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Assessing the impact of land use change on carbon and soil quality in Kashmir Himalayas

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Abstract: The Kashmir Himalayas, a region of immense ecological importance, have experienced profound degradation due to land use changes, raising concerns about sustainability. This degradation has significant global implications, including carbon loss, soil quality deterioration, habitat destruction, and loss of biodiversity. This study investigates various key land uses, including economically vital cash crops such as apples and saffron, the socially significant staple food crop rice, as well as forest and pasture systems. The findings reveal that forests and pastures maintain significantly better physical, chemical, microbial, and enzymes activities, and exhibit greater soil nutrient reserves and soil organic carbon (SOC) pools. Specifically, forest soils contain 20.21%, 28.22%, and 34.49% higher total organic carbon (TOC) stocks compared to apple, saffron, and paddy-oilseed soils, respectively. A soil quality index (SQI) was computed using principal component analysis (PCA) based on over 30 soil indicators, including soil nutrients, carbon pools, and various physical, chemical, and biological properties. The SQI ranking is as follows: forest (1) > pasture (0.87) > apple (0.80) > saffron (0.67) > paddy-oilseed (0.53). This ranking suggests that the conversion of natural ecosystems to cultivation negatively impacts soil nutrient reserves, microbiome diversity, SOC stocks, and overall soil quality. The land use changes in the Kashmir Himalayas result from a complex interplay of natural forces, demographic shifts, and economic pressures. This research provides valuable insights into comparative soil quality under economically and socially relevant crops based on diverse soil properties. The findings can guide land use planning in Kashmir Himalayas and similar regions beyond geographical boundaries, aiming to preserve the ecologically fragile environment, ensure food security, bolster the economy, and promote long-term sustainability in the face of a changing climate. The significance of this study lies in its relevance to similar regions grappling with land use changes, making its findings pertinent to the global scientific community and holding promise for the development of sustainable practices and policies worldwide.

Key words: Land use changes, carbon loss, soil organic carbon, soil quality index, total organic carbon

1. Introduction

Soil organic carbon (SOC) plays a pivotal role in conserving soil fertility and profoundly influences a spectrum of soil properties. SOC is a powerful driver of the global carbon cycle and plays a crucial role in controlling ecosystem functionality (Yadav et al., 2022). Comprising diverse compounds, spanning from simple to intricate molecules, SOC exhibits a range of stability profiles. Among these,

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labile carbon emerges as a standout component, directly providing sustenance to microbial activity and serving as the primary energy source for microbiome (Bei et al., 2022). Consequently, labile carbon stands poised to serve as a pivotal indicator of soil functions, particularly pertaining to nutrient cycling, formation of soil aggregates, carbon sequestration, and the provision of habitats for biodiversity (Yadav et al., 2019; Bashir et al., 2024a). Within the realm of SOC components, particulate organic matter (POM) assumes substantial importance due to its role in fortifying soil aggregate stability and facilitating nutrient cycling.

Microbial biomass carbon (MBC) and mineralizable carbon are recognized as crucial fractions of labile organic carbon (LOC) (Yadav et al., 2021). The labile SOC pool emerges as a critical entity in the swift release of carbon dioxide (CO_2), making it a superior gauge for assessing soil quality variations resulting from alterations in land use patterns. In contrast, the nonlabile SOC pool supplements the TOC stocks. Comprehensively, SOC encompasses all organic material within the soil, excluding coarse roots and subsurface biomass. SOC stands out as an invaluable indicator not only of soil fertility and quality but also of CO_2 fixation within ecosystems. It is worth noting that focusing on the measurement of rapidly changing SOC pools can provide highly informative insights for evaluating soil quality. Soil quality is a defined concept that pertains to a specific soil's ability to function effectively within the boundaries of natural or managed ecosystems. Its functions include sustaining plant and animal productivity, enhancing water and air quality, and supporting human health and habitation (Karlen et al., 1997; Bünemann et al., 2018). The notion of soil quality gained prominence in the 1990s, prompting the need for concrete soil indicators to assess it. Assessment typically involves a combination of physical, chemical, and biological attributes that consider how management practices influence changes in soil conditions due to alterations in land use (Raiesi, 2017). However, it is crucial to acknowledge that soil attributes are interconnected and may respond differently to various treatments and practices. Therefore, the integration of these attributes into a comprehensive and practical single index can prove invaluable for assessing soil quality (Raiesi and Kabiri, 2016). The evaluation of soil quality necessitates an understanding of the optimal range of these indicators within specific ecological contexts, which can also provide insights into the potential for soil sustainability. The SQI serves as a valuable tool for assessing and reflecting soil degradation resulting from changes in land use and management practices.

Land use change and the associated management practices have a substantial influence on SOC dynamics and, consequently, on the overall quality of soil (Babu et al., 2020). The enduring footprint of human activities has instigated notable alterations in land use patterns, notably marked by the expansion of agriculture and urbanization. A concerning trend observed in recent decades is the extensive deforestation, agricultural and infrastructural activities in northwest regions (Fayaz et al., 2020). These anthropogenic factors exhibit a remarkably persistent and profound effect on SOC stocks, surpassing even the impact of climate change (Sestras et al., 2023; Wu et al., 2023), and have notably and swiftly affected soil quality. While numerous studies have established a general pattern of soil quality degradation resulting from the conversion of natural land to croplands, it is evident that these changes have significant and complex consequences for soil health and sustainability. These challenges stem from inadequate land management practices that have resulted in the degradation of crop land soils, vulnerabilities to both natural and human-induced disruptions.

The Kashmir Himalaya, distinguished by its diverse landscape and rich tapestry of vegetation ecosystems (Dar and Parthasarathy, 2022), holds significant status within the broader Himalayan biodiversity hotspot. This region boasts abundant natural flora and supports the cultivation of various crops on its fertile land. However, this delicate biodiversity hotspot faces persistent threats, primarily due to mounting population pressure and the consequent surge in food demands. The escalating temperatures leading to the melting of glaciers in the Kashmir Himalaya have adverse effects on the region's natural vegetation and land use practices. This, in turn, results in a depletion of soil carbon content and a decline in soil quality. In Kashmir Himalayas, apple and saffron serve as the economic backbone, while rice holds significant social relevance as a staple food for the entire community.

Although various researchers have studied SOC pools in different hilly ecosystems (Yadav et al., 2019; Babu et al., 2020), there is a noticeable gap when it comes to conducting a comparative analysis of carbon storage and soil quality assessment for these economically crucial and socially relevant crops in the Kashmir Himalayas. Therefore, there is an imperative need for a comprehensive study that delves into various facets, including carbon pools, microbial and enzymatic activities, soil nutrient levels, and a spectrum of physical and chemical properties. Such a study would be instrumental in identifying sustainable land use system for carbon storage and soil health in the face of shifting climatic conditions.

Considering the significance of soil carbon storage and soil health in terms of reaping maximum industrial, agricultural and environmental outputs with various land use forms, this study was conducted with the following objectives: (i) to investigate the impact of land use systems (LUSs) on the physical, chemical, and biological attributes of the soil; (ii) to assess the influence of LUSs on SOC pools; and (iii) to calculate carbon stocks while constructing a SQI using principal component analysis

(PCA). The outcome of this study holds the potential to guide the selection of appropriate land, soil, and vegetation management strategies that are tailored to the unique needs of the region. Consequently, achieving a more accurate prediction and assessment of soil quality is instrumental in the development of tailored land and soil management approaches, which are vital for preserving long-term soil productivity, sustainability, and economic well-being in the region. Furthermore, the findings of this study are poised to provide valuable support to policymakers and land managers in shaping soil-friendly and environmentally resilient land use policies, thus contributes to sustainable land management under changing climate.

2. Materials and methods

2.1. Study area

This study was carried out across the Kashmir Valley, Jammu and Kashmir (J&K), India consists of altitude ranges from 1587–2640 m above mean sea level. The Kashmir Valley is in the northern part of India and lies between the coordinates of 33°20' to 34°41'N latitude and 73°55' to 75°37'E longitude, presented in Figure 1. The average temperature of the region ranges from –10 to 35 °C, with average annual precipitation of approximately 710 mm (Dar et al., 2015). Table 1 illustrates the land use types with their corresponding areas.

