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Assessment of rock phosphate enriched compost on phosphorus adsorption-desorption patterns under maize-wheat cropping system in Typic Haplustept

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Abstract

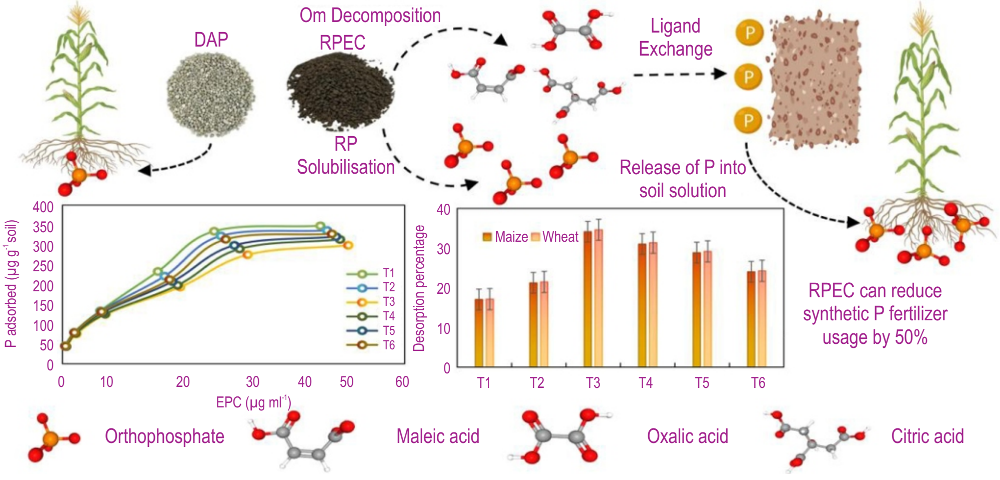
Aim: To investigate the effect of rock phosphate enriched compost (RPEC) on phosphorus (P) adsorption-desorption patterns under maize-wheat cropping system in Typic Haplustept.

Methodology: Soil samples were collected from ongoing experimental field since 2017 located at the Research Farm 8B of the ICAR-Indian Agricultural Research Institute, New Delhi, India with six different treatments replicated four times each. The treatments involved a variety of organic and inorganic sources of P. The control was labelled as T1, while T2 consisted of 100% of the recommended dose of P using diammonium phosphate (DAP), T3 only 50% of the P was supplied through DAP and the remaining 50% P through RPEC. In T4, 25% of the P was from DAP and 75% from RPEC. In contrast, 100% P in T5 came from RPEC alone, and ordinary compost served as the sole source for 100% P in T6.

Results: The bonding energy, binding affinity, maximum adsorption capacity, and maximum buffering capacity of P decreased with organic fertilizer application. The most significant effect was observed with supplementation of 50% P with RPEC. The desorption percentage and desorption index both increased with the application of RPEC, indicating an enhanced availability of P in the soil.

Interpretation: The use of RPEC can positively influence the P dynamics in soil, thereby potentially leading to improved agricultural productivity. It can be an effective alternative for sustaining soil P and reducing foreign exchange spent on importing raw materials for P-fertilizer preparation.

Key words: Adsorption-desorption, Compost, Maize-wheat cropping, Rock phosphate, Typic Haplustep



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Introduction

Phosphorus (P) is a vital element for all living organisms and it significantly influences the biological functions of plants (Rengel *et al*., 2022). In agricultural systems, effective phosphorus utilization is essential for increasing crop yield and ensuring sustainable food production. In Indian soils, phosphorus deficiency results from depleted finite reserves and intensive farming, constraining crop production (Alewell *et al.,* 2020; Kisinyo and Opala, 2020; McDowell *et al.,* 2024). In natural and agricultural systems, phosphorus tends to be the limiting factor; this is attributed to aluminium (Al), iron (Fe), and calcium (Ca) dominating the scene by binding phosphorus into highly insoluble compounds. However, its availability in soil is often limited due to the complex interplay between adsorption and desorption reactions with soil components, reducing its accessibility to plants (Asomaning, 2020; Smolders *et al.,* 2021). Understanding the mechanisms behind these processes is crucial for optimizing nutrient management practices and improving P-use efficiency in agricultural systems (Saeed *et al.,* 2021). Factors like soil pH, mineral composition, organic matter content, and land use practices have a significant impact on phosphorus adsorption-desorption behaviour (Barrow, 2021a).

Traditionally, long-term application of farmyard manure and balanced fertilization reduces soil phosphorus adsorption capacity and increases phosphorus desorption potential, enhancing availability to plants (Bhattacharyya *et al.,* 2015). Increased phosphorus application reduces soil's phosphorus buffering capacity, indicating less phosphorus retention and higher availability (Zhang *et al.,* 2019). Globally, diammonium phosphate (DAP) is the most widely used phosphorus fertilizer. However, extensive use of high-analysis fertilizers has depleted organic carbon and secondary/ micronutrients in soils, threatening agricultural sustainability. In this scenario, rock phosphate is a good alternative source of phosphorus fertilizer, but it cannot be used directly due to its low solubility. Co-composting of RP with organic materials like manures and plant residues is a promising option for sustainable agriculture (Biswas and Narayanasamy, 2006), the composting process aids solubility through microbial activity and natural acid generation (Moharana and Biswas, 2016, 2022; Roy *et al.,* 2018; Moharana *et al.,* 2020). Studies indicate that applying rock phosphate enriched compost (RPEC) can notably enhance soil health, water retention, nutrient cycling, and fertility (Billah *et al.,* 2020).

