Original Research Article

Effects of Urbanization on Soil Quality in the Rural–urban Gradient of Bengaluru, India

Abstract

Understanding the impact of urbanization 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 rural–urban gradient (RUG) zones. Twenty-four sampling sites were identified along the RUG, and soil samples were collected monthly over five months during the October to February 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 microbial biomass carbon (MBC), SOC, N, manganese (Mn), and urease for different RUG zones derived from the MDS. The rural zones had the highest SQI (0.57), followed by the peri-urban (0.47 and 0.48) and urban (0.45 and 0.47) zones.These findings emphasize the importance of sustainable land management practices to preserve and boost soil quality across diverse regions, particularly in the face of rapid urbanization and industrialization.

Key words: Soil Quality Index, Rural–urban Gradient, Urbanization, Principal Component Analysis, Minimum Data Set.

Introduction

The rapid expansion of urban landscapes into surrounding rural areas, a phenomenon known as urbanization, has accelerated globally in recent years (Sathish and AS, 2024). As of 2022, approximately one-third of India's population resided in cities. This reflects an increase in urbanization of more than 4 percent in the past decade, indicating significant migration from rural areas to urban centers for employment and livelihood opportunities. The urbanization of rural areas results in higher resource demands and intensified agriculture, which in turn alters soil microbial dynamics worldwide, particularly in tropical regions (Steinhübel and von Cramon Taubadel 2021). The expansion of urban areas into rural regions has direct and indirect impacts on soil and land use. The most evident effect of urbanization on land usage is urban sprawl (Bhagawatet al. 2017). The encroachment of urban areas into rural territories can profoundly alter agricultural dynamics at the rural–urban interface. Recent shifts in land use and land cover patterns driven by human activities have significantly affected urban–rural connections (Seto et al. 2013). The rapid expansion of metropolitan systems has had notable repercussions on soil ecosystem services and the land-use systems supporting them. Moreover, the swift increase in population and urbanization influence soil ecosystem services and the land-use patterns that sustain them (Tejashviniet al. 2023).

Conversely, rapid urban expansion has driven an increased demand for horticulture commodities, prompting a notable shift in agricultural lands toward intensive irrigated multicropping systems. These systems heavily rely on inorganic fertilizers, sporadic urban compost additions, and irrigation. Consequently, this transition has resulted in the accumulation of organic and inorganic residues in the soil, which have been demonstrated to constrain the productivity of agricultural crops. The long-term ramifications of these changes on soil productivity and quality remain poorly understood (Tejashviniet al. 2023). Such modifications can exert enduring impacts on soil characteristics (Li et al. 2019), underscoring their importance in evaluating soil quality (Liu et al. 2018). Hence, soil quality assessments play a vital role in comprehending soil conditions and formulating more effective management strategies (Qi et al. 2009; Uthappa et al. 2024).

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 (Raiesi, 2017; Uthappa et al. 2024).

However, the impact of urbanization 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 in the RUG in Bengaluru, India. (2) To establish a MDS of soil parameters for soil quality indexing to evaluate soil quality under distinct RUG zones.

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 (Tejashviniet 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.

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

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

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.

$$SQI = \sum_{i=1}^{n} (Wi \times Si) \qquad (3)$$

The subscripted variable's score is denoted as (Si), with its weighting factor from PCA represented as (Wi). 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 RUG zones; 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 RUG zones on soil properties

The one-way ANOVA results for 18 soil physicochemical and biological properties across different RUG zones are presented in Table 2.

Soil physical properties

The soil BD, PD, and porosity significantly varied across the RUG zones. BD was highest in urban zones (1.38 and 1.37 Mgm-3), followed by peri-urban zones, and lowest in rural zones (1.33 Mgm-3). PD exhibited a similar trend as BD across the transition zones. The soil porosity reached a maximum in the rural zones (39.72 and 39.71%), followed by that in the peri-urban zones, and reached a minimum in the urban zones (38.02 and 38.87%). The soil moisture content was greater in the urban zones (9.36 and 8.57%) than in the peri-urban and rural zones (8.05 and 7.96%).

