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PHOSPHORUS DISTRIBUTION IN SOILS UNDER DIFFERENT LAND USE AND LAND COVER IN SEMI-ARID REGION OF UTHAL DISTRICT LASBELA

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Abstract
This research examined how diverse agricultural land uses on phosphorus (P) distribution and availability in calcareous soils. Samples were collected from different land types to examine key p fractions, including soluble and exchangeable P (labile P), Fe and Al-bound P (moderately labile P), Ca-bound P (moderately labile inorganic P), and residual P (highly stable P). Labile P was most abundant in crop land (L2) and orchard (L5) surface soils, primarily due to fertilization and organic amendments, where bare land (L1) consistently exhibited the lowest levels due to limited P inputs and vegetation. Moderate labile P, particularly Fe and Al-bound and Ca-bound fractions, was similarly elevated in managed lands like orchards and crop lands, indicating the influence of agricultural practices such as liming and organic amendments. In contrast, forest (L3) and grassland (L4) soils showed moderate P levels, reflecting the role of natural organic matter cycling. Residual P, representing the most stable form, accumulated most in orchard (L5) and crop land (L2), driven by long-term transformations of added P into recalcitrant forms, while bare land (L1) consistently displayed the lowest concentrations (orchard, Crop land, Bare land, Grass land, Forest land) to study different P fractions: labile (easily available), Fe/Al-bound, Ca-bound, and residuum (unavailable) P. Through all land uses, calcium-bound P dominated, of total P, emphasizing the strong impact of calcium carbonate in soils on P fixation. Contrariwise, grassland soils showed the moderate P levels, perhaps due to natural organic matter rates or distinctive P cycling procedures. Remarkably, labile P was comparatively higher in soils growing the most stable orchard land and crop land, demonstrating higher P availability. Long-term fertilization guided to P accretion in inorganic forms, especially as calcium-bound P. This proposes that while manuring upsurges total P, a significant portion develops immobilized. Significant positive correlations between labile P, Fe/Al-bound P, and Ca-bound P indicate that these fractions are interrelated and predisposed by similar soil processes. The strong correlation

between Olsen-P and CaCl2-P proposes that these approaches efficiently degree of available P in calcareous soils. Principal component analysis shows that four components clarify most of the difference in P distribution, proposing complex relations between land use, soil properties, and P dynamics.

Introduction

In plants, phosphorus is an essential macronutrient for growth, development, and metabolism. It accounts for 0.2% of the dry weight of plants. It is the mineral nutrient that most frequently restricts crop growth, second only to nitrogen (Aziz et al., 2012; Tak et al., 2012). phosphorus P loading Researchers have started to look at internal loading (Cavalcante et al., 2021; Rocha and Lima Neto, 2022; Waajen et al., 2016) and non-point sources of nutrients (Le Moal et al., 2019; Mellander et al., 2022) as the primary causes of coastal areas and lakes, as well as the limited success of restoration projects. External nutrient supplies are mostly linked to changes in watershed land cover, such as deforestation, agriculture, livestock areas, and increasing exposed soil (Cunha and da Cunha, 2023; Le Moal et al., 2019; Nobre et al., 2020). The typical soil phosphorus level is around 0.05%, however only 0.1% of that amount is usable for plants (Zhu et al., 2011).ss In natural ecosystems such as rangelands, grasslands, and pastures, phosphorus availability and cycling significantly influence plant community structure and productivity (Whalen et al. 2003; Chen et al. 2004; Agbenin and Adeniyi 2005; Zhou et al. 2017) P plays a crucial role in photosynthesis, cell division, and energy transfer, primarily originating from the weathering of apatite minerals. However, Phosphorus availability in soil is often limited due to fixation processes, especially in warmer regions where adsorption in soil is more in warmer regions, where adsorption and precipitation are more pronounced. Excessive phosphorus supply can delay plant maturity, yet, as plants cannot synthesize phosphorus nor substitute, it with another element, sustainable management strategies are necessary to enhance agriculture productivity. Most of phosphorus in terrestrial ecosystems is concentrated in soil, typically within the upper one-meter depth from the land surface (Zhang et al., 2021) Soil total P concentration result from complex interaction among climatic, biotic, and landscape processes over time impacted by elements of the source soil material (Dokuchaev, 1883) A few variables can be used to describe each of these characteristics; for instance, mean annual temperature (MAT) and precipitation (MAP) can be used to describe climate. Previous investigations, mostly at local to regional scales, have documented relationships between soil total P concentration and factors such parent material type and P concentration, MAT, MAP, site slope, and 45 soil organic carbon (SOC) (Brédoire et al., 2016).