Moreover, research demonstrates RPEC's effectiveness in stimulating plant growth and yields, especially when used alongside phosphate-solubilizing microbes as these (Biswas *et al.,* 2022), microbes enhance the availability of P for plants by releasing organic acids and phosphatases enzymes (Lopes *et al.,* 2021). Co-composting green wastes with RP and sulphur addition improves P mobilization and provides P-enriched compost for organic farming systems (Bustamante *et al.,* 2016). Integrated use of RPEC and chemical fertilizers significantly improve microbial biomass P and P fractions in wheat-soybean cropping systems (Meena and Biswas, 2015). Adding RPEC to rice cultivation improves P uptake and yield, compared to sole application of chemical fertilizers (Beura *et al.,* 2022). While there is a growing interest of research on the potential benefits of RPEC use to enhance P availability and plant uptake, there remains a significant gap in understanding how this amendment influences the adsorption-desorption dynamics of P in soils. Adsorption and desorption are critical processes that regulate the long-term retention and release of P, directly impacting its availability to crops over time. Understanding these mechanisms is critical for determining the efficacy of RPEC as a sustainable alternative to synthetic fertilizers. This study seeks to fill this gap by investigating the effects of RPEC on P adsorption-desorption patterns in soil, specifically within the context of a maize-wheat cropping system. Moreover, by applying both the Langmuir and Freundlich adsorption isotherms, we aim to determine which model better predicts the adsorption-desorption behaviour of P in soils treated with RPEC *vis-à-vis* ordinary compost.

Materials and Methods

Experimental site and soil: Soil samples for adsorption-desorption studies were collected from an ongoing (since 2017) experimental field located at the research farm 8B of the ICAR-Indian Agricultural Research Institute, New Delhi, India. The treatments were applied continuously over the course of 4 years under maize-wheat cropping system. Soil samples were collected twice during the 2021–2022 cropping cycle: the first after the maize harvest on 31-10-2021 (100 days after sowing), and the second after the wheat harvest on 12-4-2022 (140 days after sowing). The experimental farm is located in the Trans-Gangetic plain region of Delhi at 28°37' to 28°39' N latitude and 77°9' to77°11' E longitude, 220 m above mean sea level. The climate of the study area is semi-arid subtropical region with hot summers (May–June), cold winters (December– January) and the average annual rainfall of 760 mm occurring mostly during the months of July to September. The soil is categorized under the Mehrauli series, which falls within the Typic Haplustepts subgroup of the Inceptisol order. After the initial soil analysis, it was found that the experimental area has sandy clay loam soil with a slightly alkaline pH (8.21), normal levels of electrical conductivity (1.13 dS m^{-1}), low, organic carbon levels (0.39%), medium available phosphorus (6.02 mg kg^{-1}), potash level (105 mg kg^{-1}) and low nitrogen level (92.4 mg kg^{-1}), respectively.

Experimental design and treatments: Individual plots (6.5 m × 7.0 m) were prepared manually using a spade to ensure precise and consistent nutrient distribution, as well as to preserve plot integrity and reduce possible confounding variables in the experimental setup. Experiment was conducted in a randomized block design with 6 treatments under maize-wheat cropping system replicated four times each. The treatments involved a variety of organic and inorganic sources of phosphorus. T1: control plot, T2: 100% of the recommended dose of P using DAP, T3: only 50% of the P supplied through DAP and the remainder through RPEC, T4: 25% of the P from DAP and 75% from RPEC,

Table 1: Elemental composition of rock phosphate enriched compost and ordinary compost

Parameters	Rock phosphate enriched compost (RPEC)	Ordinary compost
pH	7.85±0.13	7.93±0.12
EC (dS m^{-1})	2.98±0.23	2.75±0.27
Total organic carbon (%)	17.4±0.14	27.2±0.12
Total nitrogen (%)	0.89±0.07	1.32±0.06
Total phosphorus (%)	10.40±0.05	0.49±0.06
Total potassium (%)	1.25±0.06	1.79±0.05
C: N	19.6±0.01	19.1±0.02

Values are mean ±S.D.

T5: all 100% P from RPEC alone and T6: ordinary compost as sole source for 100% P

Preparation of rock phosphate enriched compost (RPEC): An enriched compost (with rock phosphate) and an ordinary compost (without rock phosphate) were prepared in bulk Windrow method following the procedure of Biswas and Narayanasamy (2006) using rock phosphate and pressmud (1:5 ratio). The composting was done layer-wise. The composting was continued for 90 days, after which it was fully decomposed and ready for use in the field experiments. At maturity, fresh compost samples were collected and analyzed for total nutrient content as per the standard procedure (Jackson, 1973). The chemical composition of RPEC and ordinary compost are shown in Table 1.

