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Characterizing Vertical Nutrient Heterogeneity and Soil Property Interactions in Agricultural Soils

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Abstract

A study was conducted during 2020-21 at experimental farms of the Department of Soil Science, Chaudhary Charan Singh Haryana Agricultural University, Hisar, where nine pedons were excavated from Typic Haplustepts/Ustochrepts to assess nutrient stratification. Soil samples were collected from distinct horizons and analyzed using standard laboratory methods. The soils were characterized as alluvial, deep, neutral to alkaline, non-saline, with textures ranging from sandy loam to sandy clay loam. Soil organic carbon content ranged from low to medium (0.15 to 0.64%), available nitrogen was low (56.00 to 144.00 kg ha^{-1}), phosphorus was low to medium (4.00 to 12.00 kg ha^{-1}) and potassium varied from medium to high (240.00 to 480.00 kg ha^{-1}). DTPA-extractable micronutrients, zinc, manganese, iron and copper ranged from 0.20 to 1.80 mg kg^{-1}, 0.64 to 3.27 mg kg^{-1}, 0.56 to 4.21 mg kg^{-1} and 0.23 to 0.97 mg kg^{-1}, respectively. A clear decreasing trend in soil organic carbon, nitrogen and phosphorus with depth was observed, whereas potassium and micronutrients displayed irregular vertical patterns, reflecting the influence of soil texture, mineralogy and organic matter. Significant positive correlations among soil organic carbon, macronutrients and selected micronutrients suggested synergistic interactions that enhance nutrient retention and cycling. Principal component analysis revealed five components explaining 77.04% of the total variance, highlighting the key soil properties driving nutrient variability.

Keywords: Vertical distribution, Typic Haplustepts, Soil organic carbon, Micronutrients, Principal component analysis

Introduction

The rapid expansion of the global population has necessitated a proportional increase in agricultural output, intensifying the pressure on finite soil and water resources (Yousif and Ahmed, 2024). Conventional food production systems, characterized by high external input dependence and intensification, have contributed to progressive deterioration of soil quality, thereby constraining productivity and ecosystem functioning (Sheoran *et al*., 2024; Singh *et al*., 2025a). Nutrient depletion from soil is primarily driven by continuous monocropping, excessive tillage, cultivation of high-yielding cultivars, imbalanced fertilization regimes, inadequate return of organic residues, residue burning, erosional losses and inefficient irrigation practices (Yadav *et al*., 2023). This trend underscores the need to better understand the dynamics of nutrient distribution within the soil profile to inform more precise and sustainable nutrient management strategies (Sadiq *et al*., 2025).

Soil organic matter plays a central role in modulating soil fertility, biogeochemical cycling, nutrient retention and microbial activity. It acts as the principal driver of soil aggregation, cation exchange capacity and soil structural stability, thereby exerting a direct influence on nutrient bioavailability, water relations and biological functioning (Kumari *et al*., 2024). Hence, accurate characterization of soil organic carbon (SOC) and related soil properties across depth profiles is indispensable for understanding soil functioning in agricultural landscapes. Evaluations of soil properties are often restricted to the surface (0–15 cm) layer; however, this approach overlooks the functional relevance of subsurface horizons. Root systems of many cultivated crops penetrate beyond the topsoil and depend on deeper horizons to acquire essential nutrients and moisture during critical phenophases (Kishore *et al.*, 2022). Thus, characterization of vertical nutrient stratification provides a more realistic understanding of nutrient availability and crop nutrition (Abd El-Aziz *et al.*, 2024). Vertical gradients of nutrients in soil are shaped by multiple competing processes, including mineral weathering, downward leaching, upward movement through capillary rise, litter deposition and in situ organic matter mineralization (Pattnaik *et al.*, 2023). These processes operate at different temporal and spatial scales, leading to heterogeneous nutrient distributions with depth.

Profiling of soil horizons also provides insight into pedogenic processes, dominant soil-forming factors and potential nutrient constraints (Sharma and Kumar, 2003). Such knowledge is critical for designing interventions such as depth-specific fertilisation, precision placement of amendments and erosion-minimising land management, which collectively optimise nutrient-use efficiency and reduce environmental losses (Vedadri and Naidu, 2018). The vertical interplay between nutrient pools and soil physico-chemical attributes is central to the development of resilient agricultural systems and to ensuring continued productivity under increasing climatic and demographic pressures (Ma *et al.*, 2023; Mengiste *et al.*, 2025). Recognizing the existing knowledge gap linking depth-wise nutrient distribution to fundamental soil properties in cultivated soils, the present study addresses this gap by investigating the vertical stratification of nutrients and their relationship with key soil properties within the experimental soils of Chaudhary Charan Singh Haryana Agricultural University (CCSHAU), Hisar. The findings are expected to provide mechanistic insight into soil–nutrient interactions across the profile, enabling refinement of nutrient-management strategies and contributing to the broader objective of sustaining crop production while conserving soil quality.

Material and Methods

The investigation was carried out during 2020-21 at the Experimental Farm of the Department of Soil Science, CCSHAU, Hisar, situated in the south-western part of Haryana, India (Fig. 1). The farm lies northwest of the CCSHAU main campus along the Hisar–Ludas road, between 29°08′58″ N to 29°09′08″ N latitudes and 75°40′39″ E to 75°41′30″ E longitudes, encompassing approximately 34.1 ha at a mean elevation of ~215 m above mean sea level. Physiographically, the site lies within the Indo-Gangetic Plains and is underlain by Pleistocene alluvium. The terrain is nearly level to very gently sloping, with a gradient of about 1% towards the north. The soils are dominantly classified as Inceptisols (Singh *et al.*, 2025a). Irrigation is supplied through both canal and tube-well sources. Prolonged irrigation has

