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ORGANIC AMENDMENTS IMPROVE ROCK PHOSPHATE SOLUBILIZATION AND PROMOTE MAIZE GROWTH UNDER ALKALINE SOIL CONDITIONS

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Abstract

Phosphorus (P) availability in alkaline soils is often limited due to its fixation and precipitation into insoluble forms. Rock phosphate (RP) is a natural P source, but its effectiveness in alkaline soils is pH constrained. Organic amendments proved to improve RP dissolution and resultantly improved the P availability and plant growth under high pH soils. This study investigated the effects of two RP types namely red (RPR) and brown (RPB) applied alone or in combination with filter cake press mud (FCP) or poultry manure (PM), on P availability and maize growth under alkaline soil conditions. Treatments included RP alone or combined with FCP or PM, plus nitrogen (N) and potassium (K) at recommended rates. A control (N and K only) was included. After 4 weeks of soil incubation, soil pH was measured, and maize was grown in pots containing 10 kg of amended soil. At harvest (60 days after sowing), plant growth parameters and P-related soil and plant traits were assessed. Application of RP alone slightly reduced soil pH, increased total and available P, and enhanced plant growth compared to the control, but had minimal effect on organic carbon. Co-application of FCP or PM with RP further decreased soil pH (3.2 % and 3.52%) and significantly improved soil organic carbon (20% and 40%), P availability (37 % and 50 %), and maize growth in the RP+PM and RP+FCP amended soil respectively. Maximum plant height (99.5 cm), shoot dry biomass (13.30 g) and root dry biomass (5.10 g), leaf P content (0.33 g kg^{-1}), relative growth rate (9.6 g g^{-1}) was observed when FCP was applied in combination with RP red. Among the organic amendments, FCP had a pronounced effect than PM. In conclusion, combining RP with organic amendments-especially FCP—can enhance P availability and uptake by improving soil chemistry, offering a sustainable strategy for managing P nutrition in alkaline soils.

Key words: Alkalinity; Maize; Organic amendments; Phosphorus; Rock phosphate

Introduction

Phosphorus (P) is an essential nutrient for plant growth, playing key roles in energy transfer, root development, metabolic functions, and seed formation (Marschner, 2012; Sabah *et al*., 2022; Ezawa *et al*., 2000; Gurmu, 2023). The optimal soil pH for P uptake is around 6.5, but in alkaline soils, P forms insoluble complexes with calcium reducing its availability (Khoshru *et al*., 2023). Globally, about 67% of soils are P-deficient, and 15–30% show low P-use efficiency (Dhillon *et al*., 2017). Soils with less than 0.05% total P are considered deficient (Achal *et al*., 2007). Low P availability is a major constraint to crop production, especially under alkaline conditions. In arid regions like Pakistan, high soil pH limits P availability, mainly due to high calcium carbonate content (Grant *et al*., 2001). Around 80% of Pakistani soils are low in P because of this (Memon, 2005; Jamal *et al*., 2023). Although inorganic P fertilizers are commonly used to address this deficiency, their efficiency under alkaline conditions is limited (Ahmad *et al*., 2023). Much of the applied P becomes fixed by Ca^{2+} and Mg^{2+}, leaving little available for plant uptake (Gyaneshwar *et al*., 2002). Therefore, even when total soil P is high, the plant-accessible fraction remains low. The poor solubility of P fertilizers in alkaline soils highlights the need for sustainable strategies to enhance plant-available P.

Phosphatic fertilizers help overcome P deficiency but have drawbacks, including low efficiency and concerns over depletion of non-renewable rock phosphate (RP) reserves used for fertilizer production. Due to rapid fixation and limited efficiency of soluble P fertilizers, alternative, cost-effective sources like RP are gaining attention. Pakistan has large RP deposits (about 6.9 million tons of resources and 4.58 million tons of reserves (Naseer & Muhammad, 2014) that can serve as raw materials for P fertilizers. RP, alone or

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combined with other materials, can increase the release of P and enhance plant-available pools in soil (Kumari & Phogat, 2008; Sande *et al*., 2024). One effective strategy is the combined use of RP and organic amendments (Klaic *et al*., 2017; Amarasinghe *et al*., 2022). In alkaline soils, organic amendments like compost, animal manures, poultry manure, and some plant residues improve P availability (Jindo *et al*., 2023). These amendments also enhance soil bulk density, porosity, pH, electrical conductivity, microbial biomass, organic matter, and macro- and micronutrient content (Menšík *et al*., 2018; Sabah *et al*., 2020; Yang *et al*., 2020). Native soil microorganisms in such systems help release P from RP by lowering local pH, secreting enzymes, and forming organic complexes, thus enhancing P availability (Matisic *et al*., 2024; Wang *et al*., 2025; Aseri *et al*., 2009; Rawat *et al*., 2021).