One of the most important markers of wetland nutrient levels is phosphorus (P), which naturally reaches a stable biogeochemical state (Grunwald et al. 2006). According to Sheklabadi et al. (2014), the measurement of the soil P fraction offers information about the availability of phosphorus and can be used to evaluate its dynamics, solubility, and availability under various land-use management schemes. There are many different external sources of phosphorus in soils, such as organic amendments, fertilizers used in agriculture, food waste, human waste, and even materials like cement, wood, and asphalt (Metson et al., 2012). Human activities significantly modify soil P concentration, as evidenced by archaeological studies where phosphorus has been used as an ancient human settlement (Holliday and Gartner, 2007) While phosphorus accumulation in managed soils may help buffer against future food security threats, it also presents challenges. Excess phosphorus represents an economic loss for farmers, depletes a non-renewable resource, and contributes to environmental issues such as eutrophication when it leaches into water bodies, triggering harmful algal bloom (Esslser and Bennett 2011) Therefore, while analyzing the depletion, maintenance, or accumulation of soil P levels and fertility, it is crucial to balance phosphorus inputs between P supply as fertilizer and P removal by crops. Remaining soil P levels are ultimately enriched in years with weak growth or when crops with low P need are produced and conversely depleted in years with great yield or crops with high P demand, because of using blanket treatments of the same P rates year after year. Thus, P fertility will be influenced by management history, tillage technique, rotation, and P fertilizer rates in connection to crop removal (Havlin et al., 2014). The variability in Phosphorus pools and their availability influenced by soil properties, cropping systems, and environmental conditions, underscoring the need for a comprehensive understanding of soil P transformation and partitioning. This knowledge is crucial for optimizing P use efficiency while reducing environmental risks. Path analysis, a multivariate technique, has been employed to investigate complex interactions between soil properties and managements practices (Bayuelo-Jiménez et al. 2020) in this sense, better fertilizer use is required to improve soil management on agricultural land. By improving the soil's consumption of P, soil management can change the dynamics of P transformations in a positive way. Conversely, it might change the dynamics of P transformations negatively by causing losses of this nutrient and making applications worse (Rheinheimer et al., 2008).

Literature Review

Kaur et al. (2021) A research was carried out in the lower Satluj basin, which is situated in the Shiwalik foothills of the Himalayas, India, to evaluate the seasonal impacts of five different land use systems (LUSs). The chosen LUSs comprised plantations of Eucalyptus globulus, sugarcane (Saccharum officinarum), an orange (Citrus sinensis) orchard, and a wheat–rice (Triticum aestivum–Oryza sativa) cropping system. There were 120 samples of soil taken over two seasons from four depths: 0–15 cm, 15–30 cm, 30–45 cm, and 45–60 cm. The soil's pH was classified as sandy loam, which is moderately alkaline. The contents of nutrients and soil organic carbon (SOC) decreased in the following sequence throughout the pre- and post-monsoon periods: forest > orchard > grassland > wheat–rice > sugarcane. Interestingly, there was a modest link between soil pH and SOC, macronutrients, and micronutrients, but there was a substantial positive correlation (r = 0.818) between these parameters. SOC, macronutrients, and micronutrients were substantially higher at the topmost soil layer (0–15 cm) than in deeper layers, mostly because of increased organic matter accumulation at the surface. To identify significant variations in soil characteristics between the five LUSs at various depths during both seasons, a Tukey's multiple comparison test ($p < 0.05$) was utilized. Electrical conductivity (EC) and SOC were determined to be the primary markers of soil quality across all land use systems by Principal Component Analysis (PCA). Additionally, it was discovered that the post-monsoon season had superior soil health than the pre-monsoon one. Assessing degraded agricultural areas and creating future soil conservation plans are made easier by these findings, which offer important insights into soil fertility and ecosystem health in general.