Five distinct land uses were carefully chosen to represent the LUSs practiced over the past three to four decades. These include forests, pastures, apple orchards, saffron fields, and paddy-oilseed cultivation areas. The selection of these land uses was intentional and based on their prevalence in the study area. A purposive random method of sampling was used for the collection of georeferenced soil samples from these preferred LUSs. In the forest, soil samples were collected from the spaces between tree rows. For pasture lands, soil samples were collected from areas with moderate grazing, from inside corm beds in saffron fields, and from within crop fields in the paddy-oilseed cropping system. All the samples were collected during the summer season at a soil depth of

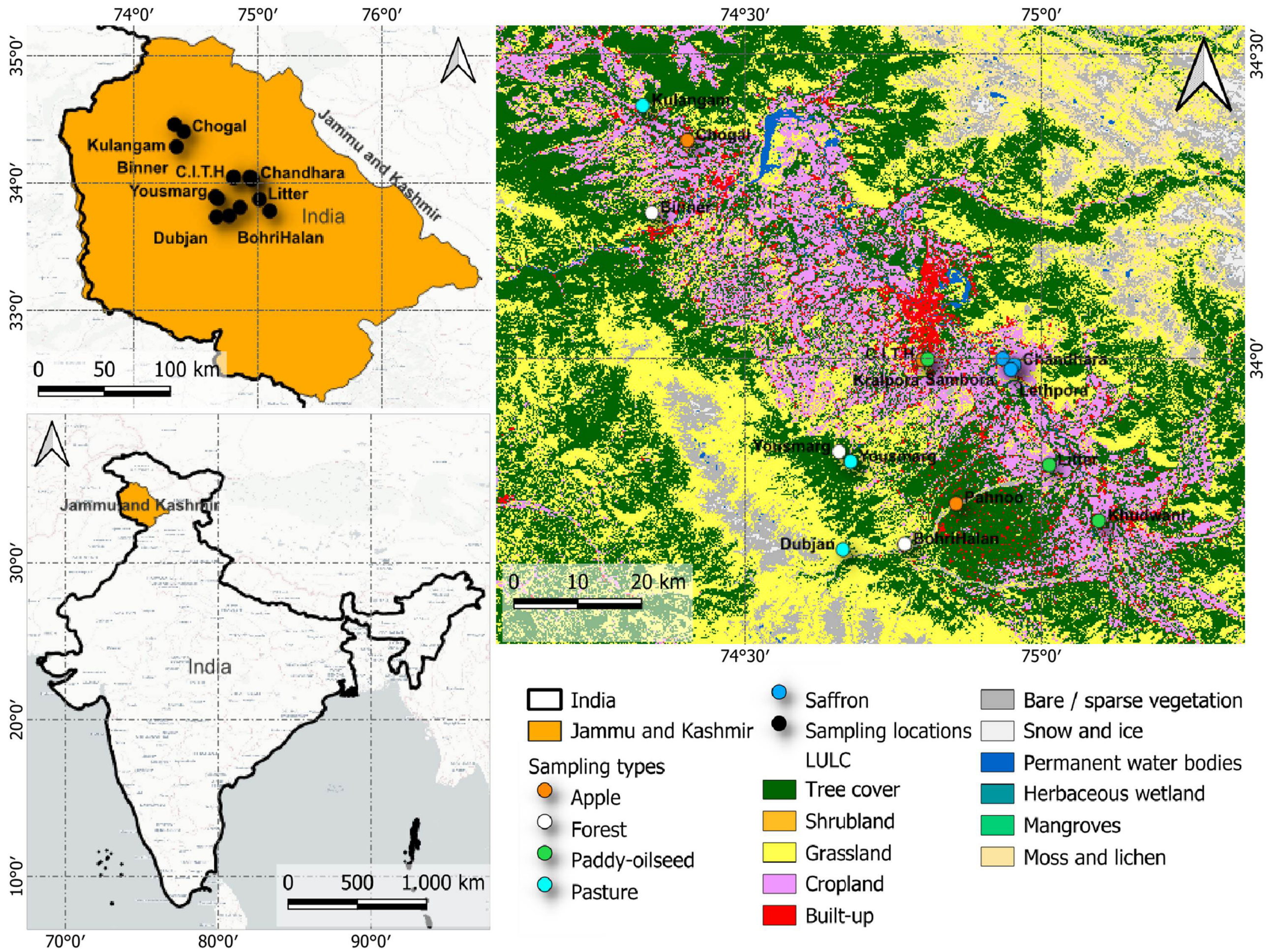

Figure 1. Study area and the respective sampling point locations.

Table 1. Distribution of land use within the study area.

Land use type	Area (in hectares)
Net sown	331,000
Forests	5240
Nonagricultural	53,850
Uncultivated land	30,820
Permanent pasture and other grazing land	34,920
Miscellaneous tree crops	10,630
Culturable waste land	36,493
Fallow	36,110
Other than current fallow	9230

0–30 cm. The collected soil samples were packed, labelled, and subjected to different preparatory procedures prior to laboratory analysis.

2.2. Soil physical properties

Soil texture was assessed using hydrometric method (Bouyoucos, 1962). Bulk density (BD) was evaluated by core method (Blake and Hartge, 1986). Particle density (PD) was evaluated using pycnometer (Gupta and Dakshinamoorthy, 1980). Porosity was calculated by using a formula based on BD and PD.

$$\%\, pore\ space = 100\left[1 - \frac{Db}{Dp}\right],$$

where Db = bulk density and Dp = particle density.

2.3. Soil chemical properties

The collected samples were air-dried, ground, and sieved (2 mm) for the estimation of different parameters. Soil reaction (pH), electrical conductivity (EC), and cation exchange capacity (CEC) were determined using the protocol as described by Jackson (1973). Organic carbon (OC) was determined by chromic acid extraction (Walkley and Black, 1934). Available nitrogen (N) was estimated using the protocol of Subbiah and Asija (1956). Available phosphorus (P) was estimated using the method outlined by Olsen et al. (1954). Available potassium (K) was determined using the method described by Jackson (1973). Exchangeable calcium (Ca) and magnesium (Mg) were determined using the versenate titration method (Schwarzenbach and Flaschka, 1969) and available sulphur (S) was determined using the turbidimetric method (Williams and Steinbergs, 1959). DTPA solution was used for the extraction of micronutrients, namely zinc (Zn), copper (Cu), iron (Fe), and manganese (Mn), following the method of Lindsay and Norvell (1978).

2.4. Soil biological properties

Fresh samples were kept at 4 °C to study the enzyme activity. The rate of formation of tri-phenyl formazan (TPF) from tri-phenyl tetrazolium chloride was used to assess the dehydrogenase activity (DHA) principle described by Klein et al. (1971). Acid phosphatase (Ac_P) and alkaline phosphatase (Alk_P) activities were measured colorimetrically at 410 nm using *p*-nitrophenyl phosphate as the substrate (Tabatabai and Bremner, 1969). The activity of arylsulphatase (Aryl) was measured colorimetrically at 405 nm using *p*-nitro phenol as the substrate (Tabatabai and Bremner, 1970). Fluorescein diacetate hydrolase (FDH) activity was assessed using the protocol of Green et al. (2006). A serial dilution approach was employed to measure viable bacterial count (VBC), viable fungal count (VFC), and viable actinomycete count (VAC) (Anija, 2001).

2.5. SOC pools

SOC pools (TOC, LOC, particulate organic carbon (POC)) were determined using air-dried and sieved (0.5 mm) soil samples, while MBC was measured employing fresh soil samples. The wet oxidation approach was employed to estimate TOC (Snyder and Trofymow, 1984). LOC was estimated using the 333 mM $KMnO_4$ procedure given by Blair et al. (1995). POC was measured by employing an approach outlined by Cambardella and Elliott (1992). An approach of chloroform fumigation-incubation was employed to assess MBC (Jenkinson and Powlson, 1976).

2.6. SOC stock

SOC stock was assessed as follows:

SOC stock (g m^{-2}) = SOC × BD × D × 10,

where SOC = soil organic carbon concentration (g kg^{-1}),

BD = bulk density,

D = depth of the soil layer (0–30 cm).

2.7. SQI computation

The methodology outlined by Karlen et al. (2003) was followed to assess SQI based on various soil properties, involving three key steps: (i) the selection of indicators for the minimum data set (MDS), (ii) the scoring of the selected indicators, and (iii) the integration of individual indicator scores into the SQI.

In the initial step, the MDS was formed by identifying soil indicators that exhibited significant treatment differences ($p < 0.05$) using the least significant difference (LSD) test. These significant variables were then chosen for the MDS formation using PCA (Andrews et al., 2002; Mandal et al., 2008). PCA was employed to reduce the number of independent variables, and only principal components (PCs) with eigenvalues ≥ 1 and explaining at least 5% of the data variation were retained. In cases where multiple variables were retained within a PC, Pearson's correlation coefficient was used to assess their redundancy and potential elimination from the MDS (Andrews et al., 2002).

The second step involved scoring the selected indicators. Scoring functions were applied to assign scores ranging from 0 to 1 to the indicators within the MDS, based on whether "more is better" or "less is better" function.