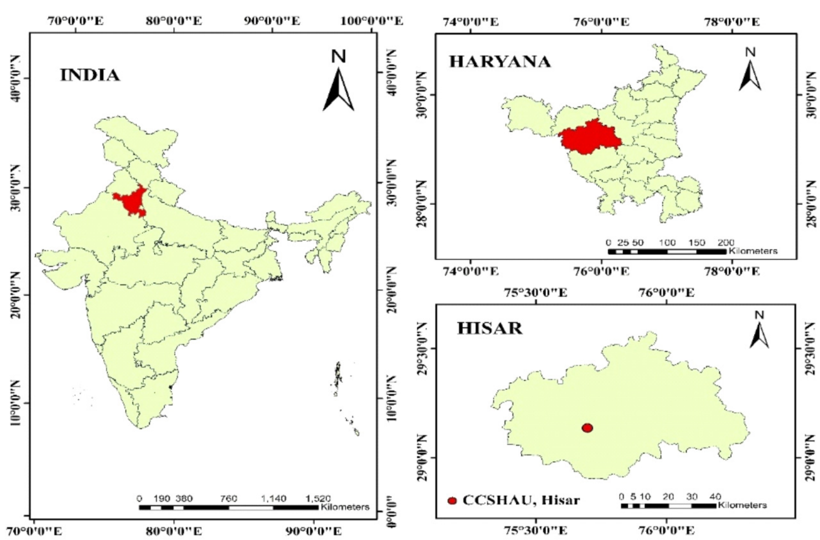

Fig. 1 Location of the study area

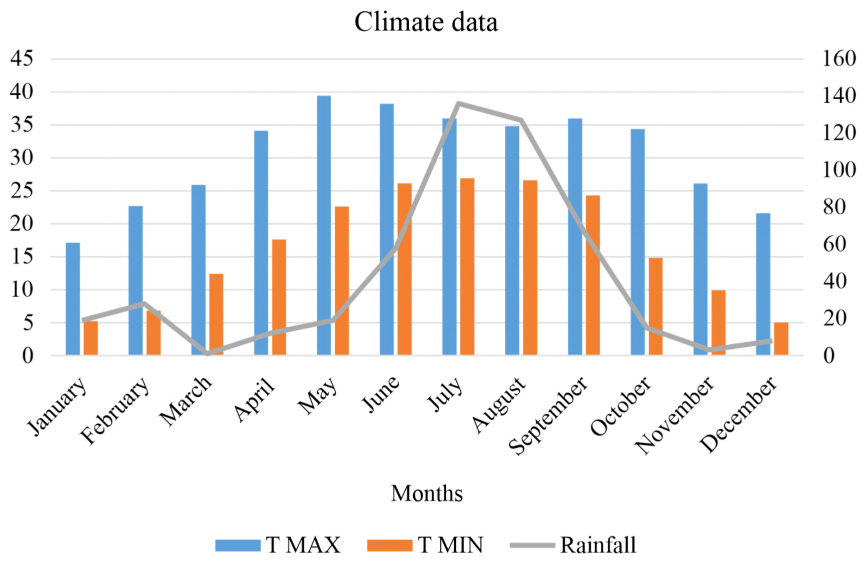

Fig. 2 Mean weather data during the experimental period

raised the groundwater table, which approaches the surface during the monsoon season and remains at ~4–5 m depth for the remainder of the year. Episodic waterlogging and associated salinity are observed in parts of the farm. Climatically, Hisar falls under a semi-arid subtropical monsoonal regime, characterized by prolonged hot summers and cool winters, with marked continentality at the fringe of the southwest monsoon zone. The mean annual rainfall is ~133 mm, while the mean annual and long-term mean average temperatures are 20.8°C and 26.27°C, respectively, placing the soils in the hyperthermic temperature regime (Fig. 2). The climate is predominantly dry, with high thermal amplitude and low precipitation. Natural vegetation is sparse and chiefly comprised of *Acacia nilotica* (Kikar), *Azadirachta indica* (Neem), *Dalbergia sissoo* (Shisham), *Prosopis cineraria* (Jandi), *Eucalyptus tereticornis* (Eucalyptus), *Capparis decidua* (Kair) and *Salvadora persica* (Jaal). Agriculture follows a bi-seasonal cropping pattern: *Kharif* (June-October) and *Rabi* (October-April). Wheat, gram and oilseeds constitute the principal *Rabi* crops, whereas barley, pulses and vegetables are cultivated as minor crops in this season.

To characterize the morphological and physico-chemical properties of the soils, a total of 45 samples were obtained from nine representative soil profiles distributed across distinct geomorphic units within the study area (Fig. 3). Sampling was carried out following a geomorphic-soil association framework to ensure