Enhancing the solubility of sparingly soluble P sources can also be achieved by environmentally friendly, low-cost methods like composting RP with farmyard manure, poultry manure, and using P-solubilizing microorganisms (Fan *et al*., 2024; Mohamed *et al*., 2024; YaRong *et al*., 2024). Filter cake mud, a byproduct of sugarcane juice filtration produced in large amounts (30–40 kg per ton of crushed cane), is rich in nutrients such as nitrogen and phosphorus and contains high organic matter (Arulazhagan *et al*., 2024; Dotaniya *et al*., 2025). It also improved wheat growth and nutrient uptake (Elgharably, 2020), reduced heavy metal uptake (Elgharably, 2020), and enhanced growth in other crops (Prado *et al*., 2013; Ram *et al*., 2024). It may enhance P availability and maize growth, but data on its interaction with RP in alkaline soils are limited.

Maize is one of the most widely consumed cereals globally, rich in starch, protein, vitamins, oils, and minerals like nitrogen (N), P, calcium (Ca), and iron (Fe). Due to its short growing cycle, maize requires high soil-available P (Lino *et al*., 2018), often needing heavy P fertilizer use in alkaline soils. Keeping in view the positive role of organic amendments in improving RP solubility, P availability and growth response of maize crop in cost effective way. Present study was carried out to evaluate P availability and maize growth in alkaline soil amended with RP and organic amendments.

Materials and Methods

Soil: A pot experiment was conducted under greenhouse conditions at College of Agriculture, University of Sargodha, Pakistan during year 2024. Soil, collected from the experimental site of college of agriculture, was subjected to several analyses after standard methods (Moodie *et al*., 1959) for evaluation of the chemical and physical properties. Pots were filled with soil @ 10 kg soil per pot. Soil saturation percentage was calculated after a saturated soil paste was prepared followed by oven drying of the paste at 105°C until a constant weight was achieved.

Soil pH as well as the soil electrical conductivity (EC), expressed as dS m^{-1}, was measured in the extract of the saturated soil paste. The hydrometer method was the method for soil textural class determination. Sodium adsorption ratio (SAR) was determined using the formula:

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}} \quad (1)$$

The exchangeable concentrations of soil cations and anions were determined after the titration method ascribed in handbook 60 of U.S. Salinity Laboratory Staff (1954). Soil organic matter content was determined after Walkley and Black (1934). Sodium carbonate fusion method was adopted for determining soil total P content (Jackson, 1958). Soil available P was estimated following Olsen *et al*., (1954) method using the Spectrophotometer. Total N concentration was determined by micro-Kjeldahl method. Calcium carbonates ($CaCO_3$) content of soil was calculated after Moodie *et al*. (1959). Soil characteristics are presented in Table 1.

Table 1. Characteristics of the experimental soil (Pre-analysis).

Parameter	
Saturation percentage (%)	29
pH_s	8.15
EC_e (dS m^{-1})	1.28
Bicarbonates (HCO_3^-) m mol L^{-1}	4.95
Chlorides (Cl^{-1}) m mol L^{-1}	4.80
Sulphates (SO_4^{2-}) m mol L^{-1}	3.05
Calcium + Magnesium (Ca^{2+}+ Mg^{2+}) m mol L^{-1}	4.81
Sodium (Na^+) m mol L^{-1}	7.41
Sodium adsorption ratio (SAR) (m mol L^{-1})$^{1/2}$	4.77
Texture	Sandy clay loam
Organic matter (%)	0.49
Calcium carbonates (%)	6.1
Available phosphorus/ Olsen P (mg kg^{-1})	8.0
Soil Total P (g kg^{-1})	1.6

Treatments: Following treatments were applied using CR design with 3 replications, T_1= Recommended NK without any external P addition (NPK @ 160:0:60 kg ha^{-1}); T_2= Recommended NK + P as RPR (Rock Phosphate Red); T_3= Recommended NK + P as RPR + FCP; T_4= Recommended NK + P as RPR + PM; T_5= Recommended NK + P as RPB (Rock Phosphate Brown); T_6= Recommended NK + P as RPB + FCP; T_7= Recommended NK + P as RPB + PM.