Soil chemical properties

The soil pH ranged from neutral to acidic across urban, peri-urban, and rural zones. The pH levels in the urban zones (7.13 and 7.18) were comparable to those in the peri-urban zones (7.08 and 7.16) but significantly differed from those in the rural zones (6.26 and 6.09). The soil EC varied significantly among the RUG zones but remained within the normal range (<0.2 dSm^{-1}). The highest EC was noted in urban zones (0.16 and 0.15 dSm^{-1}), while the lowest EC was reported in rural zones (0.10 and 0.11 dSm^{-1}). The SOC content was highest in rural zones (0.38 and 0.39%), followed by that in peri-urban zones, and was significantly lower in urban zones (0.34%). The available N in the RUG zone was low (<280 kg/ha) and differed significantly. The soil N content increased in the rural zones (165 and 164.54 kg/ha), followed by the peri-urban zone and the significantly low N content in the urban zones (129.10 and 129.97 kg/ha). In urban zones (30.65 and 29.73 kg/ha), P availability was greater than that in peri-urban and rural zones

(24.09 and 25.78 kg/ha, respectively). Available K was significantly high in peri-urban zones (184.95 and 183.55 kg/ha) and low in rural zones (147.68 and 147.70 kg/ha).

Table 2. Soil physical, chemical and biological properties among the various RUG zones.

	NU	NP	NR	SU	SP	SR
pH	7.13±0.07^{a}	7.16±0.09^{a}	6.26±0.16^{b}	7.18±0.05^{a}	7.08±0.06^{a}	6.09±0.13^{b}
EC (dSm^{-1})	0.16±0.01^{a}	0.11^{bc}	0.11±0.01^{c}	0.15±0.01^{ab}	0.11±0.01^{c}	0.11±0.01^{c}
SOC (%)	0.34±0.01^{b}	0.37±0.01^{ab}	0.38±0.01^{a}	0.34±0.01^{b}	0.37±0.01^{ab}	0.39^{a}
Moisture content (%)	9.36±0.47^{a}	8.61±0.67^{a}	8.05±0.55^{a}	8.57±0.44^{a}	8.55±0.46^{a}	7.96±0.28^{a}
Bulk density (Mgm^{-3})	1.38±0.01^{a}	1.35±0.01^{bc}	1.33^{c}	1.37±0.01^{ab}	1.35^{bc}	1.33^{c}
Particle density (Mgm^{-3})	2.23 ^{a}	2.22 ^{ab}	2.20±0.01^{b}	2.23 ^{a}	2.21±0.01^{ab}	2.21±0.01^{ab}
Porosity (%)	38.02±0.27^{b}	39.53±0.32^{a}	39.72±0.11^{a}	38.87±0.24^{ab}	39.13±0.22^{a}	39.71±0.22^{a}
N (kg/ha)	129.1±5.60^{b}	143.66±4^{ab}	164.54±7.92^{a}	129.97±4.36^{b}	144.61±4.25^{ab}	165.00±7.46^{a}
P (kg/ha)	30.65±1.99^{a}	27.81±2.01^{a}	25.78±1.28^{a}	29.73±3.15^{a}	27.97±1.20^{a}	24.09±0.86^{a}
K (kg/ha)	182.34±3.28^{a}	184.95±4.13^{a}	147.68±3.98^{b}	179.02±3.42^{a}	183.55±3.52^{a}	147.7±5.48^{b}
Zn (ppm)	0.31^{b}	0.29±0.01^{c}	0.32±0.01^{a}	0.3±0.01^{bc}	0.29±0.01^{c}	0.32±0.01^{a}
Fe (ppm)	4.11±0.57^{a}	3.9±0.48^{a}	3.22±0.44^{a}	4.02±0.37^{a}	3.84±0.54^{a}	3.15±0.37^{a}
Mn (ppm)	1.93±0.37^{b}	1.4±0.34^{c}	2.23±0.26^{a}	1.91±0.30^{b}	1.4±0.29^{c}	2.19±0.35^{a}
Cu (ppm)	0.18±0.01^{a}	0.20±0.02^{a}	0.23±0.02^{a}	0.19±0.04^{a}	0.21±0.02^{a}	0.23±0.01^{a}
Dehydrogenase (µg TPF g^{-1} soil 24 h^{-1})	77.54±5.70^{a}	83.21±4.56^{a}	99.03±4.19^{a}	74.62±5.33^{a}	86.24±7.06^{a}	95.28±5.92^{a}
Urease (µg NH$_4$- N g^{-1} soil h^{-1})	13.31±1.24^{b}	16.83±1.13^{ab}	19.06±1.24^{a}	13.72±0.92^{ab}	16.65±1.56^{ab}	18.97±0.96^{a}
MBC (µg g^{-1})	107.84±0.58^{c}	115.87±1.06^{b}	129.35±0.85^{a}	107.99±0.80^{c}	115.83±1.82^{b}	127.67±0.67^{a}
MBN (µg g^{-1})	12.58±0.07^{c}	13.5±0.13^{b}	15.15±0.13^{a}	12.54±0.09^{c}	13.52±0.21^{b}	14.84±0.05^{a}