Finally, the indicator scores were integrated into an additive index, as proposed by Andrews et al. (2003), calculated by summing the scores of each indicator and dividing by the total number of indicators.

$$SQI = \sum_{i=1}^{n} \frac{Si}{n},$$

where SQI represents the soil quality index, S denotes the score assigned to each indicator, and n signifies the number of indicators included in the MDS.

A grading system was adopted from Marzaioli et al. (2010) to interpret the SQI results. Soil quality was categorized as follows:

- SQI < 0.55: indicative of low soil quality.
- SQI ranging from 0.55 to 0.70: reflecting intermediate soil quality.
- SQI > 0.70: indicating high soil quality.

2.8. Statistical analysis

A one-way analysis of variance (ANOVA) was employed to evaluate the influence different land uses on soil physical, chemical and biological properties, and SOC pools using R studio (version 4.2.1). Tukey's test was used to compare the means, and statistical difference was determined at $p < 0.05$. For soil quality analysis (PCA, scoring functions), Microsoft Excel and SPSS version 10.0 (SPSS Inc., Chicago, IL, USA) were used.

3. Results

3.1. Soil physical properties under different LUSs

The analysis of various soil quality parameters illustrated by Figure 2 provides valuable insights, in terms of the various land uses and the variation of mineral contents, pH, EC, PD, porosity, and BD. Sand percentage varied significantly ($p < 0.05$) across the studied land uses with mean values ranging from 54.20% to 19.33%. The mean of sand percentage was the highest in forest soil (54.20%) followed by pasture (46.50%), apple (27.33%), saffron (30.80%), and paddy-oilseed had the lowest sand content (19.33%). The mean silt content was the highest in apple soils (50.53%) and the lowest in forest soils (34.20%), following the pattern: apple > paddy-oilseed > pasture > saffron > forest. Clay percentage is substantially higher within paddy-oilseed and saffron (i.e. 31.90% and 33.70%, respectively) comparing to forest, pasture, and apple soils. Forest soils had the lowest (11.60%) clay percentage, whereas the highest was recorded in saffron soil (33.70), following the pattern: forest < pasture < apple < paddy-oilseed < saffron. Therefore, depending on the particle

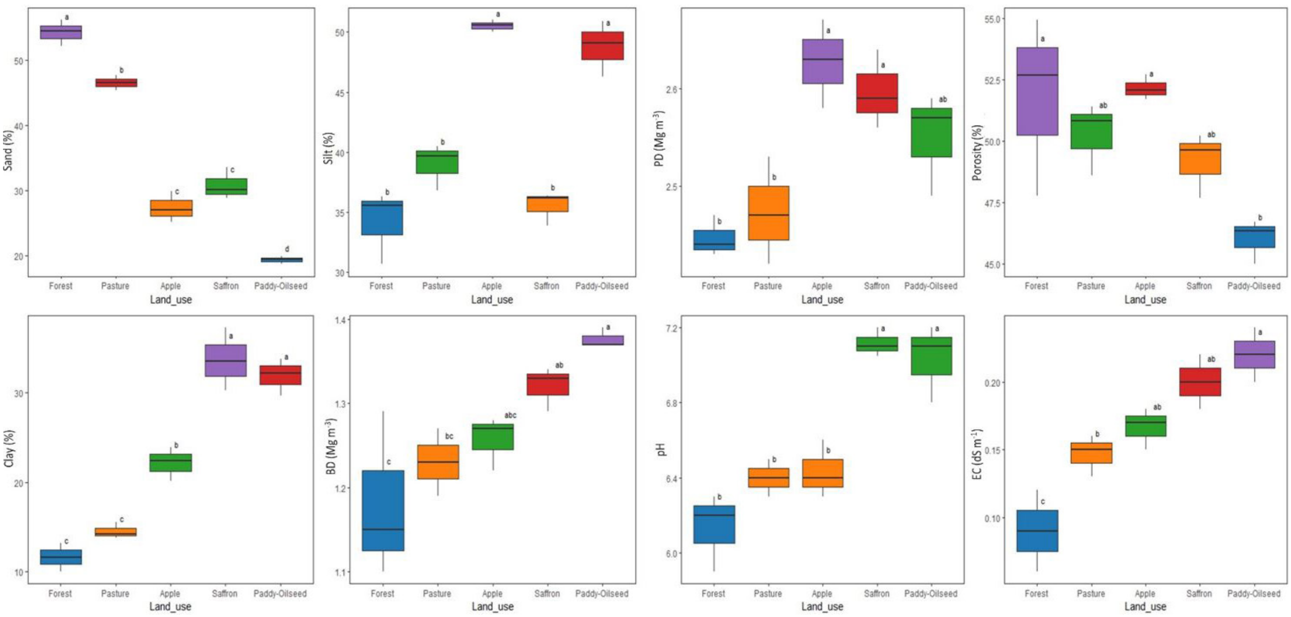

Figure 2. Effect of LUSs on soil physicochemical characteristics. Mean values exhibiting different letters differ significantly at $p < 0.05$.

size distribution, the studied land uses were categorized as sandy loam, loam, silt loam, clay loam, and silt clay loam for forest, pasture, apple, saffron, and paddy-oilseed, respectively.

There was a statistical ($p < 0.05$) difference between naturally undisturbed ecosystems and cultivated land uses with respect to soil BD. As shown in Figure 2, the mean BD ranged from 1.37 to 1.18 Mg m^{-3} across studied land uses, with the highest and the lowest values recorded under paddy-oilseed and forest soils, respectively. The cultivated land uses (apple, saffron, and paddy-oilseed) and undisturbed land uses (forest and pasture) differed significantly with respect to PD as described in Figure 2. However, nonsignificant differences were observed within the cultivated soils. The mean PD varied from 2.62 to 2.44 Mg m^{-3} across the studied land uses, with the highest values observed in apple soils and the lowest in forest soils, clearly indicating that the PD of cultivated lands tends to be higher compared to forest soils. Soil porosity was the highest in apple soil (52.16%) followed by forest (51.78%), pasture (50.26%), saffron (49.15), and paddy-oilseed (46.00) soils. Since the values are among similar ranges, it shows that the land use forms do not influence soil porosity variations significantly.

As shown in Figure 2, the soils were slightly acidic to moderately alkaline across all the land uses, with an average value ranging from 6.13 in forest soils to 7.16 in paddy-oilseed soils. The lowest pH values were recorded in forest soils and the highest in paddy-oilseed soils with a significant ($p < 0.05$) difference between cultivated (saffron and paddy-oilseed) and undisturbed land uses. However, apple soils were on par with the undisturbed soils, indicating the presence of elevated organic matter (OM) compared to saffron and paddy-oilseed soils. The EC values of cultivated soils were slightly higher than those of forest and pasture soils.

3.2. Soil chemical properties under different LUSs

The OC content varied significantly ($p < 0.05$) across the studied land uses with the mean values ranging from 22.00 to 11.70 g kg^{-1}. As shown in Figure 3, the highest and the lowest OC content was observed in forest and paddy-oilseed soils, respectively. Similarly different management practices significantly affected CEC, with the five different land uses varying from 21.24 to 15.03 cmol (p^+) kg^{-1}. CEC in forest soils was significantly ($p < 0.05$) higher compared to the cultivated soils, where apple soils were on par with pasture soils, as illustrated in Figure 3. Among the three cultivated land uses, apple soils exhibited higher OC

