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RESEARCH

Local scale variations in soil organic carbon sequestration in Lesser Himalayan coniferous and mixed forests: implications for sustainability

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Background: Soil carbon sequestration is a fundamental mechanism for mitigating climate change by capturing carbon dioxide from the atmosphere. Soils can store more carbon than both vegetation and the atmosphere combined. This study aims to quantify the organic carbon stock and evaluate various physicochemical properties of the soil to promote sustainability in the Lesser Himalayan subtropical coniferous and mixed forests of Muzaffarabad. Soil samples were collected from ten representative sites within each forest type, and soil organic carbon (SOC) was measured using the Walkley-Black method.
Results: The SOC averaged 63.86 ± 3.29 Mg ha^{-1} in coniferous forests and 50.05 ± 3.05 Mg ha^{-1} in mixed forests, with a total average of 56.95 ± 1.40 Mg ha^{-1}. SOC levels in coniferous forest soils ranged from 82.11 ± 6.52 Mg ha^{-1} to 48.63 ± 3.82 Mg ha^{-1}, while mixed forest ecosystems exhibited a SOC range of 62.29 ± 4.71 Mg ha^{-1} to 35.57 ± 2.34 Mg ha^{-1}. The average soil pH was 7.1 ± 0.14, whereas soil bulk density, and electrical conductivity were 1.1 ± 0.01 g cm^{-3} and 0.95 ± 0.07 dS m^{-1}, respectively. The sampled forests harboured 103 plant species from 48 families and 92 genera, with trees, shrubs, and herbaceous plants constituting 17%, 12%, and 71% of the flora, respectively.
Conclusions: Statistical analysis revealed a significant difference in SOC between coniferous and mixed forest types. The dominant plant families in the studied forests were Poaceae, Compositeae, Fabaceae, and Lamiaceae. The findings underscore the need for sustainable forest and soil management policies to enhance SOC levels. Implementing such policies is crucial for achieving the sustainable development goals related to environmental sustainability, economic development, and societal well-being.

Keywords: climate change, forests, *Pinus,* soil health, soil organic carbon, sustainability, sustainable development goals

Introduction

Human activities, such as fossil fuel combustion, deforestation, and land use changes, release significant amounts of greenhouse gases (GHGs) which intensify the GHG effect and global warming (Barati et al. 2023). This phenomenon induces alterations in atmospheric, oceanic, terrestrial, cryospheric, and biospheric dynamics by causing droughts, floods, food insecurity, and adverse impacts on human health (Abbass et al. 2022; IPCC 2021; Jansson and Wu 2023; Pathak 2023). In growing global warming scenario and the urgent need to achieve sustainable development goals (SDGs), it is necessary to understand and sustainably manage terrestrial ecosystems (Mujtaba et al. 2024; Xu et al. 2023). The global community acknowledges the urgent need to limit warming below 2°C and strive for worldwide net-zero emissions to prevent further environmental damage. Immediate actions are necessary to mitigate climate change impacts through both GHG emissions reduction and enhancing sequestration (Rogelj et al. 2023).

Terrestrial ecosystems globally encompass approximately 3170 gigatons of total carbon, of which nearly 80% of organic and inorganic carbon is sequestered in the soil. Notably, 73% of soil carbon is exclusively stored within forest ecosystems (Dinakaran et al. 2022; Dixon et al. 1994; Ontl and Schulte 2012; Sun and Liu 2020). The Kashmir Himalaya is an ecological hotspot with diverse forest cover where conifers constitute more than 70% of the total forest (Dar and Khuroo 2020; Dar and Parthasarathy 2022). Within these ecosystems, soil carbon levels indicate soil health, carbon sequestration potential, and overall ecosystem sustainability (Lee et al. 2023). A sophisticated equilibrium between mixed and coniferous forests in Kashmir not only enhances the regional biodiversity but also influences its carbon dynamics (Dar and Parthasarathy 2022; Shaheen et al. 2016).

The dynamics of soil carbon stock in forest ecosystems are influenced by a multitude of factors like forest succession, vegetation characteristics, environmental conditions, historical land use patterns, current land management strategies, topographic variations, biomass extraction, slope, elevation, aspect, soil texture, mineralogy, and physicochemical properties (Ibrahim et al. 2023; Mishra et al. 2023; Shi et al. 2023). The composition and features of the vegetation, such as age, terrain, elevation, canopy closure, diameter at breast height, tree height, stand density, and plant biomass inputs also exert a significant influence on soil carbon stock density (Ali et al. 2023; Wu et al. 2024). Climatic factors such as temperature and precipitation, along with the subsequent microbial decomposition of biomass, significantly influence the accumulation of soil carbon stocks (Liu et al. 2023; Puche et al. 2023; Song et al. 2017).

Research has shown that soil physicochemical properties can influence soil organic carbon (SOC) dynamics (Ibrahim et al. 2023; Li et al. 2020; Mishra et al. 2023; Yao et al. 2023). Biochemical and physical conditions like pH, organic matter, nutrient bioavailability, and minerals are key indicators of soil health soil which can either retain or deplete SOC (Horwath 2024; Miao et al. 2022; Philippot et al. 2024; Sharma et al. 2023; Zhao et al. 2023). SOC stabilization mechanisms involve soil structural and textural properties like clay and metal oxides, particularly observed in subtropical forests with high SOC accumulation rates (Feyissa et al. 2023).

SDGs comprise 17 goals established by the United Nations General Assembly in 2015 and cover a global framework for collective efforts to achieve a sustainable future (United Nations 2015; Shulla and Leal-Filho 2022). Global efforts for climate change and SDGs prioritize local-scale SOC stock assessments to plan climate actions, biodiversity conservation, responsible production, sensible consumption, and sustainable development partnerships (Dagnachew et al. 2021; Fallah Shayan et al. 2022; Mishra et al. 2023). The localization of SDGs involves the customization of the 2030 Agenda to address local challenges by defining, implementing, and monitoring SDGs at a local level. The establishment of local SDGs is vital to creating a sustainable management model that integrates social justice, economic growth, and institutional reinforcement (United Nations 2015).

A soil-based carbon economy can combat climate change by boosting local soil carbon storage and supporting global carbon offset programs like UN-REDD^{+} (Reducing emissions from deforestation and forest degradation). This strategy yields environmental, social, and economic benefits (Begum 2020; Keenor et al. 2021; Michel et al. 2015). The success of these initiatives depends on local soil carbon assessment, implementation of payment systems, and management of site-specific conditions for viable SOC conservation (Keenor et al. 2021; Morita and Matsumoto 2023; Nantongo et al. 2024; Sunderlin et al. 2024).

This study aimed to measure both the overall and varying levels of SOC in narrow yet ecologically rich subtropical coniferous (*Pinus roxburghii* Sarg.) and mixed forest ecosystems in Kashmir Himalaya. It aligns with multiple SDGs, particularly those related to environmental conservation, sustainable land use and community development in a biodiverse region. This emphasizes the importance of local-scale SOC dynamics and undertaking appropriate actions to achieve relevant SDGs. Additionally, it addresses climate change challenges through sustainable mitigation solutions, offers guidelines for policy interventions and highlights the need for socio-economic considerations of forest soil conservation.

Materials and Methods

Study area

This study was conducted in District Muzaffarabad, the capital of Azad Jammu and Kashmir covering a total area of 1,642 Km^2. The study sites were spanning between 34°09.330 to 34°26.540 N Latitude and 73°23.570 to 73°36.410 E Longitude. The district exhibits varying elevation range, with the southern region at an average height of 360 m above sea level and the northern region rising to 6,325 m. The region experiences a subtropical monsoon climate in lower areas, transitioning to a moist temperate climate and eventually a subalpine to alpine climate in higher altitudes. Muzaffarabad faces peak rainfall in July and March, while November usually remains the driest month. The most significant precipitation occurs from February to April in spring and during the monsoon months of July and August. July is the warmest while January records the coldest temperatures (Ashraf et al. 2012; GoAJK 2017). Muzaffarabad is facing a growing vulnerability to climate change, demonstrated by rising temperatures and shifting rainfall patterns. The average maximum temperature in the study region increased from 25°C to 27°C, while the average minimum temperature rose from 12.0°C to 13.0°C during the same period. The annual average precipitation changed from 1,086 mm in 1962 to 1,340 mm in 2013. Future projections indicate a 1.4°C increase in average temperature by 2060 and a 3.0°C increase by 2100 in Muzaffarabad (GoAJK 2017).

