Influence of Soil Properties on Phosphorus Dynamics and Phosphatase Enzyme Activity in Agricultural Soils of Central Nepal

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ABSTRACT

A soil system consists of physical, chemical, and biological components that interact to regulate nutrient availability, water retention, and ecosystem stability. Soil phosphorus (P) fractions, phosphatase enzyme activity, and P adsorption-desorption characteristics are crucial for sustainable P management and are influenced by various intrinsic and extrinsic factors. However, the characteristics of these parameters in Nepalese soils remain largely unexplored. This study assessed the influence of soil properties on these parameters by analyzing 225 soil samples collected from various locations in central Nepal. Key soil properties, including pH, EC, OM, $CaCO_3$, CEC, exchangeable Al, sand, silt, clay, total N, and available nutrients (P, K, Ca, Mg, S, B, Cu, Mn, Fe, and Zn), were measured, alongside response variables such as P fractions, phosphatase enzyme activity, and P adsorption-desorption characteristics, using standard analytical methods. Statistical analyses, including Pearson's correlation and redundancy analysis (RDA), were applied. The results showed that soil properties accounted for 58.63%, 53.65%, 56.62%, and 38.37% of the total variation in P fractions, phosphatase enzyme activity, P adsorption, and P desorption characteristics, respectively. Fifteen soil properties significantly influenced P fractions, ranked in decreasing order of impact: OM, Olsen P, pH, CEC, Fe, $CaCO_3$, Cu, clay content, sand content, EC, K, Ca, Zn, Mg, and total N. Twelve properties significantly affected phosphatase enzyme activity, listed in decreasing order as OM, pH, available Ca, $CaCO_3$, B, EC, P, CEC, Zn, K, sand content, and clay content. For P adsorption, twelve properties had significant effects, ranked as follows: Olsen P, sand content, pH, B, $CaCO_3$, Cu, Ca, EC, OM, K, CEC, and clay content. Thirteen properties significantly impacted P desorption, listed in decreasing order as OM, sand content, Olsen P, EC, pH, Cu, Zn, $CaCO_3$, K, B, CEC, Fe, and Ca. These findings highlight the critical role of specific soil properties in regulating P dynamics, providing valuable insights for enhancing P management strategies in diverse agricultural systems.

Keywords: P adsorption-desorption, Phosphatase enzyme activity, P fractions, Redundancy analysis, Soil properties

सारांश

माटोमा संचालित प्रणालीहरुमा भौतिक, रासायनिक र जैविक घटकहरू हुन्छन् जसले पोषकतत्वको उपलब्धता, पानीको संरक्षण, र पारिस्थितिकीय स्थिरतालाई नियमन गर्न सहकार्य गर्ने गर्दछन् । माटोमा रहेको फस्फोरसका फ्रेक्सनहरू, फस्फेटेज इन्जाइमको क्रियाकलाप,

र फस्फोरस अबशोषण-विसर्जनका गुणहरू दिगो फस्फोरस व्यवस्थापनका लागि महत्वपूर्ण हुन्छन् र विभिन्न आन्तरिक तथा बाह्य कारकहरूले प्रभावित हुन्छन ! यद्यपि, नेपालको माटोमा यी पद्धतीहरुको विशेषता अझै व्यापक रूपमा अनुसन्धान भएको छैन । यस अध्ययनमा मध्य नेपालका विभिन्न स्थानहरूबाट सङ्कलन गरिएका २२५ माटोका नमूनाहरू प्रयोग गरी यी पद्धतीहरुमा माटोका गुणहरूको प्रभावको मूल्याङ्कन गरिएको छ। मुख्य माटोका गुणहरूः पि.एच., ई.सि., प्रांगारिक पदार्थ, क्याल्सियम कार्बोनेट, सि.ई.सि., विनिमययोग्य एल्मुनियम, बालुवा, पाँगो, कच्चा माटो, कुल नाईट्रोजन, र उपलब्ध पोषकतत्वहरु (फस्फोरस, पोटासियम, क्याल्सियम, म्याग्नेसियम, सल्फर, बोरोन, तामा, म्यांगनिज, फलाम र जस्ता) साथै फस्फोरसका फ्रेक्सनहरू, फस्फेटेज इन्जाइमहरूको क्रियाकलाप र फस्फोरस अबशोषण-विसर्जनका गुणहरूको मापन मानक विश्लेषण विधिहरू प्रयोग गरी गरियो। सांख्यिकीय विश्लेषणको निम्ति पिअर्सनको सहसम्बन्ध र रिडन्डेन्सी विश्लेषण विधि प्रयोग गरियो। माटोका गुणहरूले फस्फोरसका फ्रेक्सनहरूमा ५८.६३%, फस्फेटेज इन्जाइमहरूको क्रियाकलापमा ५३.६५%, फस्फोरस अबशोषणमा ५६.६२%, र फस्फोरस विसर्जनमा ३८.३७% परिवर्तनको लेखाजोखा गरेको पाईयो । कुल अध्ययन गरिएका मध्ये १५ वटा माटोका गुणहरूले फस्फोरसका फ्रेक्सनहरूमा महत्वपूर्ण प्रभाव पारेको पाईयो, जसको प्रभाव घट्दो क्रममाः प्रांगारिक पदार्थ, फस्फोरस, पि.एच., सि.ई.सि., फलाम, क्याल्सियम कार्बोनेट, तामा, कच्चा माटोको मात्रा, बालुवाको मात्रा, ई.सि., पोटासियम, क्याल्सियम, जस्ता, म्याग्नेसियम, र कुल नाईट्रोजन रहेको छ। साथै, १२ वटा माटोका गुणहरूले फस्फेटेज इन्जाइमहरूको क्रियाकलापलाई महत्वपूर्ण रूपमा प्रभावित गरेको पाइएको थियो, क्रमशः प्रांगारिक पदार्थ, पि.एच., क्याल्सियम, क्याल्सियम कार्बोनेट, बोरोन, ई.सि., फस्फोरस, सि.ई.सि., जस्ता, पोटासियम, बालुवाको मात्रा, र कच्चा माटोको मात्रा । यसैगरी, फस्फोरस अबशोषणका लागि, १२ वटा माटोका गुणहरूले महत्वपूर्ण प्रभाव पारेका थिए, जसको क्रम यस प्रकार थियोः फस्फोरस, बालुवाको मात्रा, पि.एच., बोरोन, क्याल्सियम कार्बोनेट, तामा, क्याल्सियम, ई.सि., प्रांगारिक पदार्थ, पोटासियम, सि.ई.सि., र कच्चा माटोको मात्रा । साथै, १३ वटा माटो गुणहरूले फस्फोरस विसर्जनमा महत्त्वपूर्ण प्रभाव पारेको देखियो, क्रमशः प्रांगारिक पदार्थ, बालुवाको मात्रा, फस्फोरस, ई.सि., पि.एच., तामा, जस्ता, क्याल्सियम कार्बोनेट, पोटासियम, बोरोन, सि.ई.सि., फलाम, र क्याल्सियम । माटोमा फस्फोरसको गतिशिलता नियमनमा उल्लेखित गुणहरूको महत्वपूर्ण भूमिका रहेकाले कृषि प्रणालीमा फस्फोरसको दिगो व्यवस्थापनमा उक्त गुणहरुको ब्यवस्थापनमा पनि ध्यानदिनु आबश्यक देखिन्छ।

INTRODUCTION

Nepal, a landlocked Himalayan nation, is situated between latitudes 26°22' and 30°27' N and longitudes 80°4' and 88°12' E, covering an area of 147,181 sq. km (Lamichhane et al., 2021). Agriculture plays a vital role in the nation's economy, contributing 24.67% to the GDP and providing employment to around 57.3% of the population (MoALD, 2023). The predominant soil reference groups (RSGs) in Nepal, based on the WRB classification, include Fluvisols, Gleysols, Phaeozems, Cambisols, Regosols, Luvisols, and Umbrisols (Vaidhya and Sah, 2015). According to the USDA soil taxonomy, Nepal's main soil orders are Entisols, Inceptisols, Mollisols, and Alfisols, with occasional occurrences of Spodosols, Histosols, Ultisols, and Aridisols (Joshy, 1997).

Phosphorus (P), alongside nitrogen, is recognized as a key limiting nutrient for food production worldwide (Dieter et al, 2010) and is essential for plant growth and development. It is primarily involved in energy transfer during cellular metabolism and serves as a fundamental component of cell membranes, nucleic acids, and other vital substances (Das, 2015). Consequently, ensuring sufficient levels of soil P is crucial for the long-term viability of agricultural systems (Sharpley et al, 1994). P in soils comes from various sources, including the parent material present in the soil and the incorporation of various organic and inorganic nutrient inputs through different mechanisms (Havlin et al, 2010).

In Nepal, P is the second most frequently applied nutrient following nitrogen, which is predominantly used in the form of urea. P is mainly supplied through diammonium phosphate (DAP) and single superphosphate (SSP) (Panta, 2018). Since Nepal lacks its own fertilizer production facilities, it relies entirely on imports to meet demand. Due to supply interruptions and price fluctuations, DAP sales have often fallen short of demand, with reported quantities of 140,166.63 Mt in 2020/21, 77,719.87 Mt in 2021/22, and 110,084.30 Mt in 2022/23 (MoALD, 2023). As an agricultural nation, Nepal imported agricultural products worth NPR 378.60 billion while exporting NPR 125.51 billion in 2021/22 (Anonymous, 2022). To address the trade deficit, it is vital to boost agricultural productivity by ensuring essential inputs, such as seeds, irrigation, and fertilizer. However, the high cost of chemical fertilizers, especially without subsidies, remains a concern for farmers. To mitigate this, the government provides a 52.38% subsidy on DAP. Over the past decade, approximately one-third of the Ministry of Agriculture and Livestock Development's budget has been allocated to fertilizer subsidies (Kharel et al., 2022), with an increase of 50.86% in the last fiscal year

and 48.79% in the current fiscal year (MoF, 2024). Despite these efforts, logistical challenges persist, and many farmers face delays in receiving their fertilizer allocations.

Phosphorus in soil exists in both organic (Po) and inorganic (Pi) forms (Weihrauch and Opp, 2018). The sequential fractionation method, developed in 1957 and widely used since, is an effective technique for determining P pools and understanding their chemistry and origin (Chang and Jackson, 1958; Cross and Schlesinger, 1995). This method extracts various inorganic P fractions, including loosely bound P, aluminum-bound P (Al-P), iron-bound P (Fe-P), reductant soluble P, and calcium-bound P (Ca-P). It also allows for the extraction of organic P fractions such as labile P, moderately labile P, fluvic acid P, humic acid P, and non-labile P (Zhang and Kover, 2009). The dynamics of these P forms are complex, influenced by intrinsic soil factors like parent materials (Fairhurst et al, 1999), texture (Viegas et al, 2010), management systems (Pavinato et al, 2009), fertilization practices (Guardini et al, 2012), and both biotic and abiotic environmental factors (Resende et al, 2011; He et al, 2023).

Organic P, prevalent in soils, can enhance plant and microbial P nutrition through hydrolysis, releasing free phosphate (Condron et al, 2005). This process is mediated by phosphatase enzymes, which are released by plants and microbes as a reaction to P requirement or liberated from decaying cells (Quiquampoix and Mousain, 2005). Soil phosphatases, including phosphomonoesterases (acid and alkaline), phosphodiesterases, phosphotriesterases, and inorganic pyrophosphatases, each play distinct roles in organic P hydrolysis. The activity of these enzymes is affected by variables like climate, soil properties, and nutrient management (Tabatabai, 1982; Margalef et al, 2017; Janes-Bassett, 2022).

