

## Original Research Article

# Effects of Diverse Land Use Systems on Soil Quality in the Semi-Arid Region, Bengaluru, India

### Abstract

Understanding the impact of diverse land-use systems (LUS) on soil quality is crucial for sustainable land management practices. This study was conducted in Bengaluru, India, to estimate the soil quality index (SQI) under different LUSs. Twenty-four sampling sites were identified in four different LUSs across the Bengaluru, and soil samples were collected monthly over five months during the Rabi cropping season of 2020-2021. The soil quality assessment involved selecting the minimum data set (MDS) via principal component analysis (PCA) and correlation, scoring soil indicators, and combining these scores to create the soil quality index (SQI). PCA was used to identify key soil properties, which included soil organic carbon (SOC), pH, dehydrogenase, nitrogen (N), and urease, for different LUSs derived from the MDS. The SQI was highest in the horticulture cropping system (0.58), followed by the agro+horticulture cropping system (0.53) and the vegetable cropping system (0.49), and lowest in the pulse cropping system (0.44). These findings emphasize the importance of sustainable land management practices to preserve and boost soil quality across cropping systems.

**Key words:** Soil Quality Index, Land-use Systems, Principal Component Analysis, Horticulture Cropping System, Pulse Cropping System

### Introduction

Soil health has been a crucial determinant of the success or failure of human civilizations. Over the years, extensive deforestation has occurred to meet the increasing demands for food,

fodder, and timber driven by population growth and urbanization. This deforestation has transformed natural forests into various land uses, such as agroforestry, horticulture, tree plantations, and agriculture (Uthappa et al. 2024). Throughout this development, soil health and sustainability have often been neglected. Unscientific agricultural intensification, driven by the pursuit of self-sufficiency, has inflicted damage on soils and hastened degradation (Jinger et al. 2023). In semiarid regions, inadequate soil management practices contribute primarily to physical deterioration and soil nutrient depletion (Jinger et al. 2023). Various types of vegetation can profoundly influence the physical, chemical, and biological attributes of the soil (Tauqeer et al. 2022).

The soil quality index (SQI) is a critical tool used to assess and monitor the health and functionality of soils, particularly in agricultural and ecological contexts. Various soil properties are integrated to provide a comprehensive evaluation of soil quality, which is essential for sustainable land management and agricultural practices (Bel-Lahbib et al. 2023). According to Karlen et al. (1997), it is important to quantify all the aspects of soil properties to assess soil quality because of their significant impact on the ability of soils to accomplish specific functions. Although various assessment techniques are used to determine the quality of SQIs, SQIs developed with a minimum data set (MDS) of characteristics have been shown to reflect soil performance due to changes in management practices, such as alterations in land use patterns (Raisi, 2017; Uthappa et al. 2024).

However, the impact of diverse LUSs on soil quality has yet to be determined. Hence, to determine the significance of soil quality, this study was undertaken with the following objectives: (1) To evaluate the physicochemical and biological attributes of soil across various LUSs in Bengaluru, India. (2) To establish a MDS of soil parameters for soil quality indexing to evaluate soil quality under distinct LUSs.

## **Materials and methods**

### Site description, experimental details, and soil sampling

This study builds upon our previously published work. The detailed site descriptions, experimental procedures, and soil sampling methods have been comprehensively outlined in our earlier paper (Sathish and AS, 2024).

## Soil analysis

The soil pH was determined using a combination glass electrode immersed in a 1:2.5 soil–water slurry (Jackson 2005). The electrical conductivity (EC) was measured in a 1:2.5 soil–water suspension using an EC meter (Jackson 2005). The soil organic carbon (SOC) content was determined using the modified  $K_2Cr_2O_7-H_2SO_4$  oxidation method (Walkley and Black, 1938). The alkaline potassium permanganate method was employed to estimate the available nitrogen (N) content in the soil (Subbiah and Asija 1956). Available phosphorus (P) was determined using the Bray 1 method (Bray and Kurtz 1945). The soil available potassium (K) concentration was measured using a normal neutral 1 N ammonium acetate extractant, the pH was adjusted to 7.0, and a flame photometer was used (Jackson 2005). Inductively coupled plasma–optical emission spectrometry (ICP–OES) (Spectra Genesis, Germany) was used to estimate the concentrations of iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn).

