



Spatio-temporal dynamics of soil physico-chemical properties in *Quercus* dominated forests of Arunachal Pradesh, Eastern Himalayas

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Background: This study examines the spatiotemporal variability of soil physicochemical properties along an altitudinal gradient and soil depth in natural Oak (*Quercus griffithii* Hook. f. & Thomson ex Miq.)-dominated forest stands in western Arunachal Pradesh. Soil samples were collected from five sites at varying elevations (1,693–1,801 m) across three seasons (winter, summer, and rainy) and three depth intervals (0–10 cm, 10–20 cm, and 20–30 cm). Key soil properties, including bulk density (BD), porosity, water-holding capacity (WHC), soil moisture content (SMC), pH, soil organic carbon (SOC), and nutrient availability (nitrogen [N], phosphorus [P], and potassium [K]), were analyzed.

Results: Soil properties exhibited significant ($p < 0.05$) variation with altitude, season, and depth. BD increased with decreasing altitude and depth, with the lowest elevation site (1,693 m) exhibiting the highest BD (1.30 g cm^{-3}) in deeper soil layers. Conversely, porosity, WHC, and SOC were highest at higher elevations and in the surface soil (0–10 cm), likely due to reduced decomposition rates, greater organic matter accumulation, and improved aeration. SMC was higher at lower elevations and in surface layers, reflecting enhanced moisture retention. Soil pH varied significantly with altitude and depth, with more acidic conditions observed at higher elevations and in surface layers, possibly due to increased organic matter decomposition. Nutrient availability, particularly N and P, was strongly correlated with SOC and pH, with higher concentrations in surface soil at higher elevations. Seasonal variations indicated that SOC and nutrient levels were highest during the rainy season, reflecting increased biological activity. Correlation analysis revealed strong negative relationships between BD and porosity ($r = -0.998$) and positive correlations between SOC, SMC ($r = 0.760$), and available N ($r = 0.671$).

Conclusions: These findings underscore the significant influence of altitude, soil depth, and seasonal dynamics on soil properties, offering valuable insights for sustainable forest management and soil conservation strategies in western Arunachal Pradesh. Given the potential impacts of climate change on forest ecosystems, understanding these soil-environment interactions is critical for maintaining soil health and ecosystem stability.

Keywords: nutrient availability, *Quercus* Forest, spatio-temporal dynamics, soil organic carbon, soil properties

Introduction

Oak (*Quercus griffithii* Hook. f. & Thomson ex Miq.) forests in the Arunachal Pradesh region of the Eastern Himalayas are indeed one of the most ecologically significant areas in the region, owing to their rich biodiversity and critical role in climate regulation. These forests act as substantial C sinks, sequestering large amounts of atmospheric CO₂ and mitigating climate change. The role of these

oak forests extends beyond carbon storage to encompass vital ecological functions such as habitat provision for numerous endemic species, water regulation, and soil conservation. These forest ecosystems are integral to the livelihoods of indigenous communities that depend on resources such as fuelwood, fodder, and medicinal plants.

One of the key factors influencing the health and functionality of these *Quercus*-dominated ecosystems is the

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composition and characteristics of soil. Soil physicochemical properties, including pH, organic matter content, nitrogen (N), phosphorus (P), and potassium (K) levels, texture, and moisture, play pivotal roles in nutrient cycling, water retention, and vegetation dynamics. The interactions between these properties significantly affect plant growth and microbial activity, both of which are essential for maintaining the health of forest ecosystems. For instance, organic matter content is crucial for soil fertility and structure, whereas pH can influence the availability of nutrients to plants.

The variability in these soil properties across different depths and sites within oak forests has significant implications for conservation and sustainable management. Studies have shown that soil properties can vary not only horizontally across forest landscapes, but also vertically with soil depth, impacting root distribution, microbial communities, and water infiltration rates. For example, deeper soils may have different moisture retention capacities and nutrient availability than surface soils, affecting tree species composition and forest resilience. This vertical variation must be accounted for in conservation strategies, particularly in the context of reforestation and afforestation programs, where understanding the nutrient profiles of different soil layers can enhance the success of tree planting.

Moreover, changing climate and increasing anthropogenic pressures, such as deforestation and land-use changes, threaten the integrity of these forests. As climate change alters temperature and precipitation patterns, soil properties are likely to shift, potentially leading to changes in plant species composition and a decline in forest productivity. In this context, it is crucial to develop adaptive management strategies that consider the local variability of soil conditions and promote resilience against climate stressors, while supporting biodiversity conservation.

Studies on soil physicochemical properties in oak forests of the Eastern Himalayas are therefore not only important for understanding the ecosystem's current status but also for informing sustainable management practices. This could include practices such as soil conservation techniques, or-

ganic farming in the surrounding areas, and careful monitoring of nutrient cycles to prevent degradation. Additionally, such research is essential for developing strategies to enhance the carbon sequestration potential of these forests, which could play a key role in global efforts to combat climate change.

The present study aimed to evaluate the variations in soil properties across five oak-dominated forest sites at varying depths in the West Kameng District of Arunachal Pradesh in the Eastern Himalayan region. The insights gained from this analysis can inform conservation efforts and sustainable land management practices in this fragile and important region.

Materials and Methods

Study area

For the present study, five oak-dominated forest plots were randomly selected from Dirang in the west Kameng district of Arunachal Pradesh. All the sampling sites fall under temperate mixed broad-leaved forests with *Quercus griffithii* as dominant tree species. Other oak associated species are: *Acer pectinatum*, *Alnus nepalensis*, *Betula alnoides*, *Castanopsis tribuloides*, *Exbucklandia populnea*, *Ilex dipyrena*, *Michelia* sp., *Lyonia ovalifolia*, and *Pinus wallichiana* (Table 1). The five forest plots are located at Samtu (Site-I), Chug Dung Malyama (Site-II), Laphak (Site-III), Lyaoring (Site-IV) and Changpa (Site-V) under Dirang Circle, West Kameng District in Arunachal Pradesh (Table 1, Fig. 1). The temperature follows a clear seasonal pattern, with the lowest values in January (7.9°C) and the highest in July (22.1°C). Precipitation is lowest in November (2.1 mm) and peaks in June (42.4 mm), indicating a wetter summer and drier winter. The data suggests a monsoon-influenced climate with heavy rainfall from April to October and relatively dry conditions from November to March (Fig. S1).

The effective soil depth for sampling was maintained at 30 cm, considering the active root zone and organic matter-rich horizon. Hence, the soil samples were collected at

Table 1 Geographical locations of selected natural *Quercus* dominated forest stands in western Arunachal Pradesh

Sl. No.	Name of site	Village	Geolocation	Elevation (m)	Other co-dominant species
1.	Site I	Samtu	Lat: 27°27'15"N Long: 92°11'28"E	1,801	<i>Alnus nepalensis</i> , <i>Pinus wallichiana</i>
2.	Site II	Chug Dung Malyama	Lat: 27°24'20"N Long: 92°12'03"E	1,749	<i>Betula alnoides</i> , <i>Exbucklandia populnea</i>
3.	Site III	Laphak	Lat: 27°25'30"N Long: 92°12'17"E	1,720	<i>Castanopsis tribuloides</i> , <i>Ilex dipyrena</i>
4.	Site IV	Lyaoring	Lat: 27°26'19"N Long: 92°13'27"E	1,893	<i>Acer pectinatum</i> , <i>Alnus nepalensis</i>
5.	Site V	Changpa	Lat: 27°23'38"N Long: 92°13'06"E	1,693	<i>Michelia</i> sp., <i>Lyonia ovalifolia</i>

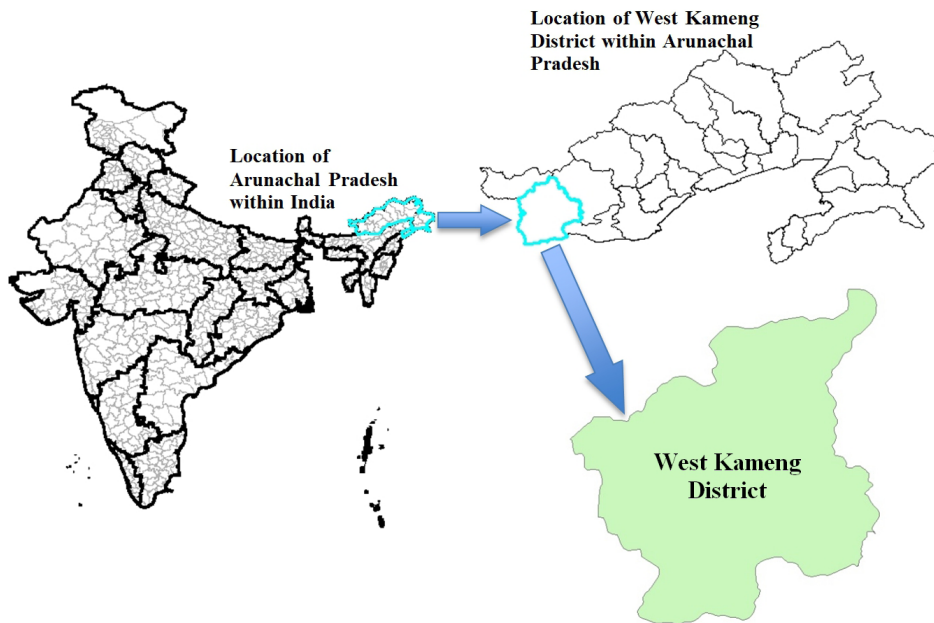


Fig. 1 Maps showing study area – West Kameng District in Arunachal Pradesh.

three different depths: 0–10 cm, 10–20 cm, and 20–30 cm. These depths were selected to capture variations in organic matter content, root activity, and nutrient distribution within the soil profile. While the total soil depth varies among the five study sites, these standardized intervals allow for meaningful comparisons of soil physico-chemical properties across locations.