Site selection and sampling

A total of ten study sites were selected in the subtropical region of Muzaffarabad district based on ecologically significant forest types including coniferous and mixed forests. Distinctive stands of pure *Pinus roxburghii* and mixed forests were identified in the study area. The altitude, latitude and longitude of each forest site were recorded by using a GPS device. Site 1 (Chatter Kalas) was situated at an altitude of 662 m and the elevation gradually increased across the subsequent sampling locations. Site 2 (Khairabad) stands at 873 m, followed by Site 3 (Darna) at 910 m, Site 4 (Davlian) at 992 m and Site 5 (Panjgran) at 1,006 m. The altitude continues to ascend through Site 6 (Chanjla) at 1,050 m, Site 7 (Kapabut) at 1,060 m, Site 8 (Noseri) at 1,177 m, Site 9 (Pattika) at 1,287 m, and peaks at Site 10 (Niazpura) with an elevation of 1,450 m (Fig. 1).

Soil sampling was independently conducted (from October 2022 to April 2023) in both the coniferous and mixed forests at each site. SOC was determined through samples collected from the default depth of 30 cm prescribed by the IPCC (2006). At each of the selected sites, five distinct plots (of 5 m^2) were established, separately for pine-dominated and mixed forest patches. Local vegetation in established plots was identified and categorized by habit and family. Soil sampling was conducted using a soil core sampler, reaching a depth of 30 cm. Within each forest plot, we collected a total of 5 samples to ensure quality. This comprised 4 samples from the plot corners and 1 sample from the centre.

Soil samples collected in polythene bags were transported to the Plant Ecology and Environmental Science Laboratory, Department of Botany, The University of Azad Jammu and Kashmir. There, they were combined to form composite soil samples for each of the five plots at every site. A total of 100 soil samples (1 mixed sample for each plot × 5 plots per forest types × 2 forest types × 10 sites) were subjected to the analysis of SOC and soil physicochemical attributes (Cihacek et al. 2014; Mosissa and Wakjira 2021). Bulk density (BD) was separately estimated using a core sampler with a diameter of 1.27 cm and a length of 30 cm (Vereecken et al. 1989).

Determination of soil carbon and physicochemical properties

SOC was estimated by using the Walkley and Black (1934) method as it is widely used in many laboratories because it is rapid and affordable. Equipment used for soil carbon analysis included analytical balance (with the resolution of 0.01 g), graduated flask, fume hood, titration stand and burette. Reagents required for analysis include 0.16 M potassium dichromate ($K_2Cr_2O_7$), 1.0 M ferrous sulphate ($FeSO_4 .7H_2O$), diphenylamine indicator, deionized water, concentrated sulphuric acid (H_2SO_4). The percentage of soil organic matter (SOM) was calculated by the following formula.

$$\mathrm{SOM}\ (\%) = (1 - \mathrm{S}/\mathrm{B}) \times 10 \times 0.68$$ (Sá et al. 2001).

SOC was calculated from SOM by dividing with conversion factor 2 (Pribyl 2010).

$$\mathrm{SOC}\ (\%) = \frac{\text{Organic Matter }\%}{2}$$

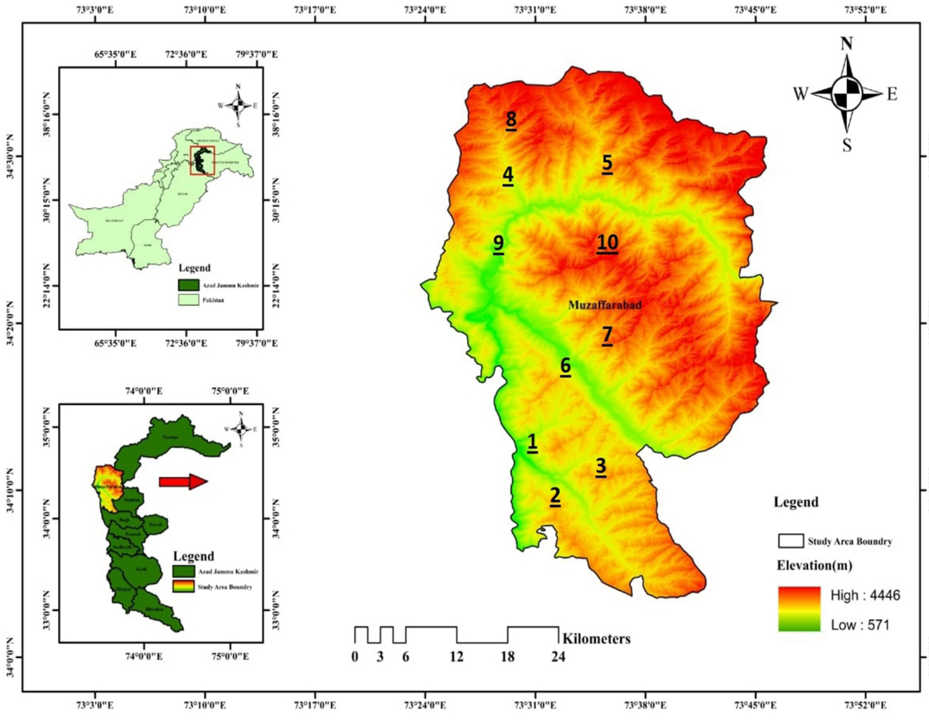

Fig. 1 Map of the study area indicating sampling sites (1 = Chatter Kalas, 2 = Khairabad, 3 = Darna, 4 = Davlian, 5 = Panjgran, 6 = Chanjla, 7 = Kapabut, 8 = Noseri, 9 = Pattika, and 10 = Niazpura) in Muzaffarabad district.

For the calculation of soil bulk density (g/cm^3), the following procedure was used (Black and Hartge 1986).

$$\mathrm{BD}\ (\mathrm{g/cm^3}) = \frac{\text{Weight of oven dried soil}}{\text{Volume of core sampler}}$$

After the calculation of BD, the percentage of carbon was converted into total SOC stock ton/ha by using the following equation (Sá et al. 2001).

$$\mathrm{SOC}\ (\mathrm{Mg\ ha^{-1}}) = \text{Organic Carbon}\ \% \times \text{Soil Bulk Density}\ (\mathrm{g/cm^3}) \times \text{Soil depth (cm)}$$

Soil physicochemical properties including pH and electrical conductivity (EC) were assessed using a pH/EC meter. After 24 hours of aeration, soil samples were crumbled within plastic bags to disintegrate any clumps and thoroughly mixed. Subsequently, 20 mg of soil was weighed into a beaker, and 100 mL of distilled water was added. The mixture was shaken for two minutes and allowed to settle for 5 minutes (Hoskins and Ross 2009). The pH and EC values were recorded by immersing the electrode 1–2 cm into the sample solution while soil texture was determined through a simple jar test by calculating the percentages of sand, silt, and clay. Once these percentages were obtained, the soil textural triangle was utilized to identify the soil type (Plante et al. 2006).

Data analysis

The analysis of multivariate data encompassed principal component analysis (PCA) utilizing nine variables, including SOC, BD, pH, and EC (separately for coniferous and mixed forests), in addition to altitude. These variables were used to derive the standardized principal components using *prcomp* function in R software v.4.4.1 (R Core Team 2024). The PCA results were visualized through a biplot generated using the *fviz_pca_biplot* function from the *factoextra* package (Kassambara and Mundt 2020). The *circlize* package (Gu 2020) was used to illustrate the soil properties and their relationships among different sites. The data were subjected to analysis of variance (ANOVA) to assess differences in soil physicochemical properties between coniferous and mixed forest groups. Bivariate regression analysis was also conducted to assess the independent relationships between mean values of SOC and each of the soil physicochemical properties (BD, pH, EC) and altitude. The significance of the regression coefficients was evaluated using t-tests.