The bulk density (BD), particle density (PD), and porosity of the soil were determined using the Keen–Raczkowski cup method. The Keen’s cup was initially weighed with filter paper, and then an air-dried soil sample was uniformly filled into it by tapping to achieve good compactness and a leveled surface. Subsequently, the cup was submerged in water for 24 hours. After saturation, the cup was removed and oven-dried at 105°C until a constant weight was achieved (Piper 1966). The soil moisture content was determined using the gravimetric method by drying the soil to a constant weight at 105°C (Black 1965).

Microbial biomass carbon (MBC) (Vance et al. 1987) and nitrogen (MBN) (Brookes et al. 1985) were measured using the chloroform fumigation extraction technique. Soil dehydrogenase activity was assessed by the reduction of 2,3,5-triphenyl tetrazolium chloride (TTC) (Casida et al. 1964). Soil urease activity was analyzed through the incubation method outlined by Kandeler and Gerber (1988).

### Assessment of the soil quality index (SQI)

Soil quality assessment entails three primary steps: selecting the MDS through principal component analysis (PCA) and determining the significance difference in correlation ( $p < 0.05$ ), scoring soil indicators, and amalgamating scores to formulate the SQI

(Andrews et al. 2002 & Uthappa et al. 2024). PCA, employing the varimax rotation technique, was also conducted to explore the relationships among these indicators. Principal components (PCs) explaining a minimum of 5% of the variance and possessing eigenvalues  $>1$  was considered for indicator selection. Within each PC, indicators with weighted loading values within 10% of the highest loading were selected for the MDS, irrespective of their sign. Multivariate correlation was used to detect and eliminate redundant data when multiple factors were retained within a single PC. In instances of high correlation ( $r > 0.60$ ) among variables, only the variable with the highest correlation was retained for the MDS and considered a "key indicator" used for computing the SQI. (Uthappa et al. 2024).

A linear scoring method was used to convert the data of each identified critical MDS indicator into scores. The indicators were ranked in ascending order to determine whether a higher or lower value corresponded to better soil function. For indicators where higher values indicated better function, each observation was divided by the highest observed value. Conversely, for indicators where lower values were preferable, the lowest observed value was divided by each observation (Tejashvini et al. 2023). This process was performed using the following formula (Vasu et al. 2016): Linear normalization ( $S_L$ ) was carried out using the maximum ( $X_{max}$ ) and minimum ( $X_{min}$ ) values for each soil indicator ( $X$ ), as shown in Eqs. 1 and 2.

$$S_L = \frac{X}{X_{max}} \quad (1)$$

$$S_L = \frac{X_{min}}{X} \quad (2)$$

Based on the PCA results, the MDS indicators for each observation were weighted following conversion into linear scores. Each PC in the data set represented a certain percentage of variance, and the weighted factor for each MDS indicator was determined by dividing the percentage variance by the cumulative variance for all PCs with eigenvalues  $>1$ . Equation 3 was used to calculate the SQI by the weighted scores of the MDS indicators for each observation.

$$SQI = \sum_{i=1}^n (W_i \times S_i) \quad (3)$$

The subscripted variable's score is denoted as ( $S_i$ ), with its weighting factor from PCA represented as ( $W_i$ ). The SQI values were standardized to a range of 0 to 1 by dividing all the SQI values by the maximum SQI value. Subsequently, the SQI was calculated as a

percentage of the average score for each element in the MDS. According to the classification of Li et al. (2018), soils are grouped into five grades based on their SQI values (Table 1).

**Table 1. Soil quality grade classification.**

Indicator	Soil Quality Grade				
	Very High	High	Moderate	Low	Very Low
	Grade-I	Grade-II	Grade-III	Grade-IV	Grade-V
SQI	>0.60	0.55–0.60	0.45–0.54	0.38–0.44	<0.38

### Statistical analysis

A randomized block design (RBD) analysis and Tukey HSD procedure were applied to compare the means of various soil parameters across different LUSs; these analyses were conducted using Origin (Pro) software, 2024, produced by Origin Lab Corporation, Northampton, MA, USA. Pearson's correlation coefficient was used to assess the relationships among the soil quality properties. PCA was carried out using SPSS 20.0 software, and these results were subsequently used to create the MDS for SQI development. Radar plots depicting the % contribution of each indicator to the SQI were generated using Origin (Pro) software, 2024, by Origin Lab Corporation, Northampton, MA, USA.

## Results

### Effects of different LUSs on soil properties

The univariate ANOVA results for 18 soil physicochemical and biological properties across diverse LUSs are shown in Table 2.