Adsorption–desorption study of phosphorus: The adsorption and desorption studies were conducted following the methods outlined by Nair *et al*. (1984) and Fox and Kamprath (1970), respectively. For adsorption study, 3.0 g of the air-dried soil was added to a 40 ml centrifuge tubes. Subsequently, 30 ml of 0.01 M $CaCl_2$ (mimicking soil solution) to achieve a soil: solution ratio of 1:10, with varying concentrations of KH_2PO_4 (5, 10, 20, 40, 60 and 80 mg P l^{-1}), and 2 drops of toluene (a microcidal) were added in each tube. The tubes were then placed on a mechanical shaker for 24 hr at an ambient temperature of 25±1 °C. Then, the tubes were centrifuged at 10000 rpm for 10 min, and 25 ml of supernatant was transferred to calibrated centrifuge tubes for determination of P. The soluble reactive P in the filtrate was analyzed using ascorbic acid as a reducing agent at a wavelength of 730 nm using a spectrophotometer. The amount of P adsorbed by the soil was calculated by subtracting the remaining P in the equilibrium soil solution from the initially added amount.

For the desorption study, residual soils with a higher P concentration of 80 mg P L^{-1} were used. After decanting 25 ml of supernatant, it was replaced with 0.01 M $CaCl_2$ (P-free). The centrifuge tubes were then placed flat on a reciprocating shaker for 6 hr. The desorption process was performed five times until there was no significant release of P (five times in our case). The concentration of P in the solution at equilibrium, referred to as desorbed P, was assessed by antimony-phosphomolybdate blue colour method. Phosphorus held in the soil (previously adsorbed P) was calculated by subtracting the initial absorbed P from the P found in the equilibrium solution during desorption.

The data obtained from the adsorption and desorption studies were analyzed by fitting to the Langmuir and Freundlich isotherm models to evaluate the different sorption parameters as given below:

Adsorption-desorption models: Adsorption and desorption isotherms were generated by plotting a graph between phosphorus concentration in the adsorbed or desorbed phase against the solution concentration at equilibrium. The graph was then analyzed using Langmuir and Freundlich isotherms to interpret the adsorption and desorption data.

Langmuir model:

$$\frac{c}{x} = \frac{c}{b} + \frac{1}{kb}$$

where, c= equilibrium concentration of P; x= quantity adsorbed per unit mass of soil. When experimental adsorption data was analyzed, a linear relationship was observed in the plot of c/x versus c. In this plot, the slope corresponds to 1/b and the intercept corresponds to 1/kb on the ordinate. The maximum adsorption capacity b (µg g^{-1}) can be calculated by taking the reciprocal of the slope; meanwhile, bonding energy or affinity constant k can be obtained by dividing the slope by the intercept; and maximum phosphorus buffering capacity (MPBC) kb can be determined using inverse value of the intercept.

Freundlich model:

$$\log x = \log a + \frac{1}{n} \log c$$

Analysis of experimental adsorption data revealed a linear relationship in the plot of log x versus log c. The slope, denoted by 1/n, indicates bonding energy, and the intercept, denoted by log a, indicates the number of adsorption sites.

Langmuir model:

$$\frac{c}{x} = \frac{c}{Rp} + \frac{1}{kRp}$$

where, c= equilibrium concentration of P, the maximum amount of P that can be retained after a series of desorption steps is expressed by R_P; X =the quantity of P retained per unit mass of soil and k represents the binding affinity.

Desorption Index (DI): It was obtained by comparing the Freundlich slopes for adsorption and desorption.

Desorption Percentage (DP): It is typically calculated to understand the efficiency of the desorption process. It can be expressed as the ratio of the maximum amount of P desorbed to the maximum amount of P initially adsorbed, multiplied by 100 to get a percentage.

Statistical analyses: The experimental data were analyzed using various statistical methods to evaluate the dynamics of P adsorption-desorption. To assess the significance of treatment effects, ANOVA was applied at a 95% confidence level ($p<0.05$). Post-hoc comparisons between treatment means were determined by Tukey's Honestly Significant Difference test to identify significant differences and assign grouping letters to treatments accordingly. All statistical analyses were performed using the Origin Pro software package (Version 2024; Origin Lab Corporation, Northampton, MA, USA), ensuring that the results were interpreted in the context of adsorption-desorption behaviour.

Results and Discussion

The phosphorus adsorption isotherms presented in Fig. 1 shows a relationship between phosphorus concentration and adsorption capacity. As the concentration of phosphorus increased, the adsorption capacity also increased up to 60 µg ml^{-1}, furthermore it reached a plateau. This suggests that at high phosphorus concentrations, the adsorption sites on the soil

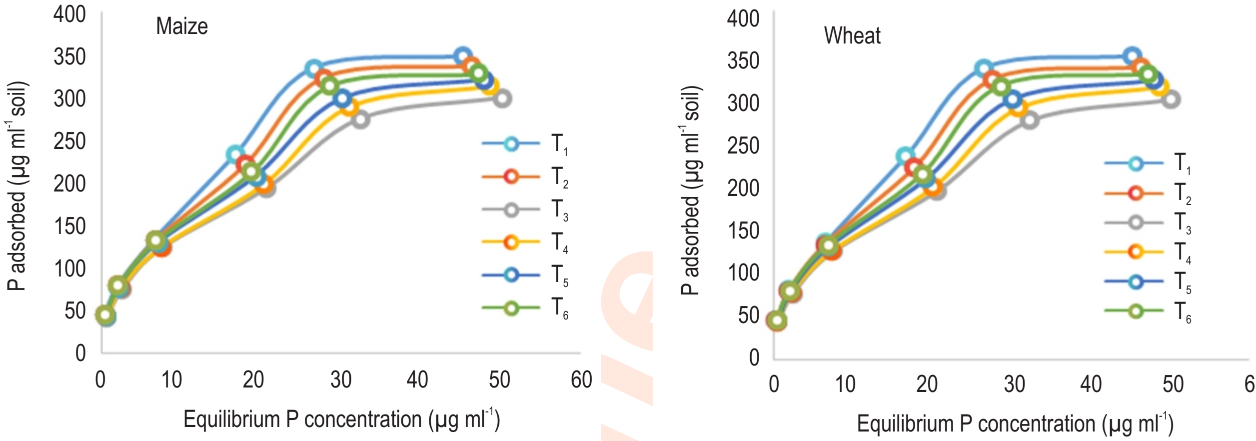

Fig. 1: Adsorption isotherms at different phosphorus concentrations under maize-wheat system.