Soil sampling and analyses

Soil samples were randomly collected from three replicates of each oak forest stand in the West Kameng District of Arunachal Pradesh. Soil samples were collected from 0–10, 10–20 and 20–30 cm depths using a stainless-steel soil auger following standard procedures to minimize contamination and maintain consistency (Blake and Hartge 1986). A composite sampling method was employed, in which three subsamples from random locations in each oak forest plot were combined. The samples were air-dried, sieved through a 2 mm mesh, and stored in airtight containers for subsequent analysis.

The soil moisture content (SMC) was determined gravimetrically by drying fresh samples at 105°C to a constant weight and calculating the difference in weight as a percentage of the dry soil (Gardner 1986). Bulk density (BD) (g cm^{-3}) was determined using the soil core method, in which undisturbed soil core samples were collected using metal cores and dried at 105°C to obtain a constant weight. BD was calculated by dividing the dry mass by the core volume (Grossman and Reinsch 2002). Soil texture was analyzed using the hydrometer method to classify the soil into sand, silt, and clay fractions, following the United States Department of Agriculture classification system (Gee and Or 2002). Porosity was estimated based on the BD and particle density using the standard equation, assuming a par-

ticle density of 2.65 g cm^{-3} . Water holding capacity (WHC) was measured by saturating the soil samples with water and draining them for 24 hours, after which the samples were oven-dried, and the WHC was calculated as the percentage of water retained relative to the dry weight.

Soil pH was measured at a 1:2.5 soil-to-water suspension using a calibrated digital pH meter (McLean 1982). Soil organic carbon (SOC) content was determined using the Walkley-Black method, which oxidizes organic matter using K dichromate, followed by titration with ferrous ammonium sulfate to determine the SOC (Nelson and Sommers 1996). Available N was determined using the alkaline permanganate method, which involves distilling the soil with alkaline K permanganate to release ammonium, followed by quantification (Subbiah and Asija 1956). Available P was measured using the Olsen method, where soil was extracted with sodium bicarbonate and P concentration was determined colorimetrically using molybdenum blue (Olsen et al. 1954). Available K was extracted using ammonium acetate and measured using a flame photometer (Knudsen et al. 1982). All analyses were performed in triplicate and the results were averaged to ensure accuracy and reproducibility. These methods were chosen because of their widespread acceptance and reliability in determining the key soil physical and chemical properties that influence soil fertility and productivity.

Statistical analysis

Statistical analyses were performed using the STATISTICA ver. 12.0 (StatSoft Inc., Tulsa, OK, USA) and OriginPro ver. 2018 (OriginLab Corporation, MA, USA). A three-way analysis of variance (ANOVA) was applied to assess the influence of oak forest stands across elevation, sampling season, and soil depth on soil physicochemical properties.

Pearson's correlation analysis was conducted to assess the significant interrelationships among the soil physicochemical properties.

Results

Spatial (site) variability in soil physico-chemical properties

BD showed a clear increase ($p < 0.05$) with decreasing altitude (Table 2). Site V (1,693 m) had a higher BD (1.30 g cm^{-3}), while Site I (1,801 m) displayed the lowest BD (1.23 g cm^{-3}) (Table 3). The higher BD at lower elevations suggests more compacted soil, which might be due to increased anthropogenic activities or natural factors affecting the soil structure. An inverse relationship between BD and porosity was evident, with Site I (54%) showing the highest ($p < 0.05$; Table 2) porosity and Site V (51%) having a lower porosity (Table 3). The WHC varied significantly ($p < 0.05$) across the sites (Table 2), with Site V (1,693 m) having the highest WHC (52%) and Site III (1,720 m) the lowest (43%) (Table 3). This difference suggests that lower elevation sites may have more fine-textured soils capable of retaining more water, which is crucial for supporting vegetation growth. SMC followed a similar pattern, with Site I (1,801 m) exhibiting the highest ($p < 0.05$; Table 2) moisture content (44%) and Site II (1,749 m) the lowest (30%) (Table 3). This significant difference in SMC may be due to varying precipitation patterns and soil texture along the gradient.

Soil pH values also varied significantly ($p < 0.05$; Table 2), with Site V (5.5) showing the weak acidic conditions, whereas Sites III and IV, located at higher elevations, had strong acidic (pH 4.8–4.9) soils (Table 3). The acidic nature of these high-altitude sites could be attributed to increased organic matter decomposition, leading to organic acid accumulation. These pH variations are critical because they directly influence nutrient availability. SOC content was

the highest ($p < 0.05$; Table 2) at Site IV (1,893 m) with 2.85 kg ha^{-1} , reflecting the accumulation of organic matter at higher elevations (Table 3), possibly due to cooler temperatures and slower decomposition rates. Conversely, Site III (1,720 m) had the lowest SOC (2.63 kg ha^{-1}), consistent with its lower WHC and SMC, which might have reduced microbial activity and organic matter breakdown (Table 3).

The available N content showed significant ($p < 0.05$) spatial variation (Table 2), with Site IV having the highest available N ($605.46 \text{ kg ha}^{-1}$) and Site III having the lowest ($571.73 \text{ kg ha}^{-1}$) (Table 3). This pattern aligns with SOC levels, as N is closely linked to organic matter. The lower available N content at lower altitudes may be due to more rapid mineralization or leaching. Available P was notably higher ($p < 0.05$; Table 2) at Site I (18.91 kg ha^{-1}) and Site V (18.73 kg ha^{-1}), while Site II (15.66 kg ha^{-1}) had significantly ($p < 0.05$) lower P content (Table 3), likely due to the acidic conditions at this elevation inhibiting P availability. Similarly, available K was highest ($p < 0.05$; Table 2) at Site I ($117.15 \text{ kg ha}^{-1}$) and lowest at Site II ($106.34 \text{ kg ha}^{-1}$), suggesting spatial variability in soil nutrient dynamics driven by altitude and local soil properties (Table 3).

Spatio-temporal (depth vs. season) dynamics in soil physico-chemical properties

BD increased ($p < 0.05$) with soil depth across all seasons (Table 2). The topsoil (0–10 cm) had the lowest BD, ranging from 1.25 g cm^{-3} in the rainy season to 1.30 g cm^{-3} in summer, while the deepest layer (20–30 cm) exhibited the highest BD, peaking at 1.34 g cm^{-3} in summer (Tables 4, 5). This trend suggests that the topsoil is generally looser and less compacted because of organic matter accumulation and biological activity, whereas deeper soils are more compacted, likely due to greater mineral content and lower organic matter. Porosity was inversely related to BD, with the highest (55%) porosity recorded in the rainy season at the 0–10 cm depth and the lowest (50%) at the 20–30 cm depth

Table 2 Main effect ANOVA of soil physico-chemical properties under different natural *Quercus* dominant forest stands in the western Arunachal Pradesh across different seasons and soil depth

Variables	Source of variations					
	Site (df = 4)		Season (df = 2)		Soil depth (df = 2)	
	F	p	F	p	F	p
Bulk density	97.96	0.000*	69.80	0.000*	22.10	0.000*
Porosity	97.44	0.000*	69.39	0.000*	21.91	0.000*
Water holding capacity	26.39	0.000*	3.19	0.053 ^{ns}	6.28	0.005*
Soil moisture content	47.28	0.000*	490.85	0.000*	0.43	0.653 ^{ns}
pH	16.00	0.000*	0.15	0.858 ^{ns}	18.88	0.000*
Soil organic carbon	17.34	0.000*	126.63	0.000*	41.88	0.000*
Available nitrogen	47.98	0.000*	138.77	0.000*	79.12	0.000*
Available phosphorus	23.16	0.000*	9.25	0.001*	49.33	0.000*
Available potassium	13.75	0.000*	12.20	0.000*	34.37	0.000*

*Values are significant at $p < 0.05$ level.

ns: not significant.

