Effect of long-term restoration on soil phosphorus transformation and desorption in the semi-arid degraded land, India postprint

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Abstract

Understanding how different vegetation-based restoration practices alter soil chemical and microbial characteristics is crucial, as restoration practices influence phosphorus (P) transformation and fractions and modify P adsorption behavior during the restoration process of degraded land. This study investigated the impacts of vegetation-based restoration practices on soil chemical and microbial parameters, P fractions, and patterns of P adsorption and desorption, and highlighted the combined influence on P availability. To evaluate the impact of vegetation-based restoration practices on P fractions and adsorption behavior in the semi-arid degraded land in India, this study compared three distinct tree-based restoration systems, including Leucaena leucocephala (Lam.) de Wit-based silviculture system (SCS), Acacia nilotica (L.) Willd. ex Delile-based silvopasture system (SPS), and Emblica officinalis Gaertn-based hortipasture system (HPS), with a natural grassland system (NGS) and a degraded fallow system (FS) as control. The soil samples across various soil depths (0-15, 15-30, and 30-45 cm) were collected. The findings demonstrated that SCS, SPS, and HPS significantly improved soil organic carbon (SOC) and nutrient availability. Moreover, SCS and SPS resulted in increased microbial biomass phosphorus (MBP) content and phosphatase enzyme activity. The P fractionation analysis revealed that ferrum-associated phosphorus (Fe-P) was the major P fraction, followed by aluminum-associated phosphorus (Al-P), reflecting the dominance of ferrum (Fe) and aluminum (Al) oxides in the semi-arid degraded land. Compared with FS, vegetation-based restoration practices significantly increased various P fractions across soil depths. Additionally, P adsorption and desorption analysis indicated a lower adsorption capacity in tree-based restoration systems than in FS, with FS soils adsorbing higher P quantities in the adsorption phase but releasing less P during the desorption phase. This study revealed that degraded soils responded positively to ecological restoration in terms of P fraction and desorption behavior, influencing the resupply of P in restoration systems. Consequently, litter rich N-fixing tree-based restoration systems (i.e., SCS and SPS) increased total phosphorus (TP) stock for plants and sustained the potential for long-term P supply in semi-arid ecosystems. With the widespread adoption of restoration practices across degraded landscapes, SCS and SPS would significantly contribute to soil restoration and improve productivity by maintaining the soil P supply in semi-arid ecosystems in India.

Full Text

Preamble

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Effect of Long-Term Restoration on Soil Phosphorus Transformation and Desorption in Semi-Arid Degraded Land, India

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Abstract

Understanding how vegetation-based restoration practices alter soil chemical and microbial characteristics is crucial, as these practices influence phosphorus (P) transformation, modify P fractions, and change adsorption behavior during the restoration of degraded land. This study investigated the impacts of vegetation-based restoration on soil chemical and microbial parameters, P fractions, and P adsorption-desorption patterns, highlighting their combined influence on P availability. To evaluate these effects in semi-arid degraded land in India, we compared three distinct tree-based restoration systems: a *Leucaena leucocephala* (Lam.) de Wit-based silviculture system (SCS), an *Acacia nilotica* (L.) Willd. ex Delile-based silvopasture system (SPS), and an *Emblica officinalis* Gaertn-based hortipasture system (HPS), using a natural grassland system (NGS) and a degraded fallow system (FS) as controls. Soil samples were collected across three depths (0–15, 15–30, and 30–45 cm). The findings demonstrated that SCS, SPS, and HPS significantly improved soil organic carbon (SOC) and nutrient availability. Moreover, SCS and SPS increased microbial biomass phosphorus (MBP) content and phosphatase enzyme activity. Phosphorus fractionation analysis revealed that ferrum-associated phosphorus (Fe-P) was the dominant fraction, followed by aluminum-associated phosphorus (Al-P), reflecting the prevalence of Fe and Al oxides in semi-arid degraded land. Compared with FS, vegetation-based restoration practices significantly increased various P fractions across all soil depths. Additionally, P adsorption-desorption analysis indicated lower adsorption capacity in tree-based restoration systems than in FS, with FS soils adsorbing more P during the adsorption phase but releasing less during desorption. This study revealed that degraded soils responded positively to ecological restoration in terms of P fractionation and desorption behavior, influencing P resupply in restoration systems. Consequently, litter-rich, N-fixing tree-based restoration systems (i.e., SCS and SPS) increased total phosphorus (TP) stocks for plants and sustained long-term P supply potential in semi-arid ecosystems. With widespread adoption of restoration practices across degraded landscapes, SCS and SPS could significantly contribute to soil restoration and productivity improvement by maintaining soil P supply in India' s semi-arid ecosystems.

Keywords: phosphorus fixation; phosphorus fraction; phosphorus adsorption; phosphorus desorption; land restoration; structural equation model

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Introduction

Land degradation severely limits agricultural productivity and ecosystem sustainability, with approximately 33% of global land degradation causing a 60% decline in ecosystem services (Bardgett et al., 2021). Unsustainable land use, overpopulation, and poor management systems accelerate degradation, leading to biodiversity loss and declining soil productivity. Restoring nutrient cycles, particularly phosphorus (P), is vital for soil health and recovery of degraded ecosystems, as P is often limited due to fixation by metal oxides (Margenot et al., 2016). Large-scale land restoration offers a sustainable solution by reestablishing vegetation, stabilizing soils, and increasing soil fertility, microbial diversity, and productivity (Hu et al., 2022; Neffar et al., 2022). Vegetation recovery improves soil structure, water infiltration, and nutrient cycling through surface litter, root exudates, and rhizodeposition (Bandyopadhyay and Maiti, 2022).

