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Research article

Residual phosphorus availability after soil application of different organic waste in varying soil P status soils

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A R T I C L E I N F O

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A B S T R A C T

Transformations of applied phosphorus (P) fertilizer to inaccessible residual soil P is the main cause of inadequate P availability to plants in the majority of the cultivated soils. This study investigated the effect of organic wastes (rice-residue biochar, farmyard manure (FYM), poultry manure (PM), green manure (GM), and wheat straw (WS) on residual-P mobilization and its bioavailability in maize crops under different P status soils. Surface soil samples of 'medium-P' (12.5–22.5 kg P ha^{-1}) and 'high-P' (22.5–50.0 kg P ha^{-1}) status soils were collected from a long-term differential P fertilization experiment on maize-wheat rotation and were subjected to examine P adsorption/desorption, phosphatase activity and microbial biomass P (MBP) after incubation with organic amendments of varying elemental composition. The incorporation of organic manures decreases P sorption with maximum decrease in FYM-treated soils, indicating increased P concentration in soil solution. In contrast, WS due to its wider C/P ratio increased P sorption and did not produce any significant impact on the bioavailability of P. High-P status soils witnessed lower P sorption than medium-P soils. The MBP increased in the order of PM > FYM > GM > WS > biochar irrespective of soil P status. The availability and mobility of residual-P with FYM and PM was significantly higher than that of residual-P from biochar, GM and WS. Organics with wider C/P ratio immobilize bioavailable P in the short term regardless of soil P status.

1. Introduction

Phosphorus (P) fertilizers are usually applied more than crop demand [1]. This practice resulted in a considerable buildup of residual-P in many agricultural soils as sparingly soluble or inaccessible compounds of variable solubility [2–4]. The surplus P

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undergoes a variety of geochemical processes, including solubilization, complexation, adsorption, and precipitation, all of which are closely linked to various soil properties [5]. In acidic soils, P is sorbed by oxides and hydroxides of iron and aluminum [6] as strengite ($FePO_4.2H_20$) and variscite ($AlPO_4.2H_20$) respectively, while in alkaline soils, P is generally sorbed as primary products dicalcium phosphate and octacalcium phosphate ($Ca_8H_2(PO_4)_6.5H_2O$) in the presence of calcite and limestone on the surface of calcium carbonate [7] and clay minerals [8]. Over time, dicalcium phosphate may transform into tricalcium phosphate and hydroxyapatite. The buildup of P in the soil in various forms is an important factor affecting the recovery of added P and response to crops. Despite increased P content in soils, the fertilizer P use efficiency rarely exceeds 20 % [9,10]. The higher amount of accumulated residual-P in light-textured soils may increase the P movement below the rhizosphere [11], and enhance the risk of surface water eutrophication of water bodies [12,13]. As most of the P sources are inorganic and non-renewable and are expected to be depleted in 50–100 years [14] demand for economically efficient P management strategies.

Environment-friendly and economically feasible approaches are desirable to enhance the availability of residual P. Addition of crop residue and organic manures offer opportunities to mobilize the residual P. The farm sector generates about 696.3 million tons of crop residues annually in India [15]. Efficient management of these residues may contribute about 1.74 million tons (taking a weighted average of 0.25 % P_2O_5) of phosphorus in soil in addition to other required nutrients. Miserably, a major chunk of these crop residues is burnt each year causing air as well as soil pollution. The potential of organic amendments (crop residues and organic manures) to mobilize soil residual-P is still indistinct. Some of the studies [3,16,17] reported increased soil P availability with the incorporation of crop residues, while others observed immobilization of soil P caused by a wider C/P ratio of crop residues like wheat straw (WS), legume stubble and canola stubble [18,19]. The immobilized soil P due to a wider C/P ratio might be efficiently accomplished by incorporating crop residues in the soil through farmyard manure (FYM). In certain geographical regions increased soil P availability with continual FYM application [20] had become an issue of P contamination in surface waters in agricultural fields. The addition of poultry manure (PM) led to significant positive synergistic effects concerning P availability in acidic soils and antagonistic response in alkaline soil [21]. The incorporation of carbon-rich solid products such as biochar has the potential to enhance plant available P [22]. However, contrasting results with minimal or slow P release with biochar addition were also reported [23,24]. Previous studies have shown that soil P availability increases after green manuring, which increases peanut pod yield [25], but reduced yields were also reported when peanuts were intercropped with green manuring crops [26].

Therefore, it becomes important to determine to what extent the addition of different organic amendments will affect the availability of residual-P across different soil test P (STP) status soils. This study will help in enhancing our understanding of P dynamics and the potential role of residual-P in facilitating plant P uptake. We hypothesized that the incorporation of organic amendments increases the potential availability and mobility of residual-P to crop plants. Therefore, the purpose of this study was to assess the impact of the incorporation of crop residue and organic manures on residual-P mobility and bio-availability to maize in varying soil P status soils under long-term experimentation.

2. Materials and methods

2.1. Soil and manure

Bulk surface soil samples (0–15 cm) were collected after 11 cycles of maize-wheat crop rotations from plots with 'medium-P' (12.5–22.5 kg P ha^{-1}) and 'high-P' (22.5–50.0 kg P ha^{-1}) soils from an ongoing long-term field experiment having different soil P build-up levels [10]. The soil samples were mixed thoroughly, dried, and sieved through 2 mm mesh size and stored. The soil of the experimental site was classified as loamy sand *inceptisol*, as per Soil Taxonomy (Soil Survey Staff, 2014). Some initial physicochemical characteristics of soils are given in Table 1.

Crop residue of wheat (WS) was collected after its harvest, while green manure (*Sesbania aculeate*) was raised at a research farm, Department of Soil Science, Punjab Agricultural University, Ludhiana, and harvested after 60 days of sowing. Collected residues were first air dried and then dried at 60 ± 1 °C, ground, and stored at room temperature. Fully decomposed FYM, PM, and rice-residue biochar were also collected. These materials were thoroughly crushed and stored. Rice-residue biochar was produced by the method described by Ref. [27]. The nutrient composition of collected organic materials is given in Table 2.