Results

The investigation into SOC stocks within subtropical coniferous forests revealed an average of 56.95 ± 1.40 Mg ha^{-1}. The site-wise ANOVA analysis conducted on SOC levels revealed a spatial heterogeneity with significant variations in SOC between the pine and mixed forest groups. Specifically, sites 1, 4, 7, and 9 emerged as focal points of interest, exhibiting statistically significant differences in SOC levels between the two groups ($p < 0.05$). Conversely, sites 2, 5, 6, 8, and 10 displayed comparable SOC levels between the forest types, with p-values exceeding the conventional threshold (Table 1).

Site 4 demonstrated the highest SOC stock at 67.45 ± 3.16 Mg ha^{-1}, while site 7 recorded the lowest at 51.64 ± 2.12 Mg ha^{-1} (Fig. 2). In the context of coniferous forest soil samples, the average total SOC was 63.86 ± 3.29 Mg ha^{-1}. Site 4 exhibited the highest SOC value of 82.11 ± 6.52 Mg ha^{-1}, while site 2 recorded the lowest at 48.63 ± 3.82 Mg ha^{-1}. Across diverse mixed forest sites, the average SOC was documented at 50.05 ± 3.05 Mg ha^{-1}. Site 5 presented the highest SOC value at 62.29 ± 4.71 Mg ha^{-1}, while site 6 recorded the lowest at 35.57 ± 2.34 Mg ha^{-1} (Table 2).

The average SOC content within the subtropical coniferous and mixed forests was determined to be 1.73 ± 0.03%, exhibiting a range from 1.6 ± 0.04% at site 3 to 1.96 ±

Table 1 SOC variation between coniferous and mixed forests with ANOVA results

Site	SOC (Mg ha^{-1}) variations in coniferous vs. mixed forest		Sum Sq	Mean Sq	F value	p-value
	Coniferous forest	Mixed forest				
1	+34.6	–17.31	149.818	150	11.671	0.00578
2	–10.4	+5.22	13.624	13.6	1.063	0.32422
3	+20.7	–10.34	53.458	53.5	4.168	0.06462
4	+29.3	–14.66	107.458	107	8.375	0.01576
5	–5.39	+2.69	3.618	3.62	0.282	0.61144
6	–8.25	+4.13	8.528	8.53	0.665	0.4335
7	+32.1	–16.06	128.962	129	10.047	0.00835
8	+8.17	–4.08	8.323	8.32	0.649	0.43698
9	+31.6	–15.79	124.662	125	9.72	0.01036
10	+5.66	–2.83	4.004	4	0.312	0.586

SOC: soil organic carbon; ANOVA: analysis of variance.

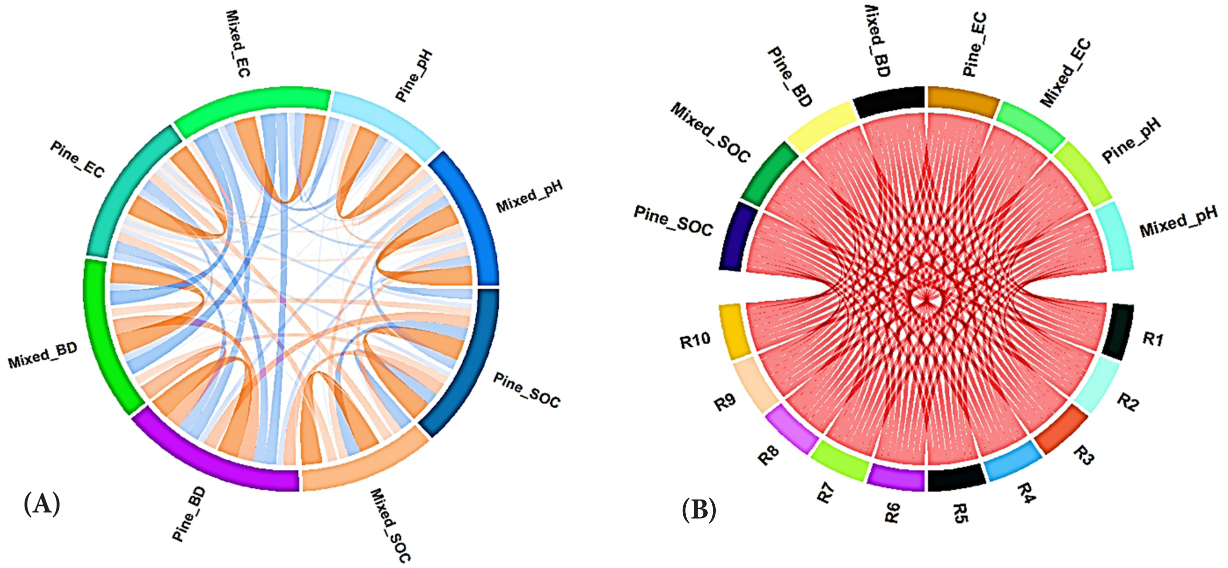

Fig. 2 (A) Correlation matrix and (B) site-wise distribution of soil physicochemical properties in subtropical coniferous and mixed forests. BD: bulk density; EC: electrical conductivity; SOC: soil organic carbon.

Table 2 Soil organic carbon (SOC) stock in subtropical coniferous and mixed forests

Site	Coniferous forests			Mixed forests		
	SOM %	SOC %	SOC Mg ha^{-1}	SOM %	SOC %	SOC Mg ha^{-1}
1	4.25 ± 0.41	2.13 ± 0.24	73.95 ± 4.61	2.26 ± 0.04	1.13 ± 0.18	39.32 ± 2.81
2	3.03 ± 0.31	1.52 ± 0.12	48.63 ± 3.82	2.94 ± 0.57	1.84 ± 0.13	59.06 ± 3.28
3	3.8 ± 0.42	1.90 ± 0.61	64.41 ± 2.81	2.58 ± 0.66	1.29 ± 0.03	43.73 ± 2.54
4	4.76 ± 0.72	2.38 ± 0.71	82.11 ± 6.52	3.03 ± 0.41	1.53 ± 0.09	52.79 ± 3.64
5	3.48 ± 0.32	1.74 ± 0.42	56.9 ± 4.36	3.81 ± 0.17	1.91 ± 0.71	62.29 ± 4.71
6	3.24 ± 0.27	1.62 ± 0.37	53.46 ± 4.54	3.72 ± 0.73	1.87 ± 0.06	61.71 ± 3.55
7	4.34 ± 0.71	2.17 ± 0.24	67.7 ± 3.83	2.27 ± 0.44	1.14 ± 0.09	35.57 ± 2.34
8	3.72 ± 0.32	1.86 ± 0.07	57.47 ± 3.11	2.74 ± 0.23	1.58 ± 0.07	49.3 ± 3.43
9	4.52 ± 0.27	2.26 ± 0.08	73.22 ± 5.58	2.57 ± 0.05	1.29 ± 0.13	41.63 ± 2.63
10	3.52 ± 0.32	1.76 ± 0.06	60.72 ± 3.22	3.22 ± 0.72	1.61 ± 0.15	55.06 ± 3.73
Average	3.87 ± 0.18	1.93 ± 0.09	63.86 ± 3.29	2.91 ± 0.17	1.52 ± 0.09	50.05 ± 3.05

Values are presented as mean ± standard deviation.
SOM: soil organic matter.

0.15% at site 4 (Fig. 2). In specific context of subtropical coniferous forests, the average SOC content of 1.93 ± 0.09% varied from 1.52 ± 0.12% at site 2 to 2.38 ± 0.71% at site 4. Meanwhile, within the mixed forest ecosystem, the average SOC content showed fluctuations from 1.13 ± 0.18% at site 1 to 1.91 ± 0.71% at site 5, resulting in an overall average of 1.52 ± 0.09% (Table 2).

The average SOM content within both subtropical forest types exhibited variations, ranging from 2.99 ± 0.23% at site 2 to 3.65 ± 0.51% at site 5, resulting in an overall average of 3.39 ± 0.08% (Fig. 2). Specifically, within subtropical coniferous forests, the average SOM content was determined to be 3.87 ± 0.18%, with fluctuations from 3.03 ± 0.31% at site 2 to 4.76 ± 0.72% at site 4. Likewise, the average SOM content for all mixed forests was appraised at 2.91 ± 0.17%, showing fluctuations between the highest value of 3.81 ± 0.17% at site 5 and the lowest at 2.26 ± 0.04% at site 1 (Table 2).