#### *Soil physical properties*

The soil bulk density (BD), particle density (PD), and moisture content did not significantly differ across the different LUSs ( $p > 0.05$ ). Among the LUSs, high soil BD was observed in the PCS, VCS, and HCS (1.35 Mg m<sup>-3</sup>), while the lowest BD was found in the A+HCS (1.34 Mg m-

3). The soil PD was greater in the VCS, HCS, and A+HCS treatments (2.22 Mg m<sup>-3</sup>), with the PCS showing a slightly lower PD (2.21 Mg m<sup>-3</sup>). The soil porosity varied significantly across the four LUSs. A+HCSs exhibited the highest soil porosity (39.41%), followed by VCSs (39.34%) and HCSs (39.03%), while PCSs had the lowest porosity (38.88%). The HCSs had the highest soil moisture content (9.00%), whereas the PCS had the lowest (7.72%).

**Table 2. Soil physical, chemical and biological properties of the different LUSs.**

	PCS	VCS	HCS	A+HCS
<b>pH</b>	6.73±0.20 <sup>b</sup>	6.95±0.18 <sup>a</sup>	6.71±0.26 <sup>b</sup>	6.87±0.20 <sup>ab</sup>
<b>EC (dSm<sup>-1</sup>)</b>	0.14±0.01 <sup>a</sup>	0.12±0.01 <sup>a</sup>	0.12±0.01 <sup>a</sup>	0.12±0.01 <sup>a</sup>
<b>SOC (%)</b>	0.34±0.01 <sup>b</sup>	0.36±0.01 <sup>ab</sup>	0.37±0.01 <sup>a</sup>	0.38±0.01 <sup>a</sup>
<b>Moisture content (%)</b>	7.72±0.36 <sup>a</sup>	8.62±0.30 <sup>a</sup>	9.00±0.41 <sup>a</sup>	8.71±0.42 <sup>a</sup>
<b>Bulk density (Mgm<sup>-3</sup>)</b>	1.35±0.01 <sup>a</sup>	1.35±0.01 <sup>a</sup>	1.35±0.01 <sup>a</sup>	1.34±0.01 <sup>a</sup>
<b>Particle density (Mgm<sup>-3</sup>)</b>	2.21±0.01 <sup>a</sup>	2.22 <sup>a</sup>	2.22±0.01 <sup>a</sup>	2.22 <sup>a</sup>
<b>Porosity (%)</b>	38.88±0.24 <sup>b</sup>	39.34±0.37 <sup>a</sup>	39.03±0.37 <sup>ab</sup>	39.41±0.22 <sup>a</sup>
<b>N (kg/ha)</b>	133.56±6.11 <sup>c</sup>	142.41±4.44 <sup>b</sup>	151.28±8.19 <sup>ab</sup>	157.33±7.72 <sup>a</sup>
<b>P (kg/ha)</b>	31.69±1.91 <sup>a</sup>	27.20±0.96 <sup>ab</sup>	25.11±1.46 <sup>b</sup>	26.68±1.06 <sup>ab</sup>
<b>K (kg/ha)</b>	181.37±6.96 <sup>a</sup>	170.30±6.21 <sup>ab</sup>	167.25±8.66 <sup>b</sup>	164.57±7.87 <sup>b</sup>
<b>Zn (ppm)</b>	0.31±0.01 <sup>b</sup>	0.31±0.01 <sup>b</sup>	0.29 <sup>c</sup>	0.32±0.01 <sup>a</sup>
<b>Fe (ppm)</b>	4.64±0.24 <sup>a</sup>	3.90±0.28 <sup>ab</sup>	3.75±0.16 <sup>b</sup>	2.54±0.18 <sup>c</sup>
<b>Mn (ppm)</b>	2.46±0.13 <sup>a</sup>	1.75±0.27 <sup>a</sup>	2.11±0.15 <sup>a</sup>	1.06±0.11 <sup>a</sup>
<b>Cu (ppm)</b>	0.19±0.02 <sup>a</sup>	0.19±0.02 <sup>a</sup>	0.21±0.02 <sup>a</sup>	0.24±0.01 <sup>a</sup>
<b>Dehydrogenase (µg TPF g<sup>-1</sup> soil 24 h<sup>-1</sup>)</b>	75.27±3.81 <sup>b</sup>	82.72±5.60 <sup>ab</sup>	87.62±4.85 <sup>ab</sup>	98.34±3.12 <sup>a</sup>
<b>Urease (µg NH<sub>4</sub>-N g<sup>-1</sup> soil h<sup>-1</sup>)</b>	13.94±1.10 <sup>b</sup>	15.41±1 <sup>ab</sup>	17.31±1.18 <sup>ab</sup>	19.03±0.98 <sup>a</sup>
<b>MBC (µg g<sup>-1</sup>)</b>	116.29±3.91 <sup>b</sup>	118.63±3.77 <sup>a</sup>	116.51±3.66 <sup>b</sup>	118.27±4.08 <sup>a</sup>