Vegetative ecosystems play a crucial role in P cycling, as deep tree roots absorb inorganic P from lower soil depths and transfer it to the upper layer via leaf litter and rhizodeposition (Schaap et al., 2021). Phosphorus is a critical nutrient for forest productivity in degraded tropical ecosystems (Yang et al., 2021), with deficiency caused by strong adsorption of $H_2PO_4^-$ onto metal oxides (Chakraborty and Prasad, 2023). Vegetative land use can increase P supply by altering P forms, reducing interactions with soil components (Roy et al., 2025), improving soil physical and chemical characteristics (Cui et al., 2019), and increasing microbial functioning (Padalia et al., 2022). Soil enzymatic activities are vital for nutrient cycling and P transformation (Sun et al., 2021), with shifts in plant and microbial communities facilitating better access to inorganic P and mineralization of organic P (Dai et al., 2020). The recycling of organic and inorganic P reduces dependence on external inputs. Afforestation of degraded land can increase topsoil available P (AP), with tree and grass species influencing soil chemistry and metal oxide distribution (Tuyishime et al., 2022). Understanding P transformation and sorption under restoration practices is essential for identifying appropriate vegetation species for degraded lands.

Phosphorus transformation is principally controlled by pH, dissolved oxygen, organic matter, microbial diversity, and metal oxides and hydroxides (Li et al., 2016). Strongly acidic and weathered soils are typically dominated by amorphous and crystalline ferrum (Fe)-aluminum (Al) associated P (Chen et al., 2024). Vegetation impacts soil chemistry by lowering pH and enhancing legacy P release (Jin et al., 2022), while also influencing biological factors such as microbial diversity and phosphatase activity, which affect P mineralization (Fu et al., 2020). Sorption reactions of P are key to environmental P management and occur in two stages: an initial phase dominated by chemical adsorption and a slower phase characterized by incorporation of P into more stable mineral forms (Barrow, 1980). Calcite, silicate clay edges, Fe and Al oxides, and organic matter can alter P adsorption on soil surfaces (Mabagala and Mng' ong' o, 2022). In contrast, P desorption releases immobilized P, making it available for reuse. Both adsorption and desorption mechanisms are crucial in determining P bioavailability.

Phosphorus fractions serve as crucial indicators of ecosystem restoration. Vegetative land systems improve P solubilization and mobilization by altering microbial biomass and phosphatase activity (Roy et al., 2025). Compared with shrubland, natural secondary forests present higher soluble P and organic P contents, indicating the benefits of forest restoration (Fu et al., 2020). Similarly, restoring native woody and perennial plants increases both P concentration and the ratio of organic P to total P (TP) over abandoned exotic grasslands (Zhong et al., 2021). Broad-leaved tree systems moderately elevate labile P over plantation systems (Zhu et al., 2021), and rejuvenated forestry systems outperform pasture systems in terms of labile and moderately labile P (Ferreira et al., 2022). Vegetative cover also increases available phosphorus (AP) levels, reinforcing the positive role of forest restoration (Chen et al., 2021). However, a meta-analysis of 217 studies revealed that afforestation significantly increases carbon (C) and nitrogen (N) stocks by 37% and 28%, respectively, while having no significant effect on TP stock (Luo et al., 2023). According to Yang et al. (2019), organic matter can significantly improve P availability by reducing adsorption sites and promoting release, though some studies reported no direct effect of organic matter on P adsorption (Borggaard et al., 1990; Guan et al., 2006; Yan et al., 2016). These conflicting results likely reflect differences in soil composition, including texture, pH, organic matter composition, and other chemical properties, emphasizing the complexity of P cycling and the need for site-specific management approaches.

Researchers have advanced understanding of P dynamics in restoration ecosystems, highlighting the roles of vegetation, soil properties, and microbial activities. While afforestation increases labile P fractions, it does not significantly increase TP stock, as P is derived solely from parent material and is not atmospherically replenished like C and N. Therefore, assessing whether high-litter and N-fixing tree species can increase soil TP through nutrient pumping, rapid organic matter decomposition, and enhanced microbial activity is crucial. The role of organic matter in P adsorption across soils and the relationships among P fractions, adsorption, and availability remain unclear. This study addressed these research gaps by comparing native N-fixing tree-based restoration systems with fallow land and evaluating impacts on P fractionation, adsorption, and microbial activity. The experimental site, degraded by erosion and extreme climates, is rich in Fe and Al oxides that enhance P fixation (Baradwal et al., 2022). Although silvopastoral land and grassland improve soil quality (Baradwal et al., 2023), their effects on P distribution are poorly understood. Investigating P fractions is crucial for identifying P sources and sinks and guiding efficient P management. A deeper understanding of long-term restoration practices on P transformation and desorption is necessary in semi-arid degraded soils.

With this background, we conducted an experiment in semi-arid degraded land in India under different vegetation-based restoration practices and analyzed soil samples for P fractions, microbial properties, and P adsorption-desorption. This research aims to investigate two issues: (1) how different land restoration measures impact soil P fractions; and (2) whether land restoration practices could alter soil adsorption-desorption behavior and reduce P fixation.

2.1 Study Area

We conducted the study at the institutional farm of the Indian Council of Agricultural Research (ICAR)-Indian Grassland and Fodder Research Institute

(IGFRI) in Jhansi City, Bundelkhand Region, Uttar Pradesh State, India (25°31 11 -25°31 28 N, 78°32 32 -78°32 53 E; 326.4 m a.s.l.). The climate is typically dry, with scorching summers and cold, foggy winters from late November to mid-March. Although annual average precipitation is approximately 841 mm, 90% occurs during the southwest monsoon season (June–September). The dry season extends from October to May with very low precipitation (85 mm). This region often experiences irregular precipitation patterns, resulting in intermittent drought episodes. Air temperature ranges from an average daily maximum of 21.4°C in January to 41.6°C in May, with summer temperatures exceeding 47.8°C. The peak mean daily evaporation rate was recorded in June at 12.7 mm/d. High wind velocities (>8 km/h) from May to July cause significant wind erosion (Baradwal et al., 2023). Annual soil loss ranges from 37.00 to 53.00 Mg/(hm^2 · a) (Baradwal et al., 2023).

