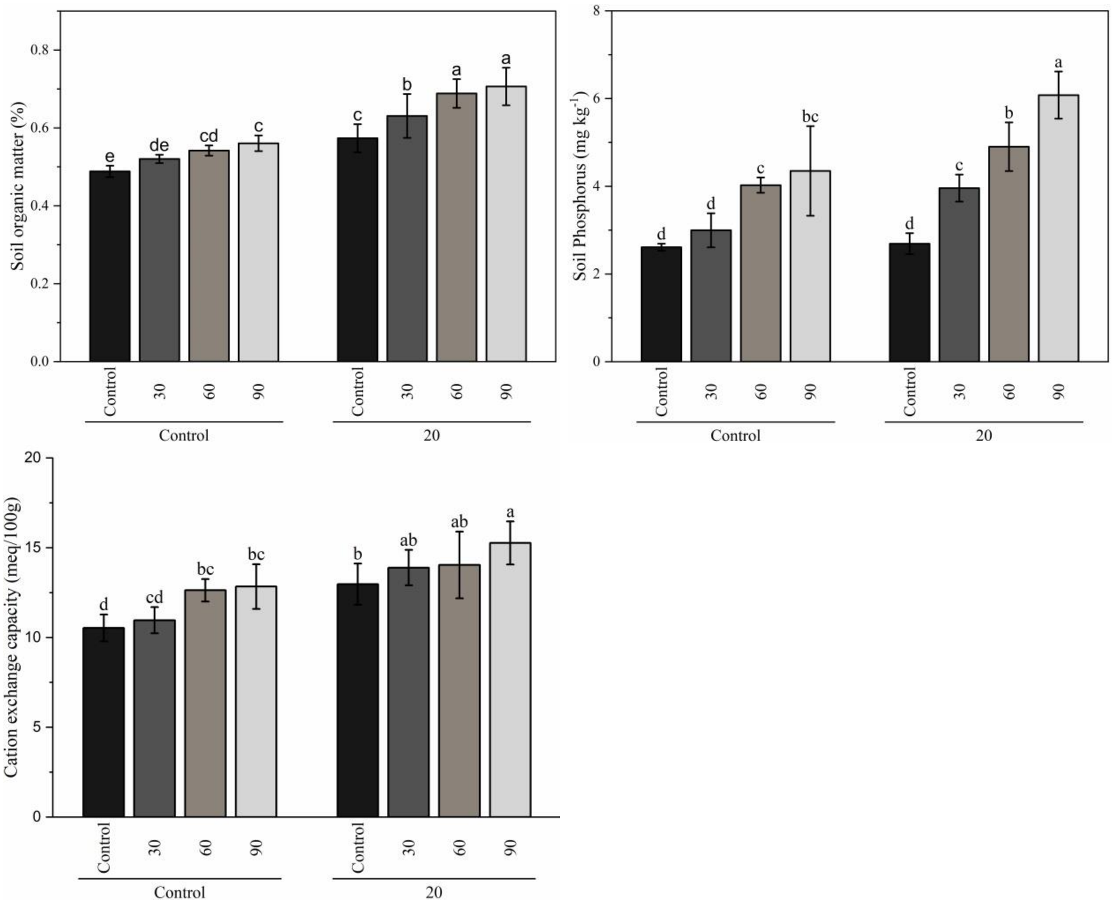

Figure 1: Soil properties as affected by combine application of phosphorus doses and farmyard manure in 2021-22. The data are reported as means of 4 replicates. Means having same letter do not vary significantly as per p ≤ 0.05 according to LSD test. Bars repres