Soil physicochemical properties in subtropical forests

In subtropical coniferous and mixed forests, the average soil BD was calculated as 1.1 ± 0.01 g cm^{-3}. Site 1 displayed the highest average BD at 1.16 ± 0.05 g cm^{-3}, while site 8 exhibited the lowest at 1.03 ± 0.01 g cm^{-3} (Fig. 2). The average soil pH in these forests was noted at 7.1 ± 0.14, showing subtle variations across different sites. Site 5 exhibited the highest pH value at 7.46 ± 0.23, suggesting slightly alkaline conditions, whereas site 9 recorded the lowest pH at 6.49 ± 0.18, indicative of a more neutral to slightly acidic environment (Fig. 2).

In most soil samples from subtropical coniferous forests, acidity prevailed, evidenced by an average soil pH of 6.91 ± 0.13. Site-specific pH levels varied from the maximum of 7.11 ± 0.21 at site 5 to the minimum of 6.7 ± 0.08, at site 1. In subtropical mixed forests, most soil samples exhibited marginally alkaline characteristics, as indicated by the average soil pH of 7.24 ± 0.20. The highest pH value of 8.4 ± 0.33 was calculated at site 3, indicative of highly alkaline conditions. Conversely, the lowest pH value, recorded as 6.18 ± 0.52 was observed at site 9, suggesting a comparatively more neutral to slightly acidic environment (Table 3). In terms of EC, the average value for subtropical coniferous and mixed forests was precisely determined at 0.95 ± 0.07 dS m^{-1}. Site 7 demonstrated the highest EC value at 1.26 ± 0.04 dS m^{-1}, indicating elevated ion concentration, while site 3 recorded the lowest at 0.59 ± 0.01 dS m^{-1}, presenting relatively lower ion content in the soil solution (Fig. 2).

The average soil EC in subtropical coniferous forests was determined to be 1.1 ± 0.07 dS m^{-1}. Site 7 recorded the maximum EC value at 1.36 ± 0.12 dS m^{-1}, while site 1 exhibited the minimum at 0.62 ± 0.02 dS m^{-1}. Within the subtropical mixed forests, the average soil EC was quantified at 0.81 ± 0.1 dS m^{-1}. Further exploration revealed distinct conductivity levels at different sites, with the highest EC, calculated at 1.16 ± 0.09 dS m^{-1} at site 7. In contrast, the lowest EC, recorded at 0.23 ± 0.01 dS m^{-1}, was observed at site 3 (Table 3).

Principal component analysis

PCA was conducted to explore the collective relationship in soil characteristics across ten sites. The analysis revealed that the first four principal components collectively accounted for over 90% of the total variance in the dataset. PC1, with an eigenvalue of 3.05 explained 35.9% of the variance and represented variations in SOC and BD. PC2, with an eigenvalue of 2.45 explained 22.6% of the variance and captured variations in pH and EC. PC3 and PC4, with eigenvalues of 1.42 and 1.24 respectively, accounted for additional variability related to altitude. The biplot visualization reflects the relationships between soil physicochemical characteristics and the study sites. Each site displayed distinctive loadings on the principal components by reflecting specific associations between soil characteristics and study site (Fig. 3).

Floristic composition

The floristic composition assessment in both forest types identified a total of 103 plant species distributed across 48 plant families and 92 genera. The vegetation comprised 19 tree species, 14 shrub species, and 80 herbaceous species, accounting for 17%, 12%, and 71% of the total flora, respectively. Dominant plant families included Poaceae (11 species), Compositeae (10 species), Fabaceae (8 species) and Lamiaceae (7 species). Other noteworthy families such as Polygonaceae, Pteridaceae, Moraceae, Amaranthaceae, Oxalidaceae and Rosaceae also played substantial roles in shaping the floristic composition (Table 4).

Discussion

Forest soils are important carbon sinks mitigating climate change by moderating atmospheric CO_2 concentrations. It is desirable to investigate the influence of soil properties like texture, structure, pH, and microbial activity on SOC storage in natural ecosystems (Horwath 2024; Miao et al. 2022; Sharma et al. 2023). Across ten sites of co-

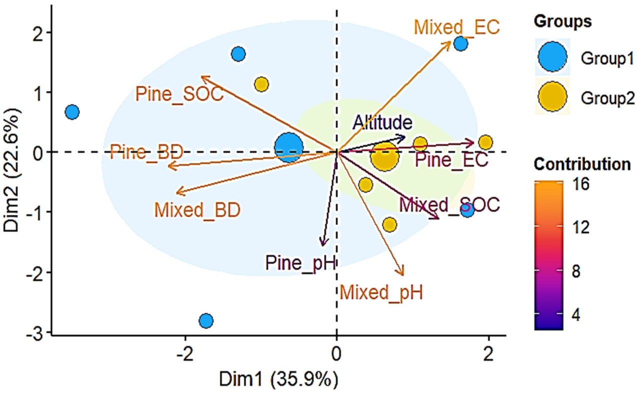

Fig. 3 PCA biplot of soil physicochemical characteristics. PCA: principal component analysis; BD: bulk density; EC: electrical conductivity; SOC: soil organic carbon.

Table 3 Soil pH and EC in subtropical coniferous and mixed forests

Site	Coniferous forests		Mixed forests	
	pH	EC (dS m^{-1})	pH	EC (dS m^{-1})
1	6.7 ± 0.22	0.62 ± 0.02	6.52 ± 0.44	0.64 ± 0.07
2	6.16 ± 0.26	1.2 ± 0.14	7.67 ± 0.36	1.12 ± 0.15
3	7.6 ± 0.43	0.94 ± 0.08	8.4 ± 0.33	0.23 ± 0.01
4	6.48 ± 0.33	1.27 ± 0.18	7.12 ± 0.42	0.96 ± 0.05
5	7.11 ± 0.21	1.16 ± 0.08	7.8 ± 0.32	0.87 ± 0.07
6	6.98 ± 0.34	1.32 ± 0.06	7.23 ± 0.43	0.59 ± 0.02
7	6.84 ± 0.22	1.36 ± 0.12	7.03 ± 0.17	1.16 ± 0.09
8	7.4 ± 0.11	0.89 ± 0.07	7.23 ± 0.65	1.14 ± 0.12
9	6.8 ± 0.13	0.98 ± 0.04	6.18 ± 0.52	0.83 ± 0.18
10	7.02 ± 0.28	1.23 ± 0.11	7.17 ± 0.25	0.58 ± 0.03
Average	6.91 ± 0.13	1.1 ± 0.07	7.24 ± 0.20	0.81 ± 0.1

Values are presented as mean ± standard deviation.
EC: electrical conductivity.