The soil belongs to the hypothermic Typic Haplustepts and is yellowish red to dark brown. Geological formations consist of gneisses, granites, ferruginous beds, and intrusions of basic igneous rocks (Baradwal et al., 2022). Nutrient retention and water holding capacity are moderate, with a saturation water holding capacity of 32.50% (Baradwal et al., 2022). Poor soil fertility (soil organic carbon (SOC): 3.49 g/kg; available nitrogen (AN): 82.52 mg/kg, AP: 3.99 mg/kg, and available potassium (AK): 110.34 mg/kg) restricts conventional agriculture and undermines soil productivity (Roy et al., 2025). Soils are also high in Fe and Al oxides, with average concentrations of 70.01 ($±5.52)*and*240.11(±$15.25) g/kg, respectively (Roy et al., 2025).

2.2 Land Restoration System

The tree-based restoration systems were established to rehabilitate degraded lands through sustainable practices, including silviculture system (SCS), silvopasture system (SPS), and hortipasture system (HPS). Native tree seedlings were manually planted after preparing soil by digging holes to support root establishment. Extensive site preparation included debris removal, vegetation clearing, terrain leveling for uneven water distribution, and plowing to improve aeration and root penetration. In addition to the three restoration systems, we included two land systems for comparison: natural grassland system (NGS) as a reference representing natural grassland, and fallow system (FS) as a control representing degraded land. Experimental site selection was based on proper spatial distribution across specific land use systems, avoiding proximity to minimize interactions and allow independent evaluation of each system’ s impact on soil P properties (Table 1).

The SCS consists of *Leucaena leucocephala* (Lam.) de Wit with naturally growing grasses such as *Cenchrus ciliaris* L., *Panicum maximum* Jacq., *Brachiaria decumbens* Stapf, and *Heteropogon contortus* (L.) P. Beauv. ex Roem. & Schult. (Fig. 1 [Figure 1: see original paper]). The SPS consists of *Acacia nilotica* (L.) Willd. ex Delile with sown grasses such as *P. maximum*, *Stylosanthes seabrana* Vogel, and *Chrysopogon fulvus* (Spreng.) Chiov. The HPS consists of *Emblica* *officinalis* Gaertn with sown grasses such as *C. ciliaris*, *P. maximum*, *Pennisetum pedicellatum* Trin., *Cenchrus setigerus* Vahl, and *B. decumbens*.

Tree species for the three restoration practices (*L. leucocephala* for SCS, *A. nilotica* for SPS, and *E. officinalis* for HPS) were selected based on ecological adaptability, environmental benefits, growth performance, and biodiversity. The primary aim was ecological restoration, with no commercial exploitation.

The NGS reference grassland system consists of naturally growing grasses such as *C. ciliaris*, *Celosia argentea* L., *Hyptis suaveolens* (L.) Poit., *Acanthospermum hispidum* DC., and *Eragrostis cilianensis* (All.) Vignolo ex Janch. Indian semi-arid natural grasslands are savanna type (i.e., 10%-20% area covered by scattered trees). Vegetation-based restoration practices were compared with FS, which has similar climate, topography, elevation, and soil origin. The FS plots, undisturbed since 1980, serve as a long-term control for evaluating ecosystem recovery, with no interventions such as fertilization, irrigation, or planting. Natural vegetation in FS is sparse, consisting mainly of hedges and bushes. Therefore, we assumed FS to be devoid of significant vegetation, with no influence on soil P properties, providing a baseline for comparing restoration practice effects on P dynamics. Before restoration, SCS, SPS, HPS, and NGS were identical to FS.

Table 1 Land system in the study area

Note: The soil erosion rate data were referred to Baradwal et al. (2023).

Land system	Coordinate	Year of establishment	Coverage area (hm^2)	Soil erosion rate ($Mg/(hm^2 \cdot a)$)
Silviculture system (SCS)	25°31 12 N, 78°32 35 E			
Silvopasture system (SPS)	25°31 11 N, 78°32 53 E			
Hortipasture system (HPS)	25°31 24 N, 78°32 32 E			
Natural grassland system (NGS)	25°31 28 N, 78°32 51 E			
Fallow system (FS)	25°31 14 N, 78°32 52 E			

Fig. 1 Landscape of land system in the semi-arid area in India. (a) *Leucaena*

leucocephala (Lam.) de Wit based silviculture system (SCS); (b) *Acacia nilotica* (L.) Willd. ex Delile based silvopasture system (SPS); (c) *Emblica officinalis* Gaertn based hortipasture system (HPS); (d) natural grassland system (NGS); (e) fallow system (FS).

2.3 Soil Sampling

In December 2022, we collected soil samples from each land system to assess soil chemical properties and nutrient dynamics at three depths: 0–15, 15–30, and 30–45 cm. Each plot was subdivided into 8 subplots (30.0 m × 30.0 m), spaced 50.0 m apart to reduce spatial bias. We collected 8 replicates at each depth interval within each plot to ensure robust representation and minimize variability, totaling 120 soil samples. Each replicate was collected from each subplot. Sampling points were selected based on soil homogeneity, slope, and tree density (considering tree density for the three tree-based restoration systems SCS, SPS, and HPS). Each sample was separated into two subsets: one subset was air-dried, pulverized, and sieved (2 mm) for chemical analysis, and the other was refrigerated at 4.0°C for microbial biomass and enzymatic activity assessment.

2.4 Soil Chemical and Microbial Properties

We determined soil pH using a 0.010 M $CaCl_2$ suspension measured with a Systronics 361 pH meter (Systronics, Ahmedabad, India) (Schofield and Taylor, 1955). Electrical conductivity (EC) was measured in a 1:2.5 soil-to-water ratio supernatant using a Systronics 306 digital EC meter (Systronics, Ahmedabad, India) (Jackson, 1973). Soil organic carbon (SOC) was estimated using the Walkley and Black (1934) method, where $K_2Cr_2O_7$ oxidizes SOC in the presence of concentrated H_2SO_4, and unreacted dichromate is titrated with ferrous ammonium sulfate (FAS) to determine SOC content. Available nitrogen (AN) was determined by extracting NO_3^- + NH_4^+ ions using a KCl solution (Jackson, 1973). Available potassium (AK) was extracted with 1.000 M ammonium acetate (pH = 7.00), shaken, filtered, and analyzed with a Systronics 128 flame photometer (Systronics, Ahmedabad, India) (Hanway and Heidel, 1952).