Air-dried and sieved soil samples (100 g) of different P status soils under long-term P fertilization were pre-treated with WS and organic manures (FYM, GM, PM, and biochar) at 1.0 % on dry weight basis were incubated in wide mouth polythene bottles at field

Table 1
Physico-chemical characteristics of the experimental soils.

Properties	Medium-P	High-P
pH	7.15	7.12
EC (dS m^{-1})	0.23	0.18
Soil organic carbon (%)	0.29	0.32
Olsen-P (mg kg^{-1})	8.1	15.2
Available N (mg kg^{-1})	37.6	39.6
Available K (mg kg^{-1})	39.8	41.6
Texture	Loamy sand	Loamy sand
Bulk density (Mg m^{-3})	1.51	1.53
Water holding capacity (%)	12.1	12.5

capacity over 30 and 60 days at 25 °C. Under similar conditions, a set of untreated (Control-P) soils was also incubated. The moisture content of the soil was kept to field capacity by adding deionized water-weighing polythene bottles every third day of incubation. The incubated soil was thoroughly mixed with a spatula once a week for a uniform mixture of soil and organics.

2.2. Phosphorus sorption and desorption experiment

After the completion of the incubation period, 1 g of soil sample was equilibrated with 0.01 M $CaCl_2$ solution having 2.5, 5.0, 10, 20, 30, 40, and 50 mg P L^{-1} in 50 ml centrifuge tubes to give soil solution ratio of 1:25 (w/v). Two drops of toluene were added to prevent microbial growth. The centrifuge tubes were shaken and equilibrated at 25 °C for 16 h [28]. The samples were centrifuged at 2500 rpm for 10 min. After centrifugation, the suspension was filtered and analyzed for P concentration through the ascorbic acid reduction method [29] on the spectrophotometer. Once the sorption experiment had been accomplished, 10 ml of 0.01 M $CaCl_2$ was added to residual soil, followed by 6 h of shaking on a horizontal shaker, filtered through Whatman filter paper No. 1, and the solution P concentration defined as desorbed P estimated by the ascorbic acid method.

2.3. Glass House experiment

A pot experiment was conducted in 2021 with maize (*cv.* DKC-9108) as a test crop in Glass House, Department of Soil Science, and PAU Ludhiana. Plastic pots (25 cm diameter) lined with polyethylene bags were used and filled with 5 kg of soil. A basal dose of N in the form of urea and K as potassium chloride was applied as per recommendations. Crop residue (WS) and organic manures (FYM, GM, PM, and biochar) were incorporated @ 1 % on a dry weight basis one day before sowing of the crop. Eight healthy maize seeds were sown in pots during the second week of June. Four superior plants of each crop were kept after thinning. Maize crop was raised for 60 days as per Punjab Agricultural University (PAU), Ludhiana recommended package of practices and were harvested manually from each pot after 60 days of sowing. Dry matter production was recorded pot-wise. P content of oven-dried ground plant samples (60 ± 1 °C) was estimated by wet digestion using a mixture of acids (HNO_3:$HClO_4$ mixed in a ratio of 3:1) and determined total P in the extract by vanadate molybdate reagent. The intensity of the yellow color was measured using a colorimeter at 470 nm wavelength [30]. P uptake was calculated by multiplying the dry matter production by plant P concentration. Alkaline phosphomonoesterase was assessed by Ref. [31] and Microbial biomass phosphorus by Ref. [32].

2.3.1. Statistical analysis

The P sorbed was estimated from the following relationship:

$$x/m \ or \ S = VC_o\left(1\text{-}C_e/C_o\right)/m \quad \text{(i)}$$

where x/m or S is the concentration of P adsorbed (mg kg^{-1} soil), C_o is the initial solution P concentration in (mg L^{-1}), C_e is the equilibrium solution P concentration (mg L^{-1}), V is a volume of equilibrium solution (l), and m is the weight of soil taken (g). The C_e/C_o ratio is used to assess the extent of phosphorus sorption onto a solid surface. If C_e/C_o is close to 1, it indicates significant sorption of phosphorus, while smaller values suggest less sorption. The P sorption data obtained in both medium-P and high-P soils was well-fitted following the Freundlich equation:

(1) Freundlich sorption equation

$$\text{x/m} = K_f\ \text{C}_e^{1/n} \quad \text{(ii)}$$

where x/m is the concentration of P adsorbed (mg kg^{-1} soil), C_e is P concentration in equilibrium solution (mg L^{-1}), K_f is sorption capacity (mg P kg^{-1} soil) and n is sorption intensity constant (mg L^{-1}). A linear plot of log x/m *vs* log C_e yields the values of '*Kf*' and '*n*' from intercept and slope respectively.

The data obtained were analyzed for P desorption using the following equations:

1) Langmuir equation

Table 2
Nutrient content of organics.

Organics	Nutrient content (%)				C: P ratio
	N	P	K	C	
Wheat straw	0.35	0.05	0.81	36	720:1
Farmyard manure	0.85	0.90	1.10	30	33:1
Green manure[a]	2.82	0.34	1.33	33	97:1
Poultry manure	0.90	1.25	2.74	33	26:1
Rice-residue biochar	0.12	0.28	0.68	46	164:1

[a] Sesbania aculeata.

$$D_e / S_{de} = 1/ K_d . D_m + D_e/D_m \quad \text{(iii)}$$

where S_{de} is the concentration of pre-sorbed P (mg kg $^{-1}$ soil), D_e is the concentration of desorbed P (mg L^{-1}), D_m is desorption maxima (mg kg^{-1} soil) and K_d is the desorption constant to P mobility (L mg^{-1}). The desorption maximum (D_m) and constant (K_d) were calculated from the slope and intercept of the linear plot of D_e/S_{de} vs D_e respectively.