Oechaiyaphum et al. (2020) studied the long-term impacts of various farming management techniques on soil fertility and soil organic carbon (SOC) in northeastern Thailand's rice-growing regions. The Khon Kaen Rice Research Center provided the data for the study. In 2007, the center used conventional compost amendment methods to measure SOC levels and soil fertility indicators in the top 20 cm of soil in Maha Sarakham Province. Data on soil fertility and SOC were collected from s130 farmers' farms near the first data collecting site throughout the course of the next ten years. The study sought to determine how SOC and soil fertility were affected by switching from traditional agriculture management to government-approved methods. A continuous compost amendment (CA) approach was used as a baseline for comparison, with additional treatments involving biofertilizer (BF), green manure (GM), and rice straw (RS) applications over the 10-year period. The findings indicated that government-promoted agricultural techniques generally improved SOC levels and soil fertility. Among the amendments, the incorporation of rice straw (RS) had the most significant impact, leading to substantial increases in total nitrogen (156%), SOC concentration (152%), and SOC density (149%) over the decade. Adugna et al. (2016) investigated Soil quality can be positively or adversely impacted by changes in land use. Assessing the effects of various land uses on certain physical and chemical characteristics of soil was the goal of this study. Three nearby land use types—forestland, grazing land, and cultivated land sampled for soil at a depth of 0 to 15 cm. When comparing farmed and grazing fields to forestland, changes in soil characteristics were evaluated, and Anova was used to establish statistical significance. Sand and silt fractions, soil organic matter, total nitrogen, acidity, cation exchange capacity, and exchangeable Ca2+ were all the greatest in forestland, according to the results. Sand and silt fractions, soil organic matter, total nitrogen, acidity, cation exchange capacity, and exchangeable Ca2+ were all the greatest in forestland, according to the results. Grazing land had the maximum amount of exchangeable magnesium (Mg^{2+}), while cultivated land had the highest levels of clay content, accessible phosphorus, and exchangeable K^{+}. Cultivated land showed more significant percentage changes in sand, clay, soil organic matter, cation exchange capacity, and exchangeable Ca2+ and Mg2+ than either grazing or forestland. Most other soil variables showed no significant associations with available phosphorus or silt, while soil organic matter, total nitrogen, cation exchange capacity, and exchangeable Ca2+ showed high positive correlations with most other soil parameters. A faster rate of soil deterioration was indicated by the fact that, overall, farmed land had lower concentrations of most soil physical and chemical parameters, apart from clay and accessible phosphorus. It is advised to use integrated land management techniques, such as spreading compost, utilizing cover crops and manure, reducing tillage, adopting crop rotation, and applying lime to lower soil acidity, to improve soil organic matter and nutrient levels in farmed land.

Rocha et al. (2024) A study was conducted to evaluate the geographical distribution of several phosphorus (P) forms in the sediments of a tropical semi-arid reservoir was examined to assess the effects of land use and land cover (LULC). It was believed that exposed soil, vegetation that may flood, and agricultural practices were the main causes of the increase in mobile P components in sediments. Moreover, the concentrations of mobile P in the sediments near the dam were expected to rise because of flow convergence. The drainage basin and its sphere of impact were the focus of the supervised approach utilized to categorize LULC. The drainage basin and its sphere of effect were the focus of the supervised method used to classify LULC. Samples of sediment were taken from four different sites in two sub-basins that make up the reservoir. Sequential chemical extraction along several reservoir sections was used to estimate the phosphorus fractions. The findings demonstrated that the terrain was dominated by sparse Caatinga, which occupied over 50% of the drainage basin and the area of effect. There is a chance that this kind of land cover will cause nutrients to be transported into aquatic environments. The sediments from the Boqueirão reservoir had high levels of phosphorus, and a sizable amount of it was in mobile forms. These fractions had a geographically varied distribution. The main causes of the rise in mobile P in the sediments were found to be floodable vegetation, bare soil, and agricultural land use. These results emphasize how crucial it is to apply focused management techniques to reduce P enrichment in the reservoir. Remarkably, sediments nearer the dam had less mobile phosphorus than those upstream, which was inconsistent with original predictions.

Result and Discussion

Soluble and Exchangeable P (Labile P)

The distribution of labile phosphorus (P), represented by the KCl – P fraction, varied significantly across different land-use types and soil depths. In the surface layer (0–5 cm), the highest labile P levels were observed in the forest (L3) and orchard (L5) soils (fig. 1). This pattern likely reflects the continuous addition of organic matter from litter in forests and the use of fertilizers in orchards (Tiessen & Moir, 1993; White, 2006). In contrast, bare land (L1) exhibited the lowest P levels, likely due to limited organic inputs and enhanced erosion effects (Frossard et al., 1995). Croplands (L2) and grasslands (L4) showed intermediate values, influenced by moderate organic inputs and nutrient use efficiency (Guo et al., 2000). In subsurface layers (5–15 cm and 15–30 cm), labile P levels generally declined across all land-use types, with the most pronounced reductions observed in bare land and cropland. However, forest and orchard soils retained relatively higher P levels even in deeper layers, indicating their stronger nutrient cycling capacity and organic matter incorporation (Negassa & Leinweber, 2009).