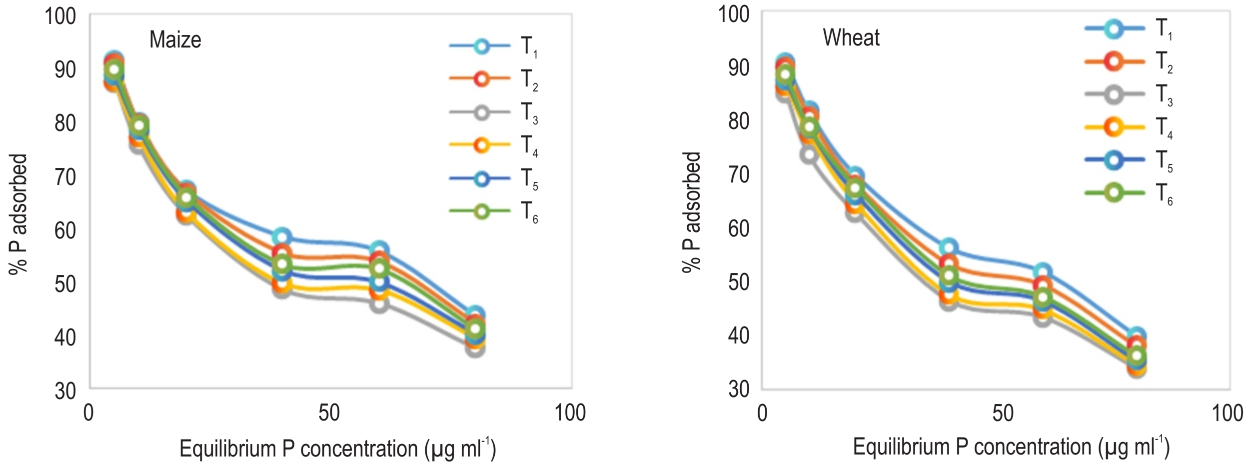

Fig. 2: Percentage of P adsorbed at different phosphorus concentrations under maize-wheat system. T_1: Control; T_2: 100% P (DAP); T_3: 50% P (DAP)+50% P (RPEC); T_4: 25% P (DAP)+75% P (RPEC); T_5: 100% P (RPEC); T_6: 100% P (Compost).

Table 2: Phosphate adsorption equations for different treatments under maize-wheat cropping system

Treatments	**Langmuir equation** **C/X = C/b + 1/kb**	**R^2**	**Freundlich equation** **log x = log a + 1/n log c**	**R^2**
Maize				
T_1: Control	c/x = c0.0026 + 0.012	0.97	log x = 1.90 + 0.48 log c	0.98
T_2: 100% P (DAP)	c/x = c0.0028 + 0.013	0.97	log x = 1.79 + 0.45 log c	0.98
T_3: 50% P (DAP)+50% P (RPEC)	c/x = c0.0035 + 0.020	0.95	log x = 1.45 + 0.36 log c	0.99
T_4: 25% P (DAP)+75% P (RPEC)	c/x = c0.0034 + 0.020	0.92	log x = 1.50 + 0.39 log c	1.00
T_5: 100% P (RPEC)	c/x = c0.0032 + 0.017	0.97	log x = 1.57 + 0.41 log c	0.98
T_6: 100% P (Compost)	c/x = c0.0031 + 0.016	0.97	log x = 1.67 + 0.42 log c	0.97
Wheat				
T_1: Control	c/x = c0.0027 + 0.012	0.94	log x = 1.88 + 0.47 log c	0.99
T_2: 100% P (DAP)	c/x = c0.0028 + 0.014	0.95	log x = 1.78 + 0.44 log c	0.99
T_3: 50% P (DAP)+50% P (RPEC)	c/x = c0.0036 + 0.021	0.95	log x = 1.42 + 0.35 log c	0.98
T_4: 25% P (DAP)+75% P (RPEC)	c/x = c0.0035 + 0.020	0.94	log x = 1.48 + 0.38 log c	0.98
T_5: 100% P (RPEC)	c/x = c0.0032 + 0.018	0.93	log x = 1.55 + 0.40 log c	0.98
T_6: 100% P (Compost)	c/x = c0.0031 + 0.016	0.91	log x = 1.65 + 0.41 log c	0.98