2) Freundlich equation

$$S_{de} = a\, D_e^{1/n} \quad \text{(iv)}$$

where S_{de} is the concentration of pre-sorbed P (mg kg $^{-1}$ soil), D_e is the concentration of P desorbed (mg L^{-1}), a is desorption capacity (mg kg^{-1}) and n is desorption strength (mg L^{-1}).

Statistical analyses were performed using SPSS 20.0 (IBM SPSS). Data were subjected to one-way ANOVA for the comparison of treatments and two-way ANOVA for the comparison of soils, followed by the least significant difference (LSD) test at the $P < 0.05$ level to calculate significant differences among the mean values.

3. Results

3.1. P adsorption

Phosphorus adsorption results elucidate that the incorporation of organic manures expressed variable responses P adsorption irrespective of soil P status (Figs. 1 and 2). Higher P adsorption was observed with the incorporation of WS and GM, while it decreased with FYM, PM, and biochar addition in both P-status soils. The results revealed that sorbed P varied from 22.5 to 427.9, 21.1 to 404.7, 10.3 to 189.1, 1.4 to 79.2, 2.2 to 86.2, and 4.9–90.0 mg P kg^{-1} respectively in control-P, WS, GM, FYM, PM and biochar amended soils with different levels of P (25–500 mg P kg^{-1} soil) application in medium-P soils at 30 days of incubation. The corresponding values in high-P soils ranged from 20.1 to 426.4, 18.9 to 352.1, 2.0 to 133.0, 0.6 to 49.6, 1.0 to 61.1, and 1.4–67.3 mg P kg^{-1} soil (Fig. 1). This expressed that the amount of P sorbed increased with increasing rates of P added irrespective of soil P status. Likewise, the equilibrium P concentration persistently increased with the increasing amount of P added in each treatment. Comparing sorption in both P-status soils, relatively lower sorption was observed in high-P soils than in medium-P soils. The amount of P adsorption increased over time in all treatments when incubated for 60 days in both P-status soils (Fig. 2).

3.2. P adsorption parameters

The phosphate adsorption isotherms illustrating the relationship between sorbed P and the equilibrium P concentration (C_e) for medium-P and high-P soils (Figs. 1 and 2) expressed that sorption data fitted well to Freundlich sorption equation with significant R^2 values varying from 0.93 to 0.99 in medium-P and 0.90 to 0.99 in high-P soils (Table 3). The Freundlich constants 'K_f' and 'n' showed wide variability in different organic amended treatments. Constant 'K_f' is a measure of the extent of P adsorption at unit equilibrium concentration and was maximum in control-P soils (21.4 and 15.5 mg kg^{-1} in medium-P and high-P soils) followed by WS, GM, biochar, PM, and FYM treated soils. The highest value of 'n' (calculated from the slope of a plot (log x/m *vs.* log C_e) was also noticed in control-P and the lowest in FYM-treated soils. A similar treatment trend was observed at 60 days of incubation, but the amount of P adsorbed was found higher at 60 days of incubation than at 30 days of incubation for all the treatments in both P-status soils (Table 4).

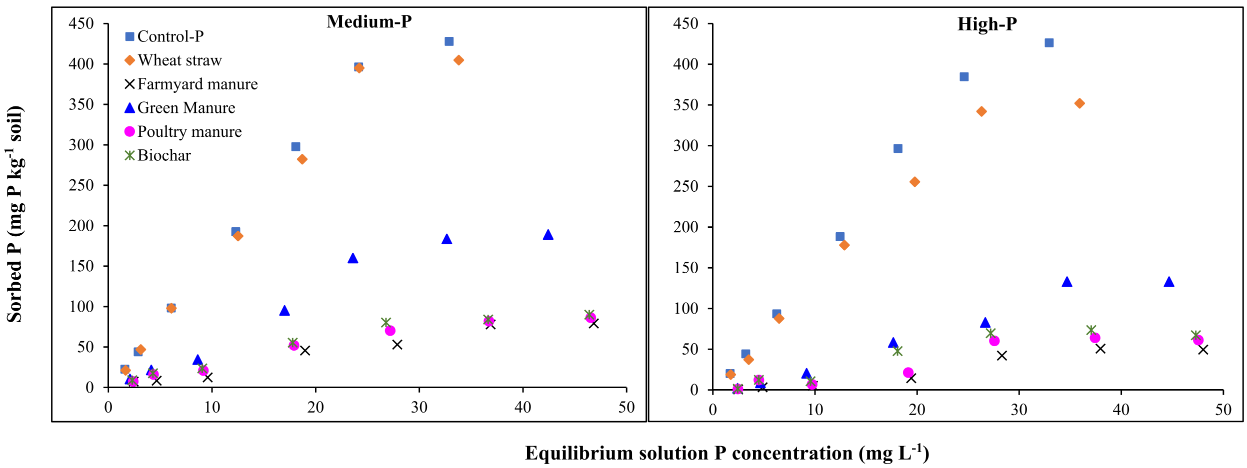

Fig. 1. P adsorption as affected by incorporation of crop residue and organic manures at 30 days of incubation in medium-P and high-P soils.