<b>MBN (<math>\mu\text{g g}^{-1}</math>)</b>	13.57 $\pm$ 0.49 <sup>a</sup>	13.82 $\pm$ 0.43 <sup>a</sup>	13.59 $\pm$ 0.42 <sup>a</sup>	13.77 $\pm$ 0.49 <sup>a</sup>
Note: PCS- Pulse cropping system, VCS-Vegetable cropping system, HCS-Horticulture cropping system, A+HCS-Agriculture + horticulture cropping system, EC- Electrical Conductivity, SOC- Soil Organic Carbon, N- Nitrogen, P- Phosphorus, K- Potassium, Zn- Zinc, Fe- Iron, Mn-, Manganese, Cu- Copper, MBC- Microbial Biomass Carbon and MBN- Microbial Biomass Nitrogen.				
<sup>z</sup> in a row value followed by similar letter specifies no significance.				

### *Soil chemical properties*

The soil pH and soil organic carbon (SOC) content differed significantly among the four LUSs ( $p < 0.05$ ). In all the systems, the soil pH was acidic. The highest soil pH was observed in the VHCS (6.95), followed by that in the A+HCS (6.87) and that in the PCS (6.73), with the lowest (more acidic) pH recorded in the HCS (6.71). The electrical conductivity (EC) of PCS was greater ( $0.14 \text{ dS m}^{-1}$ ) than that of the other three systems ( $0.12 \text{ dS m}^{-1}$ ). SOC was significantly greater in A+HCSs (0.38%), followed by HCSs (0.37%) and VCSs (0.36%), with the lowest SOC found in PCSs (0.34%). The macronutrients (N, P, and K) exhibited significant differences ( $p < 0.05$ ) between the various LUSs. The available N in these systems was generally low ( $< 280 \text{ kg/ha}$ ). A+HCSs had the highest available N ( $157.33 \text{ kg/ha}$ ), while PCS had the lowest ( $133.56 \text{ kg/ha}$ ), despite pulses being leguminous. Available P was significantly highest in the PCS ( $31.69 \text{ kg/ha}$ ) and VCS on par with A+HCS and was significantly lowest in the HCS ( $25.11 \text{ kg/ha}$ ). Among the diverse LUSs, PCS had the highest available K ( $181.37 \text{ kg/ha}$ ), while A+HCS had the lowest ( $164.57 \text{ kg/ha}$ ). Among the four LUSs, the available Fe and Zn contents exhibited significant differences, while the available Cu and Mn contents exhibited nonsignificant differences. The highest available Fe concentration was found in PCS ( $4.64 \text{ ppm}$ ), followed by VCS ( $3.90 \text{ ppm}$ ), HCS ( $3.75 \text{ ppm}$ ), and A+HCS ( $2.54 \text{ ppm}$ ). For Mn, PCS had the highest content ( $2.46 \text{ ppm}$ ), followed by HCS ( $2.11 \text{ ppm}$ ), VCS ( $1.75 \text{ ppm}$ ), and A+HCS ( $1.06 \text{ ppm}$ ). Available Zn was significantly highest in A+HCSs ( $0.32 \text{ ppm}$ ), followed by PCSs ( $0.31 \text{ ppm}$ ), VCSs ( $0.31 \text{ ppm}$ ), and HCSs ( $0.29 \text{ ppm}$ ). Available Cu was highest in A+HCSs ( $0.24 \text{ ppm}$ ) and lowest in PCSs ( $0.19 \text{ ppm}$ ).

### *Soil biological properties*

The soil MBC is an indicator of the soil microbial load and significantly differed among the LUS. The MBC concentration was highest in VCS ( $118.63 \mu\text{g g}^{-1}$ ), followed by A+HCS