RP and organic amendments were applied in a ratio of 1:2 with 1 part RP and 2 parts organic amendments. pH and EC of the organic amendments (1:10 material to water ratio (w/v) were measured using EC and pH meter. The materials were digested in HNO_3:$HClO_4$ acid mixture for measurement of total P, K, Ca, S as described above, whereas for total N content the micro-Kjeldahl method was followed. Total organic carbon was estimated following the Walkley and Black method (1934). The chemical characteristics of the amendments are presented in Table 2.

Table 2. Chemical properties of filter cake pressed mud (FCP) and poultry manure (PM).

Parameter	FCP	PM
pH (1:10)	6.80	7.24
Organic matter (%)	31.22	38.93
Organic carbon (%)	18.12	22.60
Total nitrogen (%)	1.64	1.79
C/N ratio	10.98	12.52
Total phosphorus (%)	1.29	0.80
Total potassium (%)	0.44	0.94
Total calcium (%)	8.60	12.00
Sulfur (%)	30	20

Nitrogen as urea (46% N) was added at 160 kg ha^{-1} over 2 doses whereas potassium sulfate (46% K_2O), applied at 60 kg ha^{-1}, was entirely added at the plant sowing time. Rock phosphate (RP; 28% P_2O_5) from Hazara phosphorite, KPK province, Pakistan, or Rock Phosphate Brown (RPB; 32.5% P_2O_5) imported from Egypt, was added separately, or in combination at 2 g RP and 2.25 g RPB per kg soil. FCP in the rate 6 g kg^{-1} soil and PM in the rate 5 g kg^{-1} soil were have been separately added with each RP type. A control treatment (no amendments) was included. The organic amendments were mixed up with soil and incubated for 28 days prior to maize sowing. Soil pots were then filled with 10 kg (dry weight based) of treated soil.

Five seeds of maize (*Zea mays* L. Pioneer) were sown, but only three seedlings per pot were maintained throughout the experiment. Soil moisture was maintained at 70% of the field capacity and various operations (hoeing, weed suppression and pest control) in soil pots were applied as needed till plant harvest. A day before harvest, plant height was measured using meter rod and leaf area of plants was determined using leaf area meter. Relative growth rate (g kg^{-1} day^{-1}) as proposed by Beadle (1993) was calculated as follows:

$$RGR = \frac{W2 - W1}{T2 - T1} \quad (2)$$

where RGR is relative growth and W_1 and W_2 are the total dry weights harvested at time intervals of T_1 and T_2, respectively.

At harvest, 60 days from sowing day, shoot and root samples were taken. Shoots were cut off 1 cm above soil surface. Roots were removed from pots after gentle water pressure to get rid of attached soil particles followed by washing and storage in paper bags. Plant samples were then placed in a drying oven at 70 ºC for 2 days. The dry weight of plant samples was recorded and then samples were ground using Willey mill. Wet digestion using mixture of nitric acid and perchloric acid (1:2) was considered for digesting the plant samples and measuring P content. Phosphorus use efficiency (PUE) was calculated by using equation given by Moll *et al*., (1982) as the product of P utilization efficiency (PUTE) and P uptake efficiency (PUPE). Phosphorous uptake efficiency was estimated to the procedure designated by Moll *et al*., (1982) by dividing the amount of total collected P per pot (g pot^{-1}) by exterior phosphorous amount (g pot^{-1}). Phosphorous utilization efficiency (PUTE) was determined from the procedure reported by Gabelmann & Gerloff (1983) as:

$$\text{P uptake efficiency} = \frac{\text{Total P in plant (g per pot)}}{\text{P available in soil g per pot}} \quad (3)$$

$$\text{P efficiency ratio (per)} = \frac{\text{Total plant dry mass (g per pot)}}{\text{Total P accumulated (g per pot)}} \quad (3)$$

Soil subsamples were taken from pots for measurement of soil pH, available P, total P content and organic matter. Soil pH (1:5 soil: water suspension), total and available P was extracted and measured as described above. Loss on ignition method (LOI) was adopted for determination of organic carbon using muffle furnace (Daihan lab Tech., LEF-130 S, Seoul, Korea).

Statistical analysis: The experimental treatments were randomly distributed in four replicates. Data was subjected to analysis of variance (ANOVA) and the least significant difference (LSD) test at p≤0.05 was used for various comparisons of manes (Steel *et al*., 1997) using Statictix 10.1 software.