The differences in P dynamics can be attributed to land-use practices and soil management strategies. Forests and orchards exhibited higher P concentrations due to organic matter decomposition and fertilizer inputs, which enhance nutrient availability (Frossard et al., 1995; White, 2006). Bare land, on the other hand, suffers from nutrient depletion due to erosion and a lack of organic inputs, highlighting the need for restorative measures (Tiessen & Moir, 1993). Depth-wise, the sharp decline in labile P with increasing soil depth reflects the limited movement of P in the soil profile, with the majority being retained in the surface layers (Guo et al., 2000). However, the relatively stable P levels in deeper layers of forests and orchards suggest that deeper root systems and organic matter incorporation play a crucial role in maintaining nutrient availability (Negassa & Leinweber, 2009).

These findings underscore the importance of sustainable land management in maintaining soil fertility. The high labile P levels in orchards necessitate careful fertilizer management to prevent over-accumulation and potential environmental risks, such as runoff and eutrophication (Negassa & Leinweber, 2009). Croplands, with moderate P levels, require targeted nutrient management practices to optimize crop yields without depleting soil reserves. Forests and grasslands, which showed efficient natural P cycling, highlight the value of preserving these ecosystems for sustainable nutrient dynamics (Tiessen & Moir, 1993; White, 2006). Lastly, bare land calls for urgent soil restoration efforts to mitigate degradation and improve fertility.