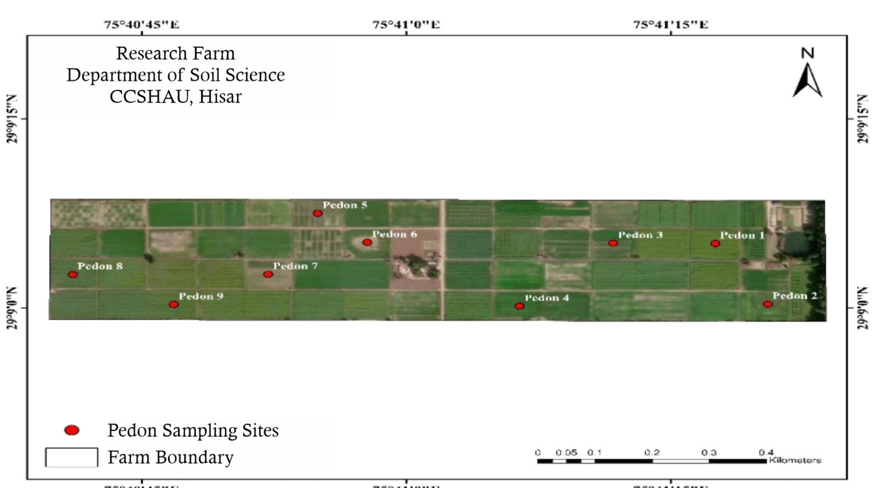

Fig. 3 Sampling sites of pedons

adequate representation of spatial heterogeneity. Morphological attributes including colour, texture, structure, consistency, horizon boundaries and root distribution were recorded in situ for each identified horizon in accordance with the FAO Guidelines for Soil Description (FAO, 1993). Following field characterization, soil samples were air-dried in shade to prevent modification of inherent physical and chemical properties. The dried samples were gently disaggregated with a wooden mortar and pestle and subsequently passed through standard mesh sieves to procure fractions suitable for laboratory analysis. Mechanical analysis (%) was performed using the international pipette method (Piper, 1950). Soil pH (1:2 soil-water) was measured with an Eutech glass-electrode pH 700 meter and electrical conductivity (EC, dS m^{-1}) was determined using an Eutech CON 700 conductivity meter in a 1:2 soil-water suspension (Jackson, 1973). Soil organic carbon (SOC, %) was quantified by the wet oxidation method (Walkley and Black, 1934). Available nitrogen (N, kg ha^{-1}) was estimated by alkaline permanganate oxidation using a Kjeldahl distillation unit (Subbiah and Asija, 1956). Available phosphorus (P, kg ha^{-1}) was determined by UV-Visible spectrophotometry following extraction with 0.5 M $NaHCO_3$ (Olsen *et al.*, 1954). Available potassium (K, kg ha^{-1}) was extracted with neutral normal NH_4OAc and measured using a flame photometer (Jackson, 1973). DTPA-extractable micronutrients [zinc (Zn), manganese (Mn), iron (Fe) and copper (Cu); mg kg^{-1}] were quantified on a Zeenit 700 P Atomic Absorption Spectrophotometer (Analytik Jena) after extraction with DTPA reagent (Lindsay and Norvell, 1978). Calcium carbonate ($CaCO_3$, %) was estimated by the rapid titration method using a hot plate (Puri, 1949). Cation exchange capacity [CEC, cmol (p^+) kg^{-1}] was determined following neutral normal ammonium acetate (NH_4OAc) extraction and quantified using a flame photometer (Hesse, 1971).

Linear relationships among the measured soil properties were quantified using Pearson's correlation coefficient, implemented in RStudio (version 4.4.2). Principal Component Analysis (PCA) was conducted on the correlation matrix of soil variables using OriginPro 2025. To improve clarity and interpretability, Varimax rotation, an orthogonal rotation technique, was applied. This method maximizes the variance explained by each principal component by concentrating high factor loadings on a limited set of variables while minimizing loadings on others, thereby facilitating the identification of coherent groups of strongly correlated soil properties (Verma *et al.*, 2021; Singh *et al.*, 2025b).

Results and Discussion

Table 1 summarizes the physico-chemical characteristics of the analyzed soil pedons. According to the USDA Soil Taxonomy (Soil Survey Staff, 2006, 2014), the soils were classified as Inceptisols with the following designations: coarse loamy, mixed, calcareous, hyperthermic, Typic Haplustepts (Pedon 1); coarse loamy, mixed, hyperthermic, Typic Haplustepts (Pedon 6); fine loamy, mixed, calcareous, hyperthermic, Typic Haplustepts (Pedons 2 and 4); fine loamy, mixed, calcareous, hyperthermic Typic Ustochrepts (Pedon 3); fine loamy, mixed, hyperthermic, Typic Haplustepts (Pedons 5, 7 and 8); and fine loamy, mixed, hyperthermic, Typic Ustochrepts (Pedon 9). Fig. 4 depicts the interrelationships between soil nutrients and selected physico-chemical properties.

Soil physical characteristics

The texture of the studied pedons ranged from sandy loam to sandy clay loam and all soils were derived from alluvial parent material. Pedons 1 and 5 exhibited sandy loam texture throughout the profile, with only a marginal increase in clay content with depth. In contrast, pedons 2, 4, 8 and 9 showed variation in texture, with surface horizons dominated by sandy loam and lower horizons transitioning to sandy clay loam. Pedons 3, 6 and 7 were consistently sandy clay loam throughout the profile, with a slight increase in clay content in subsurface horizons. Across all pedons, sand content ranged from 59.10 to 72.70%, silt from 10.10 to 15.90% and clay from 15.70 to 28.00%. Sand content exhibited significant negative correlations with silt ($r = -0.30$; $p \leq 0.05$) and clay ($r = -0.93$; $p \leq 0.001$). The predominance of sand is attributed to intensive physical weathering of the alluvial parent

Table 1. Physico-chemical parameters of pedons

Horizon	Depth (cm)	Particle size distribution (%)			Texture	pH (1:2)	EC2 (dS m^{-1})	SOC (%)	CEC [cmol (p^+) kg^{-1}]
		Sand	Silt	Clay					
Pedon 1									
Ap	0-19	69.20	12.10	17.70	sl	7.70	0.24	0.64	12.2
A1	19-50	68.50	12.50	19.00	sl	7.90	0.18	0.33	12.9
B1	50-85	71.20	11.80	17.00	sl	8.10	0.19	0.33	11.7
B2	85-135	71.40	11.60	17.00	sl	8.40	0.21	0.30	10.7
B3	135-180+	71.50	11.40	17.10	sl	8.30	0.28	0.15	10.5
Pedon 2									
Ap	0-20	71.50	11.80	17.70	sl	8.00	0.26	0.64	12.20
A1	20-40	61.60	10.40	28.00	scl	8.30	0.16	0.42	13.70
B1	40-58	64.70	11.00	24.30	scl	8.40	0.33	0.32	13.20
B2	58-90	65.60	11.20	18.90	scl	8.10	0.34	0.29	12.30
B3	90-128	69.20	10.10	20.70	scl	8.10	0.24	0.27	12.60
B4	128-160	70.10	12.50	17.40	sl	8.20	0.25	0.26	11.80
C1	160-210+	69.50	12.40	18.10	sl	8.10	0.23	0.17	11.90
Pedon 3									
Ap	0-23	62.60	10.10	27.30	scl	8.20	0.37	0.60	12.90
A1	23-55	63.70	11.20	26.10	scl	8.30	0.30	0.33	12.70
B1	55-125	64.60	11.50	24.90	scl	8.10	0.28	0.22	11.90
B2	125-149	65.20	10.50	24.30	scl	8.10	0.36	0.18	11.80
B3	149-180+	65.10	10.80	23.40	scl	8.20	0.32	0.15	11.80
Pedon 4									
Ap	0-22	71.80	11.00	17.20	sl	8.00	0.31	0.55	11.80
A1	22-50	61.00	12.40	26.60	scl	8.30	0.32	0.33	12.50
B1	50-90	63.50	13.20	23.30	scl	8.20	0.30	0.26	12.00
B2	90-125	64.60	15.90	19.50	scl	8.10	0.34	0.26	11.80
B3	125-160+	68.30	12.60	19.10	scl	8.10	0.30	0.20	11.20
Pedon 5									
Ap	0-15	69.80	12.20	18.00	sl	7.40	0.26	0.58	12.20
A1	15-59	68.20	12.10	19.70	sl	8.00	0.32	0.41	12.80
B1	59-115	70.00	12.80	19.20	sl	8.10	0.24	0.30	12.40
B2	115-145+	69.20	11.90	18.90	sl	7.90	0.24	0.27	11.80
Pedon 6									
Ap	0-16	64.20	13.40	22.40	scl	7.80	0.32	0.62	11.50
A1	16-46	61.20	12.50	26.30	scl	8.00	0.30	0.45	12.80
B1	46-77	60.00	12.90	27.10	scl	8.10	0.28	0.38	13.20
B2	77-130	61.40	13.10	25.50	scl	8.00	0.28	0.28	12.40
B3	130-160+	60.20	13.20	26.60	scl	8.00	0.24	0.26	12.80
Pedon 7									
Ap	0-20	60.60	12.80	26.60	scl	7.60	0.20	0.40	14.20
A1	20-41	59.10	13.20	27.70	scl	8.20	0.16	0.36	14.40
B1	41-80	60.10	12.90	27.00	scl	8.30	0.29	0.34	13.80
B2	80-125	61.00	13.00	26.00	scl	8.20	0.39	0.29	13.50
B3	125-155+	61.70	13.20	25.10	scl	8.10	0.39	0.27	13.20
Pedon 8									
Ap	0-17	69.80	11.40	18.80	sl	6.40	0.13	0.39	11.30
A1	17-52	64.20	12.70	21.30	scl	6.80	0.21	0.28	12.40
B1	52-100	64.00	12.50	23.50	scl	7.80	0.14	0.27	13.10
B2	100-142	65.20	12.90	21.90	scl	7.60	0.17	0.24	12.00
B3	142-170+	65.90	11.80	22.30	scl	7.50	0.09	0.24	12.50
Pedon 9									
Ap	0-18	72.20	12.10	15.70	sl	7.60	0.36	0.51	10.20
A1	18-90	64.10	13.20	22.70	scl	8.10	0.31	0.32	11.50
B1	90-135	63.80	13.40	22.80	scl	8.10	0.28	0.32	12.10
B2	135-172+	64.60	15.90	19.50	scl	8.00	0.26	0.26	10.90