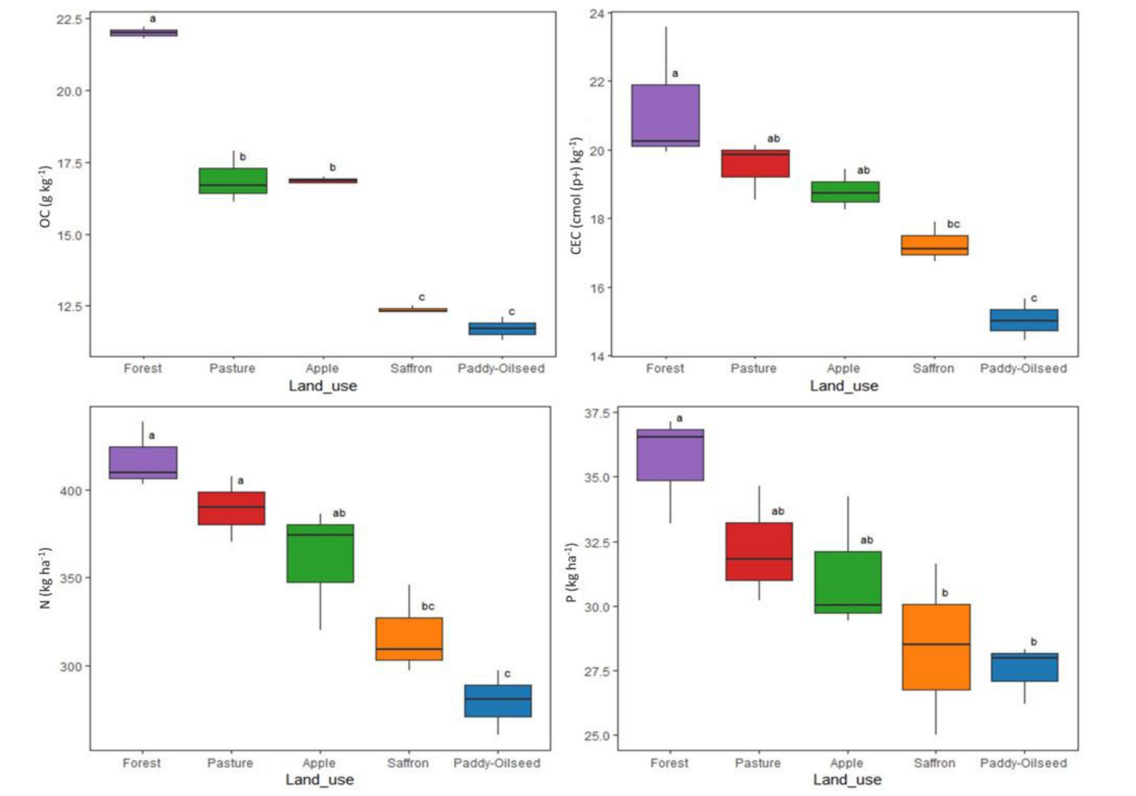

Figure 3. Effect of LUSs on soil chemical characteristics. Mean values exhibiting different letters differ significantly at $p < 0.05$.

content and CEC, indicating better conservation of soil organic matter (SOM) and enhanced chemical properties. As shown in Figure 3, the highest values of available N were observed in forest and pasture soils followed by apple soils, with the mean values ranging from 417.52 to 279.30 kg ha^{-1}. Likewise, P content varied from 35.61 to 27.51 kg ha^{-1}, following the pattern of forest > pasture > apple > saffron > paddy-oilseed. The available P was significantly higher ($p < 0.05$) in forest soils compared to the cultivated soils. The available K was observed in high rating across all the LUSs, as illustrated in Figure 4. The available K content varied from 319.12 to 286.26 kg ha^{-1} across the studied LUSs. Forest soils exhibited the highest K content (319.12 kg ha^{-1}) followed by pasture (304.94 kg ha^{-1}) and the lowest was recorded in paddy-oilseed soils (286.26 kg ha^{-1}). Apple soils exhibited higher K content (297.50 kg ha^{-1}) among the cultivated soils. In case of exchangeable Ca, saffron (Karewa) soils exhibited maximum concentration (6.32 cmol (p^+) kg^{-1}), followed by apple soils (5.64 cmol (p^+) kg^{-1}). The mean values of exchangeable Ca varied from 6.32 to 4.40 cmol (p^+) kg^{-1} among the investigated land uses, following the pattern of saffron > apple > pasture > paddy-oilseed > forest, as illustrated in Figure 4. Similarly, the exchangeable Mg was recorded the highest in saffron (Karewa) soils (3.17 cmol (p^+) kg^{-1}), followed by apple soils (2.83 cmol (p^+) kg^{-1}) with the mean values ranging from 3.17 to 2.19 cmol (p^+) kg^{-1}. A significant difference ($p < 0.05$) was observed in the available S content between naturally undisturbed forest soils and cultivated soils, whereas the cultivated soils were on par. As shown in Figure 4, the mean values of available S varied from 37.78 to 17.98 kg ha^{-1} with maximum values recorded in forest soils and minimum in paddy-oilseed soils. Since the values of macronutrients differ across the studied land uses, it clearly shows that the different land uses influence the nutrient dynamics significantly.

There was a statistically significant difference ($p < 0.05$) in Zn content between naturally undisturbed and cultivated soils. As presented in Table 2, the highest Zn content was recorded in forest soils (2.25 mg kg^{-1}), followed by pasture (1.90 mg kg^{-1}), and the lowest in paddy-oilseed soils (0.48 mg kg^{-1}). Similarly, the highest values of Cu, Fe, and Mn were observed in forest soils (2.70, 51.60, and 17.62 mg kg^{-1}) and the lowest were recorded in paddy-oilseed soils (1.71, 23.39, and 10.30 mg kg^{-1}), respectively. The studied land uses ranged from low to high in micronutrient status, with the apple soils exhibiting higher micronutrient content compared to other cultivated soils.

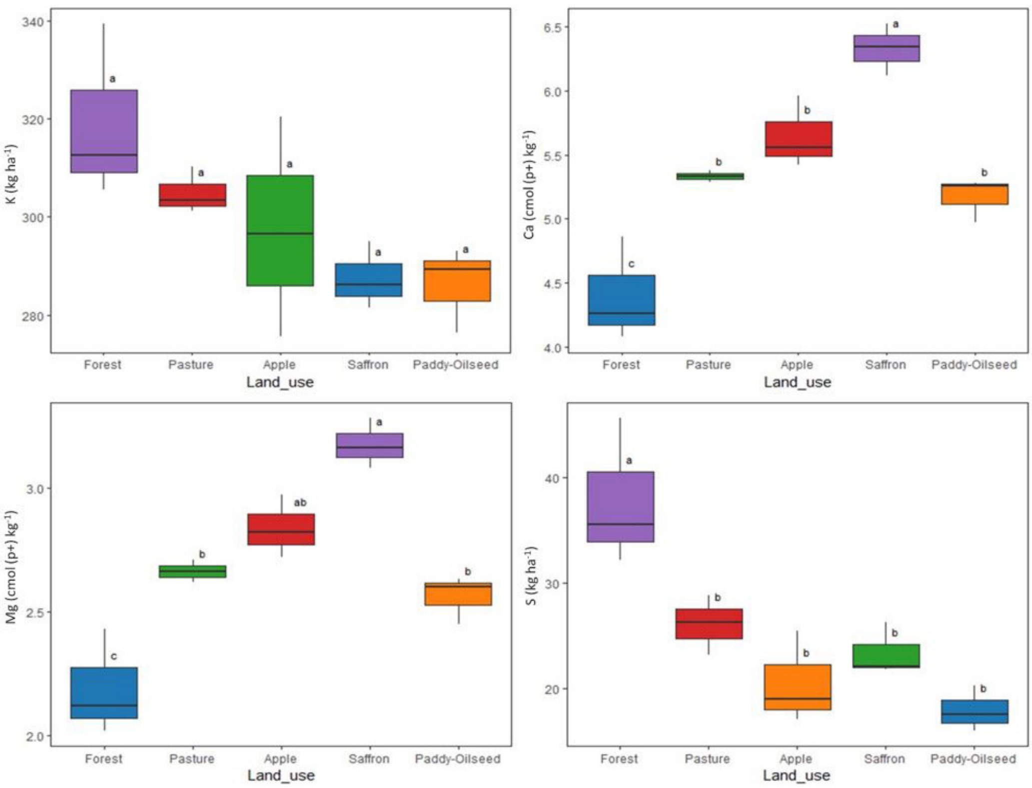

Figure 4. Effect of LUSs on soil chemical characteristics. Mean values exhibiting different letters differ significantly at $p < 0.05$.

Table 2. Effect of different LUSs on micronutrient cations.

Land uses	Zn	Cu	Fe	Mn
Forest	2.25^{a}	2.70^{a}	51.60^{a}	17.62^{a}
Pasture	1.90^{ab}	2.40^{ab}	39.67^{b}	16.49^{ab}
Apple	1.28^{b}	2.03^{bc}	36.33^{b}	14.71^{bc}
Saffron	1.25^{b}	2.00^{bc}	28.10^{c}	12.91^{c}
Paddy-oilseed	0.48^{c}	1.71^{c}	23.39^{c}	10.30^{d}
CD (p < 0.05)	**0.50**	**0.36**	**3.96**	**1.30**

DTPA extractable iron (Fe), manganese (Mn), zinc (Zn), copper (Cu) (mg kg^{-1}). Mean values exhibiting different letters differ significantly at $p < 0.05$.

3.3. Soil biological properties under different LUSs

The findings presented in Table 3 revealed the higher DHA activity in forest soils and lower in paddy-oilseed soils with mean values ranging from 11.83 to 9.97 TPF µg g^{-1} day^{-1} across the studied land uses. All the land uses exhibited variation in phosphatase (Ac_P and Alk_P) activity, with mean values ranging from 48.43 to 22.40 µg P-NP g^{-1} h^{-1} and from 61.35 to 43.50 µg P-NP g^{-1} h^{-1}, respectively. The highest value was observed in forest soils, while the lowest was found in paddy-oilseed soils. A significant difference ($p < 0.05$) was observed in phosphatase activity between undisturbed and cultivated soils, with apple soils exhibiting higher activities compared to the cultivated land uses. Similarly, a significant difference ($p < 0.05$) was observed in Aryl activity between naturally undisturbed and cultivated soils, whereas apple soils were on par with forest and pasture soils. The highest Aryl activity was recorded in forest soils (48.12 µg P-NP g^{-1} h^{-1}), and the lowest was in paddy-oilseed soils (36.33 µg P-NP g^{-1} h^{-1}), as presented in Table 3. The average values of FDH activity ranged from 21.59 to 12.18 µg g^{-1} h^{-1}, with higher activity observed in forest soils and lower activity in paddy-oilseed soils. All the enzyme activities were higher in apple soils compared to other cultivated land use system, following the pattern apple > saffron > paddy-oilseed.