Table 4 Floristic composition of the study area: species name, habit, and family

No.	Species name	Habit	Family
1	*Acacia nilotica* (L.) Willd. ex Delile	Tree	Fabaceae
2	*Achillea millefolium* L.	Herb	Compositae
3	*Adiantum andicola* Liebm.	Herb	Pteridaceae
4	*Adiantum incisum* Forssk.	Herb	Pteridaceae
5	*Adiantum venustum* L.	Herb	Pteridaceae
6	*Ailanthus altissima* (Mill.) Swingle	Tree	Simaroubaceae
7	*Ajuga integrifolia* Buch.-Ham.	Herb	Lamiaceae
8	*Alcea rosea* L.	Herb	Malvaceae
9	*Amaranthus viridis* L.	Herb	Amaranthaceae
10	*Andropogon appendiculatus* Nees	Herb	Poaceae
11	*Artemisia vulgaris* L.	Herb	Compositae
12	*Avena barbata* Pott ex Link	Herb	Poaceae
13	*Azadirachta indica* A. Juss	Tree	Meliaceae
14	*Berberis lycium* Royle	Shrub	Berberidaceae
15	*Bidens alba* DC.	Herb	Compositae
16	*Broussonetia papyrifera* (L.) Vent.	Tree	Moraceae
17	*Callicarpa macrophylla* Vahl	Herb	Lamiaceae
18	*Campanula carpatica* Jacq.	Herb	Campanulaceae
19	*Colebrookea oppositifolia* Sm.	Shrub	Lamiaceae
20	*Cannabis sativa* L.	Herb	Cannabaceae
21	*Capsella bursa*-pastoris Medik.	Herb	Brassicaceae
22	*Carrisa opaca* L.	Herb	Apocynaceae
23	*Celtis australis* L.	Tree	Cannabaceae
24	*Chenopodium album* L.	Herb	Amaranthaceae
25	*Cirsium arvense* (L.) Scop.	Herb	Compositae
26	*Commelina benghalensis* L.	Herb	Commelinaceae
27	*Convolvulus arvensis* L.	Herb	Convolvulaceae
28	*Cynodon dactylon* (L.) Pers.	Herb	Poaceae
29	*Cynoglossum lanceolatum* Forssk.	Herb	Boraginaceae
30	*Cyperus rotundus* L.	Herb	Cyperaceae
31	*Dalbergia cana* var. kurzii (Prain) Niyomdham	Tree	Fabaceae
32	*Diospyros lotus* L.	Tree	Ebenaceae
33	*Dodonaea viscosa* Jacq.	Shrub	Sapindaceae
34	*Dracaena roxburghiana* (Schult. & Schult.f.) Byng & Christenh.	Herb	Asparagaceae
35	*Desmodium elegans* f. albiflorum (P.Li) H.Ohashi	Shrub	Fabaceae
36	*Dryopteris filix-mas* (L.) Schott	Herb	Dryopteridaceae
37	*Dysphania ambrosioides* (L.) Mosyakin & Clemants	Herb	Amaranthaceae
38	*Eragrostis tremula* (Lam.) Hochst. ex Steud.	Herb	Poaceae
39	*Erigeron bonariensis* L.	Herb	Compositae
40	*Erigeron canadensis* L.	Herb	Compositae
41	*Eriophorum comosum* Nees	Herb	Cyperaceae
42	*Euphorbia helioscopia* L.	Herb	Euphorbiaceae
43	*Euphorbia prostrata* Aiton	Herb	Euphorbiaceae
44	*Ficus carica* L.	Tree	Moraceae
45	*Ficus palmata* Forssk.	Tree	Moraceae
46	*Fragaria vesca* L.	Herb	Rosaceae
47	*Hedera helix* L.	Herb	Araliaceae
48	*Imperata cylindrica* (L.) P.Beauv.	Herb	Poaceae
49	*Indigofera heterantha* Wall. ex-Brandis	Shrub	Fabaceae
50	*Isodon rugosus* (Wall.) Codd	Shrub	Lamiaceae
51	*Juncus inflexus* L.	Herb	Juncaceae
52	*Justicia adhatoda* L.	Shrub	Acanthaceae
53	*Leptopus cordifolius* Decne.	Shrub	Phyllanthaceae
54	*Lespedeza juncea* (L.f.) Pers.	Herb	Fabaceae
55	*Leucas urticifolia* (Vahl) Sm.	Herb	Lamiaceae
56	*Lindelofia longiflora* Baill.	Herb	Boraginaceae
57	*Lonicera acuminata* Wall.	Herb	Caprifoliaceae
58	*Lonicera japonica* Thunb.	Shrub	Caprifoliaceae
59	*Malva sylvestris* L.	Herb	Malvaceae

Table 4 Continued

No.	Species name	Habit	Family
60	*Medicago polymorpha* L.	Herb	Fabaceae
61	*Mentha arvensis* L.	Herb	Lamiaceae
62	*Micromeria biflora* Benth.	Herb	Lamiaceae
63	*Morus alba* L.	Tree	Moraceae
64	*Myrsine africana* L.	Shrub	Primulaceae
65	*Nepeta cataria* L.	Herb	Lamiaceae
66	*Oenothera rosea* Aiton	Herb	Onagraceae
67	*Olea europaea* L.	Tree	Oleaceae
68	*Otostegia* Benth.	Herb	Lamiaceae
69	*Oxalis corniculata* L.	Herb	Oxalidaceae
70	*Oxalis latifolia* Kunth	Herb	Oxalidaceae
71	*Oxalis stricta* L.	Herb	Oxalidaceae
72	*Parthenium hysterophorus* Adans.	Herb	Compositae
73	*Phalaris arundinacea* L.	Herb	Poaceae
74	*Phalaris canariensis* L.	Herb	Poaceae
75	*Pinus roxburghii* Sarg.	Tree	Pinaceae
76	*Pinus wallichiana* A.B.Jacks.	Tree	Pinaceae
77	*Plantago lanceolata* L.	Herb	Plantaginaceae
78	*Plantago major* L.	Herb	Plantaginaceae
79	*Poa annua* L.	Herb	Poaceae
80	*Polygonum aviculare* L.	Herb	Polygonaceae
81	*Polygonum erectum* L.	Herb	Polygonaceae
82	*Populus alba* L.	Tree	Salicaceae
83	*Pteris cretica* L.	Herb	Pteridaceae
84	*Punica granatum* L.	Shrub	Lythraceae
85	*Pyrus pashia* Buch.-Ham. ex D.Don	Tree	Rosaceae
86	*Quercus robur* L.	Tree	Fagaceae
87	*Rhus cotinus* L.	Shrub	Anacardiaceae
88	*Rubus plicatus* Weihe & Nees	Shrub	Rosaceae
89	*Rumex hastatus* D.Don	Herb	Polygonaceae
90	*Rumex nepalensis* Spreng.	Herb	Polygonaceae
91	*Sarcococca saligna* Müll.Arg.	Shrub	Buxaceae
92	*Senegalia modesta* (Wall.) P.J.H.Hurter	Tree	Fabaceae
93	*Setaria viridis* (L.) P.Beauv.	Herb	Poaceae
94	*Solanum nigrum* Acerbi ex Dunal	Herb	Solanaceae
95	*Sonchus oleraceus* L.	Herb	Compositae
96	*Tagetes minuta L.*	Herb	Compositae
97	*Taraxacum campylodes G.E.Haglund*	Herb	Compositae
98	*Themeda anathera* Hack.	Herb	Poaceae
99	*Trifolium repens* L.	Herb	Fabaceae
100	*Verbascum thapsus* L.	Herb	Scrophulariaceae
101	*Verbena urticifolia* L.	Herb	Verbenaceae
102	*Zanthoxylum armatum* DC.	Shrub	Rutaceae
103	*Ziziphus jujuba* Mill.	Tree	Rhamnaceae

niferous and mixed forests, we assessed SOC pools to elucidate ecological heterogeneity in the context of climate change. Our findings reveal significant local and site-specific variability in SOC for an improved understanding of forest dynamics and effective carbon management strategies.

Local scale variations in SOC levels

SOC levels differ across broad spatial ranges, local scale variations in SOC can exert significant effects on sustainability by affecting the capacity of soils to sequester carbon and support ecosystem services (Hertel et al. 2023). The ANOVA unveiled a significant dissimilarity in SOC content within the studied forest types (F = 14.187, p = 0.04) where coniferous forests exhibited substantially higher levels compared to mixed forests (Fig. 4).

The examination of soil BD revealed no significant distinction between coniferous and mixed forests, suggesting a comparable soil compaction status across both ecosystems. Similarly, analyses of pH (F = 0.938, p = 0.37) and EC (F = 1.869, p = 0.26) also yielded non-significant results, showing uniform soil acidity and salinity levels irre-

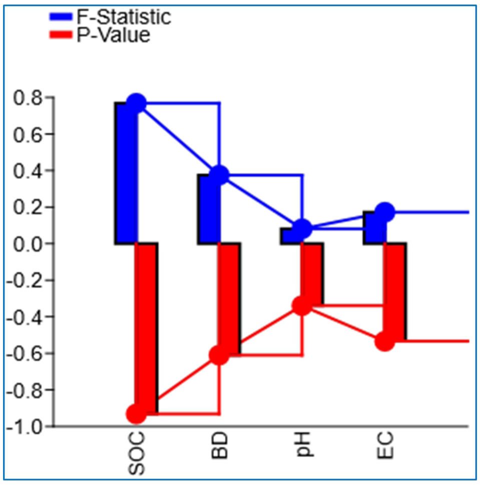

Fig. 4 ANOVA of soil physicochemical properties. ANOVA: analysis of variance; BD: bulk density; EC: electrical conductivity; SOC: soil organic carbon.

spective of forest type (Fig. 4). Despite the correlation between forest composition and SOC dynamics, other attributes showed minimal variation since the area experiences uniform exposure to anthropogenic disturbances and is primarily influenced by climatic conditions (Wani et al. 2023).