Understanding P adsorption and desorption characteristics in soils is essential for formulating effective management plans and accurately anticipating fertilizer requirements (Zhang et al, 2005). The various P adsorption-desorption characteristics, including adsorption capacity, binding energy, maximum buffering capacity, sorption efficiency, standard P requirement, degree of P saturation, buffering capacity, desorption capacity, desorption constant, desorption rate, and readily desorbable P (Fanjana et al, 2017), indicate the potential movement of P from soils to ecosystems, which is essential for optimizing crop production and protecting the environment. Research has demonstrated that soil separates and available P content are the primary variables influencing P adsorption and desorption (Jalali and Jalali, 2016; Zhang et al, 2018). Additionally, soil pH, organic matter, calcium carbonate content, and the presence of active iron (Fe) and aluminum (Al) oxides as well significantly influence these processes (Pizzeghello et al, 2016; Fang et al, 2017).

Nepal's climate, physiography, parent materials, and vegetation vary significantly, creating diverse ecosystems (Vaidya and Sah, 2015). This environmental variation strongly impacts soil landscapes, ecosystems, and P dynamics. However, there is limited information on phosphorus pools, phosphatase enzyme activity, and P adsorption-desorption within soils of Nepal. This exploration seeks to address these gaps by evaluating the influence of soil properties on phosphorus fractions, phosphatase activity, and P adsorption-desorption behaviour in central Nepal.

MATERIALS AND METHODS

Study area

The study was carried out in the central region of Nepal (**Figure 1**), focusing on three distinct ecological zones: the high-hills, mid-hills, and Terai. The high-hills, comprising the mountainous areas, are characterized by highly metamorphosed rocks such as phyllites, schists, gneisses, and quartzites (Vaidya and Sah, 2015). This region experiences a temperate climate with mild summers and cold winters, where freezing temperatures are common at night, and snow frequently covers the landscape. The high-hill study sites were Gaurishankar, Jugal, Gosaikunda, and Ruby Valley rural municipalities in Dolakha,

Sindhupalchowk, Rasuwa, and Dhading districts, respectively. Common crops in these areas include maize, wheat, millet, barley, buckwheat, potatoes, beans, cabbage, chili, kiwi, and cardamom.

The mid-hills, situated in the middle range of the country, feature a varied topography of hills and valleys. The geology of this zone includes Cambrian to Precambrian phyllites, schists, quartzites, granites, and limestone (Vaidya and Sah, 2015). The mid-hills experience a sub-tropical climate, with mild summers and cool winters, though some valley and river basin areas can have relatively higher temperatures. The mid-hill study sites included Phikkal, Bagmati, and Siddhalek rural municipalities in Sindhuli, Lalitpur, and Dhading districts, and Manthali and Namobuddha municipalities in Ramechhap and Kavrepalanchowk districts. Typical crops cultivated in these areas are maize, wheat, rice, millet, buckwheat, along with various vegetables and fruits.

The Terai, located in the southern plains, is characterized by flat or gently sloping terrain. Its geology consists of recent and post-Pleistocene alluvial deposits, with deep, fine-textured soils that are mostly stone-free (Vaidya and Sah, 2015). The Terai has a tropical climate, with hot summers and mild winters. Study sites in the Terai included Madi municipality in Chitwan, and Thori, Devtal, Chakkarghatta, and Aaurahi rural municipalities in Parsa, Bara, Sarlahi, and Dhanusha districts. Crops commonly grown in this region include rice, wheat, maize, lentils, chickpeas, mustard, sugarcane, and various fruits and vegetables.
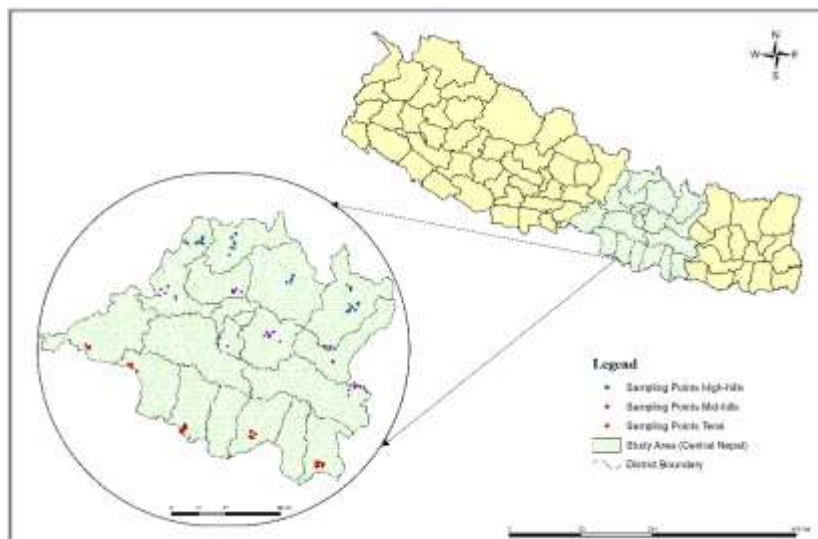

Figure 1. Location map of the study area

Soil sampling and processing

Soil samples were taken from a depth of 0–20 cm using a soil sampling auger, with the exact coordinates of each collection point recorded using a handheld GPS. A total of 225 samples were obtained from different locations throughout central Nepal, as illustrated in **Figure** 1.

For analyzing inorganic P fractions, and other parameters as well as P adsorption-desorption isotherm study, the air-dried soil samples were ground and sieved through a 2 mm sieve to ensure uniformity. On the other hand, for the determination of organic P fractions and phosphatase enzyme activity, fresh soil samples were kept at 4°C in a refrigerator until the start of analysis.

Laboratory analysis

Soil properties, namely texture, pH, electrical conductivity (EC), cation exchange capacity (CEC), calcium carbonate ($CaCO_3$), organic matter (OM), and exchangeable Al, were determined using the hydrometer

(Bouyoucos, 1927), potentiometric (Jackson, 1973), distilled water (1:5) (FAO, 2021), sodium acetate (Gupta, 2009), titrimetric (FAO, 2020), Walkley and Black (1934), and titrimetric (McLean, 1965) methods, respectively. Additionally, total nitrogen (N), Olsen P, Bray 1 P, Mehlich 3 P, and available potassium (K) were determined using Kjeldahl (Bremner and Mulvaney, 1982), modified Olsen (1954), Bray and Kurtz (1945), Mehlich (1984), and ammonium acetate (Jackson, 1973) methods, respectively. Similarly, available calcium (Ca) and magnesium (Mg), and sulfur (S) were determined using EDTA titration (Estefan et al., 2013), and turbidimetric (Verma, 1977) methods, respectively. Likewise, available boron (B), and iron (Fe), zinc (Zn), manganese (Mn) and copper (Cu) were determined using hot calcium chloride (Keren, 1996), and DTPA (Lindsay and Norvell, 1978) methods, respectively.

Total P was quantified using the sodium carbonate fusion technique followed by spectrophotometric analysis, based on the method outlined by Smith and Bain (1982). Alongside total P, different organic and inorganic P fractions were separated through the sequential chemical fractionation process detailed by Zhang and Kover (2009). Residual P was estimated by subtracting the combined organic and inorganic fractions from the total P, following the approach of Fanjana (2017), Nishigaki et al (2018), and Wierzbowska et al (2020).

Total P was measured using the sodium carbonate fusion method, followed by spectrophotometric analysis, following the procedure described by Smith and Bain (1982). In addition to total P, the various organic and inorganic P fractions were sequentially fractionated using the chemical fractionation method described by Zhang and Kover (2009). Residual P was then calculated by subtracting the sum of the organic and inorganic fractions from the total P, as suggested by Fanjana (2017), Nishigaki et al (2018), and Wierzbowska et al (2020). The activities of acid phosphomonoesterase (AcPM), alkaline phosphomonoesterase (AlPM), phosphodiesterase (PD), phosphotriesterase (PT), and inorganic pyrophosphatase (IPP) were assessed following the methodology outlined by Olinger et al (1996). For the P adsorption and desorption study, the method suggested by Pal (2011) was followed. Various characteristics were determined from the adsorption and desorption isotherm study.

Statistical analysis

Pearson's correlation analysis was conducted to evaluate the relationships between each parameter of response variables (P fractions, phosphatase enzyme activity, and P adsorption-desorption behaviors) and the explanatory variables (soil properties), separately. The redundancy analysis (RDA) was performed for assessment overall variation contribution due to explanatory variable set on response variable set. Additionally, a permutation test was conducted within the RDA model to evaluate the significance of each explanatory variable in explaining the variation in the response variable set. All the statistical was done using R programming.

RESULTS

Effect of soil properties on soil P fractions in agricultural soils of central Nepal

The correlation between soil P fractions and various soil properties is shown in **Table 1**. The loosely bound P (LB-P) showed a moderate and significant positive correlation with Olsen P, Bray 1 P, and Mehlich 3 P. Additionally, it exhibited weak but significant positive correlations with EC, $CaCO_3$, clay, available K, available Ca, available S, available B, available Mn, available Zn, and available Cu, as well as weak but significant negative correlations with sand and available Fe. Other soil properties did not show significant correlations. The aluminum bound P (Al-P) showed a strong and significant correlation with Olsen P, Bray 1 P, and Mehlich 3 P, and a moderate and significant positive correlation with CEC, available B, and available Zn. Additionally, it showed weak but significant positive correlations with OM, exchangeable Al, sand, total N, available K, available S, and available Mn, while weak but significant negative correlations were observed with pH, silt, and clay. Other soil properties did not show significant correlations.

Table 1. Correlation between soil P fractions with soil properties in agricultural soils of central Nepal