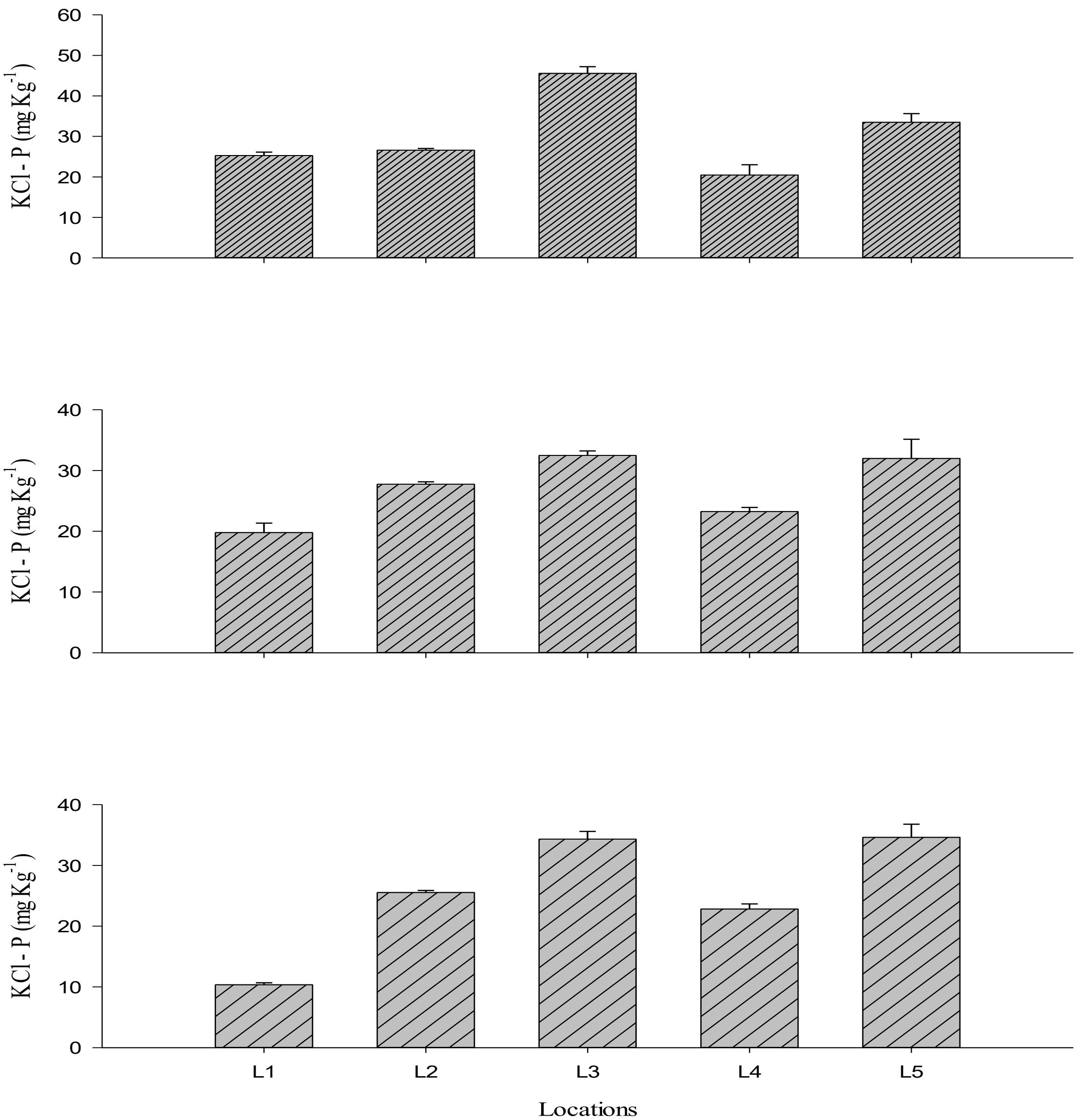

Figure 0.1: Variations in KCl – P fraction for all five sites where L1=Bare Land, L2=Crop Land, L3=Forest, L4=Grass Land and L5=Orchard. The figure from above to lower shows the three depths (0 – 5, 5 – 15 and 15 – 30 cm).

Fe and Al bound P (Moderately Labile P)

The Fe and Al-bound phosphorus, extracted by 0.1 M NaOH, displayed distinct patterns based on land use and soil depth (fig. 2). At the surface depth (0–5 cm), the P concentration was significantly higher in L2 (crop land) and L5 (orchard), which can be attributed to the application of fertilizers and organic amendments that elevate the labile P fraction. Forest soils (L3) and grasslands (L4) also exhibited relatively high P levels, potentially due to organic matter decomposition and limited P fixation compared to bare land (L1), which recorded the lowest P content. At the intermediate depth (5–15 cm), the trends remained consistent, with L5 (orchard) and L2 (crop land) maintaining higher P concentrations. This suggests the downward movement of P through leaching or bioturbation, likely facilitated by agricultural management practices in croplands and orchards. In contrast, bare land (L1) had minimal P storage, reflecting limited biological activity and inputs.

In the subsurface layer (15–30 cm), the differences between land use types became less pronounced, though L5 (orchard) still showed relatively higher P levels compared to others. This reduction in variability could be due to the diminished influence of surface management practices and the natural attenuation of labile P with depth. The observed patterns are consistent with previous studies that emphasize the role of land use in governing P dynamics in soils. For instance, agricultural lands typically exhibit higher labile P fractions due to fertilization (Zhang et al., 2019), while natural ecosystems like forests and grasslands rely on organic matter cycling (Gatiboni et al., 2020). Furthermore, the reduced P levels in bare land highlight the importance of vegetation cover in retaining and recycling P.

These findings underscore the critical influence of land management practices on soil P distribution, with implications for sustainable nutrient management and minimizing P loss through leaching or runoff.