Note: NU- North urban, NP- North peri-urban, NR- North rural, SU- South urban, SP- South peri-urban, SR- South rural, 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.

^{z} in a row value followed by similar letter specifies no significance.

Significant differences ($p<0.05$) were detected in the micronutrients Zn and Mn across the RUG zones, whereas Fe and Cu exhibited nonsignificant differences ($p>0.05$). The highest available Zn concentration was recorded in rural zones (0.32 ppm), followed by urban (0.30 and 0.31 ppm) and peri-urban zones (0.29 ppm). The Fe concentrations were highest in urban zones (4.11 and 4.02 ppm), followed by peri-urban zones, and lowest in rural zones (3.22 and 3.15 ppm). Compared with urban and peri-urban zones, rural zones exhibited significantly greater Mn concentrations (2.23 and 2.19 ppm) (1.40 ppm). Available Cu was highest in rural zones (0.23 ppm), followed by peri-urban (0.20 and 0.21 ppm) and urban zones (0.18 and 0.19 ppm).

Soil biological properties

In the rural zones (129.35 and 127.67 µg g^{-1}), the soil MBC was significantly greater than that in the peri-urban and urban zones (107.84 and 107.99 µg g^{-1}). The soil MBN status was significantly greater in the rural zones (15.15 and 14.84 µg g^{-1}) than in the peri-urban and urban zones (12.58 and 12.54 µg g^{-1}). Soil dehydrogenase activity was found to be highest in rural zones (99.03 and 95.28 µg TPF g−1 soil 24 h^{-1}), followed by peri-urban and urban zones (77.54 and 74.62 µg TPF g−1 soil 24 h^{-1}). In rural zones, a significantly greater level of soil urease activity (19.06 and 18.97 µg NH4- N g^{-1}soil h^{-1}) was observed compared to that in peri-urban areas, followed by that in urban areas (13.31 and 13.72 µg NH4- N g^{-1}soil h^{-1}).

Table 3. PCA results for soil quality indicators of various RUG zones.

Factors	**Rural–Urban Gradient Zones**	
	PC1	**PC2**
Bulk density	-0.98	0.2
Particle density	-0.91	0.21
Porosity	0.86	-0.37
pH	-0.92	-0.37