Soil parameters	Soil P fractions											
	LB-P	Al-P	Fe-P	RS-P	Ca-P	L-Po	ML-Po	FA-Po	HA-Po	NL-Po	Residual P	Total P
pH	0.03^{ns}	-0.25^{***}	-0.39^{***}	0.08^{ns}	0.28^{***}	-0.20^{**}	-0.14^{*}	-0.25^{***}	-0.33^{***}	-0.17^{*}	-0.18^{**}	-0.32^{***}
EC	0.21^{**}	0.12^{ns}	-0.05^{ns}	0.21^{**}	0.35^{***}	0.16^{*}	0.04^{ns}	0.20^{**}	-0.19^{**}	-0.01^{ns}	-0.08^{ns}	0.01^{ns}
OM	-0.14^{ns}	0.31^{***}	0.45^{***}	0.20^{**}	-0.03^{ns}	0.16^{*}	0.05^{ns}	0.34^{***}	0.44^{***}	0.37^{***}	0.06^{ns}	0.36^{***}
CaCO$_3$	0.27^{***}	0.11^{ns}	-0.11^{ns}	0.15^{*}	0.33^{***}	0.33^{***}	0.16^{*}	0.15^{*}	-0.20^{**}	0.07^{ns}	0.07^{ns}	0.11^{ns}
CEC	-0.02^{ns}	0.45^{***}	0.44^{***}	0.11^{ns}	-0.07^{ns}	0.42^{***}	0.10^{ns}	0.47^{***}	0.30^{***}	0.48^{***}	0.27^{***}	0.51^{***}
Exchangeable Al	-0.04^{ns}	0.26^{***}	0.30^{***}	0.05^{ns}	-0.12^{ns}	0.30^{***}	0.19^{**}	0.22^{***}	0.28^{***}	0.20^{**}	0.23^{***}	0.36^{***}
Sand	-0.13^{*}	0.22^{***}	0.26^{***}	0.08^{ns}	0.04^{ns}	0.03^{ns}	0.06^{ns}	0.03^{ns}	0.25^{***}	-0.08^{ns}	0.04^{ns}	0.17^{*}
Silt	0.08^{ns}	-0.16^{*}	-0.19^{**}	-0.06^{ns}	0.06^{ns}	0.03^{ns}	-0.03^{ns}	0.03^{ns}	-0.18^{**}	0.06^{ns}	-0.04^{ns}	-0.10^{ns}
Clay	0.14^{*}	-0.21^{**}	-0.24^{***}	-0.07^{ns}	-0.15^{*}	-0.08^{ns}	-0.07^{ns}	-0.09^{ns}	-0.23^{***}	0.05^{ns}	-0.03^{ns}	-0.17^{**}
Total N	-0.07^{ns}	0.35^{***}	0.47^{***}	0.25^{***}	-0.001^{ns}	0.19^{**}	0.07^{ns}	0.33^{***}	0.39^{***}	0.38^{***}	0.08^{ns}	0.37^{***}
Olsen P	0.53^{***}	0.69^{***}	0.56^{***}	0.52^{***}	0.45^{***}	0.40^{***}	0.36^{***}	0.66^{***}	0.001^{ns}	0.34^{***}	0.18^{**}	0.57^{***}
Bray 1 P	0.40^{***}	0.80^{***}	0.76^{***}	0.47^{***}	0.40^{***}	0.33^{***}	0.50^{***}	0.61^{***}	0.16^{*}	0.29^{***}	0.06^{ns}	0.57^{***}
Mehlich 3 P	0.46^{***}	0.80^{***}	0.66^{***}	0.53^{***}	0.51^{***}	0.46^{***}	0.41^{***}	0.67^{***}	0.02^{ns}	0.29^{***}	0.08^{ns}	0.56^{***}
Available K	0.14^{*}	0.32^{***}	0.41^{***}	0.25^{***}	-0.04^{ns}	0.05^{ns}	0.14^{*}	0.24^{***}	0.20^{**}	0.37^{***}	0.05^{ns}	0.28^{***}
Available Ca	0.17^{*}	-0.09^{ns}	-0.26^{***}	0.25^{***}	0.43^{***}	-0.08^{ns}	-0.12^{ns}	-0.04^{ns}	-0.35^{***}	0.05^{ns}	-0.24^{***}	-0.23^{***}
Available Mg	0.05^{ns}	0.08^{ns}	0.09^{ns}	0.07^{ns}	-0.04^{ns}	0.25^{***}	0.03^{ns}	0.20^{**}	-0.09^{ns}	0.12^{ns}	0.11^{ns}	0.13^{*}
Available S	0.28^{***}	0.19^{**}	0.06^{ns}	0.25^{***}	0.39^{***}	0.10^{ns}	0.11^{ns}	0.20^{**}	-0.17^{*}	-0.01^{ns}	-0.16^{*}	0.01^{ns}
Available B	0.34^{***}	0.40^{***}	0.32^{***}	0.56^{***}	0.45^{***}	0.31^{***}	0.18^{**}	0.51^{***}	-0.13^{*}	0.46^{***}	0.10^{ns}	0.38^{***}
Available Fe	-0.16^{*}	-0.03^{ns}	0.21^{**}	-0.24^{***}	-0.22^{***}	-0.08^{ns}	0.06^{ns}	-0.12^{ns}	0.04^{ns}	-0.22^{***}	-0.20^{**}	-0.16^{*}
Available Mn	0.15^{*}	0.25^{***}	0.29^{***}	0.08^{ns}	-0.13^{ns}	0.15^{*}	0.11^{ns}	0.35^{***}	0.19^{**}	0.43^{***}	0.18^{**}	0.34^{***}
Available Zn	0.30^{***}	0.59^{***}	0.56^{***}	0.55^{***}	0.40^{***}	0.25^{***}	0.31^{***}	0.48^{***}	0.20^{**}	0.37^{***}	0.09^{ns}	0.50^{***}
Available Cu	0.16^{*}	0.10^{ns}	0.19^{**}	0.26^{***}	0.27^{***}	0.29^{***}	0.24^{***}	0.39^{***}	-0.14^{*}	0.18^{**}	0.17^{*}	0.27^{***}

*, ** and *** indicates significant at 0.05, 0.01 and 0.001 level, respectively; ns = non-significant

The iron bound P (Fe-P) had a strong and significant correlation with Bray 1 P and Mehlich 3 P, and a moderate and significant positive correlation with OM, CEC, total N, Olsen P, available K, and available Zn. Additionally, it showed weak but significant positive correlations with exchangeable Al, sand, available B, available Fe, available Mn, and available Cu, while weak but significant negative correlations were observed with pH, silt, clay, and available Ca. Other soil properties did not show significant correlations. The reductant soluble P (RS-P) exhibited a moderate and significant positive correlation with Olsen P, Bray 1 P, Mehlich 3 P, available B, and available Zn. Moreover, it also showed weak but significant positive correlations with EC, OM, CaCO₃, total N, available K, available Ca, available S, and available Cu, while weak but significant negative correlations were observed with available Fe. Other soil properties did not show significant correlations.

The calcium bound P (Ca-P) exhibited a moderate and significant positive correlation with Olsen P, Bray 1 P, Mehlich 3 P, available Ca, available B, and available Zn. Furthermore, it also showed weak but significant positive correlations with pH, EC, CaCO₃, total N, available S, and available Cu, while weak but significant negative correlations were observed with clay and available Fe. Other soil properties did not show significant correlations.

The labile organic P (L-Po) showed a moderate and significant positive correlation with CEC, Olsen P, and Mehlich 3 P. Additionally, it showed weak but significant positive correlations with EC, OM, CaCO₃, exchangeable Al, total N, Bray 1 P, available Mg, available B, available Mn, available Zn, and available Cu, while weak but significant negative correlations were observed with pH. Other soil properties did not show notable correlations. The moderately labile organic P (ML-Po) showed a moderate and significant positive correlation with Bray 1 P and Mehlich 3 P. Additionally, it exhibited weak but significant positive correlations with CaCO₃, exchangeable Al, Olsen P, available K, available Mg, available S, available Mn, and available Cu, while weak but significant negative correlations were observed with pH. Other parameters did not show significant correlations.

The fluvic acid labile organic P (FA-Po) exhibited a strong and significant positive correlation with Olsen P, Bray 1 P, and Mehlich 3 P, along with a moderate and significant positive correlation with CEC, available B, and available Zn. Additionally, it showed weak but significant positive correlations with EC, OM, CaCO₃, exchangeable Al, total N, available K, available Mg, available S, available Mn, and available Cu, while weak but significant negative correlations were observed with pH. Other parameters did not have significant correlations. The humic acid organic P (HA-Po) showed a moderate and significant positive correlation with OM. It also showed weak but significant positive correlations with CEC, exchangeable Al, sand, total N, Bray 1 P, available K, available Mn, and available Zn, while weak but significant negative correlations were observed with pH, EC, CaCO₃, silt, clay, available Ca, available S, available B, and available Cu. Other parameters did not show significant correlations.

The non-labile organic P (NL-Po) exhibited a moderate and significant positive correlation with CEC, available B, and available Mn. Additionally, it showed weak but significant positive correlations with OM, exchangeable Al, total N, Olsen P, Bray 1 P, Mehlich 3 P, available K, available Zn, and available Cu, while weak but significant negative correlations were observed with pH and available Fe. Other parameters did not show significant correlations.

The residual P showed weak but significant positive correlations with CEC, exchangeable Al, Olsen P, available Mn, and available Cu, while weak but significant negative correlations were observed with pH, available Ca, and available Fe. Other parameters did not present significant correlations. Total P had moderate and significant positive correlations with CEC, Olsen P, Bray 1 P, Mehlich 3 P, and available Zn. Additionally, it showed weak but significant positive correlations with OM, exchangeable Al, sand, total N, available K, available Mg, available B, available Mn, and available Cu, while weak but significant

negative correlations were observed with pH, clay, available Ca, and available Fe. Other parameters did not show significant correlations.

The relationship between soil P fractions and soil properties, as analyzed through redundancy analysis (RDA), is shown in **Figure 2 (A)**. The major first two RDA dimensions accounted for 48.09% of the total variance (axis 1 = 38.80% and axis 2 = 9.29%). Based on the RDA, the studied soil properties contributed 58.63% of the total variation in soil P fractions. The correlation between soil properties and the RDA axes is presented in **Table 2**. Overall, OM (11.48%), followed by available P (10.71%) and pH (8.67%), were the top three soil properties contributing to the variation in soil P fractions (**Table 3**).
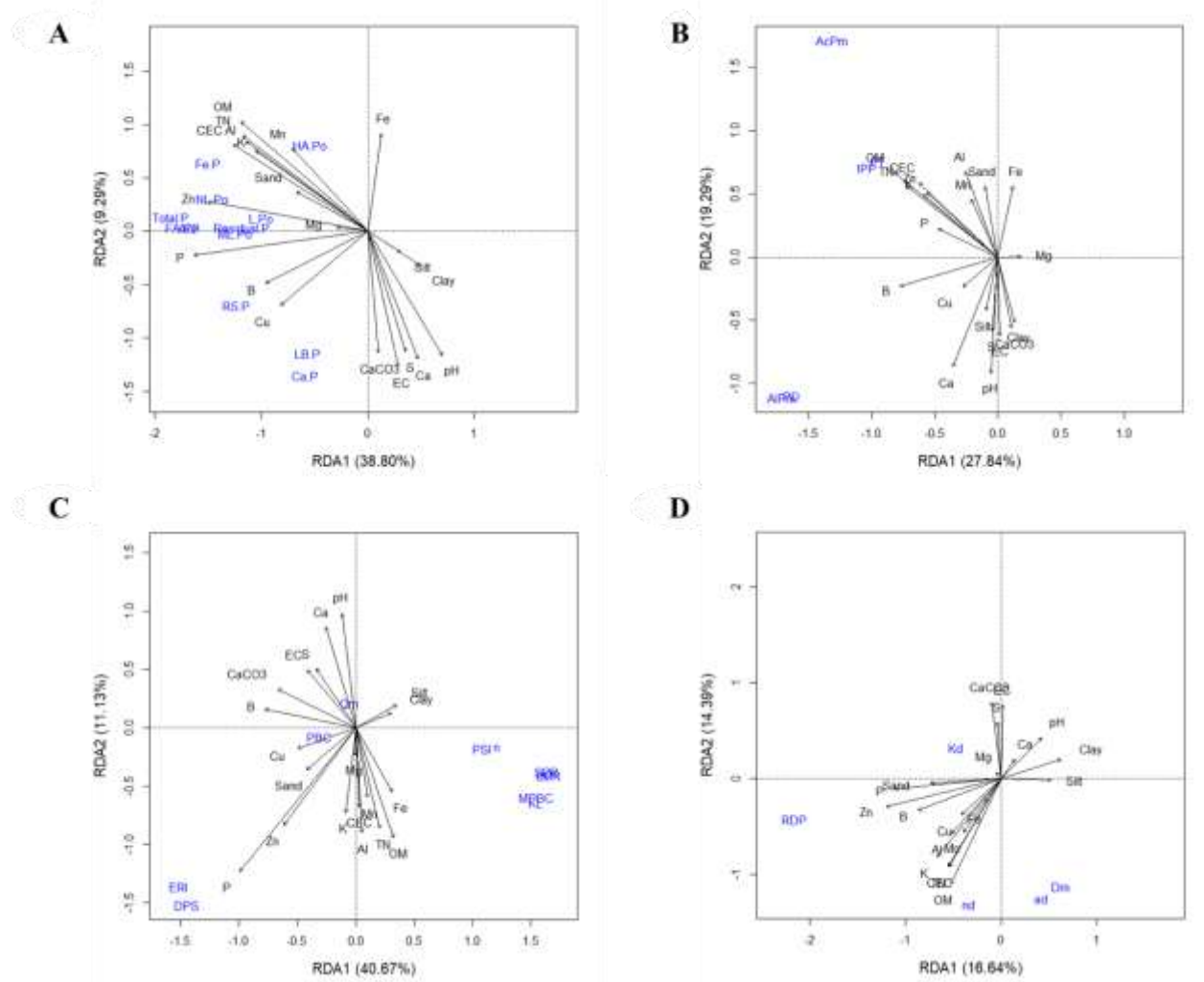