Microbial biomass and soil respiration

P doses and FYM significantly influenced soil microbial biomass and soil respiration. The highest microbial biomass nitrogen (MBN) was observed at 90 kg P ha^{-1} (5.27 mg kg^{-1}) that was statistically same the results observed in plots treated with at 60 kg P ha^{-1}, while the control recorded the lowest value (3.41 mg kg^{-1}). Similarly, microbial biomass carbon (MBC) and microbial biomass phosphorus (MBP) increased with P doses, with the highest values at 90 kg P ha^{-1} (32.21 mg kg^{-1} and 0.36 mg kg^{-1}, respectively) that was at statistical parity with 60 kg P ha^{-1} over control (29.65 mg kg^{-1} and 0.33 mg kg^{-1}). Soil respiration also peaked at 90 kg P ha^{-1} (81.15 µg CO_2 g^{-1} soil day^{-1}), compared to the control (79.73 µg CO_2 g^{-1} soil day^{-1}). FYM incorporation further enhanced soil microbial properties. At 20 tons FYM ha^{-1}, MBN, MBC, and MBP produced higher results (4.92 mg kg^{-1}, 31.41 mg kg^{-1}, and 0.35 mg kg^{-1}, respectively), compared to lower values in the control treatment (3.85 mg kg^{-1}, 29.50 mg kg^{-1}, and 0.29 mg kg^{-1}). Soil respiration also increased with FYM application at 20 tons ha^{-1} (81.19 µg CO_2 g^{-1} soil day^{-1}) compared to results recorded in the control (77.76 µg CO_2 g^{-1} soil day^{-1}). The interactive effect of P doses and FYM was observed to be non-significant for evaluated traits (**Table 3**).

Table 3: Analysis of microbial biomass nitrogen, carbon, phosphorus and soil respiration under the application of phosphorus doses and farmyard manure

Phosphorus (P) doses (kg ha^{-1})	Microbial biomass nitrogen (mg kg^{-1})	Microbial biomass carbon (mg kg^{-1})	Microbial biomass phosphorus (mg kg^{-1})	Soil respiration (CO_2 µg^{-1} g soil day^{-1})
Control	3.41 b	29.65 c	0.33 b	79.73 d
30	3.90 b	30.48 b	0.34 ab	80.30 c
60	4.95 a	31.46 ab	0.35 a	80.74 b
90	5.27 a	32.21 a	0.36 a	81.15 a
FYM (tons ha^{-1})				
Control	3.85 b	29.50 b	0.29 b	77.76 b
20	4.92 a	31.41 a	0.35 a	81.19 a
LSD for P	0.38	0.27	0.05	0.18
LSD for FYM	0.58	0.39	0.07	0.26
P×FYM	ns	ns	ns	ns

Difference among means is denoted by alphabetic letters that were obtained from LSD test at probability level of 0.05. Asterisk (*) shows significant difference while ns demonstrate non-significant difference.

Enzyme activity

Analysis of soil enzyme activity after the wheat harvest in year 2020-21 and 2021-22 showed positive impact with the incorporation of P doses and FYM. It was revealed that applying P doses and FYM combinely resulted in significantly higher results compared to sole application of P. Phosphatase activity was higher in plots treated with 90 kg P ha^{-1} along with FYM over rest of the treatments (Figure 2a) while Invertase activity was noted higher in all the plots that were incorporated with FYM regardless of P doses (Figure 2b). For glucosidase activity, 90 kg P ha^{-1} with FYM resulted in higher improved results over rest of the treatment (Figure 2c).