Dehydrogenase (DHA) activity was measured by incubating 1.0 g of soil with 2,3,5-triphenyltetrazolium chloride (TTC) and glucose solutions at 27.0°C for 24 h, followed by methanol extraction and absorbance measurement at 485 nm with a Systronics 167 spectrophotometer (Systronics, Ahmedabad, India) (Casida et al., 1964). Acid phosphatase (ACP) and alkaline phosphatase (ALP) activities were determined by incubating 1.0 g of soil with nitrophenol phosphate in Modified Universal Buffer (MUB) at pH = 6.50 and 11.00, respectively, at 37.0°C for 1 h. After incubation, 0.500 M $CaCl_2$ and 0.500 M NaOH were added, and absorbance was measured at 440 nm (Tabatabai, 1994). Microbial biomass carbon (MBC) was measured by fumigating one set of 10.0 g soil samples with chloroform and extracting fumigated and unfumigated sets with 0.500 M K_2SO_4. Extracts were digested with concentrated H_2SO_4 in the presence of $K_2Cr_2O_7$, and unreacted $K_2Cr_2O_7$ was titrated with 0.005 M FAS. The MBC extraction efficiency of K_2SO_4 was accounted for using a correction factor of 0.45 (Vance et al., 1987). Microbial biomass phosphorus (MBP) was determined by fumigating one set of 10.0 g soil samples with chloroform and extracting both fumigated and unfumigated sets using 0.500 M $NaHCO_3$ at pH = 8.50. The MBP extraction efficiency of $NaHCO_3$ was accounted for using a correction factor of 0.40 (Brookes et al., 1982). MBP absorbance was measured at 730 nm with a Systronics 167 spectrophotometer.

2.5 P Fraction

This study employed the sequential inorganic P fractionation scheme (Kuo, 1996), which includes soluble and loosely bound phosphorus (Sal-P), Al-associated phosphorus (Al-P), Fe-associated phosphorus (Fe-P), Ca-associated phosphorus (Ca-P), and reductant soluble phosphorus (Res-P) (Table 2). This scheme was chosen for its efficiency and suitability for semi-arid soils in the study area, where P availability is severely influenced by Fe and Al oxides. This method effectively separates Fe-P and Al-P, which serve as critical indicators of P cycling in degraded and restored ecosystems. Total phosphorus (TP) was estimated using the microwave digestion method (Page et al., 1982). Organic P was determined by subtracting combined inorganic P fractions from TP content (Zhang and Kovar, 2009). Available phosphorus (AP) was measured using the Bray and Kurtz (1945) method, which involves acid fluoride extraction (0.030 M NH_4F in 0.025 M HCl) to release P from soil. P concentration in the extract was measured at 730 nm using a Systronics 167 spectrophotometer (Murphy and Riley, 1962).

Table 2 Phosphorus (P) fractionation scheme used by this study

P fraction	Extractant	Condition
Soluble phosphorus (Sal-P)	0.250 M H_2SO_4	Shake for 30 min and centrifuge at 10,000 r/min
Aluminum-associated phosphorus (Al-P)	1.000 M $NaHCO_3$, and 0.5 g $Na_2S_2O_4$	Shake for 17 h, centrifuge at 10,000 r/min, and wash with saturated NaCl
Ferrum-associated phosphorus (Fe-P)		Shake for 1 h, centrifuge at 10,000 r/min, and wash with saturated NaCl
Calcium-associated phosphorus (Ca-P)		Shake for 1 h, centrifuge at 10,000 r/min, and wash with saturated NaCl

P fraction	Extractant	Condition
Reductant soluble phosphorus (Res-P)		Water bath, stir, heat at 80°C, centrifuge at 10,000 r/min, and wash with saturated NaCl

2.6 P Adsorption

We selected soil samples from the 0–15 cm layer of each land system for P adsorption and desorption research, as this layer is the most active zone for nutrient cycling where the majority of root activity and microbial processes occur (Roy et al., 2025). Deeper layers (15–30 and 30–45 cm) are generally less involved in P sorption processes, as they are outside the primary zone of root interference and biological activity.

In the P adsorption experiment, 3.0 g of soil was added to 50 mL centrifuge tubes with a solution of 0.010 M $CaCl_2$ and varying P concentrations (5, 10, 20, 30, 40, 50, 60, and 80 mg/L) plus two drops of toluene to achieve a 1:10 soil-to-solution ratio. Tubes were shaken for 24 h at 25.0°C and centrifuged at 10,000 r/min for 10 min. Then, 25 mL of supernatant was transferred for P analysis using the ascorbic acid method with a Systronics 167 spectrophotometer at 730 nm (Murphy and Riley, 1962). P adsorbed by soil was calculated by subtracting remaining P in the equilibrium solution from the initial amount added. To evaluate P adsorption characteristics, we applied two isotherm models. The Langmuir model assumes monolayer adsorption on a finite number of homogeneous sites, making it useful for estimating maximum adsorption capacity. The Freundlich model is empirical and better suited for heterogeneous surfaces with variable adsorption energies.

The Langmuir linear equation can be expressed mathematically as (Langmuir, 1918):

$$\frac{C}{X} = \frac{1}{b \times k} + \frac{C}{b}$$

where C is the equilibrium phosphorus concentration (mg/L); X is the phosphorus adsorbed per unit mass of soil (μg/g); b is the maximum phosphorus adsorption capacity (μg/g); k is the phosphorus binding affinity (mL/μg); and y is the maximum phosphorus buffering capacity (mL/g).

The Freundlich linear equation can be represented mathematically as (Freundlich, 1907):

$$\log(X) = \log(a) + \frac{1}{n} \times \log(C)$$

where a is the number of phosphorus adsorption sites; and n is the phosphorus bonding energy.