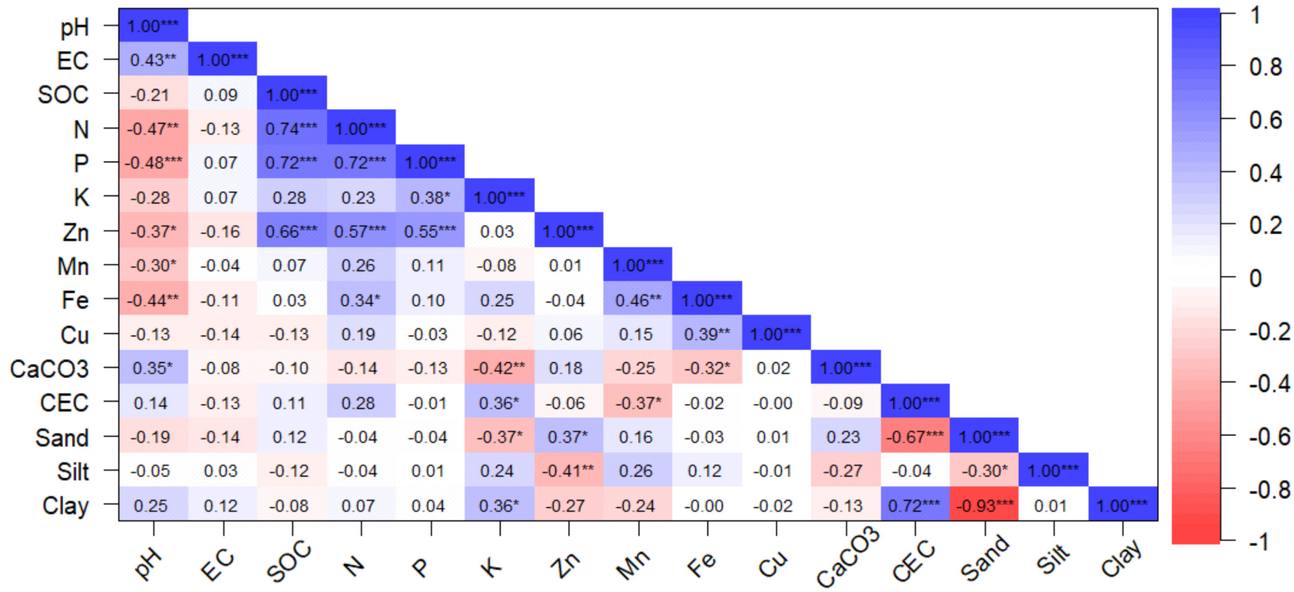

Fig. 4 Correlation between nutrients and physico-chemical parameters; *, **, *** significant at 0.05, 0.01 and 0.001 probability level, respectively

material, which is rich in quartz and other siliceous minerals, combined with limited chemical weathering under semi-arid conditions (Jangir *et al.*, 2020). The increase in clay content with depth is primarily driven by illuviation, a process in which fine clay particles are mobilized from upper horizons via percolating water and accumulate in lower horizons, enhancing subsurface clay enrichment and contributing to horizon development (Nasre *et al.*, 2013). This clay translocation not only modifies the soil texture but also affects water retention, nutrient availability and cation exchange capacity in subsurface horizons, influencing overall soil fertility and plant growth potential (Wakwoya *et al.*, 2023).