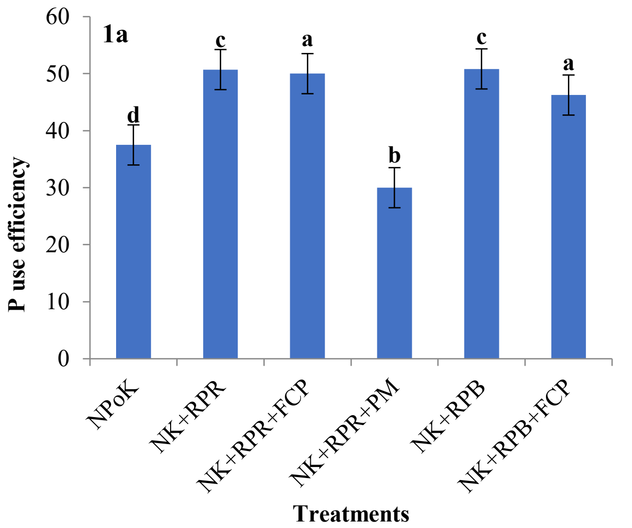
Results

Plant biomass and height: Data presented in Table 3 revealed that added amendments significantly (P<0.05) influenced the shoot and root dry weights as well as plant height. Compared to the control, the addition of RP alone significantly increased the plant biomass but insignificantly differences were noticed between rock phosphate phosphorite (RPR) and rock phosphate brown (RPB). Addition of rock phosphate along with the organic amendments resulted in much higher significance on the plant biomass more than that recorded by rock phosphate alone, Compared to the control, addition of rock phosphate with filter cake pressed mud (FCP) resulted in 48 to 60% higher shoot dry weight, whereas 26 to 32% increases in the shoot biomass were recorded in the soil amended with rock phosphate with poultry manure (PM). Similar observations were recorded for plant height and root dry weight, but compared to FCP, the addition of the PM resulted in a greater biomass only in the root dry weight.

Table 3. Shoot and root dry weights (g pot^{-1}) and plant height (cm) of maize as affected by addition of combinations of urea (N) potassium sulfate (K), filter cake pressed mud (FCP) and poultry manure (PM), rock phosphate phosphorite (RPR) and rock phosphate brown (RPB).

Treatment	Shoot dry biomass (g pot^{-1})	Root dry biomass (g pot^{-1})	Plant height (cm)
NK (no P added)	8.33 ± 1.09 c	3.20 ± 0.43 d	65.1 ± 1.20 d
NK+RPR	8.70 ± 1.11 c	4.21 ± 0.54 bc	75.2 ± 1.25 c
NK+RPR+FCP	13.30 ± 1.22 a	5.10 ± 0.60 ab	99.5 ± 1.51 a
NK+RPR+PM	10.50 ± 1.23 b	5.88 ± 0.64 a	85.3 ± 1.25 b
NK+RPB	8.65 ± 1.10 c	4.12 ± 0.51 c	76.5 ± 1.50 c
NK+RPB+FCP	12.30 ± 1.12 ab	4.60 ± 0.55 b	93.5 ± 1.60 a
NK+RPB+PM	11.00 ± 1.44 b	5.10 ± 0.61 ab	83.1 ± 1.30 b

Mean values of three replicates followed by standard errors of means (n=3). In each column, values with different letters differ significantly from each other at p<0.05



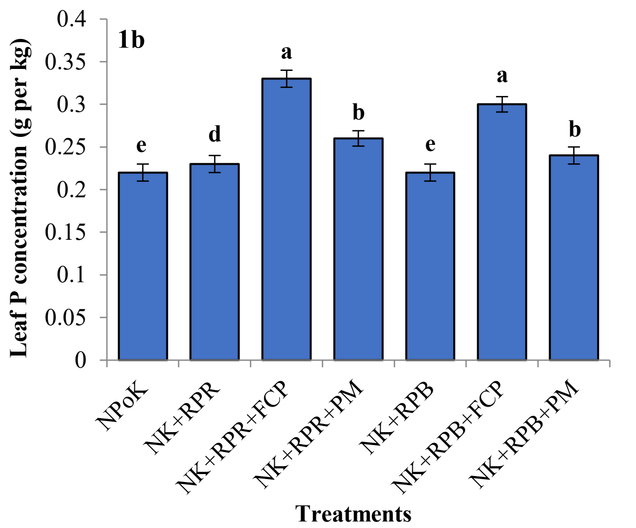


Fig. 1a. Leaf P (mg kg^{-1}) and 1b) P use efficiency (%) of maize as affected by addition of combinations of urea (N) potassium sulfate (K), filter cake pressed mud (FCP) and poultry manure (PM), rock phosphate phosphorite (RPR) and rock phosphate brown (RPB). Bars are mean values of three replicates and contain ± standard errors of means. Different letters on bars show significant treatment differences at $p<0.05$.