The highest VBC was observed in forest soils, while the lowest was found in paddy-oilseed soils. This value was significantly higher in forest soils than other LUSs. The total number of viable bacteria ranged from 123.33 in forest soils to 67.67 cfu × 10^{-6} g^{-1} in paddy-oilseed soils, as presented in Table 3.

The decrease in VBC was significantly higher in paddy-oilseed soil compared to other cultivated land uses, following the pattern: apple > saffron > paddy-oilseed. The results revealed a significant difference ($p < 0.05$) in VFC, as shown in the mean values in Table 3. The highest and the lowest values of VFC were recorded in forest (i.e. 67.00 cfu × 10^{-5} g^{-1}) and paddy-oilseed soils (i.e. 19.33 cfu × 10^{-5} g^{-1}) respectively. A similar trend was observed in VAC, which ranged from 42.33 to 12.00 cfu × 10^{-4} g^{-1} soil, with the highest and the lowest VAC recorded in forest and paddy-oilseed soils, respectively.

3.4. SOC pools and stocks under different LUSs

The TOC levels ranged from 64.32 to 36.12 Mg ha^{-1} across the studied land uses, with the maximum values in forest soils and the minimum in paddy-oilseed soils, as illustrated in Figure 5. A significant difference ($p < 0.05$) was observed in the TOC content among all the studied land uses, following the pattern: forest > pasture > apple > saffron > paddy-oilseed. Forest soils exhibited the highest TOC with 35.82% and 43.84% compared to saffron and paddy-oilseed soils, respectively, whereas apple soil exhibited TOC levels that were 14.37% and 25.08% higher than those of saffron and paddy-oilseed soils, respectively. The TOC stocks ranged from 10,249.50 to 6713.81 g m^{-2}, with the highest values recorded in forest soils, followed by pasture, apple, saffron, and the lowest in paddy-oilseed soils, as presented in Table 4. Forest soils exhibited 20.21%, 28.22%, and 34.49% higher TOC stocks compared to apple, saffron, and paddy-oilseed soils, respectively.

As shown in Figure 5, the LOC content across different land uses ranged from 7.20 to 2.33 g kg^{-1} of soil, with the maximum values observed in forest soils and the minimum in paddy-oilseed soils. The LOC content differed significantly among the investigated land uses, following the pattern: forest > pasture > apple > saffron > paddy-oilseed.

Among cultivated soils, apple soils exhibited 20.78% and 49.57% higher LOC content than saffron and paddy-oilseed soils, respectively. As presented in Table 4, the highest mean LOC stocks were recorded in forest soil, while the lowest were in paddy-oilseed soils, with the values ranging from 2549.56 to 960.92 g m^{-2}.

The POC content ranged from 1380.24 to 756.31 mg kg^{-1} across the studied LUSs, with the highest and the lowest contents recorded in forest and paddy-oilseed soils, respectively, as illustrated in Figure 5. Among cultivated land uses, apple soils exhibited 4.41% and 16.94% higher POC than saffron and paddy-oilseed soils, respectively. Table 4 presents the mean values of POC stocks, ranging from 490.42 to 312.43 g m^{-2} across the studied land uses. The highest mean POC stocks were recorded in forest soils, followed by pasture, apple, and saffron and the lowest was in paddy-oilseed soils.

Table 3. Biological properties of soils affected by different LUSs.

Land uses	DHA	Phosphatases		Aryl	FDH	VBC	VFC	VAC
		Ac_P	Alk_P					
Forest	11.83ᵃ	48.43ᵃ	61.35ᵃ	48.12ᵃ	21.59ᵃ	123.33ᵃ	67.00ᵃ	42.33ᵃ
Pasture	11.56ᵃ	45.08ᵃᵇ	59.31ᵃ	47.79ᵃ	19.05ᵃᵇ	98.67ᵇ	55.33ᵇ	32.67ᵇ
Apple	11.41ᵃ	43.82ᵇ	56.28ᵇ	46.22ᵃ	16.92ᵇᶜ	83.00ᶜ	42.67ᶜ	26.00ᵇᶜ
Saffron	10.79ᵃ	32.92ᶜ	49.55ᶜ	41.28ᵇ	14.77ᶜᵈ	72.33ᶜᵈ	40.67ᶜ	18.66ᶜᵈ
Paddy-oilseed	9.97ᵃ	22.40ᵈ	43.50ᵈ	36.33ᶜ	12.18ᵈ	67.67ᵈ	19.33ᵈ	12.00ᵈ
CD ($p < 0.05$)	**1.25**	**2.44**	**1.58**	**1.50**	**1.86**	**10.43**	**7.96**	**6.05**

DHA, dehydrogenase activity (TPF µg g^{-1} day^{-1}); Ac_P, acid phosphatase; Alk_P, alkaline phosphatase; Aryl, arylsulphatase (µg P-NP g^{-1} h^{-1}); FDH, fluorescein diacetate hydrolase (µg g^{-1} h^{-1}); VBC, viable bacterial count (10^{-6} cfu g^{-1}); VFC, viable fungal count (10^{-5} cfu g^{-1}); VAC, viable actinomycete count (10^{-4} cfu g^{-1}). Mean values exhibiting different letters differ significantly at $p < 0.05$.

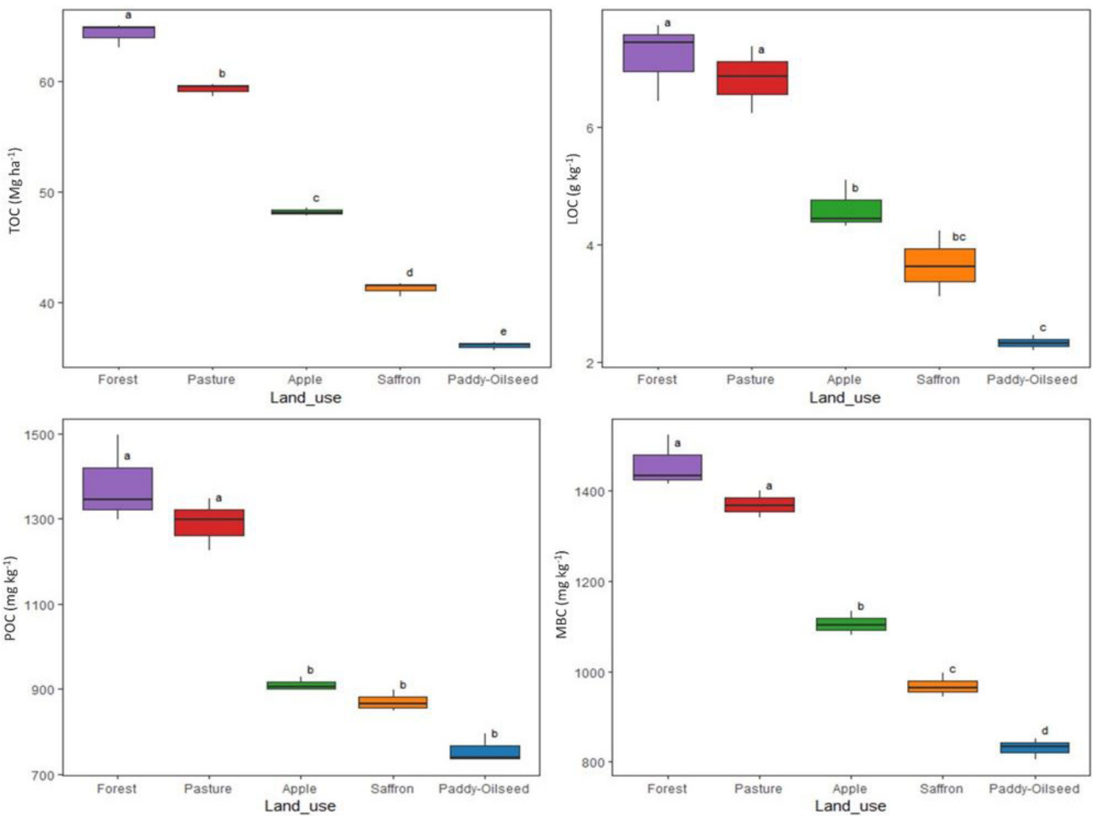

Figure 5. Effect of LUSs on SOC pools. Mean values exhibiting different letters differ significantly at $p < 0.05$.