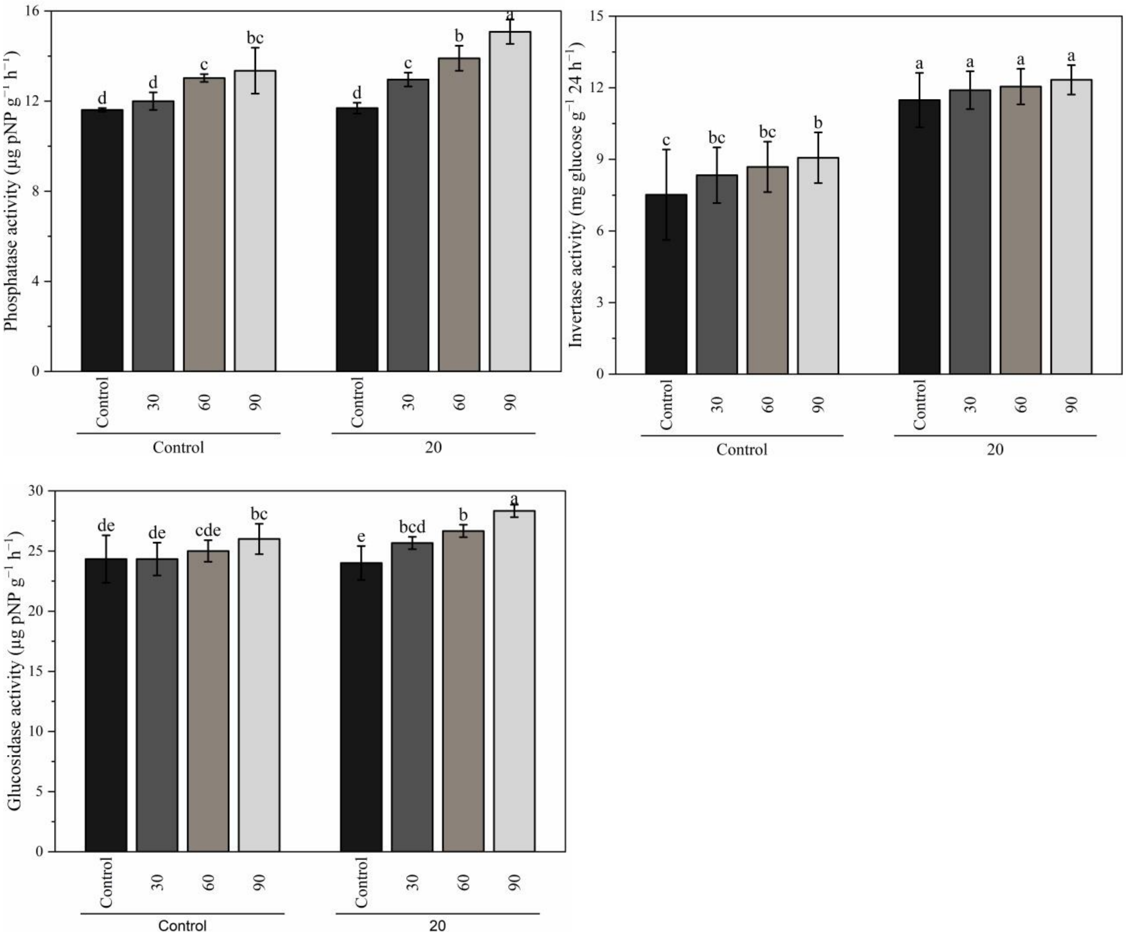

Figure 2: Soil enzyme activities as affected by combine application of phosphorus doses and farmyard manure in 2021-22. The data are reported as means of 4 replicates. Means having same letter do not vary significantly as per $p \leq 0.05$ according to LSD test. Bars

Scatter plot matrix for soil enzyme activity and soil respiration

Scatter plot matrix illustrates the relationship among soil microbial biomass and respiration under the application of P doses and FYM. It was revealed that microbial biomass nitrogen, carbon, phosphorus and soil respiration had a significant correlation. Specifically, soil respiration showed direct correlation with microbial biomasses with the higher association occurred with microbial biomass carbon according to Pearson's correlation coefficient (r = 0.76). Similarly, microbial biomass N was positively correlated with soil respiration (r= 0.72). In last microbial biomass phosphorus also had a higher association with soil respiration (r= 0.72) compared to association with other microbial biomasses (Figure 3).