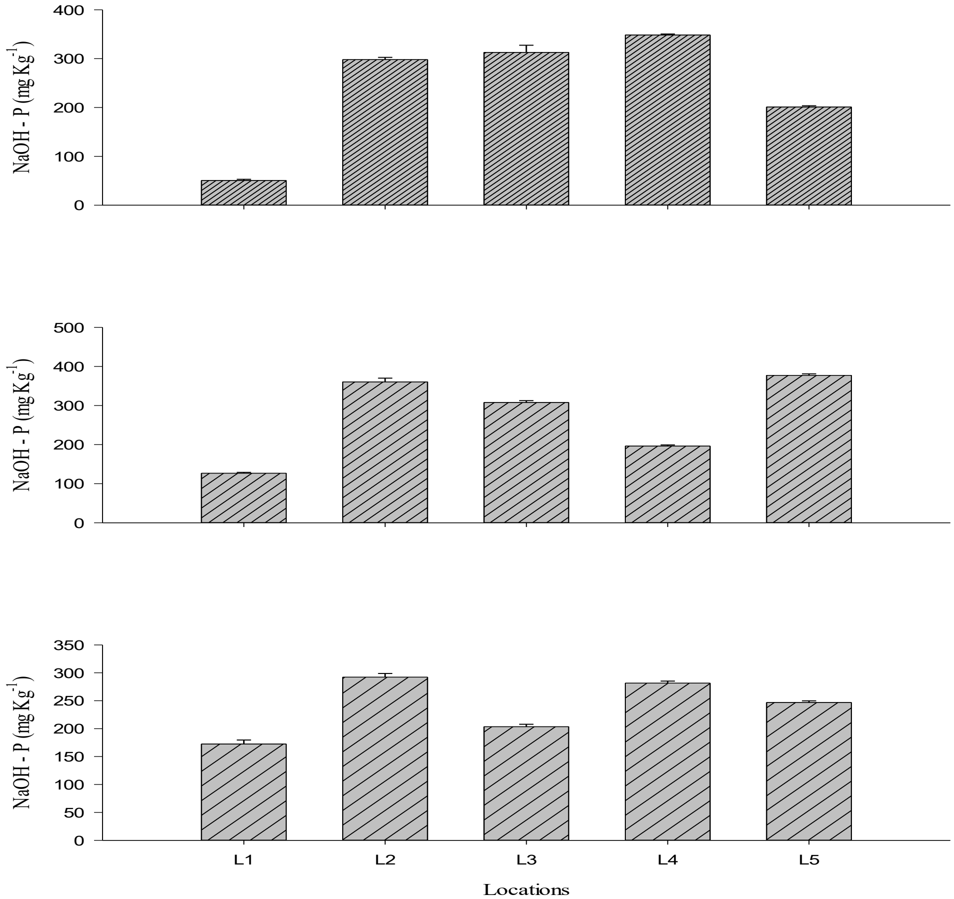

Figure 0.2: Variations in NaOH fraction for all five sites where L1=Bare Land, L2=Crop Land, L3=Forest, L4=Grass Land and L5=Orchard. The figure from above to lower shows the three depths (0 – 5, 5 – 15 and 15 – 30 cm).

Calcium bound P (Moderately Labile Inorganic P)

The concentration of Ca-bound P demonstrated clear variability across land uses and depths. At the surface layer (0–5 cm), L5 (orchard) and L3 (forest) showed the highest concentrations of Ca-bound P. The elevated levels in L5 can be attributed to agricultural lime application and organic matter inputs, while in L3, natural cycling of organic matter and limited anthropogenic disturbance likely contributed to the accumulation of Ca-bound P. L2 (crop land) and L4 (grassland) exhibited moderate levels, whereas L1 (bare land) had the lowest concentration, reflecting minimal nutrient input and biological activity (fig. 3).

At the intermediate depth (5–15 cm), a similar pattern persisted, with the highest levels of Ca-bound P observed in L3 (forest) and L5 (orchard). The persistence of high Ca-bound P levels at this depth in L5 may indicate leaching from the surface, enhanced by liming and irrigation practices. L2 (crop land) also showed substantial Ca-bound P levels, likely due to fertilizer inputs containing P minerals like apatite. In contrast, L1 (bare land) consistently displayed the lowest levels across depths, underscoring the lack of P inputs and limited capacity for P retention.

In the subsurface layer (15–30 cm), the differences between land use types became less pronounced, although L3 (forest) and L5 (orchard) continued to exhibit slightly higher levels than the other land uses. The attenuation of P concentrations with depth in all land uses suggests a gradual decrease in P availability due to reduced biological activity and precipitation reactions forming stable P complexes in deeper soil layers. These findings align with previous studies, which report higher Ca-bound P levels in agricultural and managed lands due to fertilization and liming (Rashmi et al., 2021). Similarly, natural ecosystems like forests and grasslands often exhibit moderate to high Ca-bound P concentrations due to organic matter cycling and the natural weathering of parent material (Xie et al., 2019). In contrast, bare land consistently exhibits lower P levels, emphasizing the role of vegetation and management in maintaining soil fertility.