(118.27  $\mu\text{g g}^{-1}$ ) and HCS (116.51  $\mu\text{g g}^{-1}$ ), and lowest in PCS (116.29  $\mu\text{g g}^{-1}$ ). In the VCS treatment, the turnover rate of organic carbon (OC) was also high, followed by that in the A+HCS treatment, compared to that in the other cropping systems. The same trend was observed for MBN across the four LUSs, although the differences were not statistically significant. High soil MBN was found in VCS (13.82  $\mu\text{g g}^{-1}$ ), followed by A+HCS (13.77  $\mu\text{g g}^{-1}$ ), HCS (13.59  $\mu\text{g g}^{-1}$ ), and PCS (13.57  $\mu\text{g g}^{-1}$ ). Soil dehydrogenase activity was highest in A+HCSs (98.34  $\mu\text{g TPF g}^{-1}$  soil 24 h<sup>-1</sup>), followed by HCSs (87.62  $\mu\text{g TPF g}^{-1}$  soil 24 h<sup>-1</sup>) and VCSs (82.72  $\mu\text{g TPF g}^{-1}$  soil 24 h<sup>-1</sup>), with the lowest activity occurring in PCSs (75.27  $\mu\text{g TPF g}^{-1}$  soil 24 h<sup>-1</sup>). Among the four LUSs, A+HCSs had the highest soil urease activity (19.03  $\mu\text{g NH}_4\text{-N g}^{-1}$  soil h<sup>-1</sup>), while PCS had the lowest (13.94  $\mu\text{g NH}_4\text{-N g}^{-1}$  soil h<sup>-1</sup>).

Principal component analysis (PCA) and selection of minimum data set (MDS)

*PCA and MDS for soil property determination for different LUSs*

Of the 18 soil properties assessed, 11 exhibited significant variation among the LUSs and were selected for PCA. Two principal components (PCs) with eigenvalues > 1 were chosen; these PCs collectively explained 92.03% of the cumulative variance (Table 3). Varimax rotation was employed to optimize the distribution of variance across the selected PCs. PC1, with an eigenvalue of 7.60, accounted for approximately 69.11% of the variance. SOC had the highest positive factor loading (0.97), followed by dehydrogenase (0.96), N (0.94), and urease (0.93). On the other hand, PC2 explained 22.92% of the variation, with an eigenvalue of 2.52. For this component, the soil pH exhibited the highest factor loading at 0.82.

**Table 3. PCA results for soil quality indicators of various LUSs.**

Factors	Land Use Systems	
	PC1	PC2
Porosity	0.86	0.49
pH	0.51	<b>0.82</b>
SOC	<b>0.97</b>	-0.24
N	<b>0.94</b>	-0.32

<b>P</b>	-0.79	0.44
<b>K</b>	-0.96	0.22
<b>Zn</b>	0.24	0.72
<b>Fe</b>	-0.96	-0.01
<b>Dehydrogenase</b>	<b>0.96</b>	-0.14
<b>Urease</b>	<b>0.93</b>	-0.29
<b>MBC</b>	0.68	0.68
<b>highest</b>	0.97	0.82
<b>10% of highest</b>	0.87	0.74
<b>Eigenvalue</b>	7.60	2.52
<b>Variance (%)</b>	69.11	22.92
<b>Cumulative variance (%)</b>	69.11	92.03
Note- PC- Principal Component, EC- Electrical Conductivity, SOC- Soil Organic Carbon, N- Nitrogen, P- Phosphorus, K- Potassium, Zn- Zinc, Fe- Iron, Mn-, Manganese, MBC- Microbial Biomass Carbon and MBN- Microbial Biomass Nitrogen.		

In the case of various LUSs, two PCs with eigenvalues > 1 were chosen for MDS. In the first PC, the SOC, dehydrogenase, N, and urease parameters were within 10% of the highest factor loading (Table 4). All four parameters from PC1 correlated positively with a correlation coefficient (r) greater than 0.60. Since they represent two different aspects of soil, i.e., chemical properties (organic and inorganic nutrients) and biological properties (soil enzymatic activity), they were selected for analysis (Figure 1). In PC2, pH was highly weighted and hence retained for MDS. SOC, pH, dehydrogenase, N, and urease are crucial soil quality indicators for different LUSs derived from the MDS.