became saturated, leading to a decrease in the adsorption rate (Wang *et al.,* 2017). This behaviour is consistent with the previous studies on P adsorption and indicative of the adsorption mechanism reaching saturation (Jiang *et al.,* 2023). Also the percentage of phosphorus adsorbed decreased as the concentration increased and it ranged from 85% to 91% at 5 µg ml^{-1} to 34% to 43% at 80 µg ml^{-1} (Fig. 2). This was due to the fact that P adsorption occurs in a two stage process, *i.e.,* initially, the adsorption occurs quickly as phosphate ions fill the readily accessible adsorption sites. Over time, as these sites become occupied, the adsorption rate decreases until a state of equilibrium is attained, where the rate of adsorption is equal to the rate of desorption. The addition of organic fertilizers, especially RPEC, to our experimental field had significantly altered the P adsorption behaviour. Organic matter content in manures primarily affect the phosphorus cycle, influencing the adsorption and desorption of phosphorus in soil (Szara *et al.,* 2019). Phosphorus adsorption in soils is a critical process that influences the availability of this macro nutrient for plant growth. There are several models for studying adsorption isotherms, however the Langmuir and Freundlich equations are commonly used to describe the mechanism of phosphorus adsorption by soil particles (Barrow, 2021b; Olsen and Watanabe, 1957). To determine the most suitable model for describing phosphorus adsorption in the compost-enriched soil, a comparison was made with Langmuir and Freundlich equations. The Langmuir model assumes a monolayer adsorption onto a homogeneous surface, whereas the Freundlich model is based on a multilayer and heterogeneous adsorption mechanism (Musah *et al.,* 2022).

The results presented in Table 2 showed that both the models provided a good fit to the experimental data, with high correlation coefficients. However, the Freundlich model demonstrated slightly better fit than the Langmuir model, indicating that the adsorption of phosphorus in the compost-enriched soil may be better described by a multilayer and heterogeneous adsorption mechanism. Our findings suggest that the compost-enriched soil has a complex and heterogeneous surface, which facilitates the adsorption of phosphorus through multiple layers and varying adsorption sites. It has been also found that Freundlich adsorption isotherm model shows a better fit than Langmuir for describing phosphorus adsorption in various soil types, including Calcareous, Hungarian and Greek soils, indicating its suitability for calculating phosphatic fertilizer rates and adsorption capacity (Argiri *et al.,* 2013; Saeed *et al.,* 2021).

The Langmuir and Freundlich adsorption parameters provide further insight into the phosphorus adsorption behaviour in the compost-enriched soil. The Langmuir model parameter, b, represents the maximum amount of phosphorus that can be adsorbed per unit weight of the soil or maximum number of adsorption sites when the adsorption surface is fully covered. In the maize-wheat cropping system, B value varied from 242 to 379 mg kg^{-1}, showing a statistically significant ($p<0.05$) difference among the treatments (Table 3). For maize, the phosphorus adsorption maxima was highest in the control treatment, indicating stronger phosphorus fixation in the soil. However, with compost application, the adsorption maxima decreased significantly, which enhanced phosphorus availability during maize growth. Similar trends were observed for wheat, where compost treatments reduced phosphorus adsorption, allowing for a more gradual phosphorus release during its longer growing season. The application of organic fertilizers significantly reduces the adsorption maxima, with the maximum reduction occurring when 50% of phosphorus is supplied rather than at 100% phosphorus. Previous studies have shown that the maximum effects of organic fertilizers in reducing phosphorus adsorption capacity are observed at a moderate level of phosphorus

Table 3: Parameters of phosphorus adsorption characteristics for different treatments under maize-wheat cropping system

Treatments	b (mg kg^{-1})	k (L mg^{-1})	MPBC (L kg^{-1})	1/n	log a
Maize					
T_1: Control	378 ± 8.54^{a}	0.230 ± 0.0025^{a}	86.9 ± 1.43^{a}	0.481 ± 0.0058^{a}	1.90 ± 0.021^{a}
T_2: 100% P (DAP)	359 ± 6.74^{b}	0.209 ± 0.0064^{b}	75.0 ± 1.09^{b}	0.451 ± 0.0092^{b}	1.79 ± 0.058^{b}
T_3: 50% P (DAP)+50% P (RPEC)	286 ± 7.14^{d}	0.171 ± 0.0054^{e}	48.9 ± 0.86^{d}	0.356 ± 0.0100^{e}	1.45 ± 0.074^{e}
T_4: 25% P (DAP)+75% P (RPEC)	292 ± 6.89^{d}	0.175 ± 0.0044^{de}	51.0 ± 0.54^{d}	0.385 ± 0.0124^{d}	1.50 ± 0.052^{e}
T_5: 100% P (RPEC)	315 ± 8.69^{c}	0.187 ± 0.0030^{cd}	58.9 ± 0.48^{c}	0.407 ± 0.0128^{cd}	1.57 ± 0.030^{cd}
T_6: 100% P (Compost)	324 ± 7.92^{c}	0.192 ± 0.0043^{c}	62.1 ± 1.21^{c}	0.416 ± 0.0087^{c}	1.67 ± 0.039^{c}
Wheat					
T_1: Control	376 ± 5.91^{a}	0.225 ± 0.0050^{a}	84.6 ± 1.87^{a}	0.470 ± 0.0104^{a}	1.88 ± 0.042^{a}
T_2: 100% P (DAP)	355 ± 7.94^{b}	0.208 ± 0.0056^{b}	74.0 ± 1.99^{b}	0.436 ± 0.0130^{b}	1.78 ± 0.052^{b}
T_3: 50% P (DAP)+50% P (RPEC)	282 ± 6.53^{d}	0.165 ± 0.0027^{e}	46.5 ± 0.66^{e}	0.349 ± 0.0093^{e}	1.42 ± 0.038^{e}
T_4: 25% P (DAP)+75% P (RPEC)	288 ± 5.66^{d}	0.172 ± 0.0054^{de}	49.7 ± 1.48^{e}	0.381 ± 0.0172^{d}	1.48 ± 0.067^{de}
T_5: 100% P (RPEC)	312 ± 5.10^{c}	0.181 ± 0.0044^{cd}	56.6 ± 1.37^{d}	0.402 ± 0.0118^{cd}	1.55 ± 0.047^{cd}
T_6: 100% P (Compost)	321 ± 5.70^{c}	0.189 ± 0.0035^{c}	60.6 ± 1.12^{c}	0.411 ± 0.0082^{c}	1.65 ± 0.032^{c}