Table 3 Spatial variability in soil physico-chemical properties along an elevational gradient in natural *Quercus* dominated forest stands in western Arunachal Pradesh

Sites	BD (g cm ⁻³)	Porosity (%)	WHC (%)	SMC (%)	pH	SOC (kg ha ⁻¹)	AN (kg ha ⁻¹)	AP (kg ha ⁻¹)	AK (kg ha ⁻¹)
Site-I	1.23 ± 0.01	53.67 ± 0.49	49.30 ± 0.47	44.34 ± 4.19	5.24 ± 0.02	2.82 ± 0.07	602.13 ± 8.31	18.91 ± 0.66	117.15 ± 1.40
Site-II	1.27 ± 0.01	52.20 ± 0.35	48.10 ± 0.39	29.67 ± 5.16	5.49 ± 0.14	2.77 ± 0.06	599.22 ± 6.96	15.66 ± 0.29	106.34 ± 2.11
Site-III	1.33 ± 0.01	49.81 ± 0.37	43.39 ± 1.12	31.15 ± 4.53	4.85 ± 0.14	2.63 ± 0.05	571.73 ± 5.28	17.03 ± 0.59	114.18 ± 1.52
Site-IV	1.32 ± 0.01	50.06 ± 0.35	45.04 ± 0.51	38.52 ± 4.09	4.82 ± 0.11	2.85 ± 0.08	605.46 ± 6.91	16.01 ± 0.79	116.52 ± 1.93
Site-V	1.30 ± 0.01	50.90 ± 0.42	52.20 ± 0.40	39.41 ± 4.52	5.54 ± 0.10	2.81 ± 0.07	587.66 ± 6.00	18.73 ± 0.62	110.13 ± 3.14

Values are mean ± SE; n = 9 (3 soil depth × 3 seasons).

BD: bulk density; WHC: water holding capacity; SMC: soil moisture content; SOC: soil organic carbon; AN: available nitrogen; AP: available phosphorus; AK: available potassium.

Table 4 Variations in soil physico-chemical properties across different seasons under natural *Quercus* dominant forest stands in western Arunachal Pradesh

Season	BD (g cm ⁻³)	Porosity (%)	WHC (%)	SMC (%)	pH	SOC (kg ha ⁻¹)	AN (kg ha ⁻¹)	AP (kg ha ⁻¹)	AK (kg ha ⁻¹)
Winter	1.29 ± 0.01	51.25 ± 0.42	47.43 ± 1.05	29.57 ± 1.97	5.17 ± 0.13	2.76 ± 0.04	591.67 ± 4.51	17.00 ± 0.51	112.04 ± 2.02
Summer	1.32 ± 0.01	50.29 ± 0.42	46.60 ± 1.05	26.10 ± 1.47	5.15 ± 0.10	2.60 ± 0.03	576.93 ± 3.98	16.61 ± 0.59	110.35 ± 1.86
Rainy	1.26 ± 0.01	52.45 ± 0.42	48.78 ± 0.62	54.17 ± 1.26	5.24 ± 0.12	2.96 ± 0.04	611.13 ± 5.25	18.20 ± 0.54	116.20 ± 1.51

Values are mean ± SE; n = 15 (5 sites × 3 soil depth).

BD: bulk density; WHC: water holding capacity; SMC: soil moisture content; SOC: soil organic carbon; AN: available nitrogen; AP: available phosphorus; AK: available potassium.

Table 5 Seasonal dynamics of soil physico-chemical properties across different soil depths under natural *Quercus* dominant forest stands in western Arunachal Pradesh

Soil depth	Season	BD (g cm ⁻³)	Porosity (%)	WHC (%)	SMC (%)	pH	SOC (kg ha ⁻¹)	AN (kg ha ⁻¹)	AP (kg ha ⁻¹)	AK (kg ha ⁻¹)
0–10 cm	Winter	1.28 ± 0.02	51.62 ± 0.82	48.05 ± 2.01	31.04 ± 3.58	4.90 ± 0.17	2.88 ± 0.06	607.93 ± 6.18	18.97 ± 0.67	119.42 ± 1.79
	Summer	1.30 ± 0.02	50.87 ± 0.85	48.21 ± 1.61	25.80 ± 3.61	4.91 ± 0.17	2.72 ± 0.04	589.68 ± 4.71	18.50 ± 0.78	117.20 ± 1.13
	Rainy	1.25 ± 0.02	52.98 ± 0.81	49.63 ± 1.16	54.29 ± 3.07	5.00 ± 0.18	3.06 ± 0.05	626.17 ± 9.07	19.70 ± 1.05	119.98 ± 1.39
10–20 cm	Winter	1.29 ± 0.02	51.40 ± 0.78	47.51 ± 1.99	29.41 ± 3.73	5.06 ± 0.20	2.76 ± 0.05	586.67 ± 6.01	16.18 ± 0.63	110.54 ± 2.43
	Summer	1.31 ± 0.02	50.41 ± 0.75	46.70 ± 1.79	26.10 ± 2.52	5.11 ± 0.11	2.56 ± 0.03	577.56 ± 6.26	16.18 ± 1.05	108.21 ± 3.42
	Rainy	1.26 ± 0.02	52.53 ± 0.79	48.59 ± 1.05	54.46 ± 2.01	5.15 ± 0.20	2.97 ± 0.07	609.69 ± 7.62	18.04 ± 0.73	116.50 ± 2.01
20–30 cm	Winter	1.31 ± 0.02	50.72 ± 0.70	46.74 ± 1.84	28.27 ± 3.62	5.54 ± 0.20	2.65 ± 0.03	580.41 ± 5.94	15.85 ± 0.61	106.17 ± 3.29
	Summer	1.34 ± 0.02	49.59 ± 0.58	44.88 ± 2.12	26.40 ± 1.81	5.43 ± 0.15	2.51 ± 0.03	563.55 ± 4.38	15.14 ± 0.70	105.65 ± 2.20
	Rainy	1.28 ± 0.02	51.85 ± 0.65	48.14 ± 1.12	53.77 ± 1.72	5.58 ± 0.20	2.86 ± 0.06	597.53 ± 6.75	16.85 ± 0.59	112.13 ± 3.20

Values are mean ± SE (n = 5).

BD: bulk density; WHC: water holding capacity; SMC: soil moisture content; SOC: soil organic carbon; AN: available nitrogen; AP: available phosphorus; AK: available potassium.

during summer (Tables 4, 5). Higher porosity in the top layer indicates better aeration and water movement, whereas reduced porosity in deeper layers reflects compaction and reduced root penetration capacity.

WHC was generally higher in the topsoil, particularly during the rainy season, when it reached 50% in the 0–10 cm layer (Tables 4, 5). This indicates that topsoil has a higher capacity to retain moisture, which is critical for sustaining plant growth. Conversely, the 20–30 cm depth had the lowest WHC, particularly in summer (45%), reflecting its compact nature and reduced ability to retain water (Tables 4, 5). Nonetheless, WHC did not vary ($p > 0.05$) across all seasons (Table 2). SMC showed the most significant variation ($p < 0.05$) across seasons, with the rainy season exhibiting a much higher SMC across all depths (Table 2). However, SMC did not vary significantly ($p > 0.05$) with soil depth (Table 2). The topsoil (0–10 cm) in the rainy season had the highest (54%) SMC, whereas the lowest (26%) SMC was observed in the 10–20 cm layer during summer (Tables 4, 5). This indicates that moisture availability is significantly ($p < 0.05$) influenced by seasonal precipitation, with deeper layers retaining less moisture in drier conditions.

The soil pH showed a slight increase ($p > 0.05$) with soil depth (Table 2). The topsoil remained slightly more acidic, with values ranging from 4.9 (winter) to 5.0 (rainy season) at 0–10 cm depth (Tables 4, 5). In contrast, the 20–30 cm layer became weakly acidic, particularly during the rainy season (5.6). The slight increase in acidic condition with depth is likely due to leaching of organic acids from the surface layers and accumulation of base cations in deeper layers (Tables 4, 5). SOC was the highest in the topsoil across all seasons, particularly during the rainy season (3.06 kg ha⁻¹), which indicates higher organic matter content at shallower depths due to litter decomposition and biological activity. SOC decreased with soil depth, with the

lowest values observed in the 20–30 cm depth during summer (2.51 kg ha⁻¹), reflecting lower organic matter accumulation and slower decomposition rates in the deeper layers (Tables 4, 5).

Available N followed a similar pattern to SOC, with the highest levels in the 0–10 cm depth during the rainy season (626.17 kg ha⁻¹) and the lowest in the 20–30 cm depth during the summer (563.55 kg ha⁻¹) (Tables 4, 5). N availability decreased ($p < 0.05$; Table 2) with depth, reflecting a gradual reduction in organic matter and microbial activity in the deeper layers. Available P was consistently higher in the topsoil ($p < 0.05$; Table 2), reaching its peak in the rainy season at 0–10 cm (19.70 kg ha⁻¹), while the lowest values were observed in the 20–30 cm depth during summer (15.14 kg ha⁻¹) (Tables 4, 5). P availability is higher in the surface layers due to organic matter mineralization, whereas deeper layers are more limited in P content (Tables 4, 5). Available K followed a similar trend, with the highest ($p < 0.05$; Table 2) levels in the 0–10 cm layer during the rainy season (119.98 kg ha⁻¹) and the lowest in the 20–30 cm depth during summer (105.65 kg ha⁻¹) (Tables 4, 5). K availability is closely tied to soil organic matter and texture, explaining the higher levels in the topsoil and rainy season when soil moisture and biological activity were optimal.