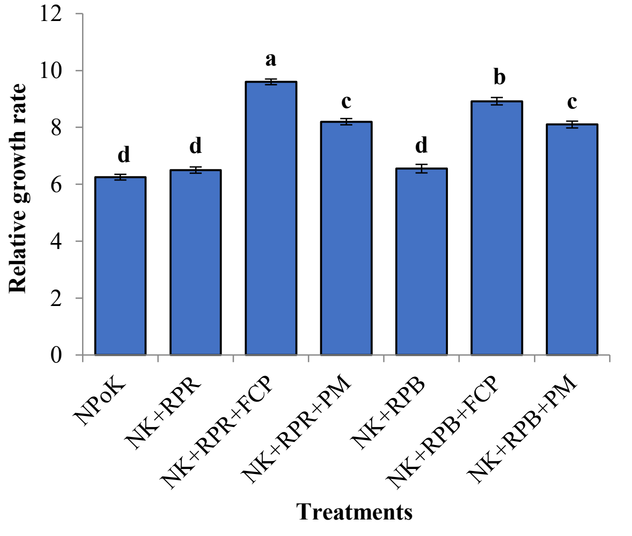


Fig. 2. Relative growth rate (g g^{-1}) of maize as affected by addition of combinations of urea (N) potassium sulfate (K), filter cake pressed mud (FCP) and poultry manure (PM), rock phosphate phosphorite (RPR) and rock phosphate brown (RPB). Bars are mean values of three replicates and contain ± standard errors of means. Different letters on bars show significant treatment differences at $p<0.05$.

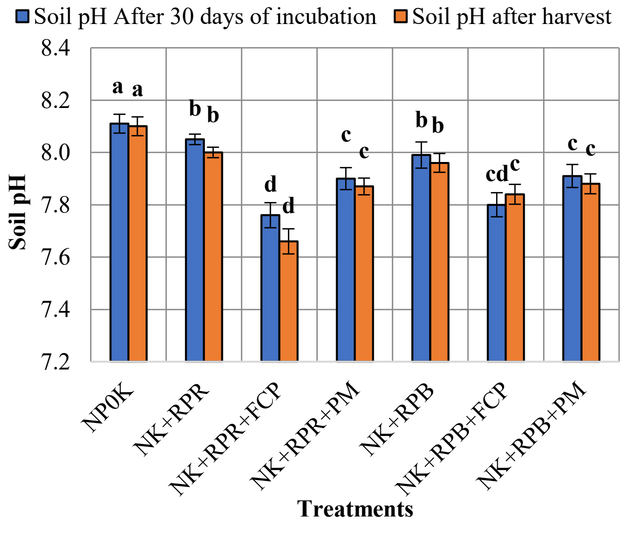


Fig. 3. Soil pH as affected by combinations of urea (N) potassium sulfate (K), filter cake pressed mud (FCP) and poultry manure (PM), rock phosphate phosphorite (RPR) and rock phosphate brown (RPB). Bars are mean values of three replicates and contain ± standard errors of means. Different letters on bars show significant treatment differences at $p<0.05$.

Leaf phosphorus concentration and P-use efficiency: Application of different combinations of organic amendments significantly ($p<0.05$) affected shoot P concentration (Fig. 1a). Compared to the control treatment, the addition of either type of rock phosphate alone had no effect. Compared to rock phosphate brown (RPB), rock phosphate phosphorite (RPR) had a greater effect on P concentration when added in conjunction with either filter cake pressed mud (FCP), or the poultry manure (PM). In all combinations, compared to PM, the effect of FCP on leaf P concentration was more pronounced. Maximum leaf P concentration (0.33 g kg-1) was noticed when FCP was used as organic amendment in conjunction with RPR. On the other hand, minimum leaf P concentration (0.22 g kg^{-1}) was depicted in T1 (control) without any additional P source.

Data (Fig. 1b) implied a significant ($p<0.05$) effect of RP on P-use efficiency (PUE) only when it is added in combination with the organic amendment; relative to PM, efficiency is higher when combined with FCP. Maximum PUE (1150) was obtained when FCP was used as organic amendment in conjunction with RPR as a source of P along with NK at recommended rate.

Relative growth rate (RGR): Impact of organic amendments (FCP and PM) in combination with rock phosphate (RPR and RPB) regarding RGR of maize is plotted in Fig. 2. The addition of RP alone in either form had no effect on RGR. Combining RP with the organic amendments significantly ($p<0.05$) influenced PGR; higher RGR was recorded with FCP compared to PM. Data suggested that minimum value (6.25 g g-1) for RGR of maize was noticed in T1 (control) receiving no externally applied P. It was approached to the maximum value of 9.6 g g-1 in T3 getting FCP as organic amendment in conjunction with RPR and NK at recommended rate.