Values are mean ±S.D.; Means that do not share common letter are significantly ($p<0.05$) different by Tukey test

supplement (Yang *et al.,* 2019; Li *et al.,* 2021).

Adding organic fertilizers to soil has been found to lower adsorption capacity and increase the concentration of available phosphorus, because it forms complexes that are less tightly bound to the soil, making them more easily accessible for plant uptake. However, research also indicates variability in the effects of organic fertilizers, which may inhibit or promote phosphorus adsorption depending on other soil conditions and characteristics (Debicka *et al.,* 2016). For instance, increasing the organic matter content has been found to increase the amount of phosphorus adsorbed by soils at pH > 6.0, but decrease at pH < 6.0 (Zhao *et al.,* 2006). The Langmuir constant, k, relates to the strength of the adsorption bond between P and the adsorption sites on the soil (Al-Ghouti and Da'ana, 2020). It indicates how strongly an adsorbate is retained by the soil, which affects its availability to plants and the ease with which it can be desorbed. In this study, the k values ranged from 0.103 to 0.223 l mg^{-1}, indicating relatively low bonding energy of phosphorus adsorption in the compost-enriched soil. The minimum value of k was observed when half of phosphorus was provided from the organic sources compared to a full dose of phosphorus (Table 3), because when organic matter is added to soil in excess, it may act as adsorbent and form stable organic complexes with phosphorus that are not easily accessible to plants, thus enhancing the bonding energy. Soil organic matter competes with phosphate ions for binding sites on metal cations, which may help maintain phosphorus availability by inhibiting the formation of stable binary metal-P complexes. Additionally, organic matter can be involved in ternary complexes that bridge between metal cations and phosphate ions. These complexes may enhance phosphorus availability if they are less stable than binary metal-P complexes or reduce availability if they form more stable complexes (Jindo *et al.,* 2023).

Maximum phosphorus buffering capacity (MPBC) represents a combined parameter that includes b and k, with a greater MPBC leading to increased phosphorus being absorbed by the soil (Holford, 1979). The MPBC values follows the same trend as the b and k values, with the lowest MPBC observed when 50% of phosphorus is supplied from organic sources (Table 3). This indicates that the combined effect of b and k parameters on phosphorus adsorption is influenced by the proportion of organic phosphorus sources. Yang *et al.* (2019) found that MPBC varies along with the bonding energy only when it exceeds the adsorption maxima. In this study, MPBC varied with both bonding energy and adsorption maxima, indicating phosphorus adsorption is controlled by both factors in compost-enriched soil. The Freundlich parameter, log a, represents the number of adsorption sites at a given equilibrium concentration (Shafqat and Pierzynski, 2014).

In this study, the log a values ranged from 1.42 to 1.90, indicating significant variations across the treatments (Table 3), suggesting that the compost-enriched soil has varied adsorption capacities for phosphorus. Moreover, the 1/n values, which reflect the binding energy or favourability of adsorption, ranged from 0.35 to 0.48. These values suggest that the compost-enriched soil had a low affinity for retaining phosphorus, further emphasizing the heterogeneous and complex nature of organic fertilizers. This lower binding energy was consistent for both maize and wheat crops, allowing phosphorus to remain more available in the soil solution. In order to understand the release of phosphorus from compost-enriched soil, desorption isotherms were analyzed following a series of five desorption steps. It provides valuable insights into the reversibility of phosphorus adsorption and its potential release back into the soil solution. The results from the desorption isotherms revealed that the release of phosphorus