Spatio-temporal (depth vs. season) dynamics in soil physico-chemical properties

The BD showed notable seasonal variation ($p < 0.05$) across all sites (Table 2). At Site I (elevation 1,801 m), BD was lowest in the rainy season (1.20 g cm⁻³) and highest during summer (1.26 g cm⁻³), reflecting looser soil due to increased moisture in the rainy season and compacted soil in the summer (Table 6). This trend was consistent across other sites, with the highest BD consistently occurring in the summer. For example, Site III (elevation 1,720 m) showed

Table 6 Seasonal dynamics of soil physical across the different *Quercus* dominated forest stands in western Arunachal Pradesh

Sites	Season	BD (g cm ⁻³)	Porosity (%)	WHC (%)	SMC (%)
Site-I	Winter	1.22 ± 0.01	53.83 ± 0.33	49.52 ± 0.44	39.18 ± 1.01
	Summer	1.26 ± 0.01	52.33 ± 0.55	48.03 ± 0.67	33.50 ± 0.87
	Rainy	1.20 ± 0.01	54.84 ± 0.45	50.33 ± 0.36	60.33 ± 0.93
Site-II	Winter	1.28 ± 0.01	51.83 ± 0.22	47.64 ± 0.37	19.64 ± 0.38
	Summer	1.28 ± 0.01	51.57 ± 0.48	47.28 ± 0.32	19.67 ± 1.36
	Rainy	1.24 ± 0.01	53.21 ± 0.55	49.38 ± 0.55	49.70 ± 3.18
Site-III	Winter	1.31 ± 0.01	50.43 ± 0.33	41.33 ± 0.33	22.87 ± 0.45
	Summer	1.37 ± 0.01	48.43 ± 0.13	41.33 ± 1.45	21.33 ± 0.33
	Rainy	1.31 ± 0.01	50.57 ± 0.22	47.51 ± 0.37	49.24 ± 0.38
Site-IV	Winter	1.34 ± 0.01	49.57 ± 0.33	45.67 ± 0.33	34.30 ± 0.59
	Summer	1.34 ± 0.01	49.31 ± 0.33	44.24 ± 1.52	27.00 ± 0.58
	Rainy	1.29 ± 0.01	51.32 ± 0.22	45.20 ± 0.48	54.27 ± 1.09
Site-V	Winter	1.31 ± 0.01	50.57 ± 0.43	53.00 ± 0.58	31.88 ± 0.88
	Summer	1.33 ± 0.01	49.81 ± 0.38	52.10 ± 0.78	29.00 ± 0.58
	Rainy	1.26 ± 0.01	52.33 ± 0.33	51.49 ± 0.65	57.34 ± 0.77

Values are mean ± SE ($n = 5$).

BD: bulk density; WHC: water holding capacity; SMC: soil moisture content.

the highest BD (1.37 g cm^{-3}) during summer and lower values in winter (1.31 g cm^{-3}) and rainy season (1.31 g cm^{-3}). Site IV (1,893 m) had a consistently high BD across all seasons (Table 6), with a slight reduction in the rainy season (1.29 g cm^{-3}). The highest porosity was consistently observed during the rainy season at all sites, with Site I having the highest porosity during the rainy season (54.84%). Conversely, the lowest porosity was found in summer at most sites, indicating a more compacted soil (Table 6). For instance, Site III had the lowest porosity in summer (48.43%), correlating with its high BD during the same season (Table 6).

The WHC did not show any significant variation ($p > 0.05$) across the seasons, but it varied significantly ($p < 0.05$) across all sites (Table 2). At Site I, WHC reached 50.33% in the rainy season (Table 6), whereas it was lower in summer (48%). Site V showed the highest WHC overall, peaking at 53% in winter and 52% in summer, indicating the site's superior water retention capability throughout the year (Table 6). Site III had the lowest WHC, particularly in the summer (41%), reflecting the compacted nature of the soil and reduced moisture retention at lower elevations. SMC showed significant ($p < 0.05$) seasonal variation, particularly between the rainy and summer (Table 6). In the rainy season, Site I exhibited the highest SMC (60%), which was driven by high precipitation and water retention (Table 6). This was in stark contrast to the summer SMC of Site II, which dropped to as low as 20%, indicating significant soil drying during the warmer months (Table 6). Site IV also demonstrated significant SMC differences, with 54% during the rainy season and 27% in the summer. This demonstrates the strong impact of seasonal rainfall on the moisture availability in these soils.

Soil pH values across the study sites varied significantly ($p < 0.05$) varied from 4.77 to 5.62, indicating a generally acidic environment typical of forest soils (Table 2, Fig. 2).

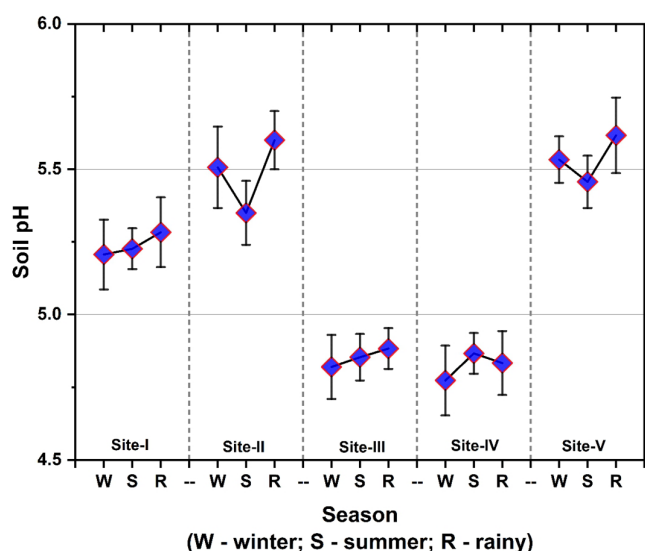


Fig. 2 Seasonal dynamics of soil pH across the different *Quercus* sp. dominated forest stands in western Arunachal Pradesh.

The lowest pH was observed at the highest elevation, Site-IV (1,893 m), with values of 4.77 in winter and 4.83 during the rainy season, reflecting increased acidity at higher elevations (Fig. 2). In contrast, Site V (1,693 m), the lowest site, exhibited the highest pH (5.62) during the rainy season, followed by Site I (1,801 m), with a pH of 5.28 in the same season (Fig. 2). The slight increase in pH at lower elevations during the rainy season can be attributed to reduced leaching and greater accumulation of basic cations (Fig. 2). Seasonal variations in pH were also evident, with a general increase during the rainy season compared with winter and summer, likely due to increased moisture and organic decomposition.

The SOC displayed significant seasonal variation ($p < 0.05$) across the study sites (Table 2). The highest SOC content was recorded at Site-IV (1,893 m) and Site-V (1,693 m) during the rainy season, both showing values of 3.07 kg ha^{-1} (Fig. 3), which suggests that higher rainfall enhances organic matter deposition and retention. Conversely, the lowest SOC values were observed in the summer at Site-III (1,720 m), with 2.48 kg ha^{-1} , indicating a seasonal decline in organic matter due to reduced moisture availability and microbial activity (Fig. 3). Overall, SOC was highest during the rainy season across all sites, indicating the role of rainfall in boosting organic carbon levels through enhanced decomposition and organic matter input.

The available N showed marked variability ($p < 0.05$) across sites and seasons (Table 2). The highest available N values were found during the rainy season at Site-IV (1,893 m), reaching $626.53 \text{ kg ha}^{-1}$, closely followed by Site-I (1,801 m), which recorded $620.06 \text{ kg ha}^{-1}$ during the same season (Fig. 4). This indicates that N mineralization rates were higher during periods of greater SMC. In contrast, lower

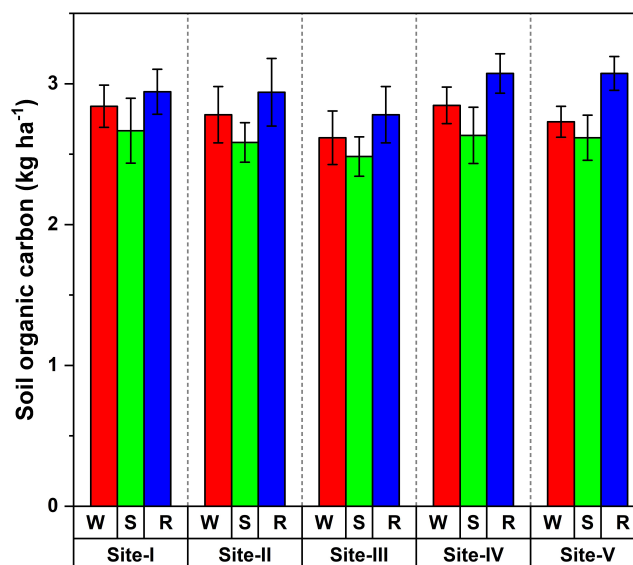


Fig. 3 Seasonal dynamics of soil organic carbon across the different *Quercus* sp. dominated forest stands in western Arunachal Pradesh. W: winter; S: summer; R: rainy.