2.7 P Desorption

For the desorption study, soil samples previously equilibrated with the highest P concentration from the adsorption study (80 mg/L) were used to examine P release. The process began by decanting 25 mL of supernatant and replacing it with 0.010 M $CaCl_2$ solution to simulate natural soil solution conditions. Centrifuge tubes were shaken for 6 h and centrifuged at 10,000 r/min for 10 min. Then, 25 mL of supernatant was collected for P analysis. Desorbed P concentration was measured with a Systronics 167 spectrophotometer at 730 nm (Murphy and Riley, 1962). The desorption process was repeated three times, as no significant amount of P was released thereafter (Roy et al., 2025).

The amount of P retained in soil was calculated as:

$$P_r = P_a - P_d$$

where P_r is the amount of P retained in the soil (mg/kg); P_a is the amount of P initially adsorbed during the adsorption phase (mg/kg); and P_d is the amount of P desorbed during the desorption phase (mg/kg).

2.8 Measurement of Aboveground Biomass, Litterfall, and Root Biomass

Aboveground biomass in tree-based restoration systems (SCS, SPS, and HPS) was estimated non-destructively using allometric equations. Tree height and diameter at breast height were measured for all individuals within randomly selected subplots (Chave et al., 2014). In other land systems (NGS and FS), aboveground biomass was estimated by clipping all herbaceous vegetation within 1 m^2 quadrats and oven-drying samples at 65°C to constant weight (Anderson and Ingram, 1993). Litterfall was collected using litter traps (0.5 m × 0.5 m) placed randomly within each subplot and oven-dried at 60°C (Hairiah et al., 2001). Traps were emptied monthly over a 12-month period. Root biomass was determined by extracting soil cores using a 10 cm diameter soil sampler (Precision Balance, Kolkata, India). After sieving and hand-sorting, roots were separated from soil, washed, and oven-dried at 65°C until constant weight (Bohm, 1979; Jackson et al., 1997).

2.9 Statistical Analysis

We evaluated the statistical significance of land restoration system impacts on soil characteristics using one-way analysis of variance (ANOVA) within a randomized block experimental design. Differences among treatments were identified using the Duncan post-hoc test. A structural equation model was adopted to evaluate direct and indirect effects of soil chemical properties, microbial activities, and P adsorption parameters on P dynamics across all land systems. The model included four latent variables: soil chemical properties (pH, EC, SOC, AN, and AK), soil microbial parameters (DHA activity, ACP activity, ALP activity, MBC, and MBP), soil P fractions (Sal-P, Al-P, Fe-P, Res-P, Ca-P, organic P, AP, and TP), and P adsorption properties (maximum phosphorus buffering capacity, number of phosphorus adsorption sites, maximum phosphorus adsorption capacity, phosphorus bonding energy, and phosphorus binding affinity). Path coefficients were estimated using maximum likelihood estimation. All variables were z-standardized (mean = 0.000, standard deviation (SD) = 1.000) prior to analysis to obtain standardized path coefficients. Only paths with $P < 0.05$ were retained in the final model. Model adequacy was evaluated using the ^{2} test, goodness of fit (GIF), and root mean squared error of approximation (RMSEA). The standard for good model fit was set as $P < 0.05$, GIF > 0.90, and RMSEA < 0.080. All statistical analyses were performed using SPSS v.29.0 software (International Business Machines Corporation, Armonk, USA).

3.1 Soil Chemical Properties and Nutrient Availability

Soil pH across different land systems was slightly acidic, ranging between 4.60 and 5.90. Across all depths, pH values for SCS, SPS, and HPS were significantly higher than FS (Table 3). For EC, FS showed lower values than SCS, SPS, HPS, and NGS across all depths. SOC within the 0–15 cm soil layer varied between 1.56 and 9.05 g/kg, decreasing with soil depth. SCS showed 4.50-, 3.29-, and 2.78-fold increases over FS in SOC at 0–15, 15–30, and 30–45 cm depths, respectively. Moreover, SCS showed 99.42%, 91.36%, and 89.56% higher AN than FS at 0–15, 15–30, and 30–45 cm depths, respectively. Meanwhile, SPS showed 85.62%, 91.36%, and 89.62% higher AN than FS at 0–15, 15–30, and 30–45 cm depths, respectively. AK was highest in SCS and lowest in SPS. Both NGS and HPS could not increase AK content over FS at 15-30 and 30–45 cm depths. Nutrient availability was higher at 0–15 cm depth than at 15–45 cm.

Table 3 Impact of land restoration on soil chemical properties

Soil depth	Land system	pH	EC (dS/m)	SOC (g/kg)	AN (mg/kg)	AK (mg/kg)
0-15 cm	SCS	5.74$±0.15a	0.049±0.004a	9.05±0.08a	104.02±10.04a	121.44±15.73a
	SPS	5.57±0.2				

Note: EC, electrical conductivity; SOC, soil organic carbon; AN, available nitrogen; AK, available potassium. Different lowercase letters within the same soil depth indicate statistically significant differences among land systems at P* < 0.05 level. Mean ± standard deviation (SD).*

3.2 Soil Biological Parameters

Microbial parameters showed significant improvement across restoration practices compared with FS (Table 4). Similar to nutrients, biological parameters exhibited highest content or activity at 0–15 cm depth. DHA activity was highest in SCS, followed by SPS, which was statistically similar to HPS and NGS across respective depths. SCS obtained 2.48 and 1.99 times higher DHA activity than FS at 0–15 and 15–30 cm depths, respectively. The lowest DHA activity was observed in FS. For all land systems, ACP activity was higher than ALP activity. ACP activity was highest in SCS, being 3.15-, 4.16-, and 5.91-fold higher than FS at 0–15, 15–30, and 30–45 cm depths, respectively. SCS, SPS, and HPS showed 4.83-, 2.71-, and 2.76-fold increases in ALP activity over FS, respectively, at 0–15 cm depth. SCS, SPS, and HPS showed significant increases in MBC content over FS. At 0–15 cm depth, SCS and SPS obtained 116.69% and 87.94% increments in MBC content over FS, respectively. At 15–30 cm depth, SCS, SPS, and HPS showed 124.38%, 96.49%, and 106.66% increments over FS, respectively. NGS increased MBC content by 59.50% and 59.29% over FS at 0–15 and 15–30 cm depths, respectively. SCS, SPS, and HPS increased MBP content by 98.65%, 84.20%, and 26.19% over FS, respectively, at 0–15 cm depth. The highest MBP content was in SCS, followed by SPS and HPS. HPS and NGS obtained the lowest increment in MBP content, statistically similar to FS.