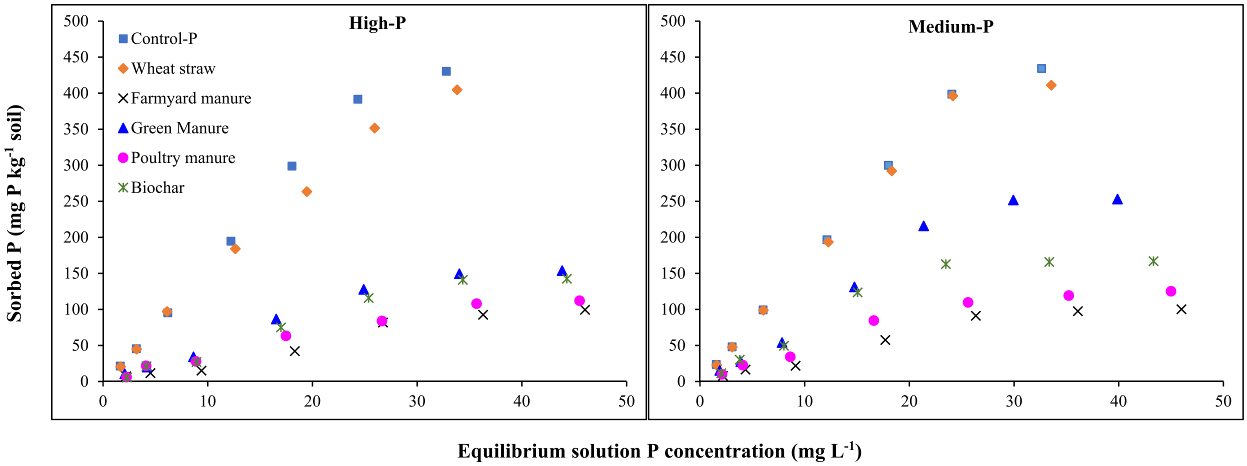

Fig. 2. P adsorption as affected by incorporation of crop residue and organic manures at 60 days of incubation in medium-P and high-P soils.

Table 3
Effect of incorporation of crop residue and organic manures on adsorption constants (Freundlich) in medium-P and high-P soils under aerobic conditions at 30 days of incubation.

Treatments	Medium-P			High-P		
	K_f (mg kg^{-1})	n (mg L^{-1})	R^2	K_f (mg kg^{-1})	n (mg L^{-1})	R^2
Control-P	21.4	1.17	0.99	15.5	1.03	0.99
Wheat straw	17.8	1.09	0.99	7.8	0.86	0.97
Green manure	3.8	0.91	0.99	1.2	0.79	0.97
Farmyard manure	0.7	0.77	0.97	0.3	0.74	0.95
Poultry manure	1.1	0.80	0.93	0.5	0.75	0.90
Biochar	1.6	0.87	0.93	0.7	0.76	0.93

3.3. P desorption

The P desorption process determines P release in soil and is inversely related to P sorption. Generally, soils that sorb a higher portion of applied P tend to release a fraction of sorbed P in soil solution. This is evident from the lower amount of P desorbed (Figs. 3 and 4) than P sorbed for each treatment in both medium-P and high-P soils. Phosphorus desorption in medium-P soils ranged from 1.27 to 18.3, 1.60 to 27.7, 1.66 to 35.2, 1.71 to 44.9, 1.74 to 40.0 and 1.67–37.2 mg P kg^{-1} and in high-P soils from 1.30 to 21.3, 1.56 to 33.8, 3.73 to 49.7, 3.75 to 56.0, 4.0 to 53.2 and 3.63 to 50.0 respectively in control-P, WS, GM, FYM, PM and biochar amended treatments with increasing levels of P concentration (25–500 mg P kg^{-1} soil) respectively at 30 days of incubation (Table 5). A similar treatment trend was observed at 60 days of incubation but with comparatively lower desorption values than at 30 days (Table 6). The results indicated that the soils treated with organic materials expressed a maximal decrease in P desorption with WS incorporation and a maximal increase with FYM addition such that P desorption increased in the order of FYM > PM > Biochar > GM > WS in both medium-P and high-P soils.

3.4. P desorption parameters

The pre-sorbed P at any specified equilibrium solution P concentration, in organic manures and crop residue incorporated

Table 4
Effect of incorporation of crop residue and organic manures on adsorption constants (Freundlich) in medium-P and high-P soils under aerobic conditions at 60 days of incubation.

Treatments	Medium-P			High-P		
	K_f (mg kg^{-1})	n (mg L^{-1})	R^2	K_f (mg kg^{-1})	n (mg L^{-1})	R^2
Control-P	22.1	1.17	0.99	17.6	1.07	0.99
Wheat straw	20.4	1.13	0.99	14.7	1.03	0.99
Green manure	7.1	0.96	0.99	3.6	0.93	0.98
Farmyard manure	1.7	0.85	0.90	1.2	0.82	0.87
Poultry manure	2.8	0.90	0.94	1.8	0.85	0.92
Biochar	3.2	0.92	0.96	2.5	0.87	0.98

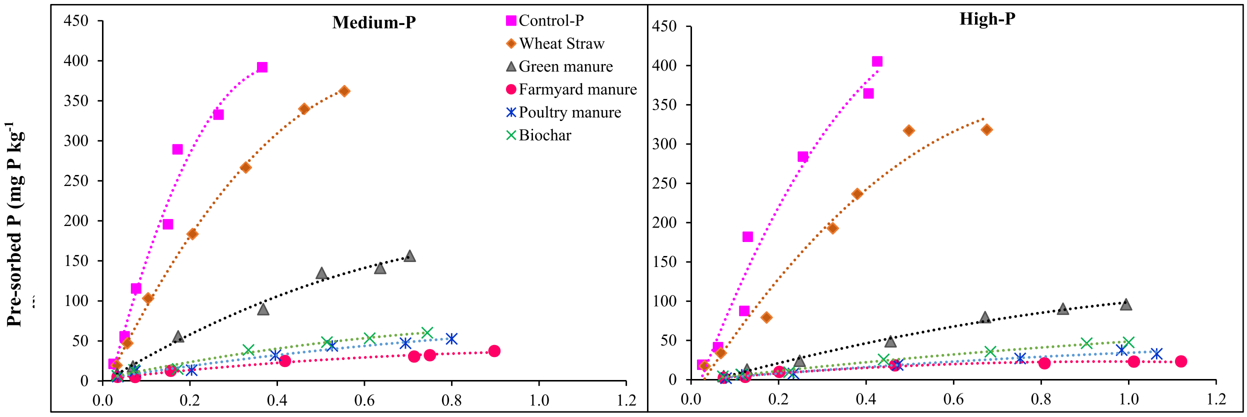

Fig. 3. P desorption as affected by incorporation of crop residue and organic manures at 30 days of incubation in medium-P and high-P soils.