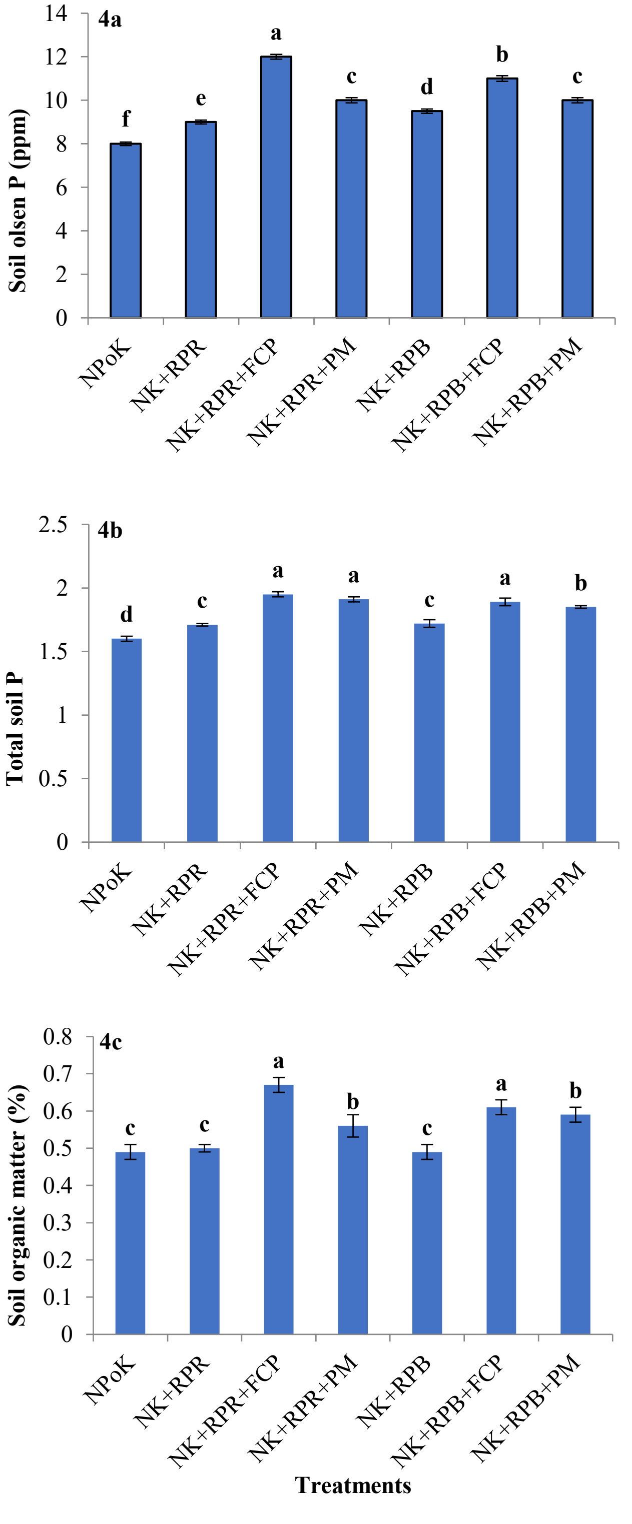


Fig. 4. Soil phosphorus (available and total) (4a &b) and total organic carbon (4c) as affected by addition of combinations of urea (N) potassium sulfate (K), filter cake pressed mud (FCP) and poultry manure (PM), rock phosphate phosphorite (RPR) and rock phosphate brown (RPB). Bars are mean values of three replicates and contain ± standard errors of means. Different letters on bars show significant treatment differences at $p<0.05$.

Soil pH: Data on soil pH after 30-day incubation with the different amendment combinations and after corn harvest is presented in Fig. 3. Significant reduction of soil pH after incubation and after maize harvest before has been noticed in the soil treated with RP alone; soil pH was lower in the RPB than in the RPR-treated soil (3.2 % and 3.52% in the RP+PM and RP+FCP amended soil respectively). Addition of RP along with the organic amendments further lowered the soil pH remarkably more with FCP compared to PM. In the organically amended soil, the pH decreased further after corn harvest.