Forest soils differ fundamentally from conventional soils due to factors such as deep-rooted trees, microbial interactions, and human-induced disturbances, all of which impact SOC accumulation (Joshi and Garkoti 2023). Coniferous and mixed forests each have unique soil properties that shape their SOC dynamics, with variations influenced by factors such as tree type, soil composition, and environmental conditions (Jandl et al. 2021).

Site-specific disparities elucidated that coniferous forests demonstrated higher SOC levels than mixed subtropical forests, with notable discrepancies. Specifically, at site 1, the SOC in coniferous forests exceeded that of mixed forests by 34.63 Mg ha^{-1}, and similarly, at sites 3 and 4, the disparities amounted to 20.68 and 29.32 Mg ha^{-1}, respectively. Additionally, discernible increases in SOC were observed at sites 7, 8, 9, and 10, registering values of 32.13, 8.17, 31.59, and 5.66 Mg ha^{-1}, respectively. Within the coniferous forests, specific sites, notably site 4, and site 1 stand out as prototypes that manifest the highest levels of SOM and SOC.

Conversely, some mixed forests exhibited marginal increases in SOC compared to coniferous forests with variations of up to 10.43 Mg ha^{-1} at site 2: 5.39 Mg ha^{-1} at site 5, and 8.25 Mg ha^{-1} at site 6. However, the observed disparities remained relatively modest. Within the mixed forests, site 5 stands out prominently by exhibiting the highest levels of SOM and SOC. This site exemplifies an optimal state of the soil carbon pool within mixed forests and portrays the richness of SOC and the multifunctional capacity of mixed forests to support both biodiversity and carbon sequestration (Pinnschmidt et al. 2023). Site 7 presented an intriguing scenario with elevated SOM but a relatively lower SOC. This observation emphasizes the factors influencing decomposition rates and ultimately soil carbon dynamics within mixed forests (Shaheen et al. 2016; Zhang et al. 2021).

Factors influencing SOC in coniferous and mixed forest ecosystems

Several factors influence SOC, including vegetation type and characteristics, soil texture and pH, microbial activity, climatic conditions, topography, land use practices, biodiversity, canopy cover, and natural or anthropogenic disturbances. These factors interact to regulate SOC storage, decomposition, and stability across ecosystems (Ibrahim et al. 2023; Li et al. 2020; Yao et al. 2023). Microclimatic conditions contribute to microscale heterogeneity and shape microhabitats, influencing factors such as soil moisture variation, nutrient distribution, and local topographic features, which collectively impact SOC storage at small spatial scales (von Haden et al. 2019). Areas with favourable conditions such as optimal soil moisture, nutrient availability, and textures conducive to carbon retention tend to store higher amounts of SOC. For example, sites 1 and 4 within coniferous forests exhibit higher SOC stocks due to the advantageous combination of these factors (Almeida et al. 2021; Getino-Álvarez et al. 2023).

Furthermore, topographic and climatic factors also play pivotal roles in SOC dynamics. Local climate conditions, including temperature and precipitation, significantly affect the rate of organic matter decomposition and SOC stability. For instance, increased precipitation can promote more vigorous plant growth and litterfall, while lower temperatures slow down microbial activity, leading to greater carbon storage in soils (Liu et al. 2023; Song et al. 2017). These findings align with studies across sites 7, 8, and 9, emphasising the influence of local environmental conditions such as shrubby and herbaceous diversity, temperature, and soil properties on SOC stability. Stable conditions in these sites, where soil moisture was abundant, nutrient availability was higher, and microbial activity was expected to be moderate, led to increased carbon sequestration (Diers et al. 2021; Puche et al. 2023).

Site-specific variations in SOC levels within coniferous forests reveal the complexity of SOC dynamics, demonstrating that both macroclimatic factors (e.g., regional climate patterns) and microclimatic factors (e.g., local temperature and moisture conditions) are crucial in determining organic matter turnover rates and SOC sequestration efficiency (Devi 2021; Kerr and Ochsner 2020). SOC levels in coniferous forests are also influenced by several interrelated factors, including needle litter decomposition and the release of root exudates that contribute to the enhancement of SOC. Needle litter decomposition is slower compared to broadleaf litter, which can lead to a higher accumulation of organic matter in the soil over time. Additionally, the release of root exudates from coniferous trees plays a role in nutrient cycling and organic matter input, influencing SOC dynamics (Adalina and Sawitri 2021; Jandl et al. 2021).

Topographic factors such as elevation, slope, and drainage also have a significant influence on SOC distribution in both coniferous and mixed forests. Higher elevations tend to accumulate more SOC due to cooler temperatures, which slow microbial activity and reduce decomposition rates (Horwath 2024; Philippot et al. 2024). In contrast, slopes are often characterized by variable SOC levels because of increased erosion risks. Soil erosion can remove organic matter before it becomes SOC, leading to lower SOC concentrations in these areas (Ziadat and Taimeh 2013).

Mixed forest ecosystems benefit from higher microbial diversity and increased decomposition rates, which facilitate the gradual accumulation of SOC over time. The diverse mix of plant species in these ecosystems leads to continuous litter input and root turnover, which, in turn, promotes stable SOC levels (Zhang et al. 2021). Greater biodiversity among tree species in mixed forests enhances the amount of aboveground carbon storage, as diverse species contribute to carbon cycling through different litter types, root exudates, and microbial interactions in the soil (Diers et al. 2021; Pinnschmidt et al. 2023).

The results showed that some sites (e.g., sites 2, 5, and 6) have demonstrated a strong relationship between forest biodiversity and SOC sequestration, as these sites exhibit higher SOC levels due to the synergistic effects of plant diversity and associated soil microbial processes. Moreover, mixed forests tend to have faster growth rates than coniferous forests (Augusto and Boča 2022), which contributes to increased carbon inputs into the soil over time. Additionally, shrubby flora in mixed forests contributes positively to SOC sequestration by improving soil structure, enhancing water retention, and promoting nutrient cycling (Yu et al. 2023).

It was observed that mixed forests present unique challenges when considering SOC dynamics, as seen in sites like site 7, where SOM levels are high, but SOC remains relatively low. This inconsistency is primarily driven by the presence of non-stabilized organic inputs and microbial activity. The decomposition of these inputs is insufficient to stabilize them into SOC due to environmental factors like frequent disturbances and soil erosion, which impede organic matter stabilization. This highlights the need to account for the various stages of organic matter decomposition when assessing SOC accumulation (Liu et al. 2021). Despite this, other sites, such as site 5, emphasized the vital role of mixed forests in maintaining soil carbon pools, which are crucial for sustaining ecosystem multifunctionality. These forests support both biodiversity and effective carbon sequestration, thus promoting ecosystem resilience (Tang et al. 2024). In terms of soil conditions, mixed forests typically maintain the most favourable hydrothermal and nutrient conditions (Guo and Gong 2024).

Forest ecosystems in the study area are also more vulnerable to anthropogenic disturbances, particularly those associated with timber and non-timber resource extraction. Activities such as fuelwood collection, timber and fuelwood harvesting, and heavy grazing lead to soil disturbance and negatively affect SOC retention. The removal of biomass through these activities decreases the organic matter input and enhances soil erosion, both of which reduce SOC stability (Purwestri et al. 2023). In contrast, some Pine forests tend to face less extraction and grazing pressure due to limited species diversity, leading to more stable SOC retention.

Moreover, the diversity of SOM is a critical factor in their resilience to environmental changes. Mixed forests show a broader diversity in SOM due to varying decomposition rates which enhances their ability to adapt to varying environmental conditions (Guo and Gong 2024). This diversity in SOM enables mixed forests to better withstand shifts in climate and other ecological disturbances, contributing to more sustainable carbon storage over time (Mäkipää et al. 2023).