The highest MBC was recorded in forest soils, followed by pasture, apple, and saffron, and the lowest was in paddy-oilseed soils. The MBC levels varied from 1458.12 to 830.21 mg kg^{-1} across the studied LUSs, as shown in Figure 5. The studied land uses differed significantly in MBC content, with forest and pasture having similar levels. Among the cultivated LUSs, apple soil exhibited higher MBC values, with 12.39% and 24.88% higher than saffron and paddy-oilseed soils, respectively. All the SOC pools followed the pattern: forest > pasture > apple > saffron > paddy-oilseed. The mean values of MBC stocks ranged from 517.22 to 342.92 g m^{-2} across the studied LUSs, as presented in Table 4. The highest (517.22 g m^{-2}) and the lowest (342.92 g m^{-2}) values were recorded in forest and paddy-oilseed soils, respectively. Among cultivated land uses, apple soils exhibited 7.97% and 17.70% higher MBC stocks than saffron and paddy-oilseed soils, respectively. The highest values for all the SOC pool stocks were found in naturally undisturbed LUSs, while lowest values were observed in cultivated systems. However, among the cultivated LUSs,

Table 4. SOC pools and stocks under different land uses.

Land use	SOC pool stocks (g m^{-2})			
	LOC	POC	MBC	TOC
Forest	2549.56^{a}	490.42^{a}	517.22^{a}	10249.50^{a}
Pasture	2522.33^{a}	476.43^{a}	505.75^{a}	9853.92^{a}
Apple	1740.43^{b}	343.31^{b}	416.68^{b}	8177.87^{b}
Saffron	1447.00^{bc}	344.75^{b}	383.47^{b}	7356.33^{bc}
Paddy-oilseed	960.92^{c}	312.43^{b}	342.92^{b}	6713.81^{c}

LOC, labile organic carbon; POC, particulate organic carbon; MBC, microbial biomass carbon; TOC, total organic carbon. Mean values exhibiting different letters differ significantly at $p < 0.05$.

apple soil exhibited better carbon storage than saffron and paddy-oilseed soils.

3.5. SQI under different land uses

In the process of selecting representative indicators with significant differences among sample plots for SQI calculation, it was imperative to address redundancy among these indicators through PCA. The dataset encompassed 30 soil quality indicators, which were grouped into components. Among these components, four PCs had eigenvalues greater than 1, collectively explaining 91.435% of the total dataset variance, as presented in Table 5. Within each PC, we focused on the highest weighted loadings (within 10% of the maximum factor loading) when identifying indicators for the MDS. In cases where multiple indicators were retained within a single PC, a Pearson correlation test was employed to reduce redundancy, as presented in Table 6.

The first PC, accounting for 72.141% of the variance, included 17 heavily weighed parameters with factor loadings within 10.0% of the maximum. As presented in Table 5, these 17 variables encompassed pH, EC, CEC, N, Zn, Fe, Ac_P, Alk_P, Aryl, FDH, VBC, VBC, VAC, OC, TOC, POC, and MBC. Based on expert opinion, CEC, Fe, VFC, Ac_P, OC, and MBC were retained, while the remaining indicators were eliminated from the MDS.

The second PC, which explained 10.236% of the variance, retained only Mg, which exhibited the highest factor loading for the MDS. The third PC explained 4.815% of the variance and retained Ca and DHA, which had the highest factor loadings. Under PC4, silt was the sole indicator with a high factor loading, explaining 4.243% of the variance, as presented in Table 5.

The selected indicators, along with their respective scores and weights, are presented in Table 7. The data obtained for the variables were converted into unitless figures ranging from 0 to 1 using a linear scoring method (Andrews et al., 2002). Scoring was based on whether a maximum value in terms of soil functions was deemed "good" or "bad". In this analysis, practically all the indicators in the MDS were rated as good for soil quality when arranged in ascending order. Therefore a "more is better" strategy was adopted, except for silt percentage, where a "lesser is better" approach was considered.

Following transformation using the linear scoring method, the scores for MDS indicators were multiplied by the weighed factors derived from PCA outcomes. Subsequently, the SQI developed through PCA for the studied land uses exhibited the following ranking, as shown in Figure 6: forest (1.00) > pasture (0.87) > apple (0.80) > saffron (0.67) > paddy-oilseed (0.53). These findings clearly indicate variations in soil quality among the studied LUSs, with forest soils demonstrating the highest soil quality (SQI > 0.70), followed by pasture and apple soils (both with SQI > 0.70). Saffron soils exhibited intermediate soil quality (SQI > 0.55 and < 0.70), while paddy-oilseed soils showed low soil quality (SQI < 0.55).

4. Discussion

4.1. Soil physical properties under different LUSs

In the present study, based on particle size distribution as shown in Figure 1, the studied LUSs were categorized into different textural classes: loam for forest, loam for pasture, silt loam for apple, clay loam for saffron, and silty clay loam for paddy-oilseed. The variation in particle size distribution across the studied land uses might be attributed to minimal water infiltration at higher altitudes, increased erosion, and reduced temperature (Bashir et al., 2024b; Bammou et al., 2024). Hence, the formation of soil is minimal in forests, resulting in lower clay content and higher sand percentage (Ali, 2017; Ouallali et al., 2024). In paddy land use, puddling destroys the soil structure and creates hardpans in the lower soil strata, which favours the accumulation of higher clay content. These findings align with those reported by Maqbool et al. (2017), who also categorized the soils in the district of Ganderbal as clay loam, silt loam, and sandy loam.

The BD and PD were recorded as the lowest in forest and pasture soils compared to other cultivated LUSs, as shown in Figure 1. This can primarily be attributed to the clay percentage, lower disturbance, and higher OM content

Table 5. Performance of soil quality indicators in terms of factor loadings/eigenvalue in PCA.

	Principal component I	Principal component II	Principal component III	Principal component IV
Eigenvalue	21.642	3.071	1.445	1.273
Percentage of variance	72.141	10.236	4.815	4.243
Cumulative percentage	72.141	82.377	87.192	91.435
Factor loadings				
N	0.937	0.132	0.238	–0.099
P	0.846	0.051	0.236	–0.355
K	0.722	–0.199	–0.344	0.090
Ca	–0.545	0.499	0.475	0.457
Mg	–0.388	0.855	0.179	0.094
S	0.812	–0.345	0.035	0.083
Zn	0.913	–0.109	–0.063	0.353
Cu	0.878	–0.233	–0.060	0.177
Fe	0.967	–0.031	–0.136	0.004
Mn	0.748	0.569	–0.281	0.070
pH	–0.920	–0.203	0.118	0.239
OC	0.953	0.036	–0.152	–0.168
CEC	0.912	0.155	0.255	–0.024
DHA	0.566	0.318	0.447	–0.399
Acid phosphatase	0.935	0.321	–0.028	0.083
Alkaline phosphatase	0.958	0.204	–0.060	0.110
Aryl	0.916	0.306	–0.055	0.176
FDH	0.963	0.032	–0.115	0.050
VBC	–0.926	–0.173	0.102	–0.239
VFC	0.960	0.037	0.227	0.091
VAC	0.968	0.024	0.137	–0.074
TOC	0.986	–0.055	0.042	–0.032
LBC	0.794	–0.326	0.420	0.023
POC	0.936	–0.197	0.201	–0.014
MBC	0.978	–0.040	0.113	–0.001
EC	–0.929	0.032	0.012	0.213
Silt	–0.530	0.477	–0.222	–0.557
BD	–0.861	–0.107	0.267	0.019
PD	–0.603	0.670	0.015	0.128
Porosity	0.674	0.494	–0.308	0.049

in these natural ecosystems (Mir et al., 2020). Conversely, the higher soil density observed in the cultivated land uses can be attributed to the factors such as increased clay content, intensive tillage practices leading to soil aggregate breakdown and compaction, and lower SOM (Page et al., 2020). The porosity of the studied land use types followed a specific order, with apple orchards having the highest porosity, followed by forest, pasture, saffron, and paddy-oilseed soils, as illustrated in Figure 1. This trend can be attributed to factors such as heavy soil texture (clay content), low organic inputs, and the use of heavy machinery, all of which contribute to soil compaction and a reduction in soil porosity.

Soil pH is recognized as the primary and the most reliable indicator of soil health. In this study, soils across different LUSs were found to be slightly acidic to moderately alkaline. Notably, as shown in Figure 1, the highest pH levels were recorded in paddy-oilseed soils, while the lowest pH values were observed in forest soils. The elevated pH in paddy-oilseed soils may be attributed to the low OM content. Conversely, the low pH in forest soils can be attributed to the high OM content, the acidic nature of decomposing debris, and the leaching of salts from the surface soils. The quantity of OM and the decomposition products of SOM in a specific land use system plays a significant role in influencing soil pH (Page et al., 2020; Babu et al., 2020).