Soil phosphorus (total and available) and organic C: Data presented in Fig. 4 a, b and c shows total P, available P and total organic C in the soil treated with RP with and without organic amendments. The amendments have significantly ($p<0.05$) affected the total as well as the available P in the treated soil. Relative to the control, with no significant difference between the RP types under investigation, addition of RP alone resulted in increasing the soil total P content as well as P availability by approximately 10%. Compared to the control, combined addition of RP with FCP or PM resulted in increasing total P content by approximately 18%. Likewise, P availability increased in the RP+PM and RP+FCP amended soil recording increases relative to the control by approximately 37 and 50%, respectively. Maximum available P content of soil was recorded when FCP was used as organic amendment in conjunction with RPR as a source of P along with NK at recommended rate showing value of 12 ppm. Maximum total P content of soil was recorded when FCP was used as organic amendment in conjunction with RPR as a source of P along with NK at recommended rate showing value of 1.95 g kg^{-1}.

Addition of RP alone had no effect on the soil organic C. Compared to the control, addition of PM and FCP resulted in increasing soil organic C by approximately 20 and 40%, approximately. Data suggested that lowest content of soil organic matter (0.49%) was observed in T1 (control) receiving recommended doses of NK without any addition of organic amendments. That was approached to the maximum value of 0.67% soil organic matter in treatment T3 receiving FCP and RPR accompanied with recommended rates of NK.

Discussion

Maize growth parameters: Results of present study implied that the positive impacts on measured maize growth parameters and soil parameters under alkaline conditions can be credited to the enhancement of the plant growth environment. Incorporation of filter cake pressed mud (FCP), or poultry manure (PM) along with rock phosphates has the potential in altering the soil chemical properties and enhancing P bioavailability and maize P uptake which consequently contributed significantly to enhanced maize growth components under alkaline conditions. These positive impacts were more pronounced with the application of FCP along with rock phosphate. Findings of this study come in agreement with the data reported in earlier studies (Muhammad & Khattak, 2009; Aziz *et al.*, 2010; Elgharably, 2020).

In the control soil of this study maize growth was not N, nor K limited (N and K fertilizers were added) but probably had insufficient amounts of other elements such as P, Ca, Mg, or micronutrients available to promote plant growth. Under alkaline soil conditions, the availability of most nutritional elements including micronutrients is limited due to volatilization, fixation/precipitation with different salts, or sorption on soil minerals, which can limit the growth of most crops. Muhammad & Khattak (2009) and Aziz *et al*., (2010) confirmed that increased soil P content as well as availability can enhance P uptake and plant growth under alkaline conditions. In this study, addition of RP resulted in enhanced shoot and root biomass (Table 3). Although total and available P concentrations increased after RP addition they had an insignificant effect on plant leaf P concentration, indicating that other nutritional elements (not measured), or at least those elements along with P, partially limited maize growth. In addition to P, rock phosphate fertilizers carry appreciable amounts of Zn and Cu. In present study, RP addition resulted in slightly decreasing the soil pH (Fig. 1) possibly to the extent that increased the bioavailability and uptake of most nutritional elements including micronutrients, resulting in enhanced maize growth. So, it could be postulated that the addition of RP can enhance the bioavailability of P and most micronutrients essential for maize growth under alkaline conditions. The alkaline soil under investigation had high soil pH, low organic matter content and low Olsen-P concentration which can result in unfavourable conditions for maize growth promotion as that found in the control soil which received only N and K fertilizers.

It would be assumed that maize growth conditions in the PM-amended soil are much better than in the FCP-amended soil due to the higher N, K, organic matter and organic C contents, but the opposite was true, and eventually maize biomass was greater in the FCP than in the PM-amended soil. Compared to PM, the addition of FCP resulted in higher organic matter content but also increased the amount of soil total P content which occurred because FCP had higher P content (Table 3). Effectiveness of FCP over PM could be due to higher concentration of sulfur (S) in FCP as compared to PM and higher content of calcium in PM (Fu *et al*., 2025). Role of S in reducing soil pH is a known fact now. Poultry manure naturally contains higher Ca content that affects its ability to release P from RP (Mahimairaja *et al*., 1995). Therefore, the addition of FCP at the same addition rate of PM resulted in more P added into the soil P reserve in the different organic and inorganic forms which eventually was utilized by maize under alkaline conditions. An improvement in plant height, leaf area, shoot biomass and root biomass was observed in this study by addition of FCP compared to PM.