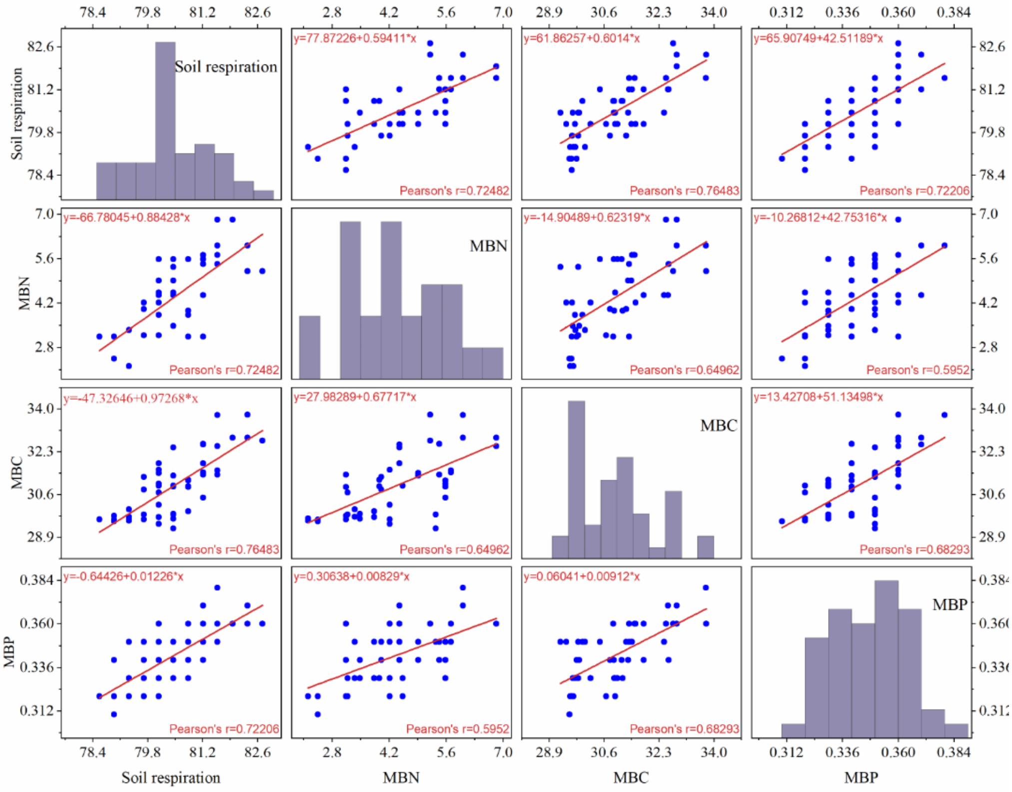

Figure 3: Correlation matrix of soil microbial biomass nitrogen, carbon, phosphorus and soil respiration under the influence of P doses and FYM

Principal component analysis and heatmap

The Principal Component Analysis (PCA) biplot illustrates the relationships between soil and plant parameters under varying P doses and FYM treatments. The two principal components, PC1 and PC2, explain 84.91% and 13.06% of the variation, respectively. Parameters such as soil P, microbial biomass nitrogen, carbon, phosphorus, phosphatase activity, and soil respiration are strongly correlated, as indicated by the close clustering of their vectors. Moreover, soil organic matter (SOM), cation exchange capacity (CEC), invertase activity, grain yield (GY), biological yield (BY), P uptake, and plant P content form another correlated cluster. Treatments that include higher P doses and FYM applications, such as FYM+90 and FYM+60, align closely with parameters indicating enhanced microbial activity, SOM, and P uptake. These treatments demonstrate strong positive effects on soil fertility and plant growth. In contrast, control treatments without FYM or with lower P doses are more distant from these vectors, reflecting their weaker associations with the key soil and plant parameters (Figure 4a).

According to heatmap, enzyme activities (glucosidase, invertase and phosphatase) exhibited a positive response to the application of FYM and increasing P doses, with the highest values recorded at FYM combined with 90 kg P ha^{-1}. Invertase and phosphatase activities peaked at 15.44% and 17.16%, respectively, under FYM+90 (Figure 4b). Similarly, microbial biomass parameters (MBP, MBC, and MBN) showed significant increases under the FYM+90 treatment, where MBN reached 17.16%. Soil respiration showed the highest value (17.06%) in the FYM+90. CEC, soil organic matter and soil P content, followed similar trends, with the highest values observed under FYM+90. In terms of crop related parameters, both GY and BY increased significantly with the addition of FYM and higher P doses. The highest GY (14.8%) and BY (15.2%) were observed in the FYM+90 treatment, that was no different than results observed with FYM+60. Higher P content and P uptake was observed under FYM+60 treatment (15.68% and 15.18%).