Soil fertility characteristics

The soils of the studied pedons were neutral to alkaline, with pH values ranging from 6.40 to 8.40, and non-saline, with EC values between 0.09 and 0.39 dS m^{-1}. Soil pH showed a significant positive correlation with EC ($r = 0.43$; $p \leq 0.01$), suggesting that higher base saturation and exchangeable sodium contribute to elevated alkalinity (Sahoo *et al.*, 2021). Subsurface horizons generally exhibited higher pH values than surface horizons, attributable to greater accumulation of organic matter in the topsoil. Organic matter acts as a buffer, moderating pH by releasing hydrogen ions during decomposition and enhancing the uptake of basic cations by plant roots, thereby reducing their contribution to soil alkalinity (Alnaimy *et al.*, 2023; Singh *et al.*, 2025c). The slightly acidic pH in Pedon 8, despite low organic carbon content, may be due to leaching of basic cations and long-term use of ammoniacal fertilizers, which can contribute to soil acidification independent of SOC levels. A slight salinity gradient was observed with depth, likely resulting from downward leaching of soluble salts from surface horizons by percolating water, followed by their accumulation in lower soil layers (Sashikala *et al.*, 2019). This pattern reflects the interplay between limited rainfall, semi-arid climatic conditions and irrigation practices, which together influence salt mobilization and redistribution within the soil profile, ultimately affecting nutrient availability and soil chemical dynamics (Munny *et al.*, 2021).

SOC content in the studied pedons ranged from 0.15 to 0.64%, exhibiting a low to medium status and decreasing consistently with depth (Fig. 5a). The relatively low SOC, coupled with its decline in subsurface horizons, likely reflects accelerated decomposition and oxidation of organic matter under hyperthermic soil temperature regimes (Kumari *et al.*, 2024). The vertical distribution pattern can be attributed to the higher accumulation of organic inputs, such as plant residues and farmyard manure in the surface horizons, which are directly exposed to litter deposition and root biomass, compared to deeper layers where organic matter input is minimal (Satish *et al.*, 2018). This surface enrichment of SOC not only influences soil structure and aggregate stability but also enhances nutrient retention and microbial activity in the topsoil, underscoring SOC's critical role in maintaining soil fertility and overall ecosystem functioning (Singh *et al.*, 2025c).

$CaCO_3$ content in the studied pedons ranged from 0.00 to 2.30% and exhibited a significant positive correlation with soil pH ($r = 0.35$; $p \leq 0.05$). The gradual accumulation of $CaCO_3$ with depth is likely driven by illuviation, wherein both $CaCO_3$ and clay particles are translocated from upper to lower horizons (Reddy and Naidu, 2016). Additionally, the higher pH conditions in subsurface layers promote the precipitation of $CaCO_3$ from soil solution, a process further enhanced by calcification under semi-arid conditions (Hussain *et al.*, 2019). This vertical enrichment of $CaCO_3$ contributes to increased alkalinity and influences soil structural stability, nutrient availability and cation exchange capacity in the deeper horizons (Singh *et al.*, 2025a). CEC of the studied pedons ranged from 10.50 to 14.40 cmol (p^+) kg^{-1} and exhibited significant positive correlations with clay ($r = 0.72$; $p \leq 0.001$) and potassium ($r = 0.36$; $p \leq 0.05$), while showing a strong negative correlation with sand content ($r = -0.67$; $p \leq 0.001$). The relatively low CEC is primarily attributable to limited clay content, low organic matter, and the predominance of coarse-sand fractions (Gogoi *et al.*, 2022). An irregular CEC gradient was observed across the soil profiles, reflecting heterogeneity in clay mineralogy and organic matter distribution. Lower CEC values may indicate the presence of low-activity clay minerals or a mixed mineralogical composition containing a substantial proportion of minerals with inherently low exchange capacity (Rekwar and Ahmed, 2022). The observed variation is also closely linked to the distribution of soil organic carbon, which generally enhances CEC in surface horizons through plant litter deposition and microbial activity, thereby contributing to higher exchangeable cation retention in topsoil compared to subsoil layers (Nungula *et al.*, 2024).

The soils of the studied pedons were low in available N (56.0 to 144.0 kg ha^{-1}), low to medium in P (4.00 to 12.00 kg ha^{-1}) and medium to high in K (240.0 to 480.0 kg ha^{-1}). Available N and P generally decreased with depth, whereas K exhibited an irregular distribution pattern (Fig. 5). Available N showed significant positive correlations with SOC ($r = 0.74$; $p \leq 0.001$), P ($r = 0.72$; $p \leq 0.001$), Zn ($r = 0.57$; $p \leq 0.001$) and Fe ($r = 0.34$; $p \leq 0.05$), indicating synergistic interactions among these nutrients. Similarly, SOC was strongly positively correlated with P ($r = 0.72$; $p \leq 0.001$), highlighting the role of organic matter in nutrient retention. The decline of N with depth is primarily attributed to decreasing SOC content, as organic carbon serves as the primary source of nitrogen through mineralization (Dinesh *et al.*, 2020; Okolo *et al.*, 2023). P availability also decreased with depth, likely due to increased clay content and the presence of specific clay minerals that promote P fixation, limiting its mobility (Patra *et al.*, 2020; Tian *et al.*, 2021). The positive correlation between P and SOC indicates that higher organic matter enhances P availability, as organic anions can displace $H_2PO_4^-$ from adsorption sites, facilitating mineralization of phosphorus from organic to inorganic forms (Dash *et al.*, 2022). The irregular vertical distribution of K can be attributed to several factors. K availability is influenced by the presence of K-bearing minerals such as mica, illite and feldspar, which release K gradually through weathering and are unevenly distributed across soil horizons (Reza *et al.*, 2014).

Additionally, K is highly mobile in the soil solution and can be leached from sandy or coarse-textured surface horizons while accumulating in clay-rich or finer-textured subsurface layers (Supriya *et al.*, 2019). Conversely, K exhibited a significant negative correlation with sand ($r = 0.37$; $p \leq 0.05$), reflecting the dominance of quartz in the sand fraction, which has negligible K retention capacity (Devi *et al.*, 2015; Sashikala *et al.*, 2019). These interactions among mineralogy, texture and