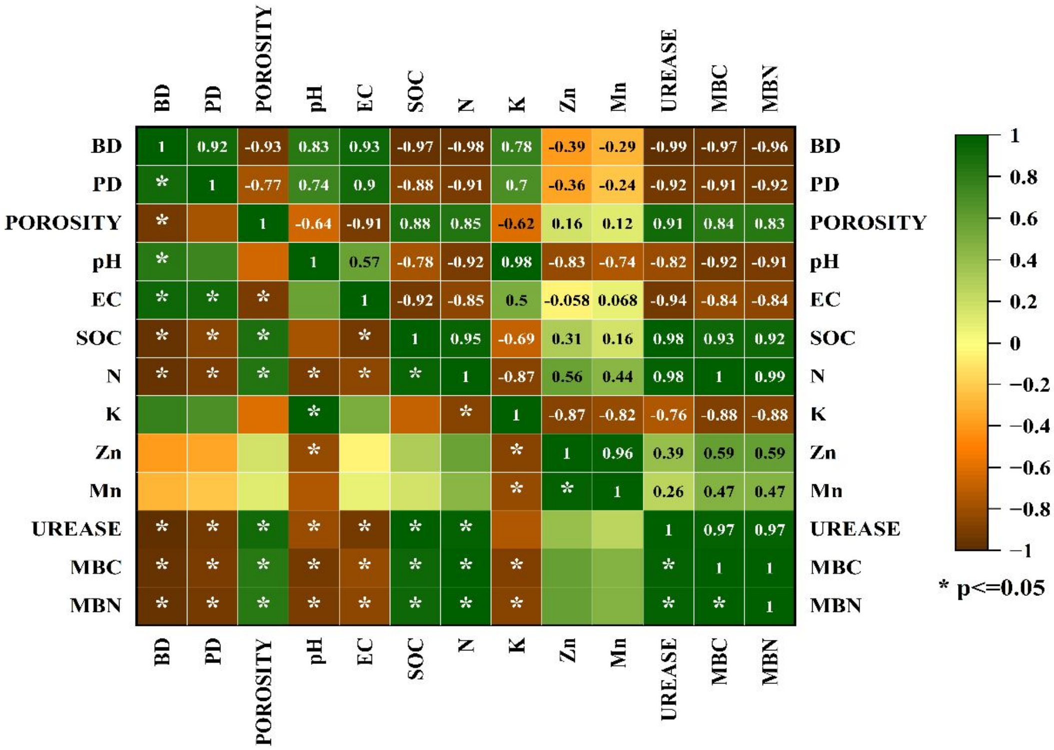
EC	-0.84	0.53
SOC	**0.93**	-0.28
N	**0.99**	-0.02
K	-0.88	-0.46
Zn	0.57	**0.81**
Mn	0.47	**0.87**
Urease	**0.97**	-0.22
MBC	**0.99**	0.01
MBN	**0.99**	0.01
highest	0.99	0.87
10% of highest	0.90	0.78
Eigenvalue	10.21	2.40
Variance (%)	78.53	18.46
Cumulative variance (%)	78.53	97.00
Note- PC- Principal 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.		

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

PCA and MDS for soil properties in various RUG zones

Among the 18 soil properties that exhibited significant variation among the various RUG zones, 13 were chosen for PCA. According to the PCA of the soil indicators in the various RUG zones, only two PCs had eigenvalues > 1 and explained 97% of the cumulative variance (Table 3). PC1 and PC2 are generated depending on the level of significance. PC1, with an eigenvalue of 10.21, explained approximately 78.53% of the variance. The variables included MBC, MBN and N, with the highest positive factor loading of 0.99, followed by urease (0.97) and SOC

(0.93). PC2 explained 18.46% of the variation, with an eigenvalue of 2.40. In this PC, soil Mn had the highest factor loading (0.87), followed by Zn (0.81).



	BD	PD	POROSITY	pH	EC	SOC	N	K	Zn	Mn	UREASE	MBC	MBN	
BD	1	0.92	-0.93	0.83	0.93	-0.97	-0.98	0.78	-0.39	-0.29	-0.99	-0.97	-0.96	BD
PD	*	1	-0.77	0.74	0.9	-0.88	-0.91	0.7	-0.36	-0.24	-0.92	-0.91	-0.92	PD
POROSITY	*		1	-0.64	-0.91	0.88	0.85	-0.62	0.16	0.12	0.91	0.84	0.83	POROSITY
pH	*			1	0.57	-0.78	-0.92	0.98	-0.83	-0.74	-0.82	-0.92	-0.91	pH
EC	*	*	*		1	-0.92	-0.85	0.5	-0.058	0.068	-0.94	-0.84	-0.84	EC
SOC	*	*	*		*	1	0.95	-0.69	0.31	0.16	0.98	0.93	0.92	SOC
N	*	*	*	*	*	*	1	-0.87	0.56	0.44	0.98	1	0.99	N
K				*			*	1	-0.87	-0.82	-0.76	-0.88	-0.88	K
Zn				*				*	1	0.96	0.39	0.59	0.59	Zn
Mn								*	*	1	0.26	0.47	0.47	Mn
UREASE	*	*	*	*	*	*	*				1	0.97	0.97	UREASE
MBC	*	*	*	*	*	*	*	*			*	1	1	MBC
MBN	*	*	*	*	*	*	*	*			*	*	1	MBN
	BD	PD	POROSITY	pH	EC	SOC	N	K	Zn	Mn	UREASE	MBC	MBN	

Figure 1. Correlation matrix of significant soil indicators under diverse RUG zones.