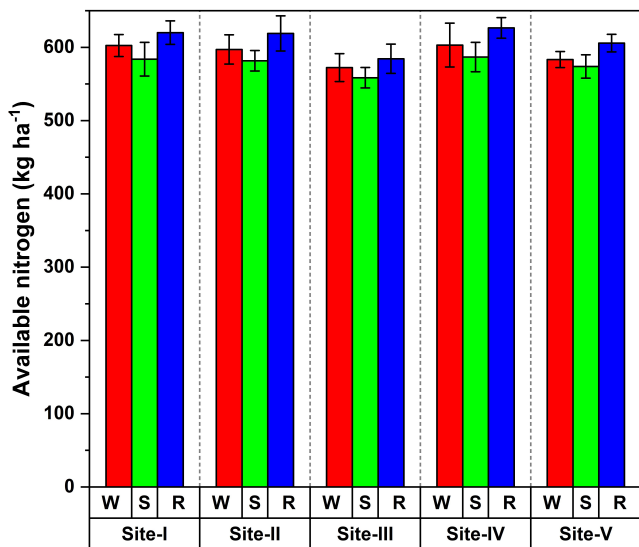


Fig. 4 Seasonal dynamics of soil available nitrogen across the different *Quercus* sp. dominated forest stands in western Arunachal Pradesh. W: winter; S: summer; R: rainy.

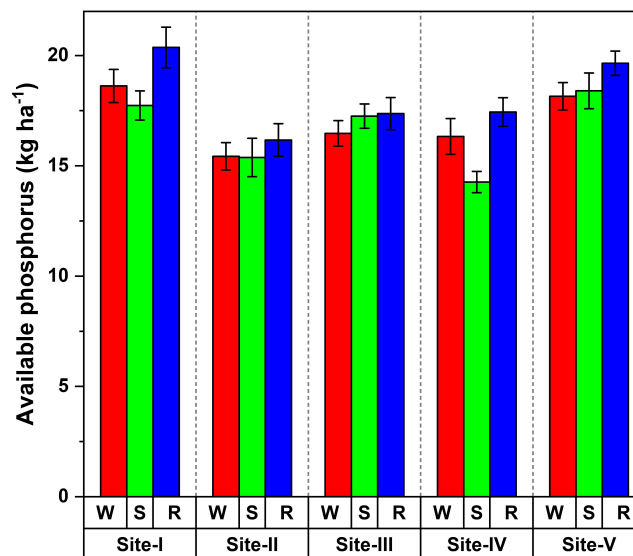


Fig. 5 Seasonal dynamics of soil available phosphorus across the different *Quercus* sp. dominated forest stands in western Arunachal Pradesh. W: winter; S: summer; R: rainy.

available N values were recorded during summer, especially at Site-III (1,720 m), where available N dropped to 558.49 kg ha⁻¹ (Fig. 4). The overall trend suggests that available N levels were significantly elevated during the rainy season due to enhanced microbial activity and nutrient cycling.

Available P concentrations were significantly ($p < 0.05$) lower across all sites and seasons (Table 2). The highest available P content was found at Site-I (1,801 m) during the rainy season, with 20.37 kg ha⁻¹ (Fig. 5), which may be linked to the increased dissolution of P under high moisture conditions. Available P was generally lower in summer, with Site-II (1,749 m) recording the lowest value at 15.38 kg ha⁻¹. This seasonal decline could be associated with the lower availability of moisture, which restricts P mobility in the soil. The available K content exhibited a strong and significant ($p < 0.05$) seasonal pattern (Table 2), with the highest values recorded during the rainy season at Site-IV (1,893 m), where it reached 120.66 kg ha⁻¹, followed by Site-I (1,801 m) at 118.70 kg ha⁻¹ (Fig. 6). The elevated K levels during the rainy season are likely due to the increased weathering of K-bearing minerals and better nutrient mobility in wet soils. In contrast, the lowest available K concentrations were observed during the summer, particularly at Site II (1,749 m), where available K was recorded at 106.33 kg ha⁻¹ (Fig. 6).

Relationship amongst soil physico-chemical properties

The correlation matrix of soil physicochemical properties in natural oak-dominant forest stands in western Arunachal Pradesh revealed significant interrelationships among various soil attributes (Table 7, Fig. 7). A strong negative correlation ($r = -0.998$) was observed between BD and porosity, indicating that as the BD increased, the porosity significantly

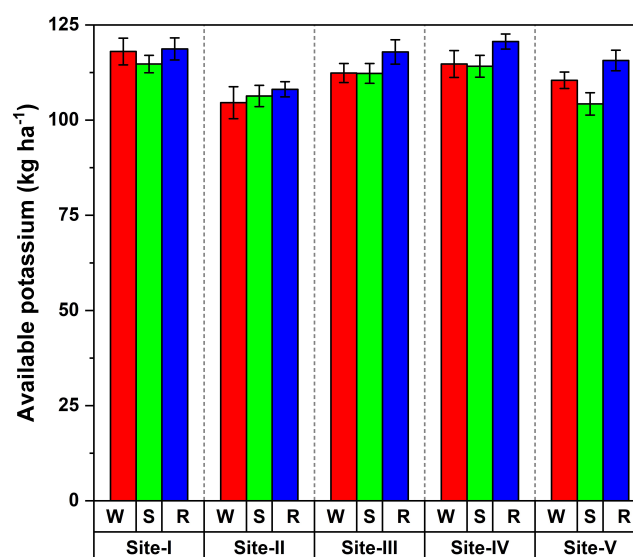


Fig. 6 Seasonal dynamics of soil available potassium across the different *Quercus* sp. dominated forest stands in western Arunachal Pradesh. W: winter; S: summer; R: rainy.

decreased (Table 7). WHC demonstrated a moderate positive correlation with porosity ($r = 0.521$) and a corresponding negative correlation with BD ($r = -0.521$), suggesting that higher porosity contributes to enhanced water retention capabilities in the soil (Table 7). Furthermore, SOC is positively correlated with SMC ($r = 0.760$) and available N ($r = 0.671$), highlighting the role of organic C in promoting water retention and nutrient availability (Fig. 7). Available N exhibited a negative correlation with pH ($r = -0.144$), though not statistically significant, and a moderate positive correlation with AP ($r = 0.461$) (Table 7). SOC displays a weak negative correlation with pH ($r = -0.086$) (Fig. 7). Additionally, available K shows a negative correlation with

Table 7 Pearson's (r) correlation amongst the soil physico-chemical properties in natural *Quercus* dominant forest stands in western Arunachal Pradesh

Variables	BD	Porosity	WHC	SMC	pH	AN	AP
Bulk density (BD)	1.000						
Porosity	-0.998*	1.000					
Water holding capacity (WHC)	-0.521*	0.521*	1.000				
Soil moisture content (SMC)	-0.549*	0.548*	0.399*	1.000			
pH	-0.221 ^{ns}	0.221 ^{ns}	0.415*	0.090 ^{ns}	1.000		
Available nitrogen (AN)	-0.671*	0.671*	0.378*	0.650*	-0.144 ^{ns}	1.000	
Available phosphorus (AP)	-0.465*	0.464*	0.534*	0.491*	-0.138 ^{ns}	0.461*	1.000
Available potassium (AK)	-0.311*	0.310*	0.041 ^{ns}	0.464*	-0.596*	0.565*	0.597*

*Correlation is significant at 0.05 *p* level.
ns: not significant.

pH ($r = -0.596$), implying that increased K levels might correlate with reduced pH (Table 7).

Discussion

Spatial (site) variability in soil physico-chemical properties

BD showed a statistically significant increase ($p < 0.05$) as altitude decreased. Site V, at the lowest elevation (1,693 m), had the highest BD (1.30 g cm^{-3}), whereas Site I, at the highest elevation (1,801 m), exhibited the lowest BD (1.23 g cm^{-3}). This pattern suggests that soil compaction increases at lower altitudes, potentially due to higher levels of anthropogenic activities such as agriculture or grazing, which are known to compact soils. Natural factors, including soil texture and formation processes, may also contribute to this trend (Weil and Brady 2016). Further, the soil structure in these high-altitude oak forests is primarily influenced by natural factors such as high precipitation leading to soil erosion, organic matter decomposition, and biological activity by soil fauna and plant roots. While direct human impact is minimal due to the remote location, occasional disturbances such as seasonal grazing and fuelwood collection by local communities may occur. The inverse relationship between BD and porosity was evident, with Site I showing the highest porosity (54%), while Site V had a lower porosity (51%). Higher BD often results in reduced pore spaces, limiting the soil's ability to hold air and water (Troeh and Thompson 2005). The compacted soils, as seen in lower-altitude sites, can restrict root growth and reduce microbial activity, thereby impacting plant health and soil biodiversity. This is consistent with findings from other studies showing that increased soil compaction reduces aeration and water movement (Gupta and Larson 1979). While porosity generally tends to decrease with increasing altitude due to compaction and reduced biological activity, Site 4 exhibited similar porosity values to the lower-altitude sites (Site 5 and Site 3). This suggests that factors such as soil texture, organic matter content, and root activity

may have a stronger influence on soil porosity than altitude alone. These site-specific variations highlight the complex interactions governing soil structure.