Table6. Intercorrelation between highly weighted variables under different PCs.

	pH	EC	CEC	N	Zn	Fe	VBC	VFC	VAC	Acid phosphatase	Alkaline phosphatase	Aryl	FDH	WBC	TOC	POC	MBC
pH	1																
EC	0.926*	1															
CEC	–0.949*	–0.958*	1														
N	–0.966**	–0.957*	0.991**	1													
Zn	–0.864	–0.931*	0.967**	0.964**	1												
Fe	–0.952*	–0.997**	0.973**	0.973**	0.934*	1											
VBC	0.931*	0.890*	–0.979**	–0.981**	–0.956*	–0.916*	1										
VFC	–0.877	–0.941*	0.980**	0.968**	0.997**	0.946*	–0.962**	1									
VAC	–0.949*	–0.988**	0.983**	0.989**	0.965**	0.993**	–0.945*	0.970**	1								
Acid phosphatase	–0.953*	–0.877	0.972**	0.970**	0914*	0.910*	–0.990**	0.928*	0.929*	1							
Alkaline phosphatase	–0.964**	–0.912*	0.982**	0.991**	0.944*	0.938*	–0.994**	0.950*	0.960**	0.992**	1						
Aryl	–0.942*	–0.856	0.960**	0.966**	0.915*	0.890*	–0.993**	0.923*	0.918*	0.996**	0.992**	1					
FDH	–0.948*	–0.977**	0.991**	0.995**	0.976**	0.985**	–0.965**	0.980**	0.998**	0.947*	0.973**	0.939*	1				
WBC	–0.964**	–0.983**	0.948*	0.948*	0.876	0.990**	–0.881*	0.894*	0.969**	0.893*	0.914*	0.866	0.956*	1			
TOC	–0.936*	–0.959**	0.959*	0.983**	0.963**	0.964**	–0.942*	0.955*	0.987**	0.914*	0.957*	0.917*	0.987**	0.932*	1		
POC	–0.854	–0.927*	0.903*	0.935*	0.954*	0.920*	–0.884*	0.934*	0.952*	0.831	0.893*	0.842	0.950*	0.870	0.981**	1	
MBC	–0.928*	–0.949*	0.958*	0.983**	0.970**	0.955*	–0949*	0.960**	0.982**	0.917*	0.960**	0.923*	0.985**	0.918*	0.999**	0.983**	1

Table 7. Selected indicators and their respective scores and weights.

Selected variables	Scores					Weights
	Forest	Pasture	Apple	Saffron	Paddy-oilseed	
CEC	1	0.92	0.88	0.81	0.71	0.79
Fe	1	0.77	0.7	0.54	0.45	
VFC	1	0.83	0.64	0.61	0.29	
Ac_P	1	0.93	0.91	0.68	0.46	
WBC	1	0.77	0.77	0.56	0.53	
MBC	1	0.94	0.76	0.66	0.57	
Mg	0.69	0.84	1	0.89	0.81	0.11
Ca	0.7	0.84	0.89	1	0.82	0.05
DHA	1	0.98	0.97	0.91	0.84	
Silt	0.68	0.77	1	0.7	0.97	0.05

CEC, cation exchange capacity; Fe, iron; VFC, viable fungal count; Ac_P, acid phosphatase; WBC, Walkley and Black carbon; MBC, microbial biomass carbon; Mg, exchangeable magnesium; Ca, Exchangeable calcium; DHA, dehydrogenase activity.

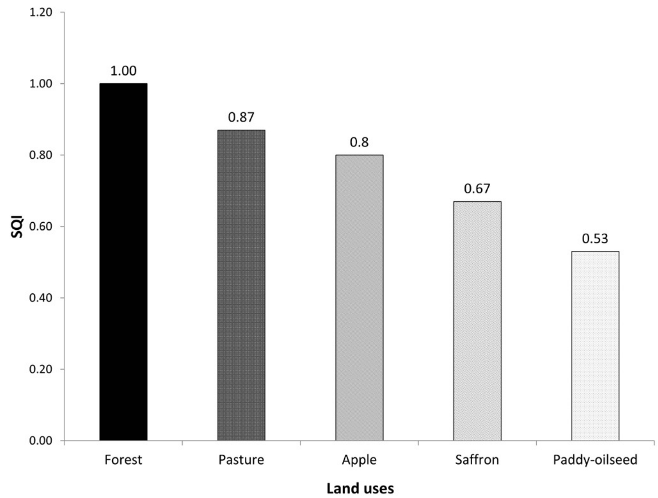

Figure 6. SQI under different LUSs.

In the cultivated land uses, the accumulation of salts, primarily due to the application of inorganic fertilizers, may contribute to higher EC values (Kiflu and Beyene, 2013). The study also indicated that the EC of soils in various land use types within Kashmir Himalayas was <1 dS m^{-1}, as shown in Figure 1, signifying the absence of prevalent salinity concerns. The low EC values in undisturbed soils could be due to the leaching of bases from surface soils and their subsequent movement out of the soil profile.

4.2. Soil chemical properties under different LUSs

The present study demonstrated that the OC and CEC of soils under studied land uses varied significantly. As shown in Figure 3, the higher values of OC and CEC recorded under forest land use might be attributed to the annual inclusion of plant litter. The higher elevation, which slows the decomposition process, thus favours the accumulation of more OM (Selassie et al., 2015). The presence of higher OM also favours the formation of soil aggregates, increases the surface area of soil, and thus enhances the CEC. Conversely, the low OC and CEC in cultivated soils could be due to the breakdown of stable soil aggregates, which exposes the OM to microbial attack and consequently favours the rapid oxidation of SOM (Chemeda et al., 2017).

Soil nutrients play a vital role in plant nutrition and other essential processes. The macronutrients assessed in this study include N, P, K, Ca, Mg, and S, as shown in Figures 3 and 4. The highest N content in forest soil, as shown in Figure 3, might be attributed to the high OM levels, enhanced enzymatic activities, and a strong positive relationship between SOM and N (Chemeda et al., 2017). Conversely, the cultivated soils had the lowest available N, which might be associated with the elevated oxidation of SOM due to cultivation practices (Selassie et al., 2015). Similarly, the highest available P in forest soils might be attributed to the synthesis of organic-phosphate complexes that are more readily absorbed by plant species, as well as the solubilization of calcium phosphates (Selassie et al., 2015).

The soil of the Kashmir Valley is dominated by illite minerals that contribute to the higher availability of K in the soils (Bashir et al., 2024c). The available K content was in the higher range across all the studied land uses. The higher K content was found in forest soils, which is mainly attributed to the intense weathering of potash-bearing minerals and the formation of clay-organic complexes. The intense cultivation and leaching of K in paddy-oilseed soils are also supported by the findings of Sahu et al. (2016).

The content of Ca and Mg in the soil, as illustrated in Figure 4, is influenced by several factors, including the presence of Ca-bearing minerals, variations in soil pH, and differences in elevation and slope. The Kashmir Valley is characterized by a dense layer of limestone with significant amounts of dolomite and shale (Wani et al., 2017). Additionally, the presence of minerals containing illite and chlorite contributes to the elevated Ca and Mg content across the studied LUSs. Similarly, the availability of S is influenced by the SOM content, as it serves as a regulatory factor for S availability. Notably, the highest and the lowest values of available S were found in forest and paddy-oilseed soils, respectively, which could be attributed to a strong association between available S and OC. These findings are consistent with the study by Padhan et al. (2016), which examined the impact of land use on the dispersion of S components in soil.

The dynamics and transformation of soil micronutrients in the form of mineral ions Fe^{2+}, Zn^{2+}, Cu^{2+}, and Mn^{2+} are governed by various factors, such as pH, EC, and SOM (Barker and Pilbeam, 2015). Micronutrients serve as cofactors for numerous enzymes involved in the metabolism of organic molecules such as carbohydrates, nucleic acids, proteins, and lipids. In the present study, micronutrient levels were observed to vary from low to high across the studied land uses, as presented in Table 2. Forest soils exhibited higher micronutrient content, which can be attributed to the greater presence of OM acting as a chelating agent, thereby preventing the leaching losses of micronutrients. On the contrary, extensive cultivation, frequent crop removal, and disturbances associated with different management approaches have led to reduced micronutrient concentrations in farmland soils. This pattern is consistent with findings from previous studies that have reported higher micronutrient levels in natural forests and the lowest in cultivated LUSs (Maqbool et al., 2017).