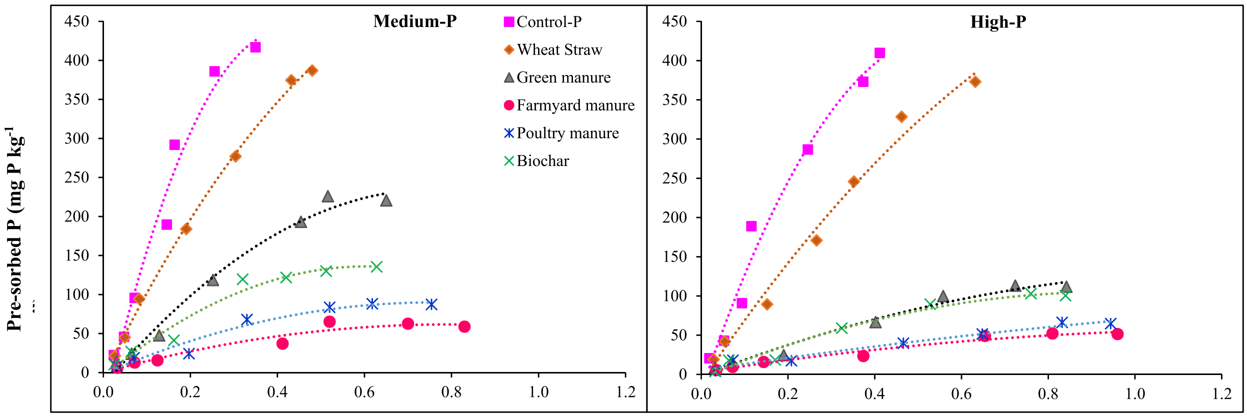

Fig. 4. P desorption as affected by incorporation of crop residue and organic manures at 60 days of incubation in medium-P and high-P soils.

Table 5
Effect of incorporation of crop residue and organic manures on amount of P desorbed (mg P kg^{-1} soil) in medium-P and high-P soils at 30 days of incubation.

Treatments	P added (mg P kg^{-1} soil)													
	Medium-P							High-P						
	25	50	100	200	300	400	500	25	50	100	200	300	400	500
Control-P	1.27	2.54	3.85	7.50	8.60	13.3	18.3	1.30	3.10	6.10	6.50	12.8	20.3	21.3
Wheat straw	1.60	2.83	5.21	10.3	16.4	23.1	27.7	1.56	3.40	8.63	16.2	19.0	24.9	33.8
Green manure	1.66	3.47	8.65	18.4	25.1	31.8	35.2	3.73	6.40	12.4	22.8	33.6	42.5	49.7
Farmyard manure	1.71	3.73	7.80	20.9	35.7	37.5	44.9	3.75	6.20	10.1	23.3	40.4	50.6	56.0
Poultry manure	1.74	3.70	10.2	19.8	26.3	34.7	40.0	4.01	5.80	11.7	23.6	37.6	49.2	53.2
Biochar	1.67	3.60	8.60	16.7	25.7	30.6	37.2	3.63	5.73	11.2	22.0	34.2	45.2	50.0

treatments, is lower than control-P in both medium-P and high-P soils (Fig. 3). Phosphorus desorption data fitted well to both Langmuir and Freundlich equations (R^2 = 0.90 to 0.95 and 0.90 to 0.98) in medium-P soils and (R^2 = 0.88 to 0.94 and 0.88 to 0.93) high-P soils and the values of different constants are presented in Table 7. Among the different organic amended soils, the highest values of desorption maxima (D_m) of 50.8 and 75.2 mg kg^{-1} and desorption constants (K_d) of 0.16 and 0.20 L mg^{-1} in medium-P and high-P soils were estimated. Likewise, higher values of desorption capacity (a) and desorption strength (n) were obtained in FYM-amended soils. The lowest values of desorption constants were found in control P and WS amended soils. A similar treatment trend with lower P desorption was observed with increasing days of incubation irrespective of P-status (Table 8).

Table 6
Effect of incorporation of crop residue and organic manures on amount of P desorbed (mg P kg^{-1} soil) in medium-P and high-P soils at 60 days of incubation.

Treatments	P added (mg P kg^{-1} soil)													
	Medium-P							High-P						
	25	50	100	200	300	400	500	25	50	100	200	300	400	500
Control-P	1.23	2.40	3.62	7.30	8.20	12.8	17.5	0.95	2.65	4.71	5.80	12.3	18.7	20.6
Wheat straw	1.33	2.46	4.12	9.52	15.2	21.6	24.0	1.42	2.71	7.60	13.3	17.6	23.1	31.6
Green manure	1.52	3.25	6.42	12.6	22.7	25.8	32.5	1.58	3.56	9.50	20.1	27.9	36.2	42.1
Farmyard manure	1.60	3.60	6.23	20.6	26.0	35.0	41.5	1.74	3.62	7.20	18.7	32.7	40.5	48.0
Poultry manure	1.55	3.53	9.84	16.5	26.0	30.9	37.7	1.62	3.65	10.4	23.3	32.4	41.6	47.2
Biochar	1.24	3.20	8.10	16.0	21.0	25.6	31.4	1.60	3.18	8.53	16.2	26.4	38.0	42.0

Table 7
Effect of incorporation of crop residue and organic manures on desorption constants (Langmuir and Freundlich) of medium-P and high-P soils at 30 days of incubation.