WHC showed significant variation ($p < 0.05$) across sites, with lower-altitude Site V having the highest WHC (52%) and Site III (1,720 m) the lowest (43%). The greater WHC in lower-altitude soils may be due to the higher clay content, which tends to retain more water due to its fine texture (Gupta and Larson 1979). Fine-textured soils, such as those rich in clay, have a greater ability to store water, which is essential for plant growth, especially during dry periods (Hillel 2004). SMC also varied significantly ($p < 0.05$) along the altitude gradient, with Site I showing the highest moisture content (44%) and Site II the lowest (30%). This variation could be attributed to several factors, including soil texture and precipitation patterns, which are influenced by altitude (Jenny 1994). Cooler temperatures at higher elevations may reduce evaporation rates, allowing soils to retain more moisture (Hillel 2004). Conversely, at lower altitudes, warmer temperatures likely increase evaporation, leading to lower SMC despite higher WHC (Gupta and Larson 1979). Rainfall distribution in the study area is influenced by orographic effects, with higher-altitude regions typically receiving more precipitation. Although direct rainfall data for each study site is now available, the rainfall records from the nearest meteorological station in Dirang, Arunachal Pradesh is shown in Figure S1. These data provide an estimate of regional temperature and precipitation trends, which likely influence soil moisture and related properties.

Soil pH is a crucial factor influencing nutrient availability, microbial activity, and overall soil fertility (McBride 1994). Soils at higher altitudes were found to be more acidic compared to those at lower altitudes (Tables 4, 5). The results showed significant ($p < 0.05$) variation in pH across the altitudinal gradient, with Site V (1,693 m) having the weak acidic soil (pH 5.5) and Sites III and IV (higher altitudes) displaying more acidic conditions (pH 4.8–4.9). This trend is consistent with previous studies in mountainous regions, where lower temperatures, increased organic mat-

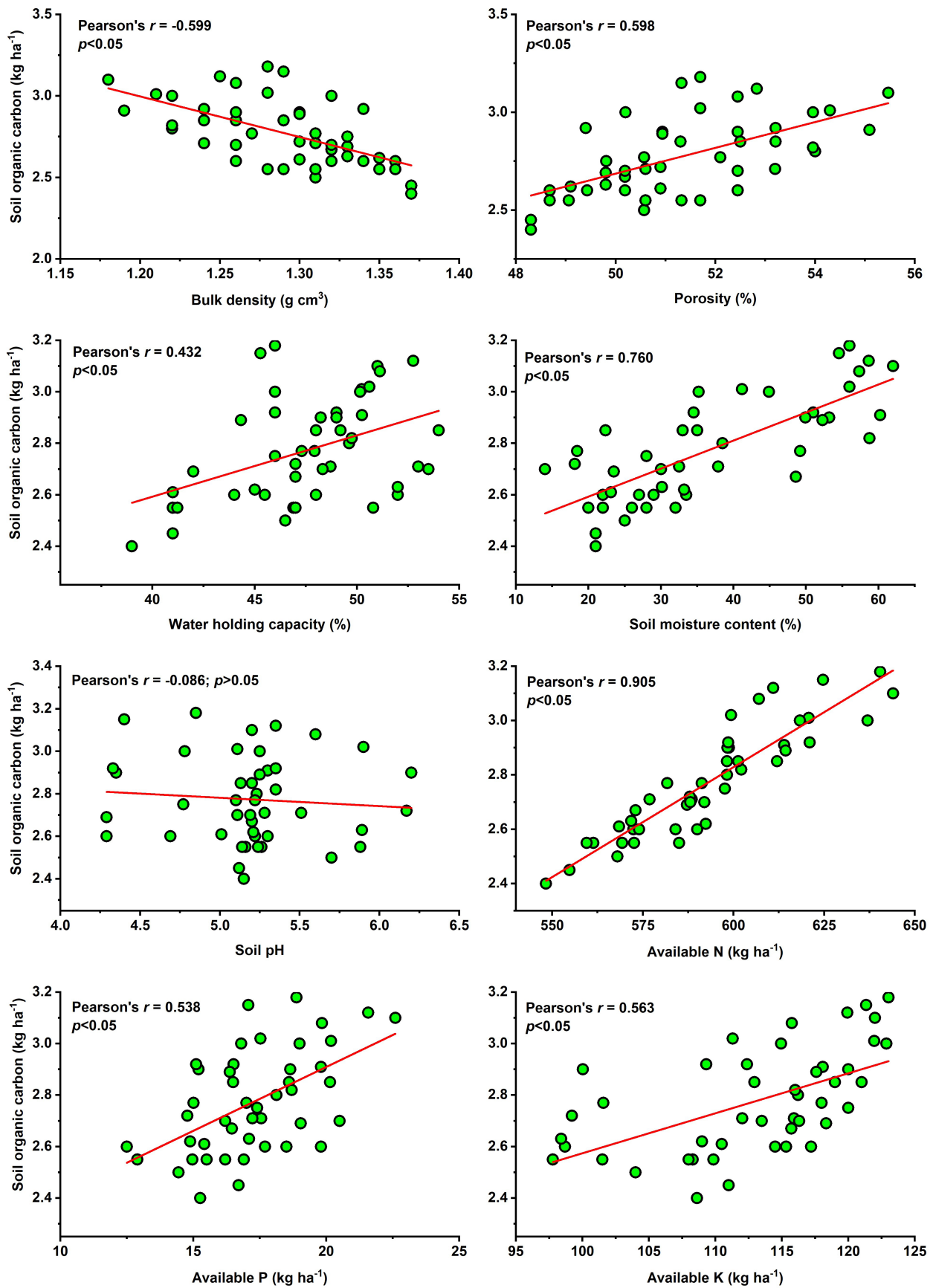


Fig. 7 Relationship between soil organic carbon with soil chemical properties in natural *Quercus* sp. dominant forest stands in western Arunachal Pradesh. N: nitrogen; P: phosphorus; K: potassium.

ter accumulation, slower decomposition rates, and enhanced leaching contribute to soil acidification (Badía et al. 2016; Bhandari and Zhang 2019; Mangral et al. 2023; Smith et al. 2002; Teron et al. 2024). The lower pH at higher elevations may also be influenced by reduced microbial activity and the accumulation of organic acids from litter decomposition. The increase in organic matter decomposition, enhance the releases organic acids into the soil (Adeleke et al. 2017; Paul 2015; Zhi-An et al. 2008). This trend is consistent with studies showing that cooler climates slow the decomposition process, leading to the accumulation of organic acids (Weil and Brady 2016). Acidic soils, such as those at higher elevations, are known to reduce the availability of P and other essential nutrients by causing them to bind with aluminum and iron oxides (McBride 1994). This could also explain the lower available P observed at higher-altitude sites, where acidic conditions may limit nutrient availability for plant uptake (Stevenson and Cole 1999).

SOC is a key indicator of soil health, as it reflects the amount of organic matter present in the soil. Site IV, at the highest elevation (1,893 m), had the highest SOC content (2.85 kg ha⁻¹), while Site III had the lowest (2.63 kg ha⁻¹). The higher SOC at elevated sites may be due to slower decomposition rates in cooler climates, which allow organic matter to accumulate over time (Jenny 1994). This relationship between altitude and SOC is consistent with findings from other studies that show cooler, higher-elevation sites tend to store more organic carbon due to reduced microbial activity and slower organic matter breakdown (Paul 2015). Contrary to the general trend observed in some regions where SOC decreases with increasing altitude due to temperature-driven microbial activity, our findings indicate a positive correlation between SOC and elevation. This pattern has been reported in other montane forests, where lower temperatures slow down decomposition, leading to greater organic matter accumulation (Bian et al. 2020; Bot and Benites 2005; Komarova et al. 2022). Additionally, the dense oak canopy at higher elevations contributes substantial litter input, further enhancing SOC storage. At Site 3, although SOC was lower compared to other sites, the slight reductions in SMC and WHC were not statistically significant ($p > 0.05$). Thus, other site-specific factors such as variations in vegetation composition, root biomass, and historical land-use impacts may also influence SOC levels (Parajuli et al. 2024; Sun et al. 2024; Yajuan et al. 2022; Yao et al., 2023). The relationship between SOC and WHC is also significant. Sites with higher SOC tend to have greater WHC because organic matter improves soil structure by enhancing porosity and water retention (Stevenson and Cole 1999). In contrast, lower SOC at lower-altitude sites may contribute to reduced WHC, as less organic matter is available to improve soil water retention (Weil and Brady 2016). This could have important implications for plant

growth, as soils with low SOC may struggle to retain sufficient moisture during dry periods (Gupta and Larson 1979).