Table 4 Impact of land restoration practice on soil microbial properties

<table>
<tr><th>Soil depth</th><th>Land system</th><th>DHA activity (g TPF/(g · 24h))</th><th>ACP activity (g PNP/(g · h))</th><th>ALP activity (g PNP/(g · h))</th><th>MBC (mg/kg)</th><th>MBP (mg/kg)</th></tr>
<tr><td>0–15 cm</td><td>SCS</td><td colspan="5">78.42$±3.33a|146.50±1.84a|44.06±7.41a|928.48±24.21a|8.80±0.67a|||SPS|46.33±4.15b|120.35</td></tr>
</table>

Note: DHA, dehydrogenase; ACP, acid phosphatase; ALP, alkaline phosphatase; MBC, microbial biomass carbon; MBP, microbial biomass phosphorus. Mean ± SD. Different lowercase letters within the same soil depth indicate statistically significant differences among land systems at P* < 0.05 level.*

3.3 P Fractions

The proportion of different P fractions under various restoration practices followed this order: Sal-P (16.30%-27.68%) < Org-P (0.35%-0.65%) < Ca-P (17.33%-29.53%) < Fe-P (37.39%-41.79%) < Al-P (4.07%-8.89%) < Res-P (6.46%-9.90%). SCS exhibited 110.16% higher Sal-P than FS at 0–15 cm depth (Fig. 2 [Figure 2: see original paper]). HPS and NGS did not show significant increments in Sal-P compared with FS. The highest Al-P was in SCS, followed by SPS and HPS. SCS exhibited 28.96%, 21.64%, and 11.93% higher Al-P than

FS at 0–15, 15–30, and 30–45 cm depths, respectively. At 0–15 cm depth, SCS, SPS, and HPS exhibited 85.18%, 72.44%, and 48.25% greater Fe-P than FS, respectively. At 15–30 cm depth, SCS, SPS, and HPS contained 66.34%, 41.93%, and 32.49% greater Fe-P than FS, respectively. At 0–15 cm depth, SCS, SPS, and HPS exhibited 31.58%, 30.36%, and 42.34% greater Res-P than FS, respectively. NGS did not demonstrate significant increases in Res-P over FS at any depth. Ca-P content in SCS was 2.99, 3.41, and 3.89 times higher than FS at 0–15, 15–30, and 30–45 cm depths, respectively. A similar pattern was observed for Org-P content. For TP, SCS exhibited significant increases over FS by 95.74%, 65.54%, and 55.19% at 0–15, 15–30, and 30–45 cm depths, respectively. SPS demonstrated 65.28% and 35.16% increases over FS at 0–15 and 15–30 cm depths, respectively. AP was significantly higher in SCS than in NGS and FS within the 0–45 cm depth. SPS and HPS exhibited 1.14 and 1.21 times higher AP than FS at 15–30 cm depth, respectively.

Fig. 2 Impact of different land restoration practices on soil phosphorus (P) fractions at different soil depths. (a) soluble and loosely bound phosphorus (Sal-P); (b) aluminium-associated phosphorus (Al-P); (c) ferrum-associated phosphorus (Fe-P); (d) calcium-associated phosphorus (Ca-P); (e) reductant soluble phosphorus (Res-P); (f) organic P; (g) total phosphorus (TP); (h) available phosphorus (AP). Different lowercase letters within the same soil depth indicate statistically significant differences among land systems at $P < 0.05$ level. Bars represent standard errors.

3.4 P Adsorption

Across all land systems, P adsorption increased with rising added P concentrations, following a typical adsorption pattern (Fig. 3 [Figure 3: see original paper]). FS exhibited the highest P adsorption capacity throughout the entire range of equilibrium concentrations. NGS showed higher P adsorption than tree-based restoration systems. In contrast, SCS consistently showed the lowest P adsorption, while SPS and HPS displayed intermediate levels.

Fig. 3 P adsorption curve under different restoration practices. Bars represent standard errors.

3.4.1 Langmuir Adsorption Parameters

At 0–15 cm depth, FS exhibited the highest maximum phosphorus adsorption capacity (315 µg/g), while SCS exhibited the lowest (190 µg/g) (Table 5). SPS, HPS, and NGS showed non-significant decreases in maximum phosphorus adsorption capacity compared with FS. Specifically, SCS, SPS, HPS, and NGS showed 39.68%, 26.67%, 13.97%, and 6.67% decreases in maximum phosphorus adsorption capacity, respectively, compared with FS. However, all vegetative restoration practices (including NGS) had significantly reduced phosphorus binding affinity compared with FS. A similar pattern was observed for maximum phosphorus buffering capacity. SCS, SPS, HPS, and NGS exhibited 3.51, 2.16, 1.99, and 2.00 times reduction in maximum phosphorus buffering capacity compared with FS, respectively.

3.4.2 Freundlich Adsorption Parameters

Restoration practices exhibited significant reductions in both Freundlich parameters compared with FS (Table 5). The minimum number of phosphorus adsorption sites was observed in SCS (21). SCS, SPS, HPS, and NGS decreased the number of phosphorus adsorption sites by 66.67%, 53.23%, 45.16%, and 41.94% compared with FS, respectively. For phosphorus bonding energy, SCS, SPS, HPS, and NGS decreased by 19.75%, 18.52%, 17.28%, and 16.05% compared with FS, respectively.