Treatments	Medium-P			High-P		
	D_m (mg kg^{-1})	K_d (L mg^{-1})	R^2	D_m (mg kg^{-1})	K_d (L mg^{-1})	R^2
Langmuir constants						
Control-P	33.3	0.09	0.90	59.5	0.13	0.93
Wheat straw	38.9	0.11	0.91	63.7	0.13	0.93
Green manure	39.5	0.11	0.95	63.7	0.13	0.92
Farmyard manure	50.8	0.16	0.94	75.2	0.20	0.94
Poultry manure	43.1	0.15	0.92	69.9	0.19	0.91
Biochar	40.3	0.14	0.95	65.8	0.17	0.88
Freundlich constants	***a* (mg kg^{-1})**	***n* (mg L^{-1})**	**R^2**	***a* (mg kg^{-1})**	***n* (mg L^{-1})**	**R^2**
Control-P	6.43	2.62	0.93	12.25	2.67	0.93
Wheat straw	8.00	2.66	0.90	14.17	2.85	0.93
Green manure	8.76	2.86	0.95	14.3	2.91	0.92
Farmyard manure	15.41	3.61	0.96	22.93	3.67	0.88
Poultry manure	12.46	3.58	0.95	20.71	3.61	0.91
Biochar	10.00	3.03	0.98	16.28	3.10	0.90

3.5. Alkaline phosphatase activity

The incorporation of organic manures and crop residue behaved differently towards alkaline phosphatase activity in medium-P and high-P soils over time. The addition of GM followed by WS and FYM significantly increased the alkaline phosphatase activity over control-P whereas the addition of PM and biochar had a non-significant impact on enzymatic activity in both P statuses (Fig. 5). Overall, higher alkaline phosphatase activity was observed in medium-P soils than high-P soils.

Table 8
Effect of incorporation of crop residue and organic manures on desorption constants (Langmuir and Freundlich) of medium-P and high-P soils at 60 days of incubation.

Treatments	Medium-P			High-P		
	D_m (mg kg^{-1})	K_d (L mg^{-1})	R^2	D_m (mg kg^{-1})	K_d (L mg^{-1})	R^2
Langmuir constants						
Control-P	32.4	0.08	0.91	51.6	0.11	0.98
Wheat straw	36.0	0.10	0.93	52.9	0.13	0.97
Green manure	36.4	0.10	0.92	52.9	0.12	0.96
Farmyard manure	44.8	0.15	0.95	61.4	0.16	0.97
Poultry manure	39.8	0.13	0.91	58.5	0.14	0.96
Biochar	37.9	0.11	0.94	57.1	0.12	0.92
Freundlich constants	**a (mg kg^{-1})**	**n (mg L^{-1})**	**R^2**	**a (mg kg^{-1})**	**n (mg L^{-1})**	**R^2**
Control-P	5.9	2.59	0.94	10.02	2.54	0.95
Wheat straw	6.44	2.46	0.96	10.74	2.57	0.96
Green manure	7.21	2.74	0.92	11.1	2.79	0.96
Farmyard manure	12.81	3.42	0.96	17.73	3.49	0.97
Poultry manure	10.45	3.34	0.95	15.84	3.43	0.89
Biochar	8.37	2.87	0.98	12.54	2.96	0.92

3.6. Microbial biomass phosphorus

Microbial biomass phosphorus (MBP) is an important indicator of soil P availability. Barring biochar, the addition of organic amendments in the form of organic manures and crop residue significantly increased the MBP over control-P. At 30 days of incubation, the highest MBP of 46.0 and 62.1 mg kg^{-1} in PM-incorporated medium-P and high-P soils was estimated, whereas the corresponding values after 60 days of incubation were 31.6 and 58.0 mg kg^{-1} (Table 9). Irrespective of soil P status, MBP increased in the order of PM > FYM > GM > WS among various treatments.

3.7. Bioavailability of soil P

The total maize P uptake increased remarkably by 12.5, 45.0, 143.5 and 208 % with the addition of PM over FYM, biochar, GM and WS amended soils respectively in medium-P soils (Fig. 6). The corresponding increase in high-P soils witnessed lower total P uptake with PM to the tune of 22.5, 48.5, 89.5 and 163.7 %.

4. Discussion

4.1. Organic amendments influence P adsorption and desorption in varying P-status soils

Phosphorus isotherms are generally used to exhibit soil capacity to replenish soil solution P, which is an important factor to demonstrate the ability of soil to supply P to plants. When sorption and desorption reactions took place, the soil with higher P sorption tended to release a smaller portion of sorbed P. Therefore, it becomes important to study the desorption behavior of soils for efficient P management.

The incorporation of organic manures (FYM, PM, and biochar) increased available P, resulting from decreased P sorption. In FYM-amended soils, organic acids released upon its decomposition compete effectively with orthophosphates for adsorption sites on Fe and Al oxides, thus, increasing P availability [3,33]. Additionally, narrow C/P ratio coupled with higher P content in PM and FYM increased the labile soil P and lowered the amount of P retained by soil resulting in increased P availability [34–37]. Conversely, a wider C/P ratio and low P content in wheat residue caused the immobilization of added P and decreased the equilibrium soil solution concentration [38]. Decreased P sorption was more pronounced in high-P environments and this can be credited to the lesser number of active sites present [27]. In contrast to the results of several studies [39,40] indicating decreased P sorption with biochar application, a higher affinity for P sorption in biochar-amended soils compared to FYM and PM in our study may be due to the pyrolysis temperature and raw material used for biochar preparation [41].

Over time, the P sorption increased as humic and organic derivatives with applied manures contribute towards the lockage of sorption on soil colloids [42]. Furthermore, the superiority of FYM in reducing P sorption among the different organic amendments can best be explained by Freundlich adsorption isotherms from the relation between P sorbed and the equilibrium P concentration (C_e). The highest value of '*n*' and '*k*' in control-P and the lowest in FYM-treated soils among the different organic amendments indicated the favorable effect of FYM incorporation on P availability.