The spatial variability in nutrient availability, particularly N, P, and K, is crucial for understanding soil fertility along altitudinal gradients. Available N content was highest at Site IV (605.46 kg ha⁻¹) and lowest at Site III (571.73 kg ha⁻¹). This is likely due to the higher SOC levels at elevated sites, as N is closely associated with organic matter (Smith and Paul 1990). The higher organic carbon content at higher elevations slows down N mineralization, allowing for greater N retention in the soil (Paul 2015). P availability, which is closely linked to soil pH, was higher at lower-elevation sites like Site I (18.91 kg ha⁻¹), where the soil was weakly acidic. In contrast, higher-altitude sites with more acidic soils exhibited lower P availability, as acidic conditions inhibit P solubility (McBride 1994). This reduction in P availability at higher altitudes could negatively impact plant growth, as P is an essential nutrient for root development and energy transfer in plants (Troeh and Thompson 2005). Similarly, K availability was highest at Site I (117.15 kg ha⁻¹) and lowest at Site II (106.34 kg ha⁻¹). K is essential for plant water regulation and enzyme activation, and its availability often reflects underlying soil texture and mineral composition (Stevenson and Cole 1999). The spatial variability in K highlights the importance of considering local soil properties when assessing nutrient dynamics along environmental gradients.

Spatio-temporal (depth vs. season) dynamics in soil physico-chemical properties

The increase in BD with soil depth ($p < 0.05$) observed in this study aligns with findings from other studies in forested ecosystems, where the topsoil (0–10 cm) consistently exhibits lower BD due to higher organic matter content and biological activity (Jobbágy and Jackson 2000). BD in the topsoil ranged from 1.25 g cm⁻³ in the rainy season to 1.30 g cm⁻³ in summer, whereas the deepest layer (20–30 cm) had the highest BD, peaking at 1.34 g cm⁻³ during summer. The slight seasonal variations in BD, which can be attributed to environmental factors rather than measurement errors (Table 3). Increased soil moisture during the rainy season may cause soil swelling and reduced BD, whereas drier conditions in winter and summer can lead to soil contraction and higher BD. Similar seasonal BD variations have been reported in other studies on forest soils (Hu et al. 2012; Zhao et al. 2021). Proper sampling protocols were followed to minimize potential measurement errors. The lower BD in the topsoil is likely due to the accumulation of organic matter from litterfall, root growth, and microbial activity, which help create a more porous soil structure (Gupta and Larson 1979). In contrast, the deeper layers, with less organic matter and higher mineral content, tend to be more compacted, leading to higher BD (Weil and

Brady 2016). The inverse relationship between BD and porosity is evident, as topsoil porosity was highest (55%) in the rainy season at the 0–10 cm depth, while the lowest porosity (50%) occurred at the 20–30 cm depth during summer. Higher porosity in the topsoil enhances aeration, water infiltration, and root penetration, making the top layer crucial for plant growth and soil biological activity (Troeh and Thompson 2005). Reduced porosity in the deeper layers, as seen in this study, limits water movement and root growth, impacting overall soil health.

WHC varied significantly with soil depth but remained generally higher in the topsoil (0–10 cm) across all seasons, with the highest value recorded during the rainy season (50%). This observation is consistent with findings in other forest types, where topsoil tends to have higher WHC due to its higher organic matter content and more porous structure, which allow for greater moisture retention (Hillel 2004). The lowest WHC values were observed at the 20–30 cm depth, particularly in summer (45%), reflecting the compact nature of the deeper soil and its reduced ability to retain water. SMC exhibited significant seasonal variation ($p < 0.05$), with the highest values recorded during the rainy season, as expected. The topsoil (0–10 cm) had the highest SMC during the rainy season (54%), while the lowest SMC (26%) occurred in the 10–20 cm layer during summer. This finding highlights the critical role of seasonal precipitation in influencing soil moisture availability, particularly in forest ecosystems where water is a limiting factor for vegetation growth during dry periods (Jenny 1994). The seasonal fluctuation in SMC across depths, though not statistically significant ($p > 0.05$), indicates that deeper layers retain less moisture, especially during dry seasons when water percolation is reduced (Gupta and Larson 1979).

Soil pH showed a slight but non-significant increase ($p > 0.05$) with depth across all seasons. The topsoil remained slightly more acidic, with pH values ranging from 4.9 (winter) to 5.0 (rainy season) at the 0–10 cm depth. In contrast, deeper layers (20–30 cm) exhibited weak acidic conditions, particularly during the rainy season (pH 5.6). This trend aligns with findings in other forest systems, where organic acids from decomposing organic matter contribute to surface soil acidity, while base cations leached from the surface accumulate in deeper layers, increasing soil pH (Paul 2015). Similar pH stratification has been observed in tropical and temperate forests, where organic acid leaching and the deposition of weathered minerals at deeper depths influence soil pH (Weil and Brady 2016).

SOC was highest in the topsoil across all seasons, particularly during the rainy season (3.06 kg ha^{-1}), indicating higher organic matter accumulation due to litterfall and biological activity at shallower depths. The decrease in SOC with depth, reaching its lowest value (2.51 kg ha^{-1}) in the 20–30 cm layer during summer, is consistent with global patterns

observed in forest soils (Jobbágy and Jackson 2000). Topsoil generally exhibits higher SOC due to the accumulation of plant residues and root biomass, while deeper layers receive less organic matter input and experience slower decomposition rates (Paul 2015). This pattern has been observed in various forest ecosystems, including temperate and tropical forests, where cooler temperatures and higher moisture content at the surface promote organic matter accumulation, while deeper layers are more mineral-rich and have lower SOC. The seasonal variation in SOC, with higher levels in the rainy season, further emphasizes the importance of moisture availability for microbial activity and organic matter decomposition (Stevenson and Cole 1999).

Nutrient availability, particularly N, P, and K, showed significant variation across depth and season. Available N was highest in the topsoil during the rainy season ($626.17 \text{ kg ha}^{-1}$), while the lowest N levels were observed in the 20–30 cm layer during summer ($563.55 \text{ kg ha}^{-1}$). The decrease in N with depth reflects the decline in organic matter and microbial activity, which are critical for N mineralization (Paul 2015). This pattern is consistent with findings in forest ecosystems, where N availability is closely tied to organic matter content and microbial decomposition rates, both of which decline with depth (Smith and Paul 1990). Available P also followed a similar pattern, with the highest levels in the topsoil (19.70 kg ha^{-1}) during the rainy season and the lowest in the 20–30 cm depth during summer (15.14 kg ha^{-1}). P availability is often limited in deeper soils due to lower organic matter content and the tendency for P to bind with iron and aluminum oxides, particularly in acidic soils (Stevenson and Cole 1999). This trend is consistent with studies in tropical and temperate forests, where P availability declines with depth due to reduced mineralization and increased adsorption to soil particles (McBride 1994). K availability was highest in the topsoil during the rainy season ($119.98 \text{ kg ha}^{-1}$) and lowest in the deeper layers during summer ($105.65 \text{ kg ha}^{-1}$). K is closely tied to soil organic matter and texture, with higher levels typically found in surface soils where biological activity is greatest (Gupta and Larson 1979). The seasonal variation in K availability, with higher levels during the rainy season, may be due to increased weathering and leaching processes that release K from soil minerals (McBride 1994).

Spatio-temporal (depth vs. season) dynamics in soil physico-chemical properties

The analysis reveals a significant seasonal variation ($p < 0.05$) in BD across all sites. For instance, at Site I (elevation 1,801 m), BD was lowest in the rainy season (1.20 g cm^{-3}) and highest during summer (1.26 g cm^{-3}), likely reflecting the increased soil compaction during the dry season when moisture levels are reduced, and the soil becomes denser due to less organic activity and root expansion (Correa et al. 2019). This seasonal fluctuation was consistently ob-

served across all sites, including Site III (elevation 1,720 m), where BD was highest during the summer (1.37 g cm^{-3}) and decreased in winter and the rainy season to 1.31 g cm^{-3} (Table 6). This pattern has been similarly noted in other forest ecosystems, such as the temperate forests of Europe, where BD also peaks during the dry season due to the compact nature of the soil. The higher BD observed during summer reflects lower soil porosity and compacted conditions due to reduced biological activity, which is more pronounced at lower elevations, as demonstrated at Site III (Table 6). Porosity displayed an inverse relationship with BD, as expected, and was highest during the rainy season, with Site I reaching 54.84%. Lower porosity was observed in summer, reflecting increased soil compaction during the drier months. Such variations in porosity and BD are typical in forest soils due to the influence of root activity and organic matter content, as reported in tropical forest studies.

WHC showed no significant seasonal variation ($p > 0.05$) but did vary significantly across sites (Table 2). The highest WHC was observed at Site V (53% in winter), suggesting that soils in this area have a higher water retention capacity, possibly due to a higher clay content or organic matter levels (Zhang et al. 2021). In contrast, Site III had the lowest WHC, particularly in summer (41%), reflecting the site's lower organic matter content and higher BD (Table 6), similar to findings from semi-arid forest ecosystems (Mee-na et al. 2016). SMC showed significant seasonal variation ($p < 0.05$), with the rainy season displaying the highest values. At Site I, SMC peaked at 60% during the rainy season (Table 6), likely due to increased rainfall and the soil's ability to retain moisture in the top layers. This aligns with similar observations in tropical rainforests, where SMC was significantly influenced by seasonal precipitation (Koehn et al. 2021). During the summer, SMC was lowest at Site II (20%), highlighting the reduced water availability in deeper soil layers during dry periods. The sharp decline in SMC across all sites during the summer indicates that forest soils, particularly in temperate regions, experience considerable moisture stress in dry conditions (Jobbágy and Jackson 2000).