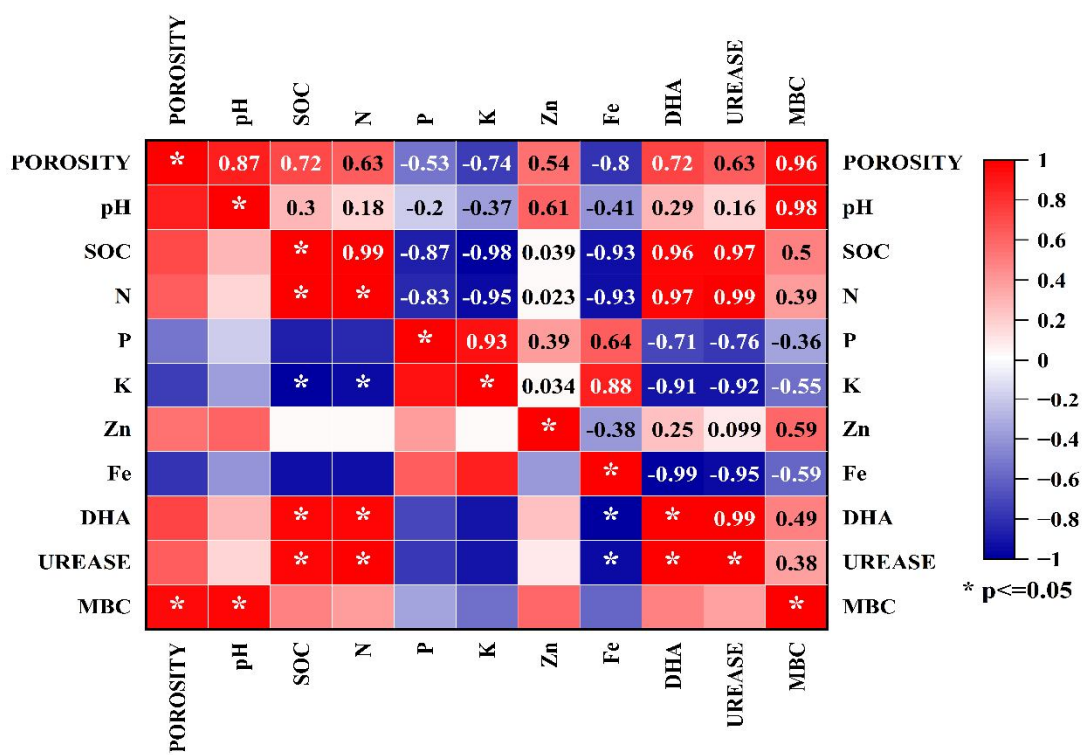
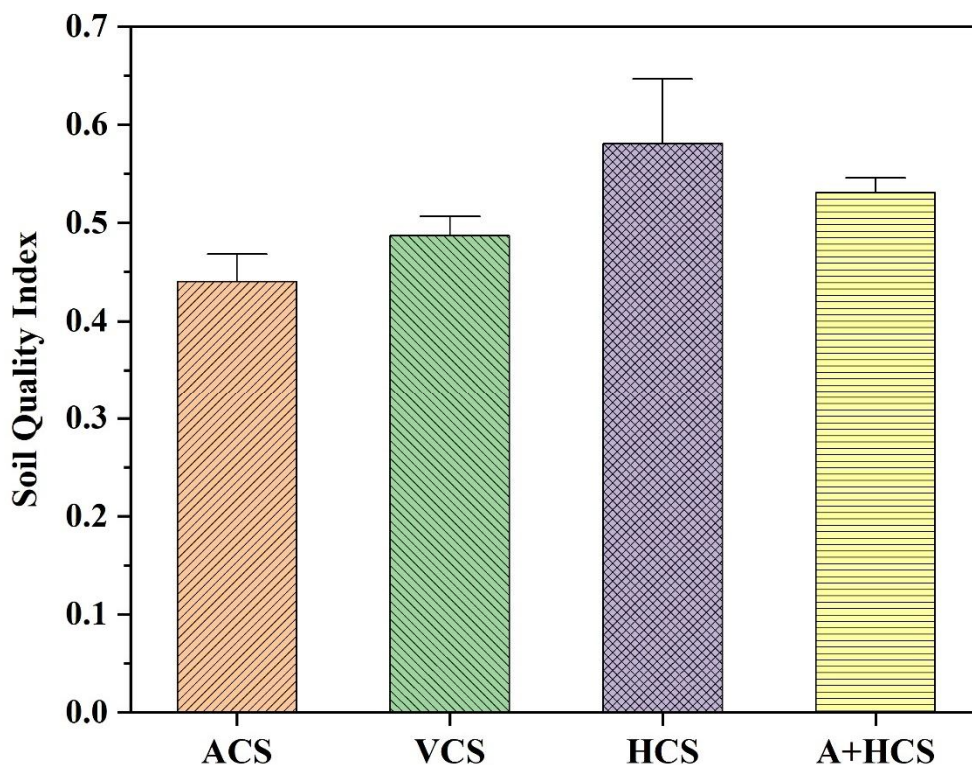


Figure 1. Correlation matrix of significant soil indicators under diverse LUSs.