For different RUG zones, two PCs with eigenvalues > 1 were selected for MDS. In the first PC, the MBC, MBN, SOC, N, and urease indices were within 10% of the highest factor loading (Table 4). All five soil properties exhibited significant positive correlations (r > 0.60 and $p \leq 0.05$) (Figure 1). Since MBC and MBN exhibited similar correlations and significance, MBC was ultimately selected for the MDS. The other three parameters represent different aspects of soil, such as soil chemical and biological properties; thus, all three parameters were considered. Soil Mn and Zn were highly weighted variables in PC2. Since Mn and Zn were significantly correlated

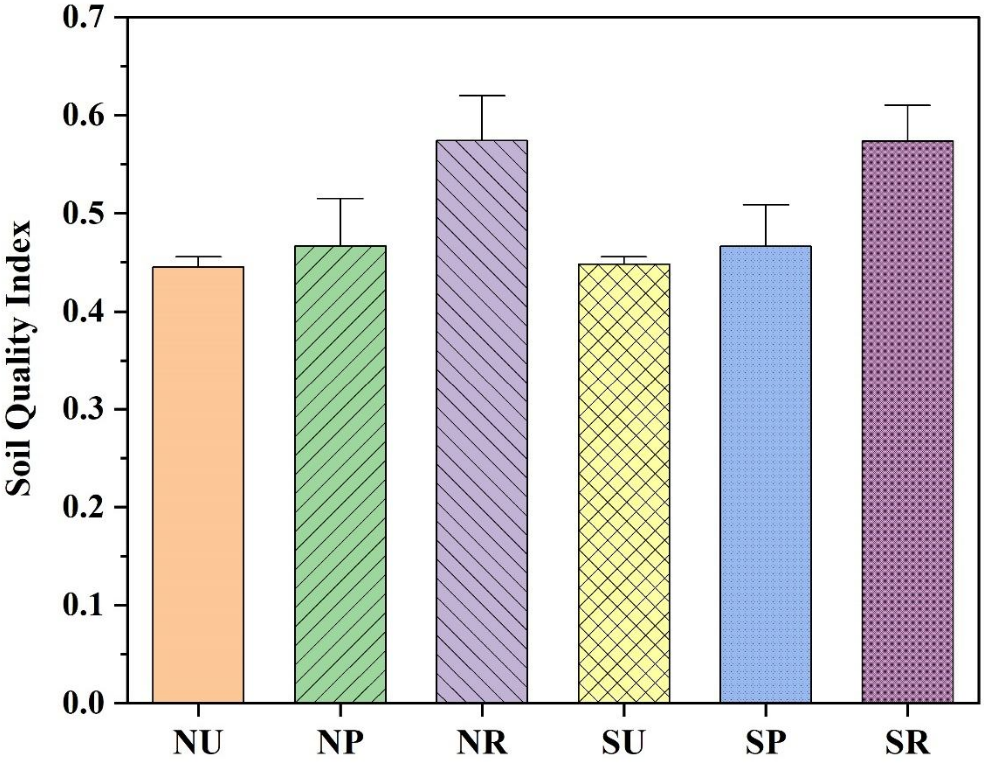


Figure 2. Soil quality indices in various RUG zones.

($r = 0.96$ and $p \leq 0.05$), only Mn was selected to represent PC2 for the MDS. MBC, SOC, N, Mn, and urease are the soil quality indicators for the different RUG zones derived from the MDS.

Soil quality index (SQI)

Figure 2 displays the values of the soil quality indices for the different RUG zones. 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).