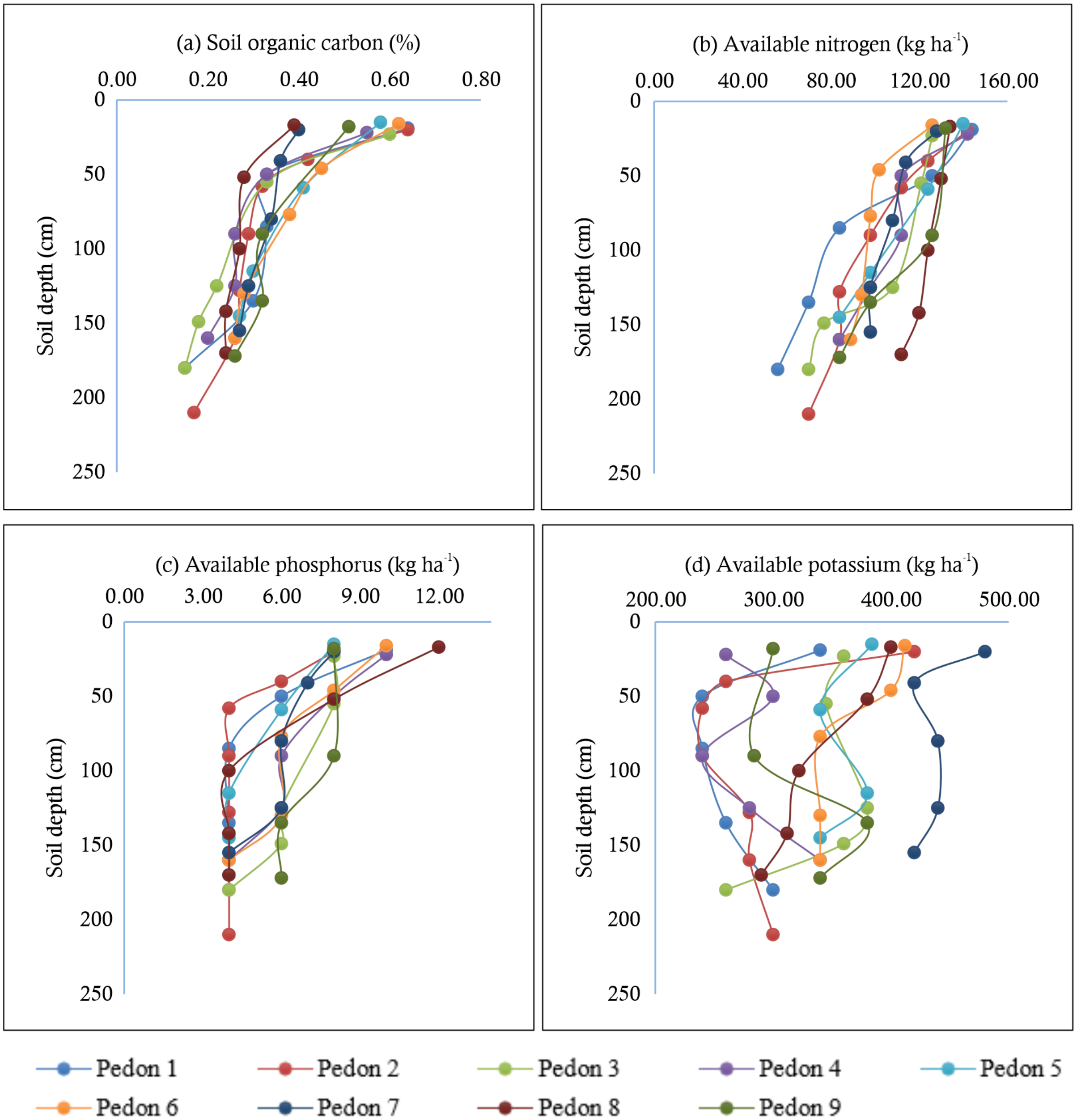

Fig. 5. Vertical distribution of (a) SOC, (b) Nitrogen, (c) Phosphorus and (d) Potassium

leaching dynamics explain the observed irregular pattern of K across soil profiles and underscore the importance of horizon-specific management for optimizing potassium availability (Sahoo *et al.*, 2020).

DTPA-extractable micronutrients in the studied pedons exhibited considerable variability across soil profiles. Concentrations ranged from 0.20 to 1.80 mg kg^{-1} for Zn, 0.64 to 3.27 mg kg^{-1} for Mn, 0.56 to 4.21 mg kg^{-1} for Fe and 0.23 to 0.97 mg kg^{-1} for Cu, reflecting differences in parent material, soil texture and organic matter content. Based on standard nutrient sufficiency criteria, the soils were generally deficient to sufficient in Zn and Mn, deficient in Fe and sufficient in Cu. The vertical distribution of these micronutrients was irregular, with no consistent trend with depth (Fig. 6), highlighting the complex interactions between soil properties, mineral composition and pedogenic processes. Correlation analysis revealed significant positive relationships between Zn and SOC ($r = 0.66$; $p \leq 0.001$), suggesting that higher organic matter enhances Zn retention and availability through the formation of labile