Figure 2. Redundancy analysis (RDA) results of the relationship between soil properties and A) P fractions, B) Phosphatase enzyme activity, C) P adsorption characteristics, and D) P desorption characteristics in agricultural soils of central Nepal

Table 2. Characteristics of the significant RDA axes linking soil properties with P fractions and phosphatase enzyme activity in agricultural soils of central Nepal

	P fractions				Phosphatase enzyme activity		
	RD1	RD1	RD3	RD4	RD1	RD1	RD3
Eigenvalue	4.66***	1.11***	0.40***	0.35***	1.39***	0.96***	0.20***
Variance (total) %	38.80	9.29	3.33	2.93	27.84	19.29	3.91
Variance (constrained) %	68.18	15.84	5.67	5.00	27.84	47.13	51.04
Soil properties				Correlation			
pH	0.36	-0.59	0.06	-0.35	-0.05	-0.83	-0.19
EC	0.14	-0.64	0.04	-0.07	0.01	-0.56	0.11
OM	-0.60	0.52	-0.18	-0.17	-0.74	0.60	-0.04
CaCO$_3$	0.05	-0.58	-0.13	0.01	0.10	-0.51	0.47
CEC	-0.64	0.41	0.24	0.04	-0.56	0.53	-0.23
Exchangeable Al	-0.58	0.43	-0.01	0.12	-0.24	0.61	0.16
Sand	-0.34	0.19	-0.28	0.55	-0.09	0.51	0.32
Silt	0.15	-0.10	0.29	-0.44	-0.08	-0.38	-0.21
Clay	0.25	-0.16	0.18	-0.60	0.12	-0.47	-0.13
Total N	-0.59	0.45	-0.14	-0.16	-0.65	0.51	-0.06
Available P	-0.83	-0.11	-0.24	0.22	-0.43	0.20	0.41
Available K	-0.53	0.38	-0.35	-0.28	-0.54	0.45	0.23
Available Ca	0.24	-0.61	-0.07	-0.61	-0.32	-0.78	-0.25
Available Mg	-0.15	0.02	0.36	-0.02	0.17	0.01	0.12
Available S	0.18	-0.57	-0.16	-0.15	-0.04	-0.53	-0.04
Available B	-0.49	-0.25	-0.25	-0.28	-0.70	-0.21	0.21
Available Cu	-0.41	-0.35	0.17	-0.18	-0.25	-0.21	0.08
Available Mn	-0.36	0.39	-0.08	-0.20	-0.19	0.41	0.02
Available Fe	0.07	0.46	-0.40	0.23	0.11	0.51	-0.10
Available Zn	-0.76	0.14	-0.42	0.25	-0.51	0.46	0.50

*** indicates significant at 0.001 level.

Table 3. Variance details of soil properties that explain P fractions, and phosphatase enzyme activity in agricultural soils of central Nepal

Soil properties	P fractions			Phosphatase enzyme activity		
	Variance	Explain %	Contribution %	Variance	Explain %	Contribution %
pH	1.04***	8.67	14.78	0.67***	13.50	25.16
EC	0.24***	2.01	3.43	0.07**	1.37	2.55
OM	1.38***	11.48	19.59	1.11***	22.17	41.33
CaCO$_3$	0.39***	3.21	5.48	0.14***	2.77	5.16
CEC	0.62***	5.19	8.85	0.06**	1.22	2.28
Exchangeable Al	0.06^{ns}	0.48	0.82	0.01^{ns}	0.27	0.50
Sand	0.25***	2.11	3.59	0.04*	0.79	1.47
Silt	0.05^{ns}	0.40	0.68	0.02^{ns}	0.31	0.58
Clay	0.26***	2.14	3.65	0.04*	0.75	1.40
Total N	0.06*	0.48	0.82	0.01^{ns}	0.21	0.39
Available P	1.29***	10.71	18.27	0.06**	1.24	2.30
Available K	0.17**	1.39	2.37	0.04**	0.87	1.63
Available Ca	0.16***	1.37	2.34	0.20***	4.04	7.53
Available Mg	0.06*	0.51	0.88	0.02^{ns}	0.42	0.78
Available S	0.02^{ns}	0.15	0.26	0.01^{ns}	0.17	0.32
Available B	0.05^{ns}	0.38	0.65	0.07**	1.38	2.58
Available Cu	0.34***	2.81	4.80	0.02^{ns}	0.45	0.83
Available Mn	0.05^{ns}	0.45	0.76	0.01^{ns}	0.29	0.54
Available Fe	0.43***	3.62	6.17	0.03^{ns}	0.51	0.95
Available Zn	0.13**	1.07	1.82	0.05**	0.93	1.73
Total	7.04	58.63	100.00	2.68	53.65	100.00

*, ** and *** indicates significant at 0.05, 0.01 and 0.001 level, respectively; ns = non-significant

Effect of soil properties on soil phosphatase enzyme in agricultural soils of central Nepal

The correlation between soil phosphatase enzyme activity and various soil parameters is shown in **Table** 4. Acid phosphomonoesterase (AcPM) activity had a strong and significant positive correlation with OM and total N, and a moderate and significant positive correlation with CEC, exchangeable Al, and available K. It also showed a moderate and significant negative correlation with pH and clay. Additionally, there were weak but significant positive correlations with sand, Olsen P, Bray 1 P, Mehlich 3 P, available B, available Fe, available Mn, and available Zn, and weak but significant negative correlations with EC, $CaCO_3$, silt, available Ca, and available S. Other soil parameters did not show significant correlations.

Alkaline phosphomonoesterase (AlPM) activity showed a moderate and significant positive correlation with available Ca and available B. Additionally, it exhibited weak but significant positive correlations with pH, EC, OM, **CaCO₃**, silt, total N, Olsen P, Bray 1 P, Mehlich 3 P, available K, available S, available Zn, and available Cu, while a weak but significant negative correlation was observed with available Fe. Other soil parameters did not show significant correlations.

Phosphodiesterase (PD) activity showed a moderate and significant positive correlation with available Ca and available B. Additionally, it exhibited weak but significant positive correlations with pH, EC, $CaCO_3$, silt, Olsen P, Bray 1 P, Mehlich 3 P, available K, available S, available Zn, and available Cu, while weak but significant negative correlations were observed with exchangeable Al, sand, and available Fe. Other soil parameters did not show significant correlations.

Phosphodiesterase (PT) activity showed a moderate and significant positive correlation with OM, CEC, total N, available Ca, and available B. Additionally, it exhibited weak but significant positive correlations with exchangeable Al, available K, available Mn, and available Zn, while weak but significant negative correlations were observed with pH and $CaCO_3$. Other soil parameters did not show significant correlations.

Inorganic pyrophosphatase (IPP) activity showed a moderate and significant positive correlation with OM. Additionally, it exhibited weak but significant positive correlations with CEC, exchangeable Al, sand, total N, Olsen P, Bray 1 P, Mehlich 3 P, available K, and available Zn, while weak but significant negative correlations were observed with pH, silt, clay, and available Ca. Other soil parameters did not show significant correlations.

The relationship between soil phosphatase enzyme activity and soil properties through redundancy analysis (RDA) is shown in **Figure** 2 (B). The two RDA dimensions account 47.13% (axis 1 = 27.84% and axis 2= 19.29%) of the total variance. Based on the RDA, the soil properties contributed 53.65% of the total variation in phosphatase enzyme activity in soils. The correlation between soil properties and redundancy analysis is presented in **Table** 2. Overall, among all the studied soil properties, OM (47.28%) followed by pH (29.09%) and available Ca (8.70%) were major three contributors to the variance in soil phosphatase enzyme activity (**Table 3**).

Table 4. Correlation between phosphatase enzyme activity with various soil properties in agricultural soils of central Nepal

Soil parameters	Phosphatase enzyme activity				
	AcPm	AlPm	PD	PT	IPP
pH	-0.48***	0.33***	0.29***	-0.16*	-0.22***
EC	-0.22***	0.26***	0.27***	-0.08^{ns}	0.03^{ns}
OM	0.79***	0.24***	0.09^{ns}	0.48***	0.47***
CaCO$_3$	-0.33***	0.21**	0.31***	-0.14*	-0.12^{ns}
CEC	0.59***	0.12^{ns}	0.10^{ns}	0.46***	0.24***
Exchangeable Al	0.43***	-0.10^{ns}	-0.13*	0.21**	0.19**
Sand	0.38***	-0.12^{ns}	-0.15*	0.11^{ns}	0.23***
Silt	-0.23***	0.17*	0.15*	-0.08^{ns}	-0.17*
Clay	-0.40***	0.03^{ns}	0.09^{ns}	-0.10^{ns}	-0.21**
Total N	0.68***	0.21**	0.10^{ns}	0.42***	0.39***
Olsen P	0.17*	0.21**	0.24***	0.07^{ns}	0.22***
Bray 1 P	0.30***	0.17*	0.16*	0.11^{ns}	0.34***
Mehlich 3 P	0.21**	0.25***	0.23***	0.08^{ns}	0.27***
Available K	0.40***	0.18**	0.18**	0.18**	0.31***
Available Ca	-0.34***	0.53***	0.43***	-0.06^{ns}	-0.23***
Available Mg	-0.09^{ns}	-0.002^{ns}	0.01^{ns}	-0.09^{ns}	-0.002^{ns}
Available S	-0.16*	0.35***	0.29***	-0.02^{ns}	0.01^{ns}
Available B	0.19**	0.59***	0.48***	0.06^{ns}	0.07^{ns}
Available Fe	0.26***	-0.23***	-0.27***	0.05^{ns}	-0.08^{ns}
Available Mn	0.29***	-0.06^{ns}	0.01^{ns}	0.17*	0.13^{ns}
Available Zn	0.37***	0.36***	0.31***	0.19**	0.38***
Available Cu	-0.04^{ns}	0.21**	0.19**	-0.05^{ns}	0.03^{ns}

*, ** and *** indicates significant at 0.05, 0.01 and 0.001 level, respectively; ns = non-significant

Effect of soil properties on soil P adsorption-desorption characteristics in agricultural soils of central Nepal

The correlation between soil P adsorption-desorption characteristics and various soil chemical parameters is shown in **Table** 5. The Langmuir P adsorption constant (Qm) had weak but significant positive correlations with pH, EC, Bray 1 P, Mehlich 3 P, and available Ca, and a weak but significant negative correlation with available Fe. The other soil parameters did not show significant correlations. The Langmuir constant (K$_L$) had a moderate but significant positive correlation with OM. Additionally, total N, available Mn, and exchangeable Al had weak but significant positive correlations, while weak but significant negative correlations were observed with pH, CaCO$_3$, Mehlich 3 P, available Ca, and available B. The other soil parameters did not show significant correlations. The Freundlich constant (K$_F$) had a moderate but significant positive correlation with OM. Furthermore, CEC, exchangeable Al, total N, and available Mn had weak but significant positive correlations, while pH, EC, Olsen P, Bray 1 P, Mehlich 3 P, available Ca, available S, available B, available Zn, and available Cu showed weak but significant negative correlations. The other soil parameters did not show significant correlations. The Freundlich constant (n) had a moderate and significant negative correlation with Bray 1 P, whereas weak but significant positive correlations with OM and available Mn, and weak but significant negative correlations with pH, EC, CaCO$_3$, Olsen P, Mehlich 3 P, available Ca, available S, available B, and available Zn. The other soil parameters did not show significant correlations.