The nutrient dynamics, encompassing both macro- and micronutrients, were more favourable in forest and pasture soils, as shown in Table 2 and Figures 3 and 4. Among the cultivated LUSs, apple orchard soils exhibited richness in available nutrients. This suggests that the management practices employed in apple orchards are conducive to soil conservation and nutrient enrichment. The presence of increased OM and the addition of leaf litter from apple trees and their decomposition products contribute to the nutrient reservoir. Conversely, paddy-oilseed was identified as the most exhausting land use system. Therefore, it is crucial to implement conservation practices to replenish soil nutrient levels in such systems.

4.3. Soil biological properties under different LUSs

Soil microbial dynamics play a pivotal role in the restoration, equilibrium, and regulation of OM within soil ecosystems. Microorganisms in the soil are responsible for producing numerous enzymes and organic acids, and they exert control over the decomposition of SOM (Kumar et al., 2021). In the present study, higher enzymatic activities of DHA, Ac_P, Alk_P, Aryl, and FDH were recorded in forest soils, while the lowest activities were observed in paddy-oilseed soils, as presented in Table 3. The variation in enzyme activities between the land uses can be attributed to the close association of enzymes with SOM content, minimal anthropogenic perturbations, increased nutrient reserves, and continuous replenishment from the addition of tree leaves (Sofi et al., 2016). Conversely, the low enzymatic activities observed in paddy-oilseed soils could be due to intense anthropogenic disturbances, the removal of crop residues, and the limited return of OM (Sofi et al., 2016). Soil enzymes play a crucial role in nutrient turnover, soil fertility improvement, and productivity enhancement, and thus, the decline in enzymatic activities in cultivated soils reflects soil degradation. Therefore, monitoring soil enzymatic activities is recommended as a valuable approach to evaluate the effectiveness of protective strategies and management practices.

Similarly, microbial activities, including VBC, VFC, and VAC, were recorded as the highest in forest soils and the lowest in paddy-oilseed soils, as presented in Table 3. Factors contributing to this variation include the presence of abundant substrate and low pH conditions in forest soils, which enhance the activity of bacteria and fungi (Babu et al., 2020). Additionally, bacterial activity in breaking down organic materials improves soil porosity, thereby enhancing infiltration capacity and preventing soil erosion (Kumar et al., 2017). The presence of tress stimulates the population of ectomycorrhizal fungi, which colonizes most trees, thereby supporting abundant fungal growth (Asadu et al., 2015). The low VBC and VFC in paddy-oilseed soil might be due to low crop biomass and the adverse impact of agrochemical usage, which limits the availability of food for microorganisms, thus constraining their growth (Dhaliwal et al., 2009).

The VAC was the highest in forest soils and the lowest in paddy-oilseed soils, as presented in Table 3. These variations likely influenced by factors such as pH, the presence of OM, relative moisture, and temperature, which favour actinomycetes in forest soils and have the opposite effect in paddy-oilseed soils (Sofi et al., 2016). Furthermore, the presence of vegetation in surface soils also promoted the growth of actinomycetes population by acting as a source of energy.

In economically and socially relevant crops, the highest microbial and enzymatic activities were observed in apple orchard soils. The addition of defoliated leaves, the release of organic substances from apple tree roots, the turnover of substantial rhizosphere microbial biomass, and the continual addition of OM and inorganic fertilizer contribute to the OM content in apple orchards (Ljavić et al., 2023). Greater returns of OM from fertilizer inputs correspond to increased biological activity in the soil. This signifies a beneficial relationship between organic substances and microorganism populations. Consequently, land conversions from natural ecosystems to cultivated lands without proper conservation measures result in a depletion of microbiome diversity—an issue that requires careful consideration.

4.4. SOC pools and stocks under different LUSs

SOC serves as a potential carbon sink, sequestering atmospheric CO_2, while simultaneously enhancing soil quality and crop productivity (Ahmed and Ahmad, 2019). SOC is a pivotal component in maintaining soil quality due to its multifaceted role in improving physical, chemical, and biological soil properties. The current study demonstrated that soils under forest system recorded the highest carbon fractions, namely, TOC, LOC, POC, and MBC, followed by pasture, apple, saffron, and paddy-oilseed soils, as shown in Figure 5. The higher carbon fractions in forest soils were due to several factors. These soils experience fewer anthropogenic disturbances and benefit from the annual inclusion of leaf litter and root biomass. Additionally, the presence of elevated lignin and tannin contents in forests slows the microbial decomposition of OC and promotes C accumulation (Zazai et al., 2018). Conversely, cultivated soils exhibited lower carbon fractions due to consistent soil disturbances, removal of residues, limited biomass return, and inappropriate land practices (Das et al., 2022). Among these, paddy-oilseed soils had the greatest carbon losses in terms of TOC, LOC, POC, and MBC compared to the forest system, followed by apple and saffron LUSs.

The higher carbon stocks in terms of TOC, LOC, POC, and MBC in forest soils are primarily attributed to litter deposition, fewer anthropogenic activities, the presence of diverse plant species with varying root structures, and slower rates of SOM decomposition compared to other cultivated LUSs (Mir et al., 2020). In contrast, apple orchard soils exhibited the least carbon losses compared to natural forest systems and had the highest carbon stocks among other cultivated LUSs. These minimal carbon losses and the highest carbon stocks in apple orchard soils can be attributed to reduced disturbances such as tillage, increased surface cover, and the addition of leaf litter from apple trees, which enrich the SOM content (Toru and Kibret, 2019). This guide on the requirements for proper land management practices in apple orchards can help strike a balance between agricultural productivity and environmental stewardship, thereby ensuring the ecological sustainability.

4.5. SQI under different land uses

Assessing overall soil quality is crucial for understanding its capacity to perform under different land uses. It is equally important to evaluate soil quality under various coexisting land use and land cover types, as unregulated land use changes and farming practices can lead to soil degradation (Paramanik et al., 2020). In this study, the MDS approach was employed to calculate SQI, providing a single quantitative value as a decision-making tool for assessing soil quality. After applying PCA and the correlation tests detailed in Table 6, only 10 indicators were selected from the initial pool of 30, as presented in Table 7. The final additive index simplifies the complexity of representing various indicators on separate numerical scales, thus eliminating the need for data normalization (Andrews et al., 2002; Ghosh et al., 2019).

The lowest SQI was observed in cultivated soils, particularly in the paddy-oilseed system, as illustrated in Figure 6. This outcome clearly indicates the poor soil quality associated with this land management approach. The factors contributing to the lower quality of soil in paddy-oilseed systems can be attributed to inadequate management practices, including minimal or complete absence of organic substrate return, high cropping intensity, excessive tillage, lack of legumes in crop rotations, and cultivation of heavy feeder crops (Deb et al., 2018; Chakraborty et al., 2019). In contrast, apple orchard soils exhibited relatively better soil quality compared to the cultivated LUSs, as shown in Figure 6. Therefore, apple and saffron crops have proven to be not only economically viable but also environmentally sustainable choices among the studied cultivated LUSs in the region.

5. Conclusion

The Kashmir Himalayas, a region of global ecological significance, face increasing anthropogenic pressures leading to substantial changes in land use patterns and soil quality. The regional economy significantly relies on cash crops, including saffron and apples. However, the maintenance of soil quality and the implementation of effective soil management strategies are identified as critical concerns for ensuring future food and economic security. This study was meticulously designed and executed to comprehensively compare the physical, chemical, and biological properties, SOC fractions and stocks, and the development of SQIs across significant land uses, including forests, pastures, apple orchards, saffron fields, and paddy-oilseed cultivation areas in the Kashmir Himalayas.

The study achieves its objectives by demonstrating that forests and pasture soils have potential for carbon storage and improved soil quality. These findings are consistent with recent research published in high-quality journals. In stark contrast, continuous cultivation practices in paddy-oilseed fields have initiated a concerning trend of soil degradation, as evidenced by the consistent decline in SQI. This decline signals a departure from sustainable land management practices, which may hinder these soils from realising their maximum potential in delivering a wide range of ecosystem services in the future. Therefore, it is imperative to employ economically and environmentally sustainable measures to maintain sustainable land uses in the region.

The implementation of conservation agricultural practices, crop diversification, rotations, incorporation of legumes, and efficient utilisation of organic amendments and biofertilizers hold significant promise in mitigating adverse effects, enhancing soil health, and fostering long-term sustainability. These approaches facilitate carbon sequestration and the preservation of ecological equilibrium, ultimately improving soil quality in fragile ecosystems. This research underscores the urgency of such measures for the Kashmir Himalayas. It also highlights that the methods and approaches in this study can serve as a model for global regions with similar traits and challenges, offering a pathway toward sustainable practices and policies.

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Conflict of interest
The authors declare that they have no conflict of interest.

Availability of data and materials
The data and materials are available from the corresponding author upon request.

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