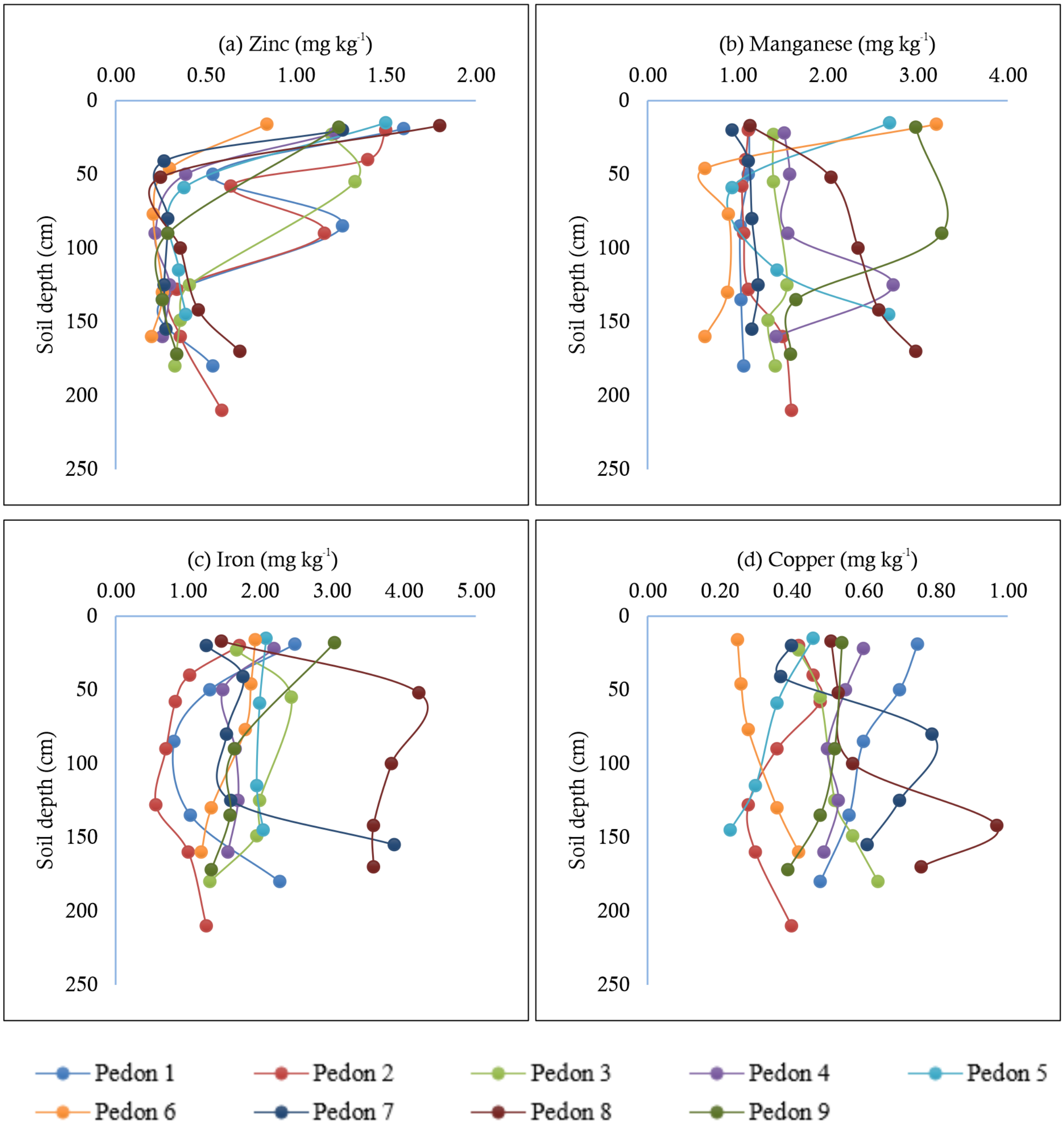

Fig. 6. Vertical distribution of (a) Zinc, (b) Manganese, (c) Iron and (d) Copper

organo-mineral complexes. Mn showed a positive correlation with Fe ($r = 0.46$; $p \leq 0.01$) and Fe and Cu were also positively correlated with each other ($r = 0.39$; $p \leq 0.01$), indicating that similar geochemical and mineralogical controls influence their distribution. In contrast, all four micronutrients showed negative correlations with soil pH, Zn ($r = -0.37$; $p \leq 0.05$), Mn ($r = -0.30$; $p \leq 0.05$), Fe ($r = -0.44$; $p \leq 0.01$) and Cu ($r = -0.13$), reflecting the well-known pH-dependent solubility dynamics of metal cations.

The influence of organic matter on micronutrient availability is multifaceted. Organic matter promotes microbial activity and produces chelating compounds that bind Cu, Fe, and Mn, limiting their immediate mobility while enhancing long-term availability through stable organometallic complexes (Jiao *et al.*, 2021). Similarly, Zn forms labile organo-mineral complexes, which increase its bioavailability in soils with higher SOC (Jain *et al.*, 2023; Saharan *et al.*, 2023). The negative correlation of Fe and

Mn with pH can be explained by chemical transformations in alkaline conditions. In higher pH soils, Fe^{2+} is oxidized to Fe^{3+}, which precipitates as insoluble $Fe(OH)_3$, reducing its bioavailability. Mn^{2+} undergoes a similar process, forming manganic oxides that are largely insoluble and inaccessible to plants (Baruah *et al.*, 2014; Supriya *et al.*, 2019). The observed high Fe and Mn concentrations in some horizons are likely linked to the presence of ferromagnesian minerals in the alluvial parent material, highlighting the influence of mineralogical composition on micronutrient distribution (Sharma *et al.*, 2004). Overall, the distribution and availability of Zn, Mn, Fe and Cu in the pedons are governed by an interplay of soil organic matter, pH, texture, mineral composition and microbial activity. These factors collectively determine the mobility, retention and long-term bioavailability of micronutrients, emphasizing the need for site-specific nutrient management strategies to enhance soil fertility and support optimal plant growth (Singh *et al.*, 2025c).

Principal component analysis

PCA, a multivariate statistical technique, was employed to reduce the dimensionality of the soil dataset and to identify the key factors governing soil variability. Given the presence of statistically significant intercorrelations among measured soil properties, PCA was applied to extract orthogonal latent variables (principal components) that maximize the explained variance. This approach facilitates the identification of the most influential soil properties, thereby informing targeted soil management and fertility improvement strategies. Components with eigenvalues greater than or equal to 1.0 were considered significant (Verma *et al.*, 2021). The first five principal components (PCs) met this criterion, collectively explaining 77.04% of the total variance (Table 2). PC1 accounted for 24.11% of the variance and was primarily associated with pH, SOC, N, P and Zn. PC2 explained 20.77% of the variance and was driven by K, CEC, sand and clay content. PC3 contributed 14.79% of the variance and was predominantly linked with Zn, Mn, Fe, $CaCO_3$ and silt. PC4, accounting for 9.93% of the variance, was strongly influenced by EC and Cu, while PC5 explained 7.43% of the variance and was associated with pH, EC and Cu. Biplot visualization of PC1 and PC2 provides a comprehensive view of the contribution of principal components to the overall variance (Fig. 7). By simultaneously displaying the scores of soil samples on the principal component axes and the

Table 2. Principal component analysis of different soil properties (PC1 to PC5 represent five Principal Components)