The maximum P buffering capacity (MPBC) had a moderate and significant positive correlation with OM. Additionally, CEC, exchangeable Al, total N, and available Mn had weak but significant positive correlations, while pH, CaCO$_3$, available Ca, and available B showed weak but significant negative correlations. The other parameters did not show significant correlations. The P buffering capacity (PBC) had weak but significant positive correlations with pH, EC, Olsen P, Bray 1 P, Mehlich 3 P, available Ca, and available Zn. The other parameters did not show significant correlations.

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The standard P requirement (SPR) and external P requirement (EPR) had moderate and significant positive correlations with OM. Similarly, CEC, exchangeable Al, total N, and available Mn had weak but significant positive correlations, while pH, EC, CaCO$_3$, Olsen P, Bray 1 P, Mehlich 3 P, available Ca, available S, available B, available Cu, and available Zn showed weak but significant negative correlations. The other parameters did not show significant correlations.

The P sorption index (PSI) showed weak but significant positive correlations with OM and total N, and weak but significant negative correlations with CaCO$_3$, Olsen P, Bray 1 P, Mehlich 3 P, available B, and available Cu. Other parameters did not show significant correlations. The degree of P saturation (DPS) and P eutrophication risk index (PERI) had strong and significant positive correlations with Olsen P, Bray 1 P, and Mehlich 3 P, as well as moderate and significant positive correlations with available B and available Zn. Additionally, they exhibited weak but significant positive correlations with EC, CaCO$_3$, CEC, exchangeable Al, available K, available S, available Mn, and available Cu, while weak but significant negative correlation with pH. Both P adsorption parameters did not show significant correlations with other soil parameters. However, only DPS had a weak but significant positive correlation with total N.

The Langmuir desorption maxima (Dm) had a moderate and significant positive correlation with OM, along with weak but significant positive correlations with CEC, exchangeable Al, total N, and available K. It also showed weak but significant negative correlations with pH, EC, available CaCO$_3$, available Ca, and available B. Other parameters did not show significant correlations. The Freundlich desorption maxima (ad) exhibited weak but significant positive correlations with OM, CEC, silt, clay, total N, and available Mn, and weak but significant negative correlations with CaCO$_3$ and sand. Other parameters did not show significant correlations. The Langmuir desorption constant (Kd) had weak but significant positive correlations with Olsen P and available B, while other parameters did not show significant correlations. The Freundlich constant (nd) showed weak but significant positive correlations with OM, CEC, exchangeable Al, total N, Olsen P, Bray 1 P, Mehlich 3 P, available K, available B, available Mn, available Zn, and available Cu, and weak but significant negative correlations with EC and available S. Other parameters did not show significant correlations. The readily desorbable P (RDP) had strong and significant positive correlations with Olsen P, Bray 1 P, Mehlich 3 P, and available Zn, and moderate and significant positive correlations with available K and available B. Additionally, there were weak but significant positive correlations with EC, OM, CEC, exchangeable Al, sand, total N, available S, available Mn, and available Cu, and weak but significant negative correlations with pH, silt, and clay. Other parameters did not show significant correlations.

Table 5. Correlation between P adsorption-desorption characteristics with soil parameters in agricultural soils of central Nepal

Soil parameters	Adsorption-desorption characteristics															
	Qm	KL	KF	n	MPBC	PBC	SPR	EPR	PSI	DPS	PERI	Dm	ad	K_d	n_d	RDP
pH	0.29***	-0.21**	-0.19**	-0.18**	-0.17**	0.18**	-0.21**	-0.19**	0.06ns	-0.20**	-0.17**	-0.18**	-0.01ns	0.06ns	-0.12ns	-0.23***
EC	0.21**	-0.12ns	-0.18**	-0.25***	-0.11ns	0.20**	-0.20**	-0.18**	-0.02ns	0.29***	0.29***	-0.20**	-0.15*	0.12ns	-0.22***	0.14*
OM	0.02ns	0.45***	0.49***	0.16*	0.46***	0.06ns	0.48***	0.49***	0.38***	0.08ns	0.02ns	0.41***	0.32***	-0.13ns	0.26***	0.31***
CaCO₃	-0.005ns	-0.25***	-0.36***	-0.27**	-0.25***	0.11ns	-0.37***	-0.36***	-0.21**	0.26***	0.29***	-0.26***	-0.22***	0.08ns	-0.07ns	0.09ns
CEC	-0.07ns	0.13ns	0.16*	0.04ns	0.13*	0.03ns	0.18**	0.16*	0.08ns	0.25***	0.18**	0.24***	0.16*	-0.07ns	0.35***	0.37***
Al	-0.09ns	0.16*	0.21**	0.09ns	0.15*	0.001ns	0.19**	0.21**	0.10ns	0.20**	0.14*	0.19**	-0.03ns	-0.09ns	0.14*	0.22***
Sand	0.01ns	0.07ns	-0.05ns	-0.11ns	0.07ns	0.07ns	-0.04ns	-0.05ns	-0.05ns	0.12ns	0.11ns	0.11ns	-0.26***	0.002ns	0.09ns	0.29***
Silt	0.06ns	-0.07ns	0.03ns	0.09ns	-0.06ns	-0.05ns	0.03ns	0.03ns	0.07ns	-0.11ns	-0.11ns	-0.10ns	0.25***	-0.004ns	-0.10ns	-0.22**
Clay	-0.008ns	-0.05	0.06ns	0.09ns	-0.06ns	-0.07ns	0.04ns	0.06ns	0.02ns	-0.08ns	-0.08ns	-0.08ns	0.17*	0.001ns	-0.06ns	-0.27***
Total N	-0.01ns	0.32***	0.36***	0.13ns	0.33***	0.04ns	0.37***	0.36***	0.25***	0.15*	0.10ns	0.35***	0.24***	-0.09ns	0.27***	0.33***
Olsen P	0.12ns	-0.10ns	-0.22***	-0.28***	-0.09ns	0.15*	-0.23***	-0.22***	-0.20**	0.96***	0.87***	-0.09ns	-0.04ns	0.17**	0.16*	0.68***
Bray 1 P	0.17*	-0.08ns	-0.17*	-0.40***	-0.07ns	0.26***	-0.19**	-0.17*	-0.19**	0.77***	0.66***	0.03ns	-0.03ns	0.08ns	0.19**	0.81***
Mehlich 3 P	0.19**	-0.14*	-0.28***	-0.32***	0.13ns	0.26***	-0.29***	-0.28***	-0.19**	0.84***	0.76***	-0.08ns	-0.09ns	0.12ns	0.16*	0.80***
K	0.02ns	0.08ns	0.06ns	-0.09ns	0.09ns	0.09ns	0.07ns	0.06ns	0.03ns	0.20**	0.18**	0.13*	0.13ns	-0.004ns	0.19**	0.43***
Ca	0.25***	-0.22**	-0.22***	-0.18**	-0.20**	0.14*	-0.23***	-0.22***	-0.01ns	-0.04ns	-0.02ns	-0.18**	0.12ns	0.05ns	-0.02ns	-0.04ns
Mg	-0.07ns	-0.01ns	0.02ns	0.08ns	-0.01ns	-0.08ns	0.04ns	0.02ns	-0.05ns	0.10ns	0.11ns	-0.07ns	0.09ns	0.05ns	0.01ns	0.07ns
S	0.12ns	-0.11ns	-0.17**	-0.20**	-0.10ns	0.13ns	-0.18**	-0.17**	-0.08ns	0.32***	0.32***	-0.17**	-0.10ns	0.12ns	-0.15*	0.22***
B	0.12ns	-0.19**	-0.34***	-0.30***	-0.17**	0.10ns	-0.32***	-0.34***	-0.26***	0.45***	0.44***	-0.16*	0.07ns	0.19**	0.27***	0.54***
Fe	-0.15*	0.02ns	0.07ns	0.13ns	-0.01ns	-0.11ns	0.07ns	0.07ns	-0.01ns	-0.01ns	-0.04ns	0.03ns	0.08ns	-0.11ns	-0.08ns	0.09ns
Mn	-0.11ns	0.19**	0.19**	0.19**	0.18**	-0.13ns	0.22***	0.19**	0.02ns	0.18**	0.15*	0.12ns	0.22***	0.07ns	0.19**	0.21***
Zn	0.12ns	-0.01ns	-0.13*	-0.23***	-0.004ns	0.19**	-0.13*	-0.13*	-0.07ns	0.48***	0.43***	0.01ns	-0.03ns	0.11ns	0.25***	0.72***
Cu	-0.01ns	-0.12ns	-0.19**	-0.11ns	-0.12ns	-0.001ns	-0.17*	-0.19**	-0.19**	0.27***	0.25***	-0.12ns	0.05ns	0.07ns	0.36***	0.30***

*, ** and *** indicates significant at 0.05, 0.01 and 0.001 level, respectively; ns = non-significant

Table 6. Characteristics of significant RDA axes linking soil properties with P adsorption-desorption characteristics in agricultural soils of central Nepal

	P adsorption characteristics			P desorption characteristics		
	RD1	RD1	RD3	RD1	RD1	RD3
Eigenvalue	4.47***	1.22***	0.43**	0.83***	0.72***	0.31**
Variance (total) %	40.67	11.13	3.94	16.64	14.39	6.21
Variance (constrained) %	71.83	19.66	6.96	43.35	37.50	16.17
Soil properties	Correlation					
pH	-0.07	0.61	0.46	0.30	0.30	-0.33
EC	-0.26	0.31	0.44	0.01	0.54	-0.20
OM	0.20	-0.59	0.13	-0.37	-0.77	0.28
CaCO_3	-0.42	0.21	0.09	-0.07	0.56	-0.02
CEC	0.02	-0.42	0.10	-0.39	-0.65	0.22
Exchangeable Al	0.03	-0.57	-0.14	-0.37	-0.40	0.24
Sand	-0.26	-0.22	0.01	-0.52	-0.03	0.43
Silt	0.22	0.12	0.04	0.37	-0.01	-0.37
Clay	0.19	0.08	-0.09	0.44	0.14	-0.36
Total N	0.13	-0.54	0.19	-0.39	-0.64	0.23
Available P	-0.63	-0.77	0.09	-0.79	-0.08	0.18
Available K	-0.05	-0.45	0.08	-0.47	-0.57	0.09
Available Ca	-0.16	0.54	0.30	0.10	0.14	-0.56
Available Mg	-0.01	-0.15	-0.30	-0.04	0.05	-0.25
Available S	-0.21	0.32	0.19	-0.03	0.41	-0.34
Available B	-0.49	0.10	0.20	-0.62	-0.23	-0.39
Available Cu	-0.31	-0.11	-0.36	-0.29	-0.27	-0.54
Available Mn	0.06	-0.37	-0.36	-0.28	-0.39	-0.10
Available Fe	0.20	-0.34	-0.26	-0.12	-0.17	0.32
Available Zn	-0.39	-0.52	0.07	-0.85	-0.21	0.27