Soil P desorption has more relevance than P adsorption as it governs the degree of P release in soil. Overall lower P desorption by 2.5–5.0 % than P sorption indicated that P desorption is not fully reversible and only a fraction of sorbed P is desorbed [43,44] in both P status soils. Our findings suggest that the addition of organic manures increased P desorption, which may be due to the release of organic acids like humic and fulvic acids upon decomposition of manures that restrict P retention on available sites by Fe and Al chelation [45,46]. The FYM contains about 60 % of the total P in available form [47] and organic acids that rapidly solubilize in soil solution and compete with orthophosphates on adsorption sites of soil colloids and further increase the P desorption [48]. found rapid mineralization of total P when poultry litter was applied, most likely due to the dissolution of soil P by root exudates [49]. The biochar application may enhance soil P availability through the weakening of P adsorption on soil colloids [40,50,51]. Since P in soil is fixed through chemical and physical sorption. Higher porosity and large surface area of biochar are useful for the physical sorption of soil P, and this part of sorbed P is readily accessible to plants due to its weak sorption [51,52]. Nonetheless, contradictory results indicating decreased P desorption with biochar application are also reported in the literature [53], and P dynamics with biochar application over time need further investigation. Nonetheless, low P content and wider C/P ratio of incorporated residue resulted in the assimilation of P by microbes that account for reduced and slow desorption in soil [54], though it may become available at a later stage during the turnover of microbial biomass. The lowest values of desorption maxima (D_m), which is the measure of pre-sorbed P and desorption constant (K_d) in WS incorporated treatment, and higher values in manure amended treatments indicated that the sorbed P in soil under manure application can be easily released as compared to WS.

Under a high P environment, increased availability of soil P concentration [10,55,56] resulted in P saturation of sorption sites on soil colloids, decreasing the binding capacity of soil P through adsorption. Our results are in agreement with [57] who reported increased P desorption by 20 % when solution P concentration was >50 mg L^{-1} compared to P concentration <20 mg L^{-1}. The incubation, carried out under aerobic conditions decreased P availability over time, which probably was due to the higher release of organically bound phosphorus during organic matter decomposition which declined thereafter [58].

4.2. Organic amendments influence phosphatase activity and microbial biomass phosphorus

The addition of organics in the soil increases the amount of soil organic matter that stimulates phosphatase activity by increasing

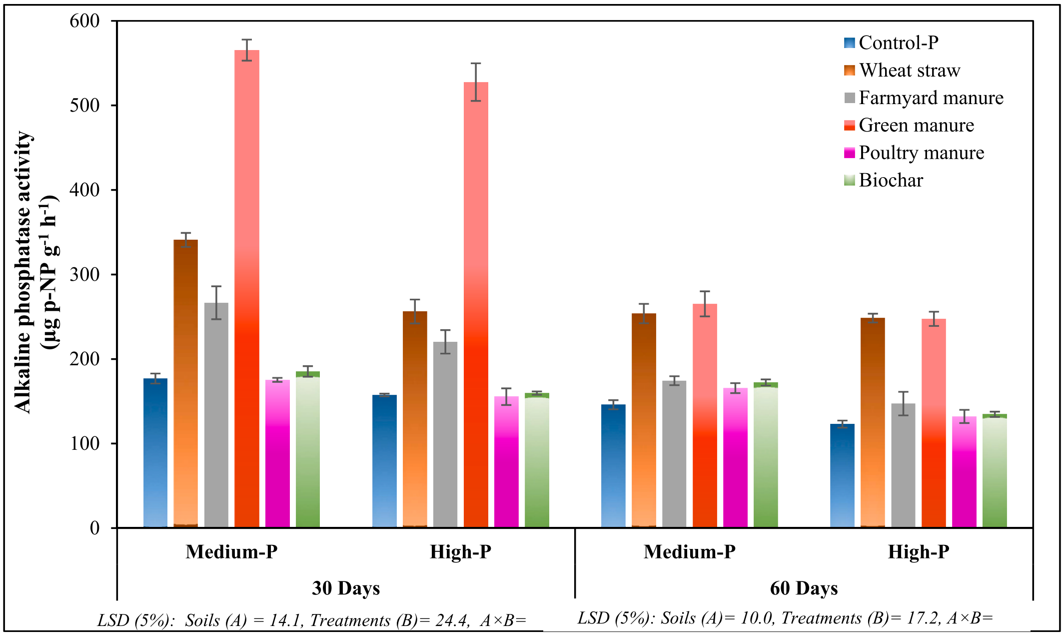

Fig. 5. Effect of incorporation of crop residue and organic manures on alkaline phosphatase activity in medium-P and high-P soils at different days of incubation. Vertical lines show standard error of the mean.

Table 9
Effect of incorporation of crop residue and organic manures on microbial biomass phosphorus (mg kg^{-1}) in medium-P and high-P soils at different days of incubation.

Treatments	30 days			60 days		
	Medium-P	High-P	Mean	Medium-P	High-P	Mean
Control-P	4.2	4.4	4.3	2.1	2.3	2.2
Wheat straw	10.8	18.7	14.7	4.7	9.0	6.9
Green manure	19.0	26.3	22.6	13.6	17.4	11.6
Farmyard manure	32.8	60.6	46.7	21.3	55.7	38.5
Poultry manure	46.0	62.1	54.0	31.6	58.0	44.8
Biochar	5.2	7.0	6.1	3.6	5.1	4.4
Mean	19.7	29.8		12.8	23.3	
LSD (5 %)	A = 1.6, B = 2.8, A × B = 3.9			A = 1.5, B = 2.6, A × B = 3.7		

A = Soil P status; B = Treatments.

microbial numbers in the soil [59]. Compared to other organic amendments, increased phosphatase activity in GM-incorporated soils is ascribed to a low C/N ratio that enhances its rapid decomposition. The results agree with [60] who reported increased fungal biomass with GM incorporation, which contributes towards organic matter decomposition and releases plant nutrients. Nonetheless, lower phosphatase activity in biochar-amended soils can be advocated to its aromatic carbon compound's structure formed during the pyrolysis process which restricts microbial activity [61]. A similar decrease in phosphatase activity with the incorporation of PM was credited to a lack of phosphomonoester, an easily degradable organic P that served as an alkaline phosphatase substrate [62,63]. However, a wealth of conflicting evidence stating increased phosphatase activity with PM incorporation was reported by Ref. [64] in sandy loam and silt loam soils [65]. further explained no direct relation of phosphatase activity with soil P status.