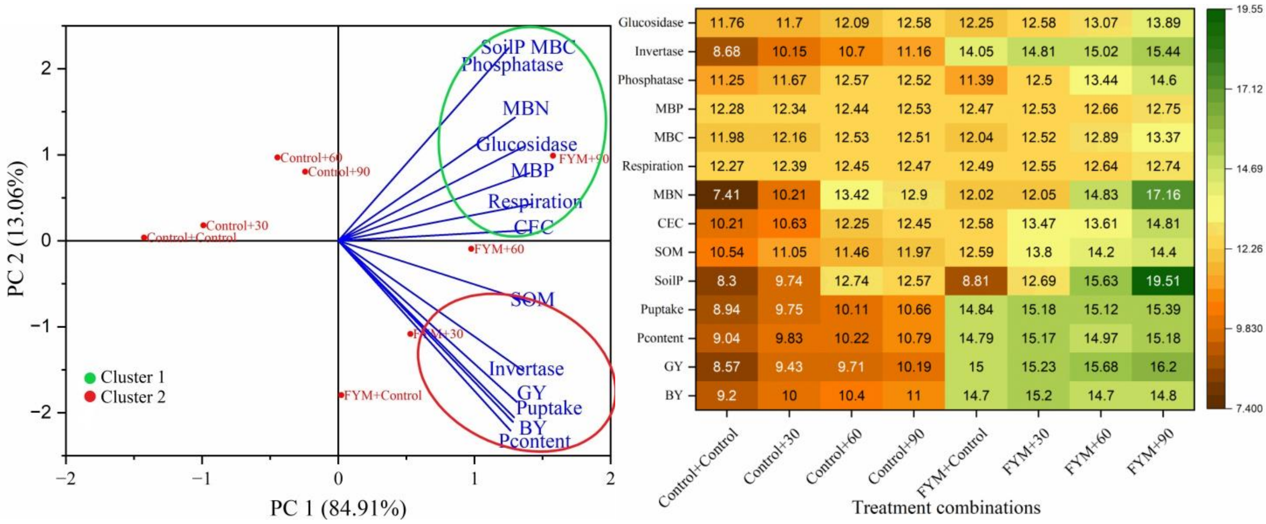

Figure 4: Principal component analysis (a) and expression heatmap (b) of evaluated parameters under the influence of phosphorus doses and farmyard manure

Discussion

In order to address the concerns related to degraded soil and crop productivity, this research focused on improving durum wheat yield and ameliorating soil health, enzyme activity, microbial and biomass through combine application of different P doses and FYM. The results demonstrated significant variation due to the application of P doses and FYM though the interactive effect was not significant, main effect of P at the rate of 90 kg P ha^{-1} and FYM produced higher biological and grain yield over control. P is a key macronutrient essential for plant energy transfer, root development, and overall growth. Similar improvement in durum wheat yield was seen in the study of Khourchi et al, (2022) who then justified that P applied at 90 kg ha^{-1} likely improved root establishment, increased nutrient uptake efficiency, and accelerated crop maturation, leading to higher yields. Meanwhile, FYM, rich in organic matter, improves moisture retention (Dhaliwal et al, 2019), and microbial activity, thereby facilitating better nutrient cycling and availability leading to higher yields. The highest plant P content and uptake observed at 90 kg P ha^{-1} across both years is due to the well-established role of P in promoting enzymatic activities, energy transfer, and root development, which in turn enhances nutrient uptake efficiency. The greater P uptake at 90 kg P ha^{-1} also suggests that P availability in the soil was optimized for plant growth, thus increasing total nutrient absorption. According to Chen et al, (2023), higher P promotes root growth and morphology, facilitating greater nutrient acquisition from the soil. FYM supplies organic compounds that bind with soil particles, reducing the immobilization of P in insoluble forms with calcium, iron, or aluminum, thereby making it more accessible for plant uptake (Rashmi and Biswas, 2018). The significant interactions (P×FYM and P×Y) for plant P content suggest that the presence of FYM and annual variability (likely due to environmental factors like rainfall or temperature) modulate P availability and uptake by plants.

The observed positive synergy between P doses and FYM in improving soil properties can be rationalized by the complementary functions of these inputs in soil nutrient dynamics and physical properties. The availability of P in soils is often limited due to fixation, particularly in alkaline and calcareous soils where it forms insoluble complexes with calcium and other minerals (Muindi, 2019). FYM, being rich in phosphate solubilizing bacteria reduce binding of P with soil minerals (Usman et al, 2024), thereby preventing P from becoming immobile and enhancing its availability for plant uptake. This explains the significant increase in soil P content when higher P doses (60 and 90 kg P ha^{-1}) were combined with 20 tons FYM ha^{-1}. Moreover, organic acids released during the decomposition of FYM help in reducing soil alkalinity (Zhang et al, 2023), thus releasing bound P and essential micronutrients like zinc and iron, making them more bioavailable to plants and the process is called pH-buffering, particularly vital in degraded soils prone to nutrient immobilization or pH imbalances. Increased soil organic matter from FYM promotes root exudation, wherein plants release sugars and amino acids into the rhizosphere, stimulating beneficial microbial populations. These microbes enhance nutrient cycling and improve P solubilization, fostering a more interactive and symbiotic soil ecosystem. Furthermore, soil organic matter from FYM improves soil CEC that is due to the release of humic substances that provide additional negative charge sites, enhancing the soil's capacity to retain these essential nutrients as also supported by Tiwari et al. (2020).