** and *** indicates significant at 0.01 and 0.001 level, respectively.

Table 7. Variance details of soil properties that explain P adsorption-desorption characteristics in agricultural soils of central Nepal

Soil properties	P adsorption			P desorption		
	Variance	Explain %	Contribution %	Variance	Explain %	Contribution %
pH	0.58***	5.28	9.33	0.17***	3.46	9.03
EC	0.33***	3.00	5.30	0.17***	3.48	9.08
OM	0.32***	2.95	5.22	0.36***	7.23	18.85
CaCO_3	0.48***	4.35	7.69	0.08**	1.56	4.05
CEC	0.18***	1.62	2.87	0.06**	1.21	3.15
Exchangeable Al	0.02^{ns}	0.15	0.27	0.02^{ns}	0.37	0.97
Sand	0.71***	6.42	11.33	0.25***	5.09	13.27
Silt	0.02^{ns}	0.20	0.36	0.01^{ns}	0.22	0.58
Clay	0.09*	0.80	1.42	0.005^{ns}	0.09	0.24
Total N	0.04^{ns}	0.32	0.57	0.02^{ns}	0.31	0.80
Available P	1.73***	15.71	27.75	0.19***	3.85	10.05
Available K	0.29***	2.66	4.70	0.08**	1.56	4.06
Available Ca	0.37***	3.37	5.95	0.05*	0.98	2.55
Available Mg	0.03^{ns}	0.23	0.40	0.02^{ns}	0.49	1.29
Available S	0.02^{ns}	0.21	0.37	0.02^{ns}	0.36	0.93
Available B	0.48***	4.38	7.74	0.08**	1.55	4.05
Available Cu	0.46***	4.22	7.46	0.14***	2.89	7.54
Available Mn	0.02^{ns}	0.15	0.27	0.03^{ns}	0.68	1.77
Available Fe	0.03^{ns}	0.31	0.54	0.05*	1.02	2.65
Available Zn	0.03^{ns}	0.26	0.47	0.10***	1.96	5.10
Total	6.23	56.62	100.00	1.92	38.37	100.00

*, ** and *** indicates significant at 0.05, 0.01 and 0.001 level, respectively; ns = non-significant

The relationship between soil P adsorption characteristics and soil properties through redundancy analysis (RDA) is shown in **Figure** 1 (C). The two RDA dimensions account 51.80% (axis 1 = 40.67% and axis 2 = 11.13%) of the total variance. Based on the RDA, the soil properties contributed 56.62% of the total variation in soil P sorption characteristics. The correlation between soil properties and redundancy analysis is presented in **Table** 6. Overall, available P (15.71%) followed by sand proportion (6.42%) and pH (5.28%) were major three soil properties contributing to variance in the soil P sorption characteristics (**Table** 7).

The relationship between soil P desorption characteristics and soil properties through redundancy analysis (RDA) is shown in **Figure** 2 (C). The two RDA dimensions account 31.03% (axis 1 = 16.64% and axis 2 = 14.39%) of the total variance. Based on the RDA, the soil properties contributed 38.37% of the total variation in soil P desorption characteristics. Overall, OM (7.23%) followed by sand proportion (5.09%) and Olsen P (3.85%) were major three soil properties contributing to variance in the soil P desorption characteristics (**Table** 7).

DISCUSSION
Effect of soil properties on P fractions in agricultural soils of central Nepal
Determining P fractions is important for understanding P chemistry in soils. The studied soil properties could explain 58.63% of the total variance in soil P fractions. The 15 properties showed significant effects on the compositions of the P fractions, in decreasing order, were OM > available P > pH > CEC > available Fe > CaCO$_3$ > available Cu > clay content > sand content > EC > available K > available Ca > available Zn > available Mg > total N (**Table** 3). Changes in these properties significantly affected the variation in soil P fractions. The OM contributed comparatively higher (11.48%) for variation in P fractions may largely be attributed to ability of OM for supply of inorganic P (Pi) through mineralization (Qiong et al, 2022). Byproducts from the decomposition of soil OM, such as organic acids, sulfates, and fluorides, can compete with phosphate ions in the soil solution for adsorption onto specific sites. If the phosphate ions are already adsorbed, these byproducts can alter the surface charge of iron or aluminum oxides, leading to the electrostatic displacement of the phosphates (Redel et al, 2007; Zamuner et al, 2008). The OM-derived phosphate ions play an important role in the differentiation of P fractions.

Similarly, available P is another soil property contributed significantly (10.71%) to the variation in P fractions after OM (**Table** 3). The high variation contributed by available P (Olsen P) might be due to its immediate binding with other elements like Fe, Al, and Ca, forming inorganic P fractions (Ismat et al., 2018). Additionally, plant roots absorb available P from the soil and translocate it to the shoots, where it acts as an organic P fraction (Zhu et al, 2020). Olsen P exhibited significantly positive correlations with nearly all the P fractions (except HA-Po) (**Table** 5). This indicates that as available P (Olsen P) increases, soil P fractions also increase, and vice versa.

Another soil property, pH, contributed significantly (8.67%) to the variation in soil P fractions after OM and available P (**Table** 3). The changes in P fractions with pH may be attributed to shifts in the abundance and types of microbial populations responsible for phosphatase enzyme activity (Zhao et al, 2008). Phosphatase enzyme activities are crucial for the transformation of organic P into inorganic forms (Weil and Brady, 2017). Additionally, changes in soil pH altered the forms of P associated with iron, aluminum, calcium, and other soil minerals, as well as P adsorbed onto soil colloids, by influencing the precipitation-dissolution and adsorption-desorption equilibria of P (Javot et al, 2007). In acidic soils, P was predominantly bound to iron and aluminum oxides, hydroxides, and clay minerals, forming different complexes. In contrast, P retention in alkaline soils was primarily driven by precipitation reactions, though it could also be adsorbed calcium carbonate and clay minerals, rendering it inaccessible to plants (Ismat et al, 2018). Soil pH had significantly negative correlations with Al-P, Fe-P, L-Po, ML-Po, FA-Po, HA-Po, NL-Po, residual P, and total P (**Table** 1), indicating that as soil pH increased, these P fractions decreased, and vice versa. In contrast, a significantly positive correlation was observed with Ca-P (**Table** 5), implying that as pH increased, Ca-P content also increased, and vice versa.

The other soil properties, including CEC, available Fe, CaCO₃, available Cu, clay content, sand content, EC, available K, available Ca, available Zn, available Mg, and total N, also contributed to the variation in soil P fractions. The variation may have been due to their influence on ionic balance, soil structure, phosphatase enzyme activity, and the overall environment in which the P fractions were generated.

Effect of soil properties on phosphatase enzyme activity in agricultural soils of central Nepal

Soil phosphatase enzymes are crucial for P transformation, facilitating the conversion of soil phosphate into forms of P that plants can readily adsorb. The studied soil properties accounted for 53.65% of the total variance in phosphatase enzyme activity. The 12 properties that contributed significantly, in decreasing order, were OM > pH > available Ca > CaCO₃ > available B > EC > available P > CEC > available Zn > available K > sand content > clay content (**Table** 3). Changes in these soil properties can significantly affect the abundance and activities of the microbial community, thereby influencing soil phosphatase enzyme activities. Phosphatase enzymes are produced by organisms as well as plant roots (Xu et al, 2010). Among all the studied properties, OM contributed significantly higher (22.17%) to the variation in phosphatase enzyme activity (**Table 3**). The significant positive correlations were observed with AcPM, AlPM, PD, and IPP activity (**Table 4**), symbolize with the increase in OM increases activity of these enzyme also, and vice-versa in soils. Microorganisms require energy for their growth and development, which is supplied through OM. Soil OM serves as the primary source of carbon and nitrogen for microorganisms, which impacts enzyme activity by affecting both the quantity and diversity of microbial communities (Floch et al, 2009).

Soil pH, another key soil property, contributed (13.50%) to the variation in phosphatase enzyme activity after OM (**Table 3**). The different soil enzymes have different pH optima for their activity (Xu et al, 2017). The growth and development of both organisms and plants was influenced by soil pH (Havlin et al, 2010). Consequently, the growth and development of organisms and plants responsible for producing phosphatase enzymes were also affected by soil pH, which may have explained its contribution to the variation in phosphatase enzyme activity. Kompala-Baba et al (2021) also observed a significant impact of soil pH on the variance of acid and alkaline phosphatase enzyme activities. A significant positive correlation was observed with AlPM and PD activity (**Table 4**), indicating that as pH increased, their enzyme activity also increased, and vice versa. Conversely, a significant negative correlation was observed with AcPM, PT, and IPP activity (**Table 4**), meaning that as pH increased, their activity decreased, and vice versa. AcPM and AlPM activity were found to be dominant in acidic and alkaline soils, respectively (Rocabruna et al, 2024).

The other soil properties mentioned as available Ca, CaCO₃, available B, EC, available P, CEC, available Zn, available K, sand content, and clay content also contributed to the variation in phosphatase enzyme activity. This variation may have been due to their influence on enzyme production, structure, and the overall environment in which the enzymes functioned.

Effect of soil properties on P adsorption characteristics in agricultural soils of central Nepal

The study of P adsorption-desorption isotherms is important for understanding P adsorption-desorption behavior in soils and is crucial for long-term P management (Yang et al, 2019). The studied soil properties could explain 50.92% of the total variance in P adsorption characteristics. The 12 properties significantly influenced the composition of P adsorption characteristics, in decreasing order, were Olsen P>sand content> pH > available B>CaCO₃> available Cu>available Ca>EC>OM>available K>CEC > clay content (**Table 7**). Changes in these properties significantly affected the variation in soil P sorption characteristics. The available P contributed comparatively higher (15.71%) role for variation in P sorption characteristics (**Table 7**). The increased available P, decreases P adsorption capacity of soils because as excess phosphate ions occupy the adsorption sites, thereby hindering further reactions. Tang et al (2022) observed a reduction of P adsorption capacity with P application when compared to the control. Additionally, DPS and PERI was significantly positively correlated with available P (Olsen P) (**Table 5**), hence with the increase in available P, DPS and PERI also increases, and vice-versa. In contrast, SPR and EPR exhibited significant

negative correlation with available P (Olsen P) (**Table 5**), hence with the increase in available P, SPR and EPR decreases, and vice-versa. Therefore, available P contributed significantly higher for variation in adsorption characteristics.

Sand content did not show a significant correlation with P adsorption characteristics (**Table** 5), but it contributed significantly (6.42%) to the variation in P adsorption characteristics after available P (**Table 7**). Gou et al (2019) also found significant contribution of sand content in soil P adsorption characteristics. Generally, sand has a smaller surface area compared to other soil particles. This could also be related to the relatively lower number of positive charges available for interaction with and strong binding of negatively charged phosphate ions in the soil solution, thereby reducing P adsorption capacity (Getie et al, 2021).