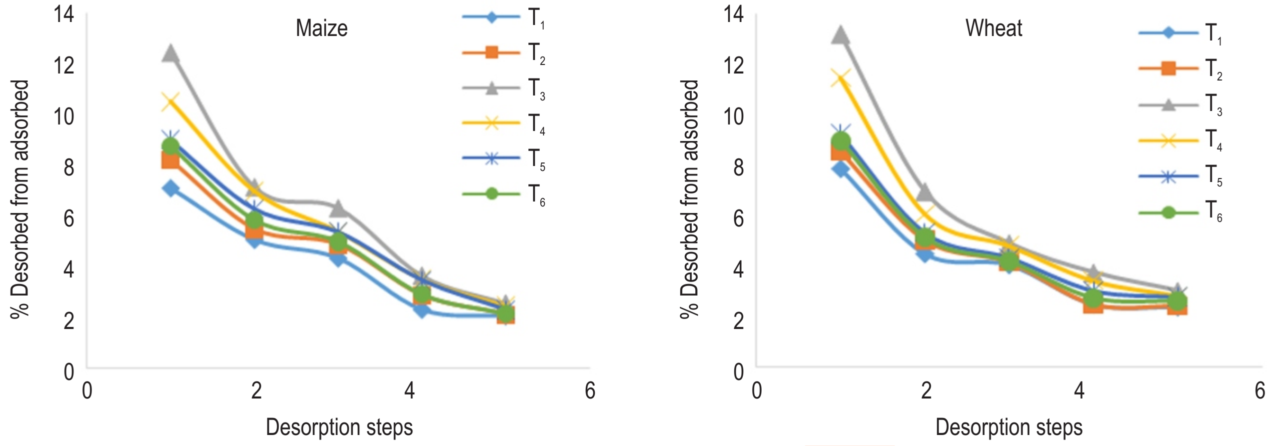

Fig. 3: Stepwise desorption curves of 80 µg ml^{-1} concentration under maize-wheat cropping system. T_1: Control; T_2: 100% P (DAP); T_3: 50% P (DAP)+50% P (RPEC); T_4: 25% P (DAP)+75% P (RPEC); T_5: 100% P (RPEC); T_6: 100% P (Compost)

Table 4: Phosphate desorption equations for different treatments under maize-wheat cropping system

Treatments	**Langmuir equation** **C/X = C/b + 1/kb**	**R^2**	**Freundlich equation** **log x = log a + 1/n log c**	**R^2**
Maize				
T_1: Control	C/X = c0.0032 + 0.00069	1.00	log x = 2.46 + 0.063 log c	0.84
T_2: 100% P (DAP)	C/X = c0.0035 + 0.00088	1.00	log x = 2.36 + 0.053 log c	0.95
T_3: 50% P (DAP)+50% P (RPEC)	C/X = c0.0062 + 0.00242	1.00	log x = 1.90 + 0.033 log c	0.95
T_4: 25% P (DAP)+75% P (RPEC)	C/X = c0.0053 + 0.00186	1.00	log x = 2.01 + 0.038 log c	0.89
T_5: 100% P (RPEC)	C/X = c0.0045 + 0.00137	1.00	log x = 2.14 + 0.043 log c	0.91
T_6: 100% P (Compost)	C/X = c0.0041 + 0.00110	1.00	log x = 2.22 + 0.046 log c	0.90
Wheat				
T_1: Control	C/X = c0.0032 + 0.00070	1.00	log x = 2.42 + 0.061 log c	0.84
T_2: 100% P (DAP)	C/X = c0.0036 + 0.00089	1.00	log x = 2.33 + 0.051 log c	0.88
T_3: 50% P (DAP)+50% P (RPEC)	C/X = c0.0063 + 0.00252	1.00	log x = 1.87 + 0.033 log c	0.85
T_4: 25% P (DAP)+75% P (RPEC)	C/X = c0.0054 + 0.00191	1.00	log x = 1.99 + 0.037 log c	0.88
T_5: 100% P (RPEC)	C/X = c0.0045 + 0.00141	1.00	log x = 2.11 + 0.041 log c	0.86
T_6: 100% P (Compost)	C/X = c0.0041 + 0.00113	1.00	log x = 2.19 + 0.044 log c	0.87

from the compost-enriched soil followed a non-linear pattern, indicating complex desorption dynamics (Fig. 3). The desorption curves exhibited hysteresis, suggesting that the desorption process was not simply mirroring the adsorption process, and there was a delay in the release of phosphorus from the soil particles (Smolders *et al.,* 2021).

Furthermore, the desorption isotherms displayed a higher release of phosphorus at initial desorption step, indicating that there might be a fraction of phosphorus loosely bound to the soil and can be readily desorbed. As the desorption process continued, the phosphorus release decreased, indicating another fraction of phosphorus more strongly bound to the soil and required more energy to be released. This suggests that the desorption of phosphorus from compost-enriched soil over the time mainly depends on the strength of the binding sites. The desorption isotherms also showed that the percentage of phosphorus desorbed at each step was higher in the treatments with lower organic fertilizer application rates, implying that the availability of phosphorus for plant uptake may be influenced by the amount of organic fertilizers applied (Debicka *et al.,* 2016). The desorption data were analyzed with Langmuir and Freundlich models, however, it is important to note that these models primarily describe adsorption events rather than desorption; nonetheless, desorption can often be considered the reverse process of adsorption (Smolders *et al.,* 2021).

Table 5: Parameters of phosphate desorption characteristics for different treatments under maize-wheat cropping system