Forest management practices, including selective logging, controlled burning, and no-tillage methods, can significantly influence SOC levels. No-tillage forestry helps retain SOC by minimizing soil disturbance and SOC loss (Mayer et al. 2020). On the other hand, selective logging can reduce SOC by removing significant biomass from the system, leading to a decrease in organic matter input and a reduction in SOC retention. Practices that reduce erosion and enhance organic matter inputs are essential to maintain high SOC levels across forest types. Erosion control measures, reforestation, and the preservation of organic matter inputs are all key strategies to prevent SOC depletion and ensure long-term carbon sequestration (Zhao et al. 2023).

Relationship between SOC and soil properties

The regression analyses investigated the relationships between mean SOC and soil properties, including mean values of soil BD, pH, EC, and altitude. For SOC and BD, a moderate positive correlation ($r = 0.59$) was observed. Yet, the slope coefficient was not statistically significant ($p = 0.074$), indicating a potential relationship without statistical significance (Fig. 5A). Similarly, SOC and pH exhibited a weak negative correlation ($r = -0.25$), but the slope coefficient lacked significance ($p = 0.49$), demonstrating no significant linear relationship between the variables (Fig. 5B). Furthermore, SOC and EC showed minimal correlation ($r = -0.016$), with a non-significant slope coefficient ($p =$

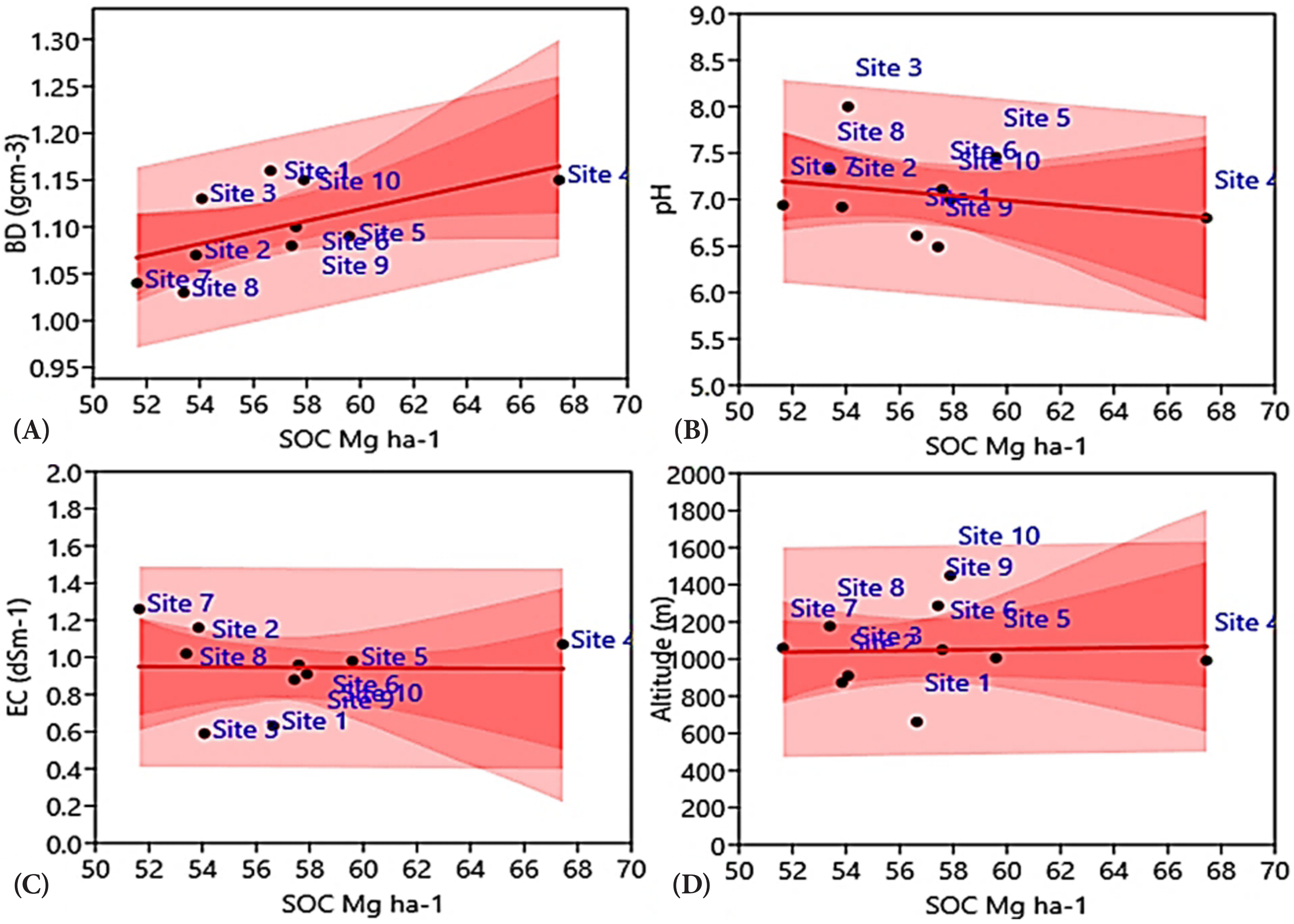

Fig. 5 Relationships between SOC and (A) soil BD, (B) soil pH, (C) EC, and (D) altitude. BD: bulk density; EC: electrical conductivity; SOC: soil organic carbon.

0.96), suggesting no meaningful linear relationship (Fig. 5C). Similarly, SOC and altitude demonstrated a weak positive correlation (r = 0.04) with a non-significant slope coefficient (p = 0.92), indicating no significant linear relationship (Fig. 5D). Overall. In contrast, some correlations were observed between SOC and other soil physicochemical variable, none of the relationships were statistically significant at the 0.05 significance level.

The relationship between SOC and soil BD is important for understanding soil health. A moderate positive correlation indicated that BD and SOC may increase together, though the connection is weak. Organic matter enhances soil structure, which can reduce BD through better aggregation (Tisdall and Oades 1982). However, mechanical and anthropogenic soil compaction can elevate BD, possibly masking the positive impact of organic matter on soil structure and SOC levels (Reintam et al. 2005). The correlation lacks statistical significance indicating other factors likely influence this relationship. Soil texture and moisture impact BD and SOC separately as sandy soils often have low BD, regardless of SOC, while clay soils tend to have higher BD due to dense particles (Blanco-Canqui and Lal 2007). This complexity shows how both inherent soil properties and human activity affect BD.

Soil pH is essential for SOC dynamics, as it influences microbial activity and nutrient availability. The weak negative correlation between SOC and pH showed higher pH levels might align with lower SOC, though this relationship is statistically non-significant. Acidic soils tend to have higher SOC due to slow microbial decomposition and organic matter accumulation (Bailey et al. 2002). In forests, where organic matter decomposes slowly in acidic conditions, there may be a stronger link between low pH and increased SOC (Leifeld et al. 2005) while in agricultural soils where lime is added to raise pH, increased microbial activity can accelerate organic matter breakdown, reducing SOC. This interaction among pH, microbes, and land management complicates the SOC-pH relationship.

Soil EC indicated a negligible correlation with SOC. High salinity can restrict plant growth, reducing organic input and indirectly influencing SOC. However, SOC levels depend more directly on organic inputs and decomposition than on salinity. High EC may affect SOC in specific conditions, such as saline or sodic soils where excess salts inhibit plant and microbial productivity, reducing organic inputs (Setia et al. 2011). This lack of connection between EC and SOC highlights the need to consider local environmental factors in soil health assessment.

Altitude is an influential but complex factor for SOC accumulation in forest soils. A weak positive correlation suggested that altitude changes have little direct effect on SOC. Higher elevations with low temperatures and more moisture may increase SOC by slowing decomposition. However, altitude effects are mediated by vegetation, soil types, and climate. At higher elevations, vegetation shifts to more coniferous forests, which produce different organic matter than lower elevation grasslands or mixed deciduous forests (Sheikh et al. 2009; Tashi et al. 2016). Furthermore, steeper slopes may increase erosion, reducing SOC accumulation benefits from cooler and moist conditions (Ziadat and Taimeh 2013).