The pH is another soil property that contributed significantly (5.28%) to the variation in P adsorption characteristics after available P and sand content (**Table** 7). Soil pH is a major influencing factor for available P, which play important role for variation in P adsorption characteristics. At low pH, phosphate ion is bound with Fe/Al, while at high pH bound with Ca. Moreover, the nature of Fe-Al oxides in soils also depends on pH, which also plays important role for P adsorption through their surface area and active sites for reaction (Ruttenberg and Sulak, 2011). At high pH (alkaline), hydroxide ions compete with phosphate for adsorption sites on iron-aluminum oxides and hydroxides, while at low pH (acidic), the protonation of the iron-aluminum compounds enhances P adsorption (Xu et al, 2016). The soil pH (4.65-9.13) was significantly negatively correlated with K_L, K_F, n, MPBC, SPR, EPR, DPS, PERI, while significantly positively correlated with Qm and PBC (**Table** 7) might also cause of variation in P adsorption characteristics.

The other soil properties, including available B, $CaCO_3$, available Cu, available Ca, EC, OM, available K, CEC, and clay content, also contributed to the variation in soil P adsorption. The variation may have been due to their influence on ionic balance, surface area, phosphatase enzyme activity, and the overall environment which enable phosphate ion reactions in soils.

Effect of soil properties on P desorption characteristics in agricultural soils of central Nepal

Desorption is the process that occurs in reverse to adsorption. The studies soil properties could explain 38.37% of the total variance in desorption characteristics. The 13 properties had notable influences on the compositions of P desorption characteristics, in decreasing order, were OM>sand content>Olsen P>EC>pH>available Cu>available Zn> $CaCO_3$>available K>available B>CEC>available Fe>available Ca (**Table** 7). Changes in these properties significantly affected the variation in soil P desorption characteristics. The OM contributed significantly higher (7.23%) for variation in P desorption characteristics (**Table** 7). The OM exhibited significantly positive correlations with Dm, ad, nd, and RDP (Table 5). The organic anions produced by OM can compete with the phosphate ions for releasing adsorbed P (Bhadha et al, 2010).

Sand content was another soil property contributed significantly (5.09%) after OM to the variation in P desorption characteristics (**Table 7**). The sand content exhibited significantly positive correlation with RDP, while significantly negative correlation with a_d (**Table** 5). Generally, sand has a smaller surface area compared to other soil particles. This feature was also associated with a lower quantity of positive charges available to interact with and strongly bind the negatively charged phosphate ions in the soil solution, which in turn enhanced P desorption capacity (Getie et al, 2021).

The available P was another property contributed significantly (3.85%) after OM and sand content for variation in P desorption characteristics (**Table 7**). The increased available P, increases P desorption capacity of soils, as an excess of phosphate ions occupies the adsorption sites, thereby hindering further reactions. The available P (Olsen P) exhibited significant positive correlation with K_d, n_d, and RDP (**Table 5**), with the increase in available P also increases these desorption parameters and vice-versa.

The other soil properties, including EC, pH, available Cu, available Zn, CaCO₃, available K, available B, CEC, available Fe, and available Ca, also contributed significantly to the variation in soil P desorption. The variation may have been due to their influence on ionic balance, surface area, phosphatase enzyme activity, and the overall environment which enable phosphate ion reactions in soils.

CONCLUSION

P fractions, phosphatase enzyme activity, and P adsorption-desorption characteristics are key for making decisions regarding sustainable P management in specific regions. This study assessed the influence of soil properties-including pH, EC, OM, CaCO₃, CEC, exchangeable Al, sand, silt, clay, total N, and available nutrients (P, K, Ca, Mg, S, B, Cu, Mn, Fe, and Zn) on P fractions, phosphatase enzyme activity, and P adsorption-desorption characteristics in agricultural soils of central Nepal using Pearson's correlation and redundancy analysis (RDA). The soil properties explained 58.63%, 53.65%, 56.62%, and 38.37% of the total variation in P fractions, phosphatase enzyme activity, P adsorption, and P desorption characteristics, respectively. Out of the studied variables, 15 properties significantly influenced P fractions, with OM, available P, and pH being the most important. For phosphatase enzyme activity, 12 properties had significant effects, with OM and pH being the primary factors. Similarly, 12 properties significantly affected P adsorption characteristics, with available P, sand content, and pH being the major contributors. In terms of P desorption, 13 properties had significant effects, with OM and sand content being the most influential. This study highlights the critical role of specific soil properties in regulating phosphorus dynamics, providing a foundation for enhancing P management strategies in diverse agricultural environments.

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REFERENCES

Anonymous. 2022. Nepal's import of agricultural products jumps more than double to around Rs 379 billion in the past seven years. my Republica. https://myrepublica.nagariknetwork.com/news/nepal-s-import-of-agricultural-products-jumps-more-than-double-to-around-rs-379-billion-in-the-past-seven-years/

Bhadha JH, WG Harris and JW Jawitz. 2010. Soil phosphorus release and storage capacity from an impacted subtropical wetland. Soil Sci. Soc. Am. J. **74**(6):1816-1825. **DOI:** https://doi.org/10.2136/sssaj2010.0063

Bouyoucos GJ. 1927. The hydrometer as a new method for the mechanical analysis of soils. Soil Sci. **23**:343-353. **DOI:** https://dx.doi.org/10.1097/00010694-192705000-00002

Bray RH and LT Kurtz. 1945. Determination of total organic and available forms of phosphorus in soils. Soil Sci. **59**:39-45. **DOI:** https://dx.doi.org/10.1097/00010694-194501000-00006

Bremner JM and CS Mulvaney. 1982. Nitrogen—Total. In AL Page (Ed.), Methods of soil analysis: Agron. No. 9, Part 2: Chemical and microbiological properties (2nd ed., **pp**. 595-624). Am. Soc. Agron. **DOI:** https://doi.org/10.2134/agronmonogr9.2.2ed.c31

Chang SC and ML Jackson. 1958. Soil phosphorus fractions in some representative soils. J. Soil Sci. **9**(1):109-119. https://doi.org/10.1111/j.1365-2389.1958.tb01903.x

Condron LM, BL Turner and BJ Cade-Menun. 2005. Chemistry and dynamics of soil organic phosphorus. In TJ Sims, AN Sharpley (Eds.), Phosphorus: Agriculture and the environment (Agron. Monogr. 46:87-121). Am. Soc. Agron. **DOI:** https://doi.org/10.2134/agronmonogr46.c4

Cross AF and WH Schlesinger. 1995. A literature review and evaluation of the Hedley fractionation: Applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. Geoderma **64**(3-4):197-214. **DOI:** https://doi.org/10.1016/0016-7061(94)00023-4

Das DK. 2015. Introductory soil science. Kalyani Publishers.

Dieter D, H Elsenbeer and BL Turner. 2010. Phosphorus fractionation in lowland tropical rainforest soils in central Panama. Catena **82**(2):118-125. **DOI:** https://doi.org/10.1016/j.catena.2010.05.010

Estefan E, R Sommer and J Ryan. 2013. Methods of soil, plant, and water analysis: A manual for the West Asia and North Africa region*.* Int. Cent. Agric. Res. Dry Areas (ICARDA), 244.

Fairhurst TR, R Lefroy, E Mutert and N Batijes. 1999. The importance, distribution, and causes of phosphorus deficiency as a constraint to crop production in the tropics. Agrofor. Forum **9**:2-8.

Fang H, Z Cui, G He, L Huang and M Chen. 2017. Phosphorus adsorption onto clay minerals and iron oxide with consideration of heterogeneous particle morphology. Sci. Total Environ. **605**:357-367. **DOI:** https://doi.org/10.1016/j.scitotenv.2017.05.133

Fanjana F, W Haile and G Mitike. 2017. Phosphorus fractionation and P sorption capacities of Fincha Sugar Estate soils, Western Ethiopia. Afr. J. Agric. Res. 12(25):2131-2139. **DOI:** https://doi.org/10.5897/ajar2016.12394

Food and Agriculture Organization (FAO). 2020. Standard operating procedure for soil calcium carbonate equivalent*:* Titrimetric method. Rome.

Food and Agriculture Organization (FAO). 2021. Standard operating procedure for soil electrical conductivity, soil/water, 1:5. Rome.

Floch C, Y Capowiez and S Criquet. 2009. Enzyme activities in apple orchard agroecosystems: How are they affected by management strategy and soil properties? Soil Biol. Biochem. **41**(1):61-68. **DOI:** https://doi.org/10.1016/j.soilbio.2008.09.018

Getie A, A Kiflu and G Meteke. 2021. Phosphorus sorption characteristics of Luvisols and Nitisols in north Ethiopian soils. Appl. Environ. Soil Sci. 2021:8823852. **DOI:** https://doi.org/10.1155/2021/8823852

Gou X, Y Cai, C Wang, B Li, Y Zhang, X Tang, J Shen and Z Cai. 2019. Effects of different long-term cropping systems on phosphorus adsorption and desorption characteristics in red soils. J. Soils Sediments **20**:1371-1382. **DOI:** https://doi.org/10.1007/s11368-019-02493-2

Guardini R, JJ Comin, DE Schmitt, T Tiecher, MA Bender, DS Rheinheimer and G Brunetto. 2012. Accumulation of phosphorus fractions in typic Hapludalf soil after long-term application of pig slurry and deep pig litter in a no-tillage system. Nutr. Cycl. Agroecosyst. **93**:215-225. **DOI:** https://doi.org/10.1007/s10705-012-9511-3

Gupta PK. 2009. Soil, plant, water and fertilizer analysis. 2nd ed, Agribios.

Havlin HL, JD Beaton, SL Tisdale and WL Nelson. 2010. Soil fertility and fertilizers: An introduction to nutrient management. 7th ed, PHI Learning Private Limited.

He X, L Augusto, DS Goll, B Ringeval, YP Wang, J Helfenstein and E Hou. 2023. Global patterns and drivers of phosphorus fractions in natural soils. Biogeosciences **20**(19):4147-4163. **DOI:** https://doi.org/10.5194/bg-20-4147-2023

Ismat A, IM Shoffikul, AKM Abul and KT Osman. 2018. A comparative study of phosphorus availability in an acidic soil and an alkaline soil amended with organic and inorganic phosphorus sources. J. Soil Sci. Plant Nutr. **DOI:** https://doi.org/10.4067/S0718-95162018005001402

Jackson ML. 1973. Soil chemical analysis. Prentice Hall of India Pvt. Ltd., New Delhi.

Jalali M and M Jalali. 2016. Relation between various soil phosphorus extraction methods and sorption parameters in calcareous soils with different texture. Sci. Total Environ. 566-567:1080-1093. **DOI:** https://doi.org/10.1016/j.scitotenv.2016.05.133

Janes-Bassett V, MSA Blackwell, G Blair, J Davies, PM Haygarth, MM Mezeli and G Stewart. 2022. A meta-analysis of phosphatase activity in agricultural settings in response to phosphorus deficiency. Soil Biol. Biochem. **165**:108537. **DOI:** https://doi.org/10.1016/j.soilbio.2021.108537

Javot H, N Pumplin and MJ Harrison. 2007. Phosphate in the arbuscular mycorrhizal symbiosis: Transport properties and regulatory roles. Plant Cell Environ. **30**(3):310-322. **DOI:** https://doi.org/10.1111/j.1365-3040.2006.01617.x

Joshy D. 1997. Soil fertility and fertilizer use in Nepal. Soil Science Division, NARC, Khumaltar, Lalitpur, Nepal.

Keren R. 1996. Boron. **In**: Methods of soil analysis, Part 3: Chemical methods (DL Sparks and AL Page, eds.). Soil Sci. Soc. Am. and Am. Soc. Agron.; **pp**. 603-626.