Table 5 Langmuir and Freundlich adsorption parameters for different land systems

Land system	Langmuir adsorption parameter			Freundlich adsorption parameter	
	b (μg/g)	*k* (mL/μg)	*y* (mL/g)	*a*	*n*
SCS	190±10*b*	0.069±0.013*b*	12.9±1.6*b*	21±1*c*	1.95±0.05*b*
SPS	231±21*ab*	0.093±0.013*b*	21.0±1.2*b*	29±	

Note: b, *maximum phosphorus adsorption capacity;* k, *phosphorus binding affinity;* y, *maximum phosphorus buffering capacity;* a, *number of phosphorus adsorption sites;* n, *phosphorus bonding energy. Mean ± SD. Different lowercase letters within the same parameter indicate statistically significant differences among land systems at* P* < 0.05 level.*

3.5 P Desorption

Across all land systems, the highest proportion of P was desorbed during the first desorption stage, with subsequent stages showing progressively lower P desorption (Fig. 4 [Figure 4: see original paper]). The lowest cumulative P desorption was observed in FS, with only 1.95% of adsorbed P released. Cumulative P desorption in SCS, SPS, HPS, and NGS was 14.46%, 10.19%, 7.92%, and 6.81%, respectively.

Fig. 4 P desorption curve under different restoration practices. Bars represent standard errors.

3.6 Aboveground Biomass, Litterfall, and Root Biomass

The highest aboveground biomass was recorded in SCS, followed by HPS and SPS (Table 6). Higher aboveground biomass in tree-based restoration systems compared with NGS and FS might be due to tree species with larger canopy and greater wood biomass. HPS had the highest litterfall, attributed to the combined contribution of horticultural species with high leaf turnover and pasture grasses. SCS had the highest root biomass in the topsoil (0–15 cm), indicating a dense fibrous root network. However, SPS and HPS had relatively higher root biomass in deeper layers (15–45 cm), possibly due to foraging behavior of pasture species and their adaptation to access deeper soil moisture.

Table 6 Aboveground biomass, litterfall, and root biomass in different land systems

Land system	Aboveground biomass (Mg/hm^2)	Litterfall (g/m^2)	Root biomass (g/m^2)		
			0–15 cm	15–30 cm	30–45 cm
SCS	12.53$±1.24*a*	147.44±11.02*b*	84.67±7.22*a*	58.64±5.42*b*	40.33±4.02*c*
SPS	9.89±0.97*b*	126.25±12.6			

Note: Mean ± SD. Different lowercase letters within the same variable indicate statistically significant differences among land systems at P* < 0.05 level.*

3.7 Linking Soil Properties and P Availability via Structural Equation Model

The structural equation model showed good fit (^{2} = 213.17, GIF = 0.92, and RMSEA = 0.068), meeting favorable thresholds. It revealed that soil microbial properties directly and indirectly influenced P bioavailability and significantly impacted the distribution of various P fractions (Fig. 5 [Figure 5: see original paper]). Microbial characteristics enhanced organic P mineralization and inorganic P solubilization, thereby increasing soluble P. Soluble P forms subsequently interacted with Fe and Al ions to form moderately available inorganic P fractions, maintaining equilibrium with Sal-P and ensuring long-term P supply. P adsorption and desorption properties showed an inverse relationship with both P fractions and bioavailability. Declines in binding affinity, adsorption capacity, number of adsorption sites, and maximum buffering capacity created conditions favoring P availability. Evidence for enhanced P availability was further supported by litterfall and root biomass data from restoration practices. Litter inputs enriched soil with organic substrates that promoted microbial activity and organic P breakdown, while rhizodeposition from root biomass enhanced rhizosphere nutrient richness, fostering microbial P solubilization.

Fig. 5 Structural equation model illustrating the influence of microbial, soil chemical, and P adsorption properties on soil P fraction distribution and P availability. Numbers in frames represent the proportion of variance explained for respective latent variables; numbers above arrows represent z-standardized path coefficients, where positive numbers indicate positive relationships and negative numbers indicate negative relationships. , P* < 0.05 level.

4.1 Effects of Different Land Systems on Soil Chemical Properties and Nutrient Availability

Soil pH decreased in FS due to leaching of base-forming cations beyond sampled depths and drainage into streams by accelerated erosion (Yegna et al., 2024). In contrast, gradual base release and deposition over time in tree- and grass-based restoration systems increased pH (Nyameasem et al., 2020). Higher pH values might reduce P fixation by preventing development of insoluble P compounds in Fe and Al oxide-rich soils (Johan et al., 2021). Slightly acidic to neutral pH could support microbial activity and phosphatase production, enhancing organic P mineralization. Conversely, low microbial activity and enzyme efficiency in acidic FS could restrict P cycling. Thus, land restoration systems that improved pH could minimize P fixation and support microbial-driven P turnover. Furthermore, restoration systems showed higher EC than FS due to soil organic matter (SOM) mineralization (Meena et al., 2023). Tree-based restoration systems had more litterfall and denser rhizosphere networks, promoting SOC buildup (Berhongaray et al., 2019). SCS showed the highest SOC due to greater rhizodeposition, litter, and root biomass. Higher SOC in restoration systems was attributed to organic matter inputs that stabilize C (Singhal et al., 2025). Restoration practices promoted microbial activity, forming recalcitrant C and microbial organic matter while interactions with clay further protected SOC (Roy et al., 2025). Additionally, SOM boosted AP content by gradually releasing P via microbial mineralization. Leaf litter decomposition also increased bioavailable N (Yan et al., 2022). SCS and SPS contributed biologically fixed N in the root zone (Smercina et al., 2019). Higher N availability promoted microbial activity, facilitating P mineralization and solubilization (Luo et al., 2020). AK decreased across soil depth under restoration practices, possibly due to uptake from deeper depths and return via litterfall (Kaur et al., 2021; Phillips and Courtney, 2022).