Parameters	PC1	PC2	PC3	PC4	PC5
pH	-0.376	0.052	0.234	0.128	0.387
EC	-0.099	0.081	0.086	0.532	0.563
SOC	0.403	0.042	0.281	0.211	0.121
N	0.456	0.113	0.083	-0.110	0.189
P	0.426	0.093	0.151	0.201	0.065
K	0.190	0.355	-0.065	0.195	-0.267
Zn	0.369	-0.160	0.334	-0.102	0.001
Mn	0.182	-0.125	-0.418	0.103	0.280
Fe	0.217	0.060	-0.432	-0.209	0.210
Cu	0.076	-0.036	-0.212	-0.494	0.463
$CaCO_3$	-0.137	-0.215	0.343	-0.237	0.172
CEC	-0.007	0.447	0.188	-0.296	-0.074
Sand	0.098	-0.521	0.026	0.058	-0.103
Silt	-0.029	0.149	-0.380	0.296	-0.090
Clay	-0.093	0.506	0.095	-0.147	0.129
Eigen values	3.617	3.116	2.219	1.490	1.114
Variance (%)	24.11	20.77	14.79	9.93	7.43
Cumulative variance (%)	24.11	44.89	59.68	69.61	77.04

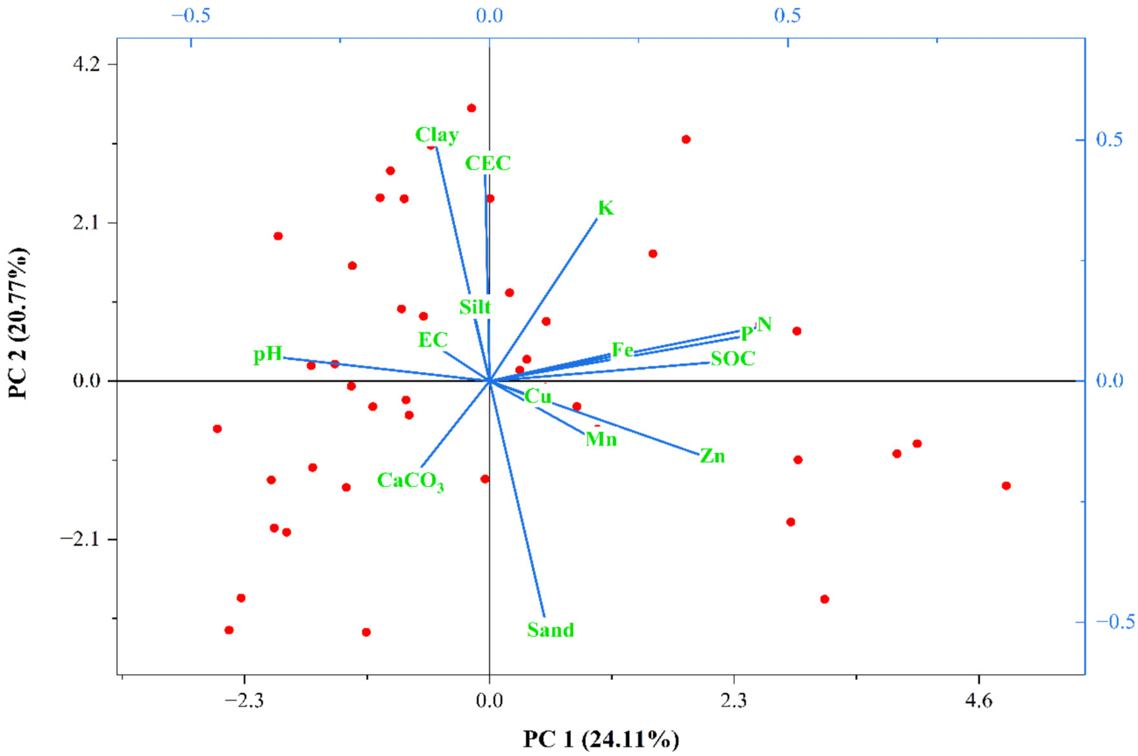

Fig. 7 PCA bi-plot (PC1 vs PC2) of different soil properties

loadings of individual soil properties, biplots elucidate interrelationships among variables and highlight clusters of highly correlated properties. Such graphical representation allows for the identification of soil attributes that exert the greatest influence on overall soil quality, thereby aiding in the development of optimized nutrient management practices and enhancing strategies for soil fertility restoration (Behera *et al.*, 2018; Singh *et al.*, 2025b).

This investigation highlights the intricate and significant interplay between nutrient distribution and key soil properties, emphasizing the critical importance of comprehensive soil characterization as a foundation for optimizing nutrient management and ensuring sustainable crop production. The analysis of the studied pedons revealed that the soils were deep, exhibited minimal to slight erosion and ranged from well to imperfectly drained. Soil reaction varied from neutral to alkaline and the soils were non-saline. Soil organic carbon content was low to medium, reflecting limited organic matter inputs and accelerated decomposition under hyperthermic conditions. Macronutrient availability varied across the profiles, with nitrogen being low, phosphorus ranging from low to medium and potassium ranging from medium to high. Micronutrient assessment indicated that zinc and manganese ranged from deficient to sufficient, iron was deficient and copper remained sufficient across all pedons. A pronounced vertical depletion of soil organic carbon, nitrogen and phosphorus was observed, whereas potassium and micronutrients exhibited irregular depth-wise patterns. These trends suggest a stronger positive correlation between soil organic carbon and macronutrient concentrations compared to micronutrients, highlighting the pivotal role of soil organic carbon in enhancing nutrient retention, availability and cycling through synergistic interactions within the soil matrix. Comprehensive land evaluation identified several pedological constraints limiting soil productivity, including restricted pedogenesis, impeded drainage, low cation exchange capacity and insufficient soil organic carbon stocks. To address these limitations, management strategies that enhance soil organic carbon sequestration are recommended, including cover cropping, incorporation of compost and crop residues and adoption of reduced or conservation tillage practices. Such practices not only improve nutrient retention and cycling but also enhance soil structure, water-holding capacity and overall fertility. Further research is warranted to investigate the spatial variability of nutrient-soil property interactions across diverse landscapes, to elucidate the mechanistic processes underlying nutrient stratification and to assess the long-term effects of organic amendments on nutrient dynamics.

Investigating the influence of specific cover crop species and compost types on nutrient distribution could provide additional insights for refining nutrient management in semi-arid regions. By comprehensively characterizing soils and understanding the complex relationships among nutrients, soil properties and crop growth, targeted nutrient management strategies can be developed that move beyond generalized applications. Such site-specific approaches will optimize crop productivity, improve plant health, enhance soil quality and promote the long-term sustainability and resilience of agroecosystems.

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