SQI under diverse RUG zones

The SQI, calculated using the PCA linear approach across different RUG zones, was highest in rural zones (NR and SR-0.57), followed by peri-urban zones (NP-0.47 and SP-0.48), with the lowest SQI recorded in urban zones (NU-0.45 and SU-0.47). Overall, the southern zones exhibited higher SQIs than did the northern zones, likely due to the comparatively lesser impact of urbanization in the southern zones, with rural zones reporting the highest SQIs among all zones. The rural zone soils displayed a high SQI (0.57), which fell within the range of 0.55–0.60 (Grade II; Table 1). The overall relevance and ranking of the indicators in terms of percent contribution to the SQI were Mn > urease > N > MBC > SOC. The soils in the peri-urban zones (NP-0.47 and SP-0.48) exhibited moderate SQI values, ranging from 0.45–0.54 (Grade III). For the overall SQI, soil urease activity contributed significantly, followed by SOC, while Mn availability made a relatively lesser contribution to peri-urban soils. Finally, in the urban zones (NU-0.45 and SU-0.47), the SQI values ranged from 0.45–0.54 (Grade III), indicating moderate soil quality. In urban zones, the ranking of indicators in terms of percent contribution to the SQI was Mn (23.79 & 23.21%) > SOC (20.46 & 20.34%) > MBC (20.07 & 19.99%) > N (19% & 19.07%) > urease (16.68 & 17.38%).

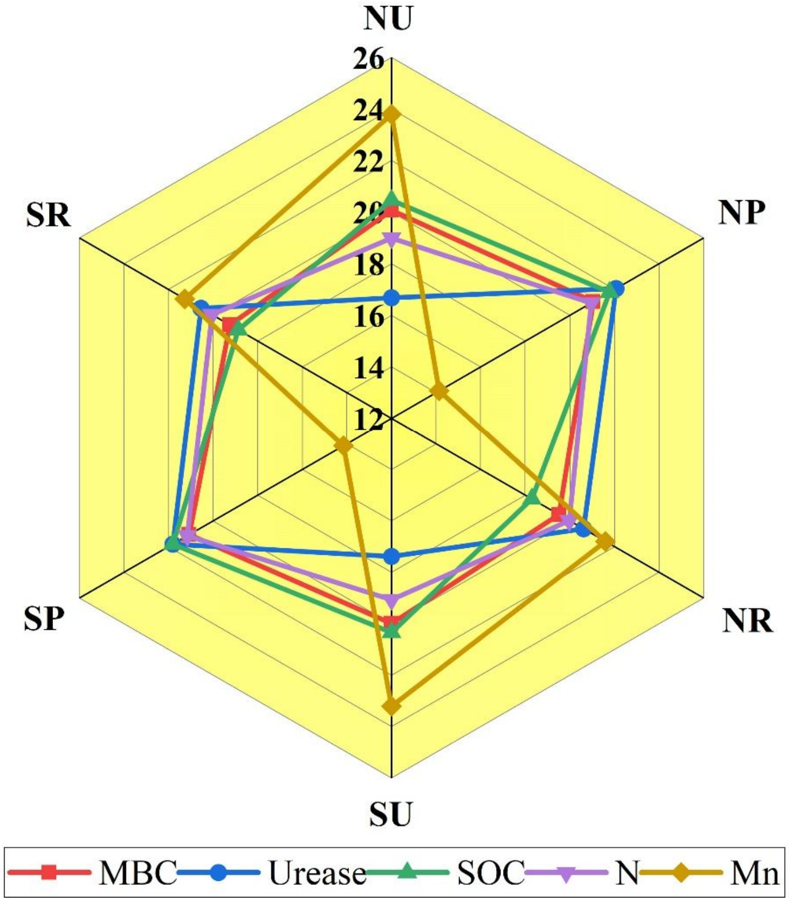


Figure 3. Radar plot of the percentage contributions of selected soil indicators of the MDS to soil quality indices under different RUG zones.