Treatments	**RP**	**k (L mg^{-1})**	**1/n**	**log a**	**DP**	**DI**
Maize						
T_1: Control	314± 6.90^{a}	4.62±0.102^{a}	0.063±0.0014^{a}	2.46±0.049^{a}	17.10±0.70^{d}	7.66±0.26^{d}
T_2: 100% P (DAP)	282±6.60^{b}	4.04±0.094^{b}	0.053±0.0013^{b}	2.36±0.048^{b}	21.30±1.00^{c}	8.44±0.24^{c}
T_3: 50% P (DAP)+50% P (RPEC)	161±8.18^{e}	2.56±0.130^{e}	0.033±0.0017^{e}	1.90±0.028^{e}	34.10±0.44^{a}	10.70±0.23^{a}
T_4: 25% P (DAP)+75% P (RPEC)	190±4.01^{d}	2.84±0.060^{e}	0.038±0.0008^{de}	2.01±0.028^{d}	31.00±0.62^{a}	10.10±0.17^{a}
T_5: 100% P (RPEC)	224±5.44^{c}	3.25±0.079^{d}	0.043±0.0010^{cd}	2.14±0.059^{c}	28.90±0.57^{b}	9.54±0.20^{b}
T_6: 100% P (Compost)	246±4.62^{c}	3.69±0.069^{c}	0.046±0.0009^{c}	2.22±0.029^{c}	24.10±0.64^{b}	9.11±0.11^{b}
Wheat						
T_1: Control	312±6.16^{a}	4.61±0.062^{a}	0.061±0.0006^{a}	2.42±0.047^{a}	17.20±0.25^{d}	7.77±0.20^{d}
T_2: 100% P (DAP)	279±4.08^{b}	4.01±0.068^{b}	0.051±0.0013^{b}	2.33±0.063^{b}	21.50±0.72^{c}	8.52±0.15^{c}
T_3: 50% P (DAP)+50% P (RPEC)	158±6.31^{e}	2.51±0.048^{e}	0.033±0.0009^{e}	1.87±0.066^{e}	34.60±0.63^{a}	10.70±0.11^{a}
T_4: 25% P (DAP)+75% P (RPEC)	187±1.83^{d}	2.80±0.055^{e}	0.037±0.0012^{de}	1.99±0.050^{d}	31.40±0.70^{a}	10.30±0.24^{a}
T_5: 100% P (RPEC)	221±3.44^{c}	3.22±0.112^{d}	0.041±0.0006^{cd}	2.11±0.070^{c}	29.20±0.58^{b}	9.75±0.14^{b}
T_6: 100% P (Compost)	243±4.25^{c}	3.65±0.070^{c}	0.044±0.0009^{c}	2.19±0.035^{c}	24.30±0.85^{b}	9.34±0.26^{b}

Values are mean ±S.D.; Means that do not share common letter are significantly ($p<0.05$) different by Tukey test

The desorption data were successfully fitted using Langmuir and Freundlich equations (Table 4). The analysis of phosphorus desorption equations further elucidated the dynamics of nutrient release from the compost-enriched soil. The Langmuir desorption equation described the process of P release from the soil particles as a mono-layer adsorption, where the release of phosphorus was limited by the availability of specific desorption sites. On the other hand, the Freundlich desorption equation characterized the desorption process as a multi-layer adsorption, reflecting the heterogeneous nature of phosphorus release from the compost-enriched soil (Jiang *et al.,* 2023). The successful application of the Freundlich model in describing P desorption indicated the heterogeneous nature of the desorption process, emphasizing the varying sorption intensities and the complex interactions between phosphorus and the soil matrix.

The Langmuir desorption constant, k, ranged from 2.51 to 4.62 l mg^{-1}, indicating the strength of phosphorus binding to the soil particles (Table 5). These values signify the affinity of phosphorus for the soil matrix, with lower k values suggesting weaker binding and higher potential for phosphorus release into the soil solution. The parameter RP, derived from the Langmuir equation, relates to the maximum amount of phosphorus retained after a series of desorption steps. If RP is lower, the desorption amount will be higher, resulting in better phosphorus availability. The treatment receiving 50% phosphorus from RPEC exhibited significantly lowest R_P value, indicating highest potential for phosphorus release from the soil particles (Table 5). Another important derived Langmuir parameter is the desorption percentage (DP), which enables us to understand the efficiency of the desorption process. The treatment with the moderate application rate of organic fertilizers showed the highest desorption percentage values, indicating a more efficient desorption process and a larger proportion of initially adsorbed phosphorus being released back into the soil solution (Bhattacharyya *et al.,* 2015).

The Freundlich parameter 1/n indicates the affinity of phosphorus for adsorption, indicating lower affinity and easy of desorption. Values ranging from 0.033 to 0.062 for 1/n indicate favourable to highly favourable desorption of P from the compost-enriched soil, highlighting the ease of desorption and the potential for phosphorus release into the soil solution (Table 5). Similarly, the log a value of the Freundlich desorption equation ranged from 1.87 to 2.46, further confirming significant variation in adsorption sites and sorption intensities across the treatments. Similar trends in desorption were observed for both maize and wheat soils, where phosphorus was desorbed more easily from compost-treated soils. The consistent desorption patterns across both crops suggests that the compost treatment, rather than the crop type, played the primary role in enhancing P release.

The DI value is related to desorption index, which further characterizes the desorption properties of the compost-enriched soil. The of DI values ranged from 7.66 to 10.72, indicating desorption of phosphorus from the soil was influenced by its binding capacity and availability of adsorption sites. A higher DI value suggests a greater potential for phosphorus release, while a lower value indicates strong binding of phosphorus to the soil particles, limiting its release. These findings emphasize the complex nature of phosphorus desorption from compost-enriched soil and illustrate how various factors govern the release of phosphorus back into the soil solution (Barrow, 2015). In the stepwise desorption process, phosphorus was released in increments, simulating the gradual depletion of Pin agricultural soils over time (Azeez *et al.,* 2019; Somavilla *et al.,* 2022). For both maize and wheat, stepwise desorption ensures a steady release of phosphorus over time, supporting crop nutrition.

Thus, the findings of this study highlight the potential of rock phosphate as a valuable tool for enhancing phosphorus content of the compost reducing reliance on synthetic fertilizers. Further utilization of native phosphorus is made possible by the organic component present in RPEC.

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