Soil pH values ranged significantly ($p < 0.05$) from 4.77 to 5.62, indicating a generally acidic soil environment typical of forested ecosystems (Table 2, Fig. 2). Site IV (1,893 m), at the highest elevation, showed the lowest pH values (4.77 in winter and 4.83 during the rainy season), indicating higher organic acid accumulation at these altitudes due to slower decomposition rates and the greater input of organic material (Weil and Brady 2016). Conversely, the lower-elevation sites, such as Site V (1,693 m), exhibited higher pH (5.62 during the rainy season), likely due to increased leaching of acidic compounds and the accumulation of base cations, as reported in other forest ecosystems, including coniferous and temperate forests (Malcomb et al. 2020).

SOC levels displayed significant seasonal variations ($p < 0.05$), with higher values during the rainy season. The highest SOC content was recorded at Site IV (3.07 kg ha^{-1}) and Site V (3.07 kg ha^{-1}) during the rainy season (Fig. 3), which reflects the increased input and retention of organic matter during periods of high moisture (Oades 1988). In contrast, Site III showed the lowest SOC levels in summer (2.48 kg ha^{-1}), suggesting that organic matter decomposition and microbial activity are reduced during dry periods, resulting in lower carbon content. This pattern has also been observed in other forest types, such as montane and boreal forests, where seasonal moisture variations strongly influence SOC dynamics (Sayer et al. 2011). The overall trend of higher SOC in rainy seasons is consistent with studies in temperate deciduous forests, where soil moisture plays a crucial role in organic matter decomposition (Kotrocó et al. 2023).

Available N levels varied significantly ($p < 0.05$) across seasons, with the highest concentrations found during the rainy season at Site IV ($626.53 \text{ kg ha}^{-1}$), reflecting enhanced N mineralization due to increased microbial activity under moist conditions (Fig. 4). This seasonal variability in N content aligns with findings from tropical and temperate forests, where available N is typically highest during wet periods due to favorable conditions for nitrification and organic matter decomposition (Binkley and Fisher 2013). Lower N availability was observed in the summer, particularly at Site III ($558.49 \text{ kg ha}^{-1}$), when reduced moisture limits microbial activity and N cycling. Available P was significantly higher during the rainy season, reaching 20.37 kg ha^{-1} at Site I (Fig. 5). This pattern is consistent with studies from tropical rainforests, where P availability increases during wet seasons due to greater leaching and mineral weathering (Walker and Syers 1976). In contrast, summer P levels were lower across all sites, reflecting the reduced mobility of P under dry conditions. Similarly, available K levels followed a distinct seasonal trend, with the highest concentrations observed during the rainy season at Site IV ($120.66 \text{ kg ha}^{-1}$) (Fig. 6). The higher K levels during wet periods are attributed to the enhanced weathering of K-rich minerals, as observed in temperate and tropical soils (Hinsinger et al. 2006).

The relationship amongst soil physico-chemical properties

One of the most pronounced relationships was the strong negative correlation ($r = -0.998$) between BD and porosity, which underscores the inverse relationship where an increase in soil compaction leads to a reduction in pore space. This finding is consistent with observations in other forest ecosystems, such as mixed temperate forests, where soil compaction due to high BD has been shown to reduce air and water permeability, leading to lower porosity (Nazari et al. 2021). This relationship plays a critical role in

influencing root penetration, water movement, and microbial activity in forest soils (Hartmann et al. 2014).

WHC displayed a moderate positive correlation with porosity ($r = 0.521$) and a corresponding negative correlation with BD ($r = -0.521$). These relationships suggest that soils with greater porosity can retain more water, which is crucial for sustaining vegetation, particularly in montane ecosystems where water availability is seasonal. A study in natural forests of Northern India showed similar patterns, with higher WHC correlating with increased porosity and reduced BD (Gorems and Goshal 2020). This relationship between WHC and porosity is pivotal in forest ecosystems, especially during dry seasons, as higher water retention helps mitigate the impact of moisture deficits on plant growth and microbial activity.

SOC was positively correlated with SMC ($r = 0.760$) and available N ($r = 0.671$). This is consistent with the role of organic matter in enhancing soil structure, thereby improving water retention and nutrient availability. Forest soils rich in SOC tend to have better moisture-holding capacity, which facilitates higher microbial activity and nutrient cycling. These findings align with studies in temperate soils where SOC was found to improve SMC and N availability, leading to better plant productivity and soil health (Gangopadhyay 2023). SOC's role in regulating nutrient availability and moisture is critical in forest soils, as it directly influences plant productivity and ecosystem resilience to environmental stressors such as drought.

Available N demonstrated a strong positive correlation with soil pH ($r = 0.650$) and a moderate correlation with available P ($r = 0.538$). This suggests that N availability is influenced by soil acidity and P levels, as N mineralization tends to be more efficient in soils with neutral or slightly acidic pH (Paul 2015). In oak-dominated forests, where the decomposition of organic matter releases organic acids, the correlation between N and pH is particularly relevant. Similar findings have been reported in Mediterranean forest ecosystems, where N availability was closely linked to soil pH, as slightly acidic conditions promote microbial activity, which enhances N mineralization (Rodríguez et al. 2011). Furthermore, the correlation with available P suggests that N availability can be constrained by P dynamics, especially in nutrient-limited soils typical of high-altitude forest ecosystems.

SOC exhibited a very weak negative correlation with pH ($r = -0.086$), which is not statistically significant. This suggests that soil pH may not be a strong determinant of SOC variations in the studied sites (Fig. 7). The accumulation of organic acids from decomposing litter, which acidifies the soil (Weil and Brady 2016). In forest ecosystems, organic carbon inputs from leaf litter and root exudates are known to reduce soil pH, especially in soils with slower decomposition rates, as observed in montane and boreal forests (Sarıyıldız et al. 2005). Lastly, the negative correlation between

available K and pH ($r = -0.596$) implies that higher K concentrations are associated with lower pH values. This is consistent with the role of K in forest soils, where high K availability often coincides with acidic conditions, which can enhance cation exchange capacity and the solubility of K ions (Fageria 2012). Similar relationships have been noted in tropical rainforest ecosystems, where K mobility increases in more acidic soils, enhancing its availability to plants (Ernani et al. 2012).

Conclusions

The present study on the spatial and temporal variability of soil physico-chemical properties across altitudinal gradients revealed significant insights into how altitude, season, and soil depth interact to influence soil characteristics in *Quercus* dominated forests of western Arunachal Pradesh. The result showed that BD increased significantly ($p < 0.05$) with decreasing altitude, where the lowest elevation site (Site V, 1,693 m) exhibited the highest BD of 1.30 g cm^3 , while the highest elevation site (Site I, 1,801 m) showed the lowest BD of 1.23 g cm^3 . This trend suggests a relationship between altitude and soil compaction, likely exacerbated by anthropogenic activities at lower elevations. Conversely, soil porosity exhibited an inverse relationship with BD, with Site I showing the highest porosity (54%) and Site V the lowest (51%). Further, the study found that WHC and SMC were influenced by both altitude and seasonal variations, with Site V demonstrating the highest WHC (52%) and Site II showing the lowest moisture content (30%). Correlations among the soil characteristics were significant, particularly between BD and porosity ($r = -0.78$), and between SMC and WHC ($r = 0.83$), highlighting how these physical properties interrelate and respond to changes in altitude and environmental conditions.

Temporal analysis indicated significant seasonal variations ($p < 0.05$) in BD, WHC, and nutrient availability at different soil depths, reflecting the influence of rainfall patterns. Notably, BD was lowest during the rainy season, suggesting that increased moisture levels reduce soil compaction, while the summer months recorded the highest BD. The topsoil consistently exhibited higher WHC and SOC levels due to organic matter accumulation, positively correlating with nutrient availability for N, P, and K, which varied significantly across depths and seasons. Higher nutrient concentrations were observed during the rainy season, indicating that moisture enhances nutrient leaching and availability. These findings carry important implications for forest management practices, suggesting that soil conservation strategies should consider the spatio-temporal dynamics and interrelationships of soil properties to enhance forest soil health and ecosystem productivity. Understanding these relationships is crucial for developing ef-

fective forest management practices and conserving biodiversity, particularly in western Arunachal Pradesh which is vulnerable to climate change.

Supplementary Information

Supplementary information accompanies this paper at <https://doi.org/10.5141/jee.24.110>.

Fig. S1. Mean monthly variation in temperature and precipitation.

Abbreviations

BD: Bulk density

N: Nitrogen

P: Phosphorus

K: Potassium

WHC: Water holding capacity

SOC: Soil organic carbon

SMC: Soil moisture content

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Authors' contributions

YJS, LSL, and KSK conceived the original idea, designed the experiment. YJS performed field works, collected data, statistical analysis and prepared the manuscript. YJS and DB co-written the first draft and revised the manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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