In our study, 90 kg P ha^{-1} improved microbial biomass nitrogen, carbon and phosphorus, with a similar trend observed at 60 kg P ha^{-1}, showing that P levels above the threshold improve microbial activity. This is due to P role in microbial energy metabolism. Microorganisms metabolize reduced P compounds like phosphite, which are oxidized to phosphate, releasing electrons that aid in energy production and enzyme synthesis, promoting increased microbial growth (Mao et al, 2023; Sosa et al, 2018). The elevated soil respiration observed at higher P doses further confirms the enhanced microbial activity and organic matter breakdown, both crucial for nutrient mineralization and availability. FYM incorporation also positively impacted microbial properties, improving microbial biomass and soil respiration. This is because FYM serves as an organic carbon source, fostering microbial growth and activity, which leads to better nutrient cycling and soil health. The increase in microbial biomass and respiration aligns with recent studies that emphasize its ability to improve microbial enzymatic activities, such as phosphatases, which are critical for phosphorus mineralization and availability (Wu et al, 2023). Study by Javaid et al. (2010) also highlights that FYM can introduce beneficial microorganisms that also count with existing microbial biomass and work in symbiosis with native soil microbes, enhancing nutrient cycling and creating a more resilient soil ecosystem capable of sustaining long-term fertility.

The enhanced soil enzyme activities observed with the combined application of P and FYM may be attributed to a synergistic interaction between organic and inorganic amendments that optimizes soil micro-environmental conditions. The presence of FYM not only adds organic carbon but also introduces a diverse array of microbial communities and exo-enzymes capable of breaking down complex soil organic matter that facilitate the microbial colonization and proliferation necessary for effective enzyme production. Moreover, the combined presence of P and FYM might create micro-niches within the soil that enhance the stability and activity of specific enzymes. For instance, phosphatases, responsible for releasing inorganic phosphorus from organic sources, could be more active due to the enhanced organic carbon and associated microbial biomass provided by FYM (Saha et al, 2008). The presence of FYM could influence soil pH dynamics and moisture levels (Bhanwaria et al, 2022), which are critical factors affecting enzyme activity. In contrast, applying P alone might not fully leverage these benefits due to the lack of organic matter that could otherwise optimize soil microbial conditions and enzyme activity. Soil respiration and microbial biomass was positively correlated according to scatter plot suggesting that increased microbial biomass supports higher microbial respiration rates (Spohn and Chodak, 2015), facilitating organic matter decomposition and nutrient cycling. Moreover, PCA and heatmap data collectively indicate that integrating FYM with elevated P doses enhances key soil and plant parameters that are driven by the synergistic effects of FYM and high P levels on microbial activity, soil organic matter, and phosphorus availability.

CONCLUSION

In summary, the application of phosphorus (P) and farmyard manure (FYM) significantly improved both biological and grain yields of wheat over two years. The highest biological and grain yields were achieved with 90 kg P ha^{-1} and 20 tons FYM ha^{-1}, with FYM consistently enhancing these yields compared to control treatments. Phosphorus content and uptake in plants also increased with higher P levels and FYM application. Soil properties benefited from combined P and FYM applications, showing improvements in soil organic matter, soil phosphorus content, and cation exchange capacity. Microbial biomass and soil respiration were enhanced by both P doses and FYM, particularly at 90 kg P ha^{-1} and 20 tons FYM ha^{-1}. Soil enzyme activities, such as phosphatase and invertase, were highest with the combined application of 90 kg P ha^{-1} and FYM. Principal component analysis and heatmap results confirmed the strong positive impact of these treatments on soil bioactivity and crop improvement.

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