**Figure 2. Soil quality indices in various LUSs.**

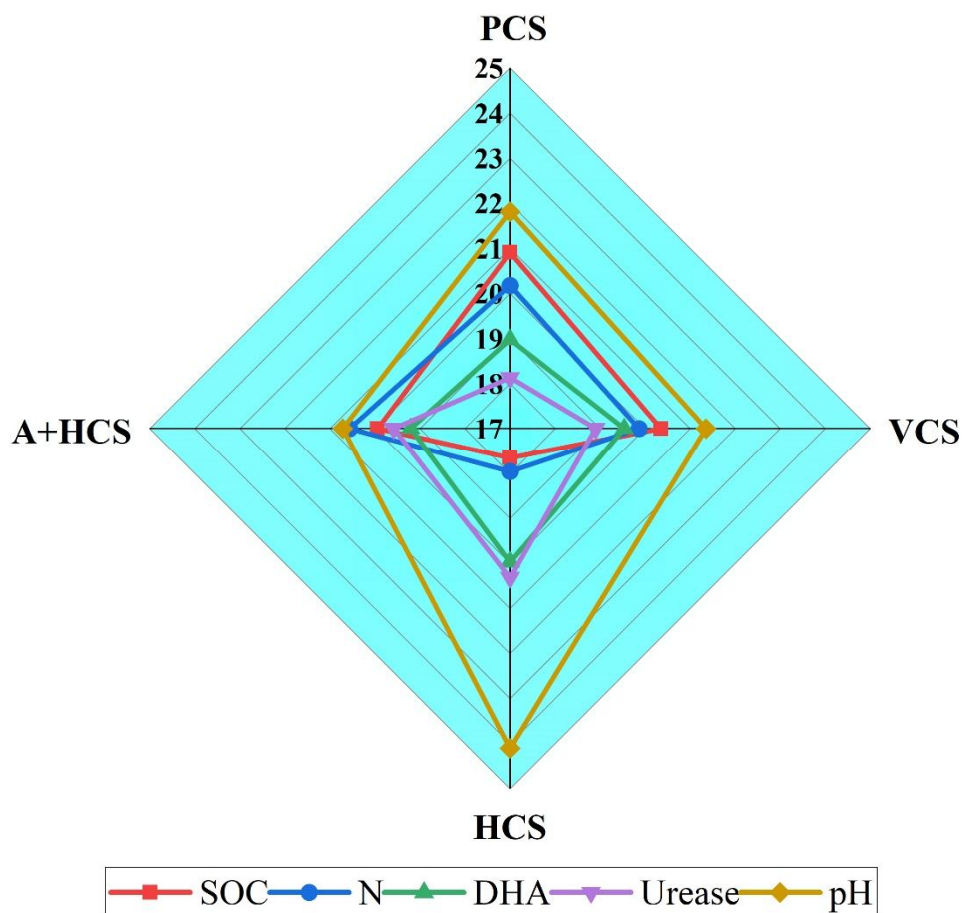
Soil quality index (SQI)

Figure 2 displays the values of the soil quality indices for the various LUSs. Radar plot diagrams depict the contributions of soil indicators to the SQI under different land-use systems across various rural–urban transition zones (Figure 3).

*SQIs under various LUSs*

The linear scoring method used to calculate the SQI was highest under HCSs (0.58), followed by A+HCSs (0.53) and VCSs (0.49), with the lowest SQI recorded in the PCS (0.44). The HCSs exhibited a high SQI (0.58), which fell within the range of 0.55–0.60 (Grade II; Table 1), indicating good soil quality maintenance. In the HCSs, the contributions of the indicators to soil quality, in terms of percentage, were ranked as follows: pH (24.1%) > urease (20.3%)

>dehydrogenase (20%) > N (18%) > SOC (17.7%) (Figure 3). The soil in A+HCS (0.53) and VCS (0.49) exhibited moderate SQI values, which fell within the range of 0.45–0.54 (Grade III). In the A+HCSs, the contributions of the indicators to soil quality, in terms of percentage, were ranked as follows: pH (20.7%) > N (20.6%) > SOC (19.9%) > urease (19.6%) > dehydrogenase (19.2%). In the VCSs, pH (21.3%) was the highest contributor, and urease (18.9%) was the lowest contributor. The PCS soils displayed a low SQI (0.44), which fell within the range of 0.38–0.44 (Grade IV), indicating poor soil quality maintenance. In the PCS, the contributions of the indicators to soil quality, in terms of percentage, were ranked as follows: pH (21.8%) > SOC (20.9%) > N (20.2%) > dehydrogenase (19%) > urease (18.1%).