4.2 Impact of Restoration Practices on Soil Microbial Properties

DHA activity was higher in SCS than in FS, likely due to higher organic substrate availability (Li et al., 2024), consistent with previous findings from Meena and Rao (2021) showing higher DHA activity in forest soil than agricultural soil under semi-arid climate. N-rich leaf litter in SCS and SPS promoted mineralization, stimulating microbial activity (Brkljača et al., 2019). Increased DHA activity contributed to P availability by producing organic acids that increase P desorption and reduce P adsorption. Phosphatase activity (both ACP and ALP) was also higher in tree-based restoration practices than in FS due to greater supply of organic P from leaf litter (Bai et al., 2021). SCS exhibited the highest phosphatase activity because of its extensive root system, mycorrhizal relationships, N fixation capacity, and rapid biomass production (Azene et al., 2023). Phosphatase enzymes could improve P availability by converting organic P into plant-available forms. Increased MBC content in restoration systems was driven by organic matter inputs from diverse tree species through litter breakdown (Agbeshie et al., 2020). MBC, with its rapid turnover, could serve as a nutrient reservoir, releasing P during microbial decomposition. Previous studies reported the highest MBC content under mixed forests compared with agricultural and horticultural lands in semi-arid areas (Kumar et al., 2018; Meena and Rao, 2021). SCS exhibited the highest MBP content, likely associated with increased SOC and TP.

4.3 Impact of Restoration Practices on P Availability

Increased Sal-P in SCS across soil depths compared with FS is likely due to enhanced biological recycling via greater litter input (Wei et al., 2022). Continuous decomposition of organic matter can provide a steady supply of AP. Higher Fe-P and Al-P fractions in tree-based restoration systems were attributed to litterfall, rhizodeposition, and subsequent decomposition, which release Fe^{2+} and Al^{3+} into soil solution (Karadihalli Thammaiah et al., 2023). Increased P availability promoted more interactions with Fe and Al ions, increasing P fractions (Wang et al., 2021). Moderately available fractions (Fe-P and Al-P) serve as long-term P sources through desorption, dissolution, and microbial breakdown. Similarly, Res-P, strongly associated with Fe and Al oxides, increased in restoration systems compared with FS and could be mobilized during wetting events (Martinengo, 2024).

FS exhibited the lowest Ca-P due to low pH and Ca content (Ren et al., 2021). In contrast, tree- and grass-based restoration systems showed higher Ca-P, likely due to reduced leaching from canopy cover and Ca recycling from deeper layers (Velescu et al., 2021). Ca-P, being soluble in acidic conditions under organic matter decomposition, contributes to P supply (Tian et al., 2021). Higher TP in restoration practices might be linked to extensive root networks drawing P from deeper layers and returning it to the surface via rhizodeposition and litterfall. Organic P increased due to inputs from litter and root exudates (Niederberger et al., 2019). Organic P plays a key role in long-term P availability through microbial mineralization (Chen et al., 2020). AP increased under restoration strategies due to organic matter decomposition from leaf litter, root exudates, and rhizodeposition, which release P and organic acids (Ma et al., 2022), solubilization of mineral P (Wang et al., 2023), and overall rise in inorganic and organic P fractions (Zhang et al., 2021).

In vegetation-based restoration practices (including NGS), phosphorus binding affinity declined as SOC increased, indicating weaker P binding (Yang et al., 2019). Maximum phosphorus adsorption capacity declined under restoration practices. This reduction might result from: (1) organic anions from organic matter mineralization competing with P for adsorption sites (Mabagala and Mng' ong' o, 2022); (2) interaction between organic matter and Fe and Al oxides reducing phosphorus binding affinity (Yang et al., 2022); and (3) organic matter forming a surface barrier that inhibits P adsorption (Wang et al., 2023). These changes allowed more P to remain in soil solution. In SCS, significantly lower maximum phosphorus adsorption capacity and phosphorus binding affinity correlated with greater P desorption and soil solution P, improving bioavailability. FS showed higher P adsorption due to higher Fe and Al oxide content (Ayenew et al., 2018). The number of phosphorus adsorption sites decreased with organic matter addition in restoration practices (Yu et al., 2013). Lower values for number of adsorption sites and phosphorus bonding energy in SCS suggested higher desorption potential. Maximum phosphorus buffering capacity, an inverse indicator of P availability, was reduced under vegetation-based restoration practices due to declines in maximum adsorption capacity and binding affinity (Modak et al., 2024). P desorption was limited in FS due to its higher Fe and Al oxide content and lower organic matter content (Roy et al., 2025). In contrast, increased P desorption observed in restoration practices might be due to higher litter and root biomass-derived organic matter and enhanced microbial activity (Wang et al., 2017). Furthermore, restoration practices contained lower amounts of Fe and Al oxides than FS, which helps increase P availability by minimizing fixation (Roy et al., 2025).

5 Conclusions

This study comprehensively evaluated the impact of different restoration practices, particularly N-fixing and high litter-producing tree species, on P dynamics in semi-arid degraded soils of India. The findings demonstrated that tree-based restoration practices, especially SCS and SPS, significantly improved soil P availability by enhancing organic P mineralization and inorganic P solubilization. Implementation of tree-based restoration practices significantly altered P fractions and changed P adsorption behavior, including reduced phosphorus binding affinity, decreased maximum phosphorus adsorption capacity, and lowered number of phosphorus adsorption sites. Tree-based restoration practices can directly influence soil phosphorus availability by altering adsorption-desorption behavior and enhancing microbial-mediated P mineralization in Fe- and Al-rich soils of semi-arid areas in India. By identifying specific tree species (*L. leucocephala* and *A. nilotica*) that promote favorable changes in soil chemical and microbial properties, this study contributes to the design of site-adapted restoration practices. The findings can supplement ongoing global efforts in climate-resilient and sustainable land management in nutrient-limited ecosystems. However, instead of focusing on a specific agroecological zone, further multi-regional research is necessary to test the generality and robustness of restoration practices. Future investigations should adopt an integrated approach combining microbial ecology, biogeochemistry, and restoration science to better understand soil-plant-microbe interactions.

Conflict of Interests

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

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Note: Figure translations are in progress. See original paper for figures.