Discussion

Effects of different RUG zones on soil properties

The high BD in urban soils is likely due to the greater soil compaction typically found in urban soils than in peri-urban and rural soils (Pouyatet al. 2010). The use of mechanized irrigation practices in urban and peri-urban areas can aid in maintaining better soil moisture levels. In rural areas, soils tend to be slightly acidic, but with increased urbanization, soils become alkaline (Acosta-Martinez and Tabatabai, 2000), likely due to the release of carbonates from calcareous construction waste, which is more prevalent in urban zones. Similar trends across rural–urban zones were reported by Sakandari (2014). Urban soils are likely to accumulate higher concentrations of salts due to increased chemical application in the cultivation process and the use of deeper underground water for irrigation (Jim 1998). The high SOC in rural zones may be attributed to the higher clay content in rural soils than in peri-urban or urban soils (Hassink and Whitmore 1997), which aids in better aggregation of soil organic matter (Jim, 1998). The low N status in urban zones is attributed to the high soil pH, which affects N mineralization and nitrification processes in urban soils (Baxter et al. 2002), causing the urban soil N content to decline in comparison to that in rural and peri-urban zones (Zhang et al. 2010). Reduced organic inputs and intensive cultivation of crops in urban and transition zones require high P inputs. Even though K is moderately available in the RUG zones, cultivation of crops will exhaust K in the soil. The quantity of K utilized by crops cultivated in urban and transitional zones is much greater than that utilized by crops cultivated in rural areas (Khan et al. 2017). Increased OC and its rapid mineralization could enhance soil microbial populations in rural zones, as suggested by Groffman et al. (1995). Conversely, urban zones exhibit a greater proportion of passive carbon pools due to a faster carbon turnover rate, resulting in lower soil MBC. In urban environments, factors such as trampling and elevated levels of heavy metals can lead to a decline in soil organisms, thereby reducing nitrification and mineralization processes and ultimately affecting MBN levels in urban soil (White and Mcdonnell, 1988). Anthropogenic activities and the presence of organic pollutants such as polycyclic aromatic hydrocarbons

(PAHs) and inorganic pollutants such as lead (Pb) are known to decrease soil microbial populations, as reflected in dehydrogenase activity (Naylo et al. 2019).

Assessment of the SQI through PCA of diverse RUG zones

Soil urease activity is a valuable index of soil quality due to its role in regulating the N supply to plants after urea fertilization (Piotrowska-Dlugosz and Charzynski 2015). It effectively discriminates between various soil management practices and can provide information integrating environmental factors and N cycling, making it a useful tool for assessing soil fertility (Adetunji et al. 2017). The MBC is a sensitive indicator of changes in pollutant toxicity, climate, and crop rotation due to its rapid turnover. Soil quality integrates soil physico-chemical properties and responds to anthropogenic activities, making it a suitable biological indicator of soil quality (Rice et al. 1997). Mn is an essential micronutrient for plant growth and development, as well as for soil quality. It influences microbial activity, soil physicochemical properties, and nutrient availability (Dewangan et al. 2023).

Similarly, Tejashvini et al. (2023) noted that a reduced salt content and higher organic matter content favored high SQIs in rural soils. The elevated SQI in rural areas might be attributed to factors such as high SOC content, nearly neutral soil pH, and robust soil biological properties such as MBC, MBC, dehydrogenase, and urease (Kuntoji and Subbarayappa 2022). Mn influences various microbial activities, soil physicochemical properties, and nutrient availability (Dewanganet al. 2023). Urbanization activities, industrialization, intensive farming activities, acidification, imbalanced fertilizer use, and soil erosion may be attributed to moderate soil quality in urban and peri-urban zones (Bilgili et al. 2017).

Conclusion

The study revealed that soil quality is significantly influenced by RUG zones. Geographically, the rural zones (NR and SR) exhibited the highest SQIs, benefiting from high SOC and nearly neutral soil pH.The peri-urban zones (NP and SP) had moderate SQIs, while the urban zones (NU and SU) had the lowest SQIs, with industrialization and heavy metal accumulation affecting soil quality. MBC, SOC, N, Mn, and urease are the soil quality parameters for the different RUG zones derived from the MDS. These findings highlight the need for efficient land use and management practices to improve soil quality across different regions and 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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