Kharel M, BM Dahal and N Raut. 2022. Good agriculture practices for safe food and sustainable agriculture in Nepal: A review. J. Agric. Food Res. 100447. **DOI:** https://doi.org/10.1016/j.jafr.2022.100447

Kompała-Bąba A, W Bierza, E Sierka, A Błońska, L Besenyei and G Woźniak. 2021. The role of plants and soil properties in the enzyme activities of substrates on hard coal mine spoil heaps. Sci. Rep. **11**(1):5155. **DOI:** https://doi.org/10.1038/s41598-021-84673-0

Lamichhane S, L Kumar and K Adhikari. 2021. Updating the national soil map of Nepal through digital soil mapping. Geoderma 394:115041. **DOI:** https://doi.org/10.1016/j.geoderma.2021.115041

Lindsay WL and WA Norvell. 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci. Soc. Am. J. **42**:421-428.

Margalef O, J Sardans, M Fernández-Martínez, R Molowny-Horas, IA Janssens, P Ciais, and J Peñuelas. 2017. Global patterns of phosphatase activity in natural soils. Sci. Rep. **7**:1337. **DOI:** https://doi.org/10.1038/s41598-017-01418-8

McLean EO. 1965. Aluminum. **In**: Methods of soil analysis: Part 2. Chemical methods (CA Black ed). Am. Soc. Agron., Madison, Wisconsin; **pp**.978-998.

Mehlich A. 1984. Mehlich 3 soil test extractant: A modification of the Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. **15**:1409-1416. **DOI:** https://dx.doi.org/10.1080/00103628409367568

Ministry of Agriculture and Livestock Development (MoALD). 2023. Statistical information on Nepalese agriculture. Singhdurbar, Kathmandu, Nepal.

Ministry of Finance (MoF). 2023. Budget speech of fiscal year 2023/24. Government of Nepal.

Nishigaki T, S Sugihara, K Kobayashi, Y Hashimoto, M Kilasara, H Tanaka, T Watanabe and S Funakawa. 2018. Fractionation of phosphorus in soils with different geological and soil physicochemical properties in southern Tanzania. Soil Sci. Plant Nutr. **64**(3):291-299. **DOI:** https://doi.org/10.1080/00380768.2018.1436406

Ölinger R, R Margesin and E Kandeler. 1996. Enzymes involved in phosphorus metabolism. **In**: Methods in Soil Biology (F Schinner, R Öhlinger, E Kandeler, R Margesin, eds). Springer, Berlin, Heidelberg; **pp**. 208-227. **DOI:** https://doi.org/10.1007/978-3-642-60966-4_13

Olsen SR, CV Cole and FS Watanbe. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circ. No. 939. U.S. Government Printing Office.

Pal SK. 2011. Phosphorus sorption-desorption characteristics of soils under different land use patterns of eastern India. Arch. Agron. Soil Sci. **57**(4):365-376. **DOI:** https://doi.org/10.1080/03650341003605743

Panta HK. 2018. Supply chain of subsidized chemical fertilizers in Nepal. J. Inst. Agric. Anim. Sci. **35**(1):9-20. **DOI:** https://doi.org/10.3126/jiaas.v35i1.22509

Pavinato PS, A Merlin and CA Rosolem. 2009. Phosphorus fractions in Brazilian Cerrado soils as affected by tillage. Soil Tillage Res. 105:149-155. **DOI:** https://doi.org/10.1016/j.still.2009.07.001

Pizzeghello D, A Berti, S Nardi and F Morari. 2016. Relationship between soil test phosphorus and phosphorus release to solution in three soils after long-term mineral and manure application. Agric. Ecosyst. Environ. **233**:214-223. **DOI:** https://doi.org/10.1016/j.agee.2016.09.015

Qiong W, Zhen-han Q, Wei-wei Z, Yan-hua C, Ping Z, Chang P, Le W, Shu-xiang Z and G Colinet. 2022. Effect of long-term fertilization on phosphorus fractions in different soil layers and their quantitative relationships with soil properties. J. Integr. Agric. **21**(9):2720-2733. **DOI:** https://doi.org/10.1016/j.jia.2022.07.018

Quiquampoix H and D Mousain. 2005. Enzymatic hydrolysis of organic phosphorus. **In**: Organic phosphorus in the environment (BL Turner, E Frossard and DS Baldwin). CABI Publishing; **pp**. 89-112. **DOI:** https://doi.org/10.1079/9780851998220.0089

Redel YD, R Rubio, JL Rouanet and F Borie. 2007. Phosphorus bioavailability affected by tillage and crop rotation on a Chilean volcanic derived Ultisol. Geoderma **139**:388-396. **DOI:** https://doi.org/10.1016/j.geoderma.2007.02.018

Resende JCF, MMC Bustamante, D Markewitz, CA Klink and EA Davidson. 2011. Phosphorus cycling in a small watershed in the Brazilian Cerrado: Impacts of frequent burning. Biogeochemistry **105**:105-118. **DOI:** https://doi.org/10.1007/s10533-010-9531-5

Rocabruna PC, X Domene, C Preece and J Peñuelas. 2024. Relationship among soil biophysicochemical properties, agricultural practices, and climate factors influencing soil phosphatase activity in agricultural land. Agriculture **14**(2):288. **DOI:** https://doi.org/10.3390/agriculture14020288

Ruttenberg KC and DJ Sulak. 2011. Sorption and desorption of dissolved organic phosphorus onto iron (oxyhydr)oxides in seawater. Geochim. Cosmochim. Acta **75**(13):4095-4112. **DOI:** https://doi.org/10.1016/j.gca.2010.10.033

Sharpley AN, JT Sims and GM Pierzynski. 1994. Innovative soil phosphorus availability indices: Assessing inorganic phosphorus. **In**: Soil testing: Prospects for improving nutrient recommendations (J Havlin and J Jacobsen, eds). Soil Sci. Soc. Am.; **pp**. 115-142.

Smith BF and DC Bain. 1982. A sodium hydroxide fusion method for the determination of total phosphate in soils. Commun. Soil Sci. Plant Anal. **13**:185-190. **DOI:** https://doi.org/10.1080/00103628209367257

Tabatabai MA. 1982. Soil enzymes. **In**: Methods of soil analysis (AL Page, RH Miller and DR Keeney, eds). 2nd ed, Am. Soc. Agron., Soil Sci. Soc. Am.; **pp**. 903-947. **DOI:** https://doi.org/10.2134/agronmonogr9.2.2ed.c43

Tang X, M Liu, J Sheng, Z Chai, G Feng, and B Chen. 2022. Inorganic phosphorus transformation and phosphorus adsorption–desorption properties of soil in a cotton field under mulched drip irrigation in Xinjiang: A four-year field assessment. Front. Environ. Sci. **10**:874902. **DOI:** https://doi.org/10.3389/fenvs.2022.874902

Vaidya SN and K Sah. 2015. Preparation of database and soil map of Nepal using WRB 2010 classification system. **In**: Proceedings of the Second National Soil Fertility Research Workshop (KB Karki, BP Tripathi, R Manandhar, BH Adhikary, eds). Nepal Agricultural Research Council, Soil Science Division, Khumaltar, Lalitpur, Nepal; **pp**. 393-402.

Verma BC. 1977. An improved turbid-metric procedure for the determination of sulphate in plants and soils. Talanta **24**:49–50.

Viégas RA, RF Novais and F Schulthais. 2010. Availability of a soluble phosphorus source applied to soil samples with different acidity levels. Rev. Bras. Cienc. Solo **34**:1126-1136. **DOI:** https://doi.org/10.1590/S0100-06832010000400012

Walkley A and IA Black. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. **37**:29-38. **DOI:** https://dx.doi.org/10.1097/00010694-193401000-00003

Weihrauch C and C Opp. 2018. Ecologically relevant phosphorus pools in soils and their dynamics: The story so far. Geoderma 325:183-194. **DOI:** https://doi.org/10.1016/j.geoderma.2018.02.047

Weil RR and NC Brady. 2017. The nature and properties of soils. 15th ed. Pearson.

Wierzbowska J, S Sienkiewicz, M Zalewska et al. 2020. Phosphorus fractions in soil fertilized with organic waste. Environ. Monit. Assess. 192:315. **DOI:** https://doi.org/10.1007/s10661-020-8190-9

Xu RK, NP Qafoku, E Van Ranst, JY Li and J Jiang. 2016. Adsorption properties of subtropical and tropical variable charge soils: Implications from climate change and biochar amendment. Adv. Agron. **135**:1–58. **DOI:** https://doi.org/10.1016/bs.agron.2015.09.001

Xu Z, G Yu, X Zhang, N He, Q Wang, S Wang, R Wang, N Zhao, Y Jia and C Wang. 2017. Soil enzyme activity and stoichiometry in forest ecosystems along the North–South Transect in eastern China (NSTEC). Soil Biol. Biochem. **104**:152–163. **DOI:** https://doi.org/10.1016/j.soilbio.2016.10.020

Xu ZF, R Hu, P Xiong, C Wan, G Cao and Q Liu. 2010. Initial soil responses to experimental warming in two contrasting forest ecosystems, Eastern Tibetan Plateau, China: Nutrient availabilities, microbial properties, and enzyme activities. Appl. Soil Ecol. **46**(2):291–299. **DOI:** https://doi.org/10.1016/j.apsoil.2010.07.005

Yang X, X Chen and X Yang. 2019. Effect of organic matter on phosphorus adsorption and desorption in a black soil from Northeast China. Soil Tillage Res. **187**:85–91. **DOI:** https://doi.org/10.1016/j.still.2018.11.016

Zamuner EC, LI Picone and HE Echeverría. 2008. Organic and inorganic phosphorus in Mollisol soil under different tillage practices. Soil Tillage Res. **99**:131-138. **DOI:** https://doi.org/10.1016/j.still.2007.12.006

Zhang H and JL Kovar. 2009. Fractionation of soil phosphorus. **In**: *Methods of phosphorus analysis for soils, sediments, residuals, and waters* (JL Kovar and GM Pierzynski, eds). 2nd ed., Southern Cooperative Series Bulletin, **408**.

Zhang H, JL Schroder, JK Fuhrman, NT Basta, DE Storm and ME Payton. 2005. Path and multiple regression analyses of phosphorus sorption capacity. Soil Sci. Soc. Am. J. **69**:96-106. **DOI:** https://doi.org/10.2136/sssaj2005.0096dup

Zhang Y, S Huang, D Guo, S Zhang, X Song, K Yue, K Zhang and D Bao. 2018. Phosphorus adsorption and desorption characteristics of different textural fluvo-aquic soils under long-term fertilization. J. Soils Sediments **19**:1306-1318. **DOI:** https://doi.org/10.1007/s11368-018-2122-0

Zhao Q, DH Zeng, ZP Fan and DK Lee. 2008. Effect of land cover change on soil phosphorus fractions in southeastern Horqin sandy land, northern China. Pedosphere **18**(6):741–748. **DOI:** https://doi.org/10.1016/S1002-0160(08)60069-7

Zhu X, X Zhao, Q Lin, Alamus, H Wang, H Liu, W Wei, X Sun, Y Li and G Li. 2020. Distribution characteristics of soil organic phosphorus fractions in the Inner Mongolia steppe. J. Soil Sci. Plant Nutr. **20**:2394-2405. **DOI:** https://doi.org/10.1007/s42729-020-00305-y

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