Soil parameters: Soil total P or micronutrients content depends greatly on many factors including soil organic matter content, climatic conditions, parent material nature and fertilizers addition (Hinsinger, 2001; Kashem & Warman, 2009). Organic amendments can increase the bioavailability of plant essential elements in the ambient rhizosphere as well as the soil organic matter content, which has a significant impact on soil chemical, physical and biological properties of alkaline soils (Menšík *et al*., 2018; Elgharably, 2020; Sabah *et al*., 2020; Yang *et al*., 2020), a key indicator of soil health.

In this study, the amendments FCP and PM upgraded the soil organic matter fraction and increased soil total P content as well as P availability. An improvement in available P content of soil and leaf P content of maize could be subjected to release of fixed P from RP dissolution as a result of organic amendments action. Due to the high organic matter and organic C contents of the FCP and PM (Table 2) it is assumed that after incorporation the soil physical and biological properties have improved (not evaluated) as occurred with the soil chemical properties. In the soil amended with RP along with the organic amendments expectedly increased total P concentration (Fig. 4b) and decreased soil pH significantly decreased. Lowering the pH in the alkaline soil can result in dissolution of P from different forms and increasing P availability (Fig. 4a) which was significantly utilized by maize as indicated by data (Fig. 1) of the leaf P concentration and P use efficiency (Fig. 1) and resulted in increased plant growth.

Soils amended with organic amendments involve a major role for soil native microorganisms to enhance phyto-available soil P pools, thus, enhancing mobility by lowering localized soil reaction, secreting certain acids and making stable organic complexes. Organic materials release many types of organic acids during the process of degradation. Those acids contribute toward lowering soil reactions that ultimately make apatite P available (Aseri *et al*., 2009). P availability increases as the soil pH falls close to the range 6.5-7.5 (Aziz *et al*., 2010).

Mixing organic amendments with RP resulted in P dissolution and subsequently higher P contents in soil. Addition of FCP, or PM increases sulfur concentration in soil which contributes to soil pH lowering (Joggi *et al*., 2005; Soares *et al*., 2024; Singh *et al*., 2024; Fatimah *et al*., 2024), thereby, assist RP dissolution and resultant P release. Improved leaf P content could be due to improved P availability from soil due to improved conditions after organic amendments incorporation (Sabah *et al*., 2018a; Sabah *et al*., 2018b). It is well documented that acid release during the course of organic amendments decomposition block the P fixation cites thereby improved P release and avoiding its re-fixation (Fuentes *et al*., 2006; Khan & Joergensen, 2009). Mahimairaja *et al*., (1995) also reported the secretion of many organic acids during decomposition of organic amendments that contribute to RP dissolution and resultantly P release. Addition of FCP seems has resulted in increasing the soil organic matter fraction and RP dissolution and accordingly increased the amount of available P more than PM did in the alkaline soil.

All the treatment receiving organic amendments in either form performed well in this regard. However, this improvement was more prominent when FCP was used as organic amendment. This can be attributed to the upgradation of soil organic matter fraction as a result of organic amendment addition. Other researchers reported such correlation of organic matter content and PUE (Ali *et al*., 2015; Lahori *et al*., 2024; Singh *et al*., 2025). An improvement in P uptake efficiency and P utilization efficiency contributed to an improvement in P use efficiency which could be attributed to reduction in re-fixation of P caused by organic matter coating of organic amendments and reduction of soil pH.

Conclusions

Based on the present study, plant growth appeared to be limited by P uptake due to low P availability. Both types of RP exhibited similar effects in terms of P release, whether applied alone or in combination with organic amendments. Addition of FCP and PM improved maize growth under alkaline soil conditions by positively lowering the soil pH, increasing soil organic matter content, possibly enhancing microbial activity, and, most importantly, facilitating RP breakdown and P dissolution. This ultimately led to increased P availability and uptake, promoting growth-related parameters in maize. Among the organic amendments tested, FCP proved more effective than PM in enhancing RP dissolution. This indicates FCP's potential to improve soil properties—especially soil pH—and create favorable growth conditions for crops, particularly maize, in alkaline soils. Therefore, the combined use of FCP with RP is recommended, pending further validation under field conditions and across different crop types.

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Author Contributions: N. Sabah and M. Tahir conceived the presented idea and carried out the experiment. M. Tahir and M. Zeeshan Khan contributed to sample preparation. N. Sabah, Ikram Ullah and A. Elgharably developed performed the computations and took the lead in writing the manuscript. S. Shoukat, Abdullah, Tahreem Iftikhar, Johar Jamil, Khadija Gilani and S. Salahuddin Lodhi contributed to the interpretation of the results, reviewed and structured the manuscript. N. Sabah and Ikram Ullah supervised the work and did critical revision. All authors contributed to shaping the research, analysis, and manuscript.

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