**Figure 3. Radar plot of the percentage contributions of selected soil indicators of the MDS to soil quality indices under different LUSs.**

Discussion

## Effects of different LUSs on soil properties

The high moisture content in HCSs and A+HCSs can be attributed to two factors: first, they are generally irrigated, unlike pulse crops; second, the greater canopy cover of perennial horticultural crops reduces soil moisture evaporation. Similar trends in these soil physical traits were reported by Scharenbroch et al. (2005), corroborating our findings. The high SOC content may be attributed to the deposition of large quantities of litter in mixed cropping systems (A+HCSs). In contrast to croplands, perennial crops sustain continuous vegetation cover and undergo frequent root turnover, thereby augmenting the input of SOC. In general, crops characterized by high biomass export and the reintroduction of crop residues into the soil directly impact SOC levels (Graham et al. 2002). This low N status in PCS could be due to intensive cultivation leading to increased N mineralization. High P fertilizer application in the PCS enhances rhizobial activity in the root zone. Agricultural crops require high amounts of K fertilizer to achieve higher grain and protein yields (Srinivasarao et al. 2003). Dehydrogenase activity, an indirect indicator of overall microbial soil activity, and urease activity, which catalyzes the hydrolysis of urea to CO<sub>2</sub> and NH<sub>3</sub>, also varied significantly among the LUSs and followed a similar pattern. Tillage treatments were found to significantly influence urease activity, with a decrease in activity associated with increased soil disturbance in the PCS (Lorenz and Kandeler, 2004).

## Assessment of the SQI through PCA of different LUSs

Dehydrogenase activity is considered an important soil quality indicator (Biswas et al. 2017; Klimkowicz-Pawlaset al. 2019). Soil nutrient availability, organic compound oxidation, and microbial activity related to N cycling are crucial indicators of SQ (Bünemann et al. 2018; Uthappa et al. 2024). N is vital for plant growth, exclusive biomass production, and leaf area increase (Diaz et al. 2006). A decrease in SOC leads to a decrease in crop yield, aggregate stability, and soil cation exchange capacity, which makes SOC a key soil quality component (Freixo et al. 2002). Soil pH controls numerous soil properties (physicochemical and biological) and processes (nutrient regulation and microbial activity) (Schoenholtz et al. 2000; Tejashvini et al. 2023).

This superior SQI under HCSs can be attributed to factors such as high SOC levels and optimal biological enzymatic activities. Reduced soil disturbance and litter accumulation in HCSs promote the growth of soil microorganisms and mesofauna, favoring high SQIs (Sathish and AS 2024). Soil pH has emerged as a primary indicator for these soils, regulating various physicochemical and biological properties, microbial activity and OM turnover (Schoenholtz et al. 2000). Despite containing an optimal amount of soil chemical and biological properties, A+HCSs and VCSs face challenges due to the short duration of agricultural and vegetable crop cultivation, necessitating the use of heavy equipment in farming practices, pesticide management, and fertilization, all of which can diminish soil quality. Anthropogenic activities such as land practices can lead to changes in soil quality in agroecosystems, affecting soil functions (Yang et al. 2020). Larger soil organisms such as worms and arthropods contribute nutrients to the soil through their waste as they feed on SOM. Sathish and AS (2024) also noted a lower population of soil fauna in the PCS due to mechanized farming and high disturbance. SOC and soil pH are crucial indicators of soil quality because they influence the nutrient supply capacity and nutrient availability in soil (Kuntoji and Subbarayappa 2022).

## **Conclusion**

The study revealed that soil quality is significantly influenced by different LUSs. HCSs demonstrated the highest SQI due to their high SOC content and optimal biological activities, with pH emerging as a critical indicator. The A+HCSs and VCSs had moderate SQIs, which were affected using heavy farming equipment and management practices. The PCS had the lowest SQI and was impacted by mechanized farming and high soil disturbance. SOC, pH, dehydrogenase, N, and urease are the crucial soil quality indicators for different LUSs derived from the MDS for PCA. These findings highlight the need for efficient land use and management practices to improve soil quality across different cropping systems.

## **Statements & declarations**

### **Data availability statement**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

### **Ethical Responsibilities of Authors**

All the authors have read, understood, and complied with the statement on "Ethical responsibilities of Authors", as found in the Instructions for Authors.

### **Consent to Publish**

Not applicable.

### **Consent to Participate**

Not applicable.

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