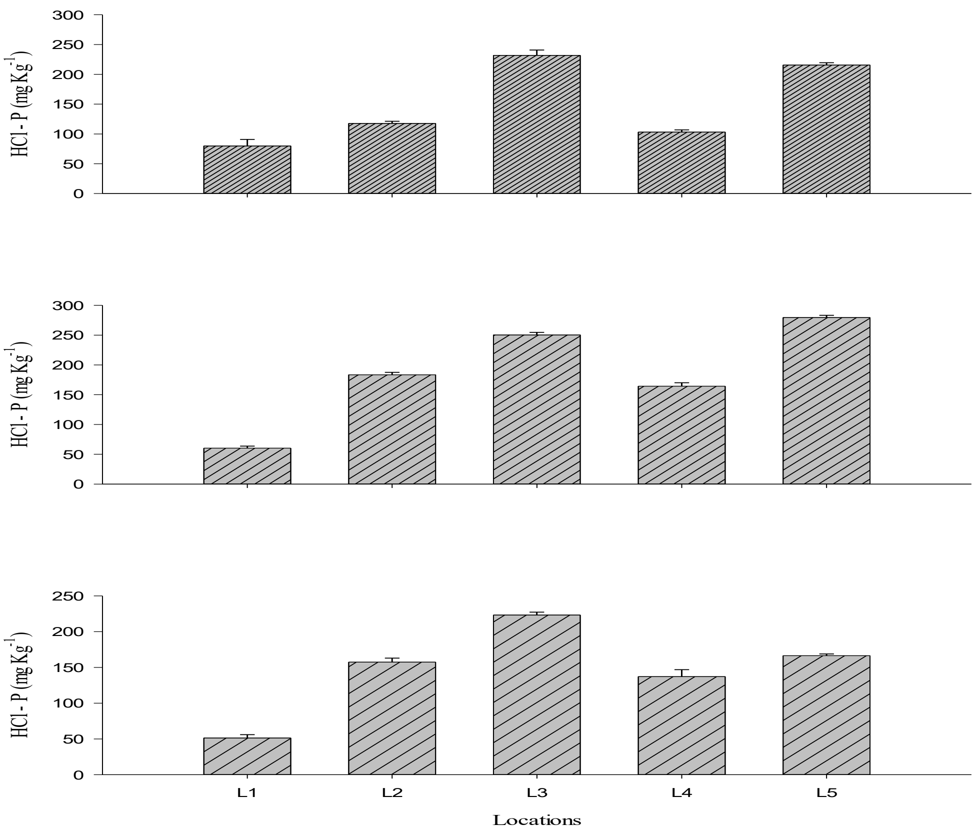

Figure 0.3: Variations in HCl fraction for all five sites where L1=Bare Land, L2=Crop Land, L3=Forest, L4=Grass Land and L5=Orchard. The figure from above to lower shows the three depths (0 – 5, 5 – 15 and 15 – 30 cm).

Residual P

Residual P showed significant variation across land use types and depths, reflecting differences in P stabilization mechanisms and long-term soil management practices. At the surface depth (0–5 cm), residual P concentrations were highest in L5 (orchard) and L2 (crop land), likely due to the accumulation of fertilizer-derived P that has undergone gradual conversion into less labile forms through adsorption and precipitation reactions. L3 (forest) and L4 (grassland) displayed moderate levels of residual P, which can be attributed to natural cycling of organic and slow weathering processes. Bare land (L1) consistently recorded the lowest residual P, reflecting limited P inputs and the absence of vegetation to mediate P stabilization (fig. 4).

At the intermediate depth (5–15 cm), a similar trend was observed, with L5 (orchard) maintaining the highest residual P levels, followed by L2 (crop land). The movement of P downward into this layer is likely driven by leaching and incorporation of surface-applied P into deeper soil horizons. L3 (forest) and L4 (grassland) also exhibited moderate levels, consistent with the contributions of litter decomposition and natural mineralization processes. Bare land (L1) again showed the lowest residual P content, reinforcing the influence of vegetation and management in P dynamics.

In the subsurface layer (15–30 cm), residual P concentrations in L5 (orchard) were markedly higher than in the other land use types. This reflects the cumulative effects of long-term fertilization and irrigation, which facilitate the conversion of labile P into stable residual forms. The levels in L3 (forest) and L4 (grassland) were relatively consistent with the intermediate depth, suggesting minimal redistribution of P in unmanaged ecosystems. Bare land (L1) remained the lowest across all depths, indicating limited P transformation processes. These results align with previous studies highlight that residual P accumulates over time in soils with repeated fertilizer applications (Tang et al., 2020). Similarly, ecosystems with organic matter inputs, such as forests and grasslands, tend to have moderate residual P levels due to slower transformation rates (Chen et al., 2018). Bare land, with its lack of biological activity and inputs, typically exhibits lower residual P levels.

The findings underscore the importance of sustainable management practices in agricultural systems to optimize P utilization and minimize the build-up of residual P, which is largely unavailable for plant uptake. In natural ecosystems, the balance between organic matter inputs and mineral weathering processes plays a crucial role in determining residual P levels.