Regional variations in SOC levels

This study found lower SOC values in the region compared to subtropical forests in China (Dong et al. 2021; Tang et al. 2017) and the eastern Himalayas (Tashi et al. 2016). The observed SOC values align more closely with those from community-managed forests in Nepal (Mandal et al. 2016) and other nearby areas like Himachal Pradesh (Panwar and Gupta 2013) and northwestern India (Rizvi et al. 2011). In the subtropical coniferous forests of Kashmir, SOC was notably lower than in the Garhwal Himalaya (Sheikh et al. 2009) and other regions of China and Pakistan (Brown et al. 1995; Nizami et al. 2009). For the studied broadleaf forest, SOC is similar to values from Lehtrar forests of Pakistan (Sajjad et al. 2022) but lower than those in subtropical forests in China (Sun and Guan 2014). Lower SOC values were also observed by Amir et al. (2019) in nearby Muree Hills and Shaheen et al. (2016) in Kashmir Himalaya (Table 5). The causes of the disparities in SOC levels between coniferous forests and mixed forests are complex and influenced by a variety of factors. SOC fluctuations in different types of forest stands can be attributed to differences in tree species, the variables associated with soil, climate, topographical features forest harvest practices and changes in land systems in the highly populated Himalayan region (Devi 2021; Waring et al. 2022).

Synergizing SOC management with SDGs

Soil quality enhancement is crucial for achieving SDGs, requiring a multidisciplinary approach aligned with global sustainability objectives (Bonfante et al. 2020; Lal 2020). Carbon sequestration supports environmental sustainability (SDGs 13, 14, 15), economic goals (SDGs 8, 9, 12), and other SDGs (10, 17), while society-related goals (SDGs 1–7, 11, 16) show varying levels of association with SOC sequestration (Lal et al. 2021; Mikunda et al. 2021).

SOC management is key to addressing SDGs, including SDG 1 (No Poverty) through climate financing and carbon offsets (FAO 2011; Lal et al. 2021; Yeluripati et al. 2019; Yin et al. 2022), and SDG 2 (Zero Hunger) via SOC conservation to improve soil fertility and food production (Lal et al. 2021; Mikunda et al. 2021; Tóth et al. 2018; Yin et al. 2022). SDG 3 (Good Health and Well-being) is linked to better climate conditions and the transfer of nutrients from the soil to humans (Lal et al. 2021; Mikunda et al. 2021; Tóth et al. 2018; Yin et al. 2022). SDG 4 (Quality Education) can be promoted through social awareness and educational initiatives on soil and climate (Lal et al. 2021; Yin et al. 2022).

SDG 5 (Gender Equality) is addressed by equitable access to resources, education, financial inclusion, and the active participation of women in soil management (Yin et al. 2022). SDG 6 (Clean Water and Sanitation) is supported by soil practices that enhance water retention and nutrient cycling (Keesstra et al. 2018; Mikunda et al. 2021; Puczko and Jekatierynczuk-Rudczyk 2020; Tóth et al. 2018). SDG 7 (Affordable and Clean Energy) underscores the interconnected impact of SOC management on broader SDGs (Mikunda et al. 2021; Yin et al. 2022), while SDG 8 (Decent Work and Economic Growth) benefits from sustainable soil management practices (Keesstra et al. 2018).

SDG 9 (Industry, Innovation, and Infrastructure) is indirectly related to soil, as sustainable agricultural and forest-

Table 5 SOC values reported from various regions

No.	Region	SOC (Mg ha^{-1})	Reference
1	China (Subtropical)	135	Brown et al. 1995
2	Pakistan	99 to 126	Nizami et al. 2009
3	Garhwal Himalaya	185.6	Sheikh et al. 2009
4	Northwestern India	52.11	Rizvi et al. 2011
5	Himachal Pradesh	55.2	Panwar and Gupta 2013
6	China	72.12 to 105.73	Sun and Guan 2014
7	North-east India	60.2	Ramesh et al. 2015
8	Nepal	32.02 to 35.93	Mandal et al. 2016
9	Pakistan	25.64 to 43.76	Shaheen et al. 2016
10	Eastern Himalaya	91.3 to 126	Tashi et al. 2016
11	China (Subtropical)	90 to 108.53	Dong et al. 2021; Tang et al. 2017
12	Pakistan	29.15 to 36.49	Amir et al. 2019
13	Pakistan	47.75	Sajjad et al. 2022

SOC: soil organic carbon.

ry practices that enhance SOC can mitigate the environmental impacts of industrial activities (Luken et al. 2022; Mikunda et al. 2021). SDG 10 (Reduced Inequalities) addresses disparities among nations due to soil resource variations (Mikunda et al. 2021; Yin et al. 2022). SDG 11 (Sustainable Cities and Communities) benefits from sustainable soil management, urban agriculture, green infrastructure, and soil hydrology regulation to purify and conserve water (Lal et al. 2021; Mikunda et al. 2021; Tóth et al. 2018; Yin et al. 2022). SDG 12 (Responsible Consumption and Production) involves soil conservation to optimize resource use, ensure sustainable food production, and decouple economic growth from resource consumption (Keesstra et al. 2018; Mikunda et al. 2021; United Nations 2015; Yin et al. 2022).

SDG 13 (Climate Action) is addressed through carbon sequestration, supporting biodiversity, ecosystem services, and sustainable agriculture (Lal et al. 2021; Mikunda et al. 2021; Tóth et al. 2018; Yin et al. 2022). SDG 14 (Life Below Water) is impacted by poor soil management practices, erosion, runoff, and sediment transport to water bodies (Mikunda et al. 2021; Tóth et al. 2018; Yin et al. 2022). SDG 15 (Life on Land) benefits from land management practices such as sequestration, conservation, effective forest management, combating desertification, and restoring degraded land (Keesstra et al. 2018; Lal et al. 2021; Mikunda et al. 2021; Tóth et al. 2018; Yin et al. 2022). SDG 16 (Peace, Justice, and Strong Institutions) involves policy and institutional measures for soil-mediated climate stability and addressing illegal land practices (Lal et al. 2021; Yin et al. 2022). SDG 17 (Partnerships for the Goals) requires collaborative cross-regional efforts to reinforce soil conservation and enhance SOC capture (Yin et al. 2022).

Conclusions

This research explored the spatial patterns of SOC and other physicochemical characteristics within subtropical coniferous and mixed forests of the Lesser Himalayas by using established protocols. The integration of soil quality enhancement strategies aligns with SDGs, emphasizing the interconnectedness of soil health with environmental, economic, and societal well-being. The analysis revealed that subtropical coniferous forests generally exhibit higher SOC levels compared to mixed forests. Site-specific analysis unveiled complex interactions of environmental, biological, and physicochemical factors which influence SOC levels, emphasizing the importance of forest type and local conditions in shaping soil carbon dynamics. Local-scale variations in SOC levels are influenced by site-specific factors such as the composition of tree species, environmental conditions, and management practices. The study concluded that an elevated SOC stock in coniferous forests encourages the strategic conservation and sustainable management of regions predominantly covered by coniferous forests. Conservation initiatives directed towards the preservation and restoration of mixed forests can contribute not only to carbon storage but also to the SDGs through the maintenance of ecological resilience and biodiversity. By integrating policy initiatives and SOC management practices, we can effectively advance progress toward achieving SDGs, including climate action, sustainable agriculture, biodiversity conservation, and poverty alleviation. Future research could focus on conducting more comprehensive and deeper soil sampling, evaluating the influence of microbial activity on SOC, and investigating additional ecological factors such as soil texture, litter quality, microhabitats, and climatic variations. Additionally, the integration of long-term observational studies and advanced modelling techniques can predict SOC dynamics under varying environmental conditions.

Abbreviations

ANOVA: Analysis of variance
BD: Bulk density
EC: Electrical conductivity
GHG: Greenhouse gas
IPCC: Intergovernmental Panel on Climate Change
PCA: Principal component analysis
SDGs: Sustainable development goals
SOC: Soil organic carbon
SOM: Soil organic matter

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Authors' contributions

These authors contributed in the article for publication. RWAK supervised the research and prepared the manuscript. MQ collected the field data and prepared initial draft of the manuscript. HS, KH, and ABM assisted in formatting, data analysis, visualization and proof reading.

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Availability of data and materials

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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