Furthermore, comparatively, reduced phosphatase activity in high-P soils was greater as the increased soil P availability in high-P soils [66] resulted in decreased affinity of the enzyme for substrate than in medium-P soils [67]. also reported similar results in varying soil P-status soils amended with organics. The decreased enzymatic activity over time was likely due to the reduction of the phosphatase substrate required to produce alkaline phosphatase [68,69].

The variable response of MBP to different organic materials depends on its C/P and N/P ratio [70]. No response to biochar application at 30 and 60 days of incubation might be due to its aromatic structure, and resistant nature to biological degradation in soil [53]. The soils with high-P status had higher microbial biomass phosphorus compared to medium-P soils as microbial biomass phosphorus meticulously depends on carbon and the available P status of soil [27]. Lower MBP in both P status soils at 60 days of incubation than 30 days was due to decreased P desorption as already discussed in the P desorption section.

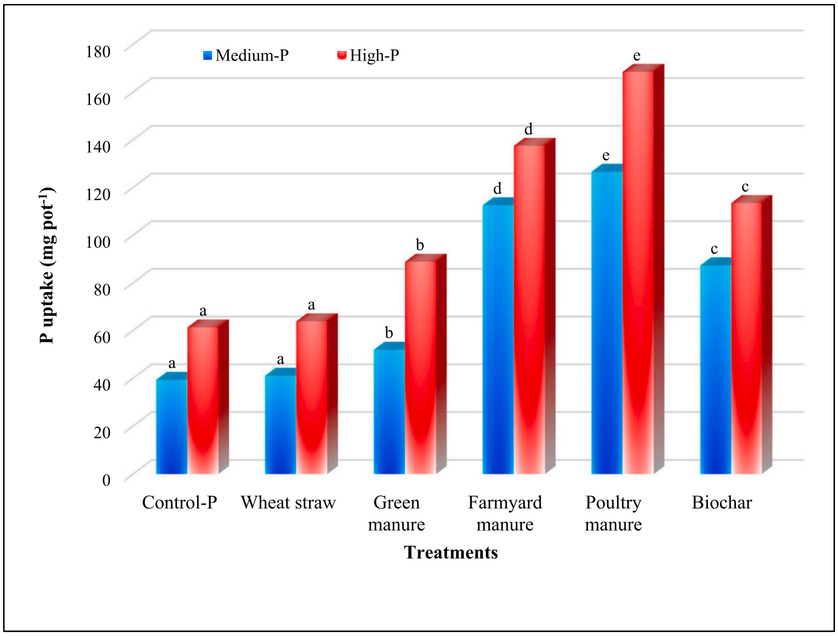

Fig. 6. Effect of fertilizer P application, incorporation of crop residue and organic manures on P uptake in maize crop. Lower case letters indicate a significant difference between treatments at $p < 0.05$ by Duncan's multiple range test.

4.3. *Role of organic amendments in enhancing soil P uptake*

The increased P uptake registered in PM-amended soil was certainly due to a higher amount of P added by PM (Table 2) and a higher release of P upon PM mineralization [71]. On the other hand [72], ascribed it to the reduced P fixation sites on soil that favored P uptake by maize. Similarly, in FYM-amended soils, the anions and organic acids released during their decomposition by microbes decreased P sorption and increased P uptake [73]. Moreover, improved soil physical properties with FYM promote root growth thereby P uptake [74]. The results in Fig. 6 expressed increased P uptake in high-P soils than medium-P, as high-P *soils* contribute largely to soil P availability that led to increasing P uptake.

5. Conclusions

Organics regulate a significant influence on P release and their ability to affect plant P availability varies greatly. The incorporation of FYM and PM resulted in the lowest values of sorption capacity and adsorption strength specifying decreased P sorption over rice-residue biochar and GM. Furthermore, higher total P content in FYM and PM increased microbial biomass phosphorus in soil. Adding organic material with a wider C/P ratio and low P content like WS reduces P availability and for reliable outcomes long-term investigations should be carried out. Contrary to our hypothesis biochar application did not yield satisfactory results in increasing soil P availability and more research related to varying levels of biochar application and pyrolysis temperature on production is needed. The incorporation of organics transformed more residual-P to plants available in high-P soils than in medium-P soils. Farmers can benefit significantly from using FYM and PM as organic amendments, as these have proven to be the most effective in mobilizing residual phosphorus in soil for crop uptake. This approach not only saves costs by reducing the need for P fertilizers but also aligns with sustainable agriculture practices, lowering the environmental impact of farming. To enhance results further fertilizer P recommendations should not be exclusively based on adsorption-desorption parameters estimated from analysis of soil samples. However, the role of root exudates (crop effects) in mobilizing residual-P and matching P release from organics towards yield improvement should be considered for more sustainable low-input agriculture.

CRediT authorship contribution statement

Palvi Kataria: Supervision, Software, Data curation, Conceptualization. **Jagdeep Singh:** Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gobinder Singh:** Writing – review & editing, Visualization. **M.S. Mavi:** Writing – review & editing, Visualization, Formal analysis. **Mika Sillanpää:** Writing – review & editing, Software. **Saleh Al-Farraj:** Writing – review & editing, Validation, Funding acquisition, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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