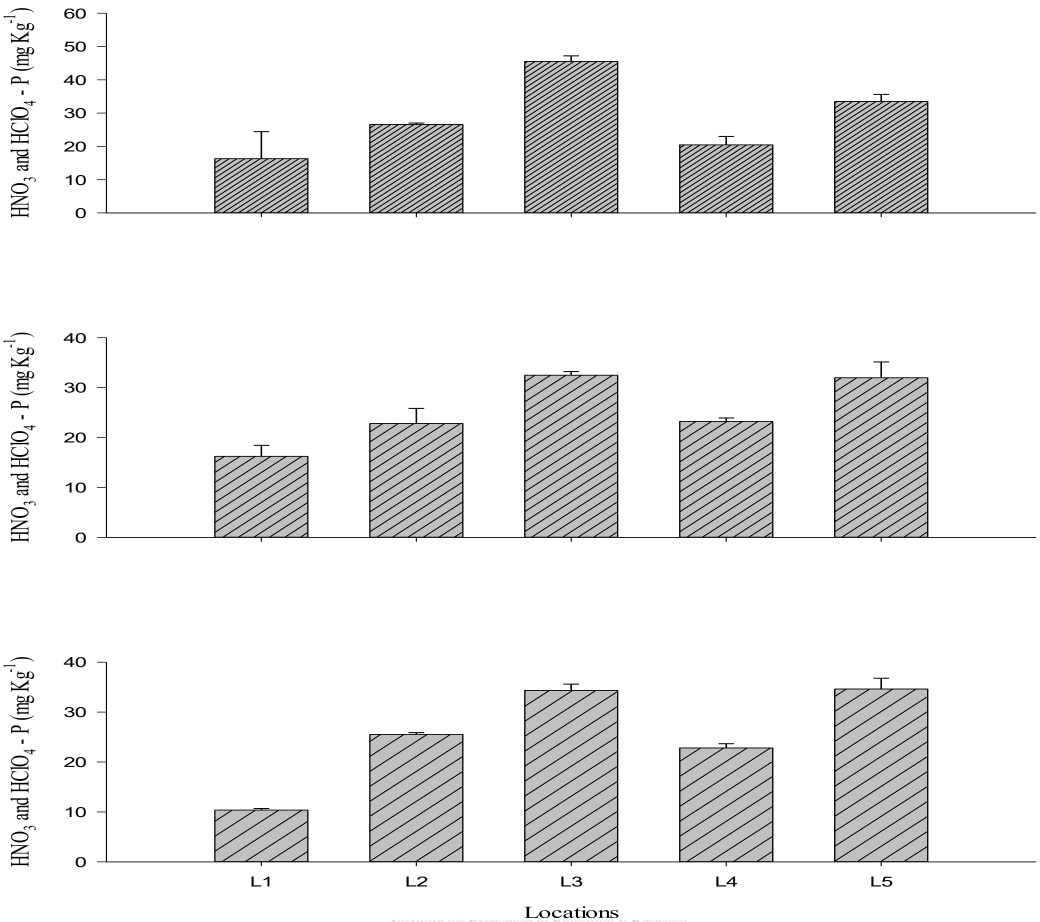

Figure 4.4Variations in HNO3 and HClO4 fraction for all five sites where L1=Bare Land, L2=Crop Land, L3=Forest, L4=Grass Land and L5=Orchard. The figure from above to lower shows the three depths (0 – 5, 5 – 15 and 15 – 30 cm).

Conclusion

highlights the significant influence of land use and soil depth on the distribution of various phosphorus (P) fractions, including soluble and exchangeable P (labile P), Fe and Al-bound P (moderately labile P), Ca-bound P (moderately labile inorganic P), and residual P (highly stable P). Labile P was highest in crop land (L2) and orchard (L5) soils at the surface layer, driven by fertilization and organic inputs, while bare land (L1) consistently exhibited the lowest levels due to limited P inputs and vegetation. Moderately labile P, extracted as Fe and Al-bound and Ca-bound fractions, was similarly elevated in managed lands like orchards and crop lands, indicating the influence of agricultural practices such as liming and organic amendments. In contrast, forest (L3) and grassland (L4) soils showed moderate P levels, reflecting the role of natural organic matter cycling. Residual P, representing the most stable form, accumulated most in orchard (L5) and crop land (L2), driven by long-term transformations of added P into recalcitrant forms, while bare land (L1) consistently displayed the lowest concentrations. Across all fractions, P availability declined in depth, underscoring the role of surface inputs and biological activity in P cycling. These findings emphasize the need for sustainable land management practices to enhance P availability, minimize environmental risks, and improve soil fertility, particularly in agricultural and degraded systems.

Recommendations

- Fertilization practices should be optimized to minimize excessive P inputs, which can lead to environmental risks and decreased P availability.
- Organic amendments, such as compost or manure, can enhance P availability and reduce the need for synthetic fertilizers.
- Conservation tillage practices can reduce soil disturbance, promote soil organic matter accumulation, and enhance P cycling.
- Degraded lands, such as bare lands, should be restored through afforestation or re-vegetation efforts to enhance soil fertility and P cycling.
- Agroforestry practices can enhance soil organic matter accumulation, reduce soil erosion, and promote P cycling.
- Strategies should be implemented to minimize P losses through erosion, leaching, or runoff, which can lead to environmental risks.
- Regular monitoring of P levels in soils and water bodies is essential to detect potential environmental risks and take corrective measures.
- Further research is needed to investigate P cycling mechanisms in different land use systems and soil types.
- Research should focus on developing sustainable P management practices that enhance availability, minimize environmental risks, and improve soil fertility.
- Policy frameworks should be developed to promote sustainable P management practices and minimize environmental risks

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