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RESEARCH ARTICLE

Assessment of soil quality index (SQI) in irrigated paddy and sugarcane ecosystems within the Thonnur Kere distributary of the Southern Dry Zone of Karnataka

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Abstract

Soil quality assessment is vital for sustainable land management, particularly in intensively irrigated agroecosystems. This study evaluates the soil quality index (SQI) of irrigated paddy and sugarcane ecosystems within the Thonnur Kere distributary of the Southern Dry Zone of Karnataka, using a principal component analysis (PCA) linear score-based approach. To measure and categorize soil quality and find sensitive markers impacting total soil health, soil samples from 3 regions-upper, middle and tail-end-were examined. The "very high" quality class (Grade I, >0.547) was occupied by the upper, middle and tail-end areas, with corresponding SQI scores of 0.74, 0.68 and 0.78. The tail region's sensitivity index, which was 1.15, showed that soil health was very susceptible to management techniques. Overall soil quality is generally good across the command area, despite regional variations in particular soil metrics. By highlighting important factors affecting soil functioning, the PCA technique successfully decreased the complexity of the data. The importance of nutritional status in determining soil health was demonstrated by the essential indicators that emerged: bulk density, organic carbon, cation exchange capacity, exchangeable nutrients and accessible macronutrients. Interestingly, the tail-end region's strong SQI points to either natural soil resilience or efficient management techniques. This study highlights the necessity of site-specific soil management techniques to maintain soil quality, with an emphasis on nitrogen balance and soil physical quality. The study offers a useful paradigm for the long-term sustainability of irrigated farming systems in semi-arid canal command regions and supports evidence-based planning.

Keywords: linear scoring; non-linear scoring; principal component analysis; sensitivity index; soil quality; soil quality index

Introduction

Soil quality is a key determinant of agricultural sustainability, environmental health and economic productivity. The long-term viability of production systems in irrigated agro-ecosystems, especially those with intensive cultivation of crops like sugarcane and paddy, depends on preserving the soils' functional ability to support plant growth, withstand degradation and provide ecosystem services (1). A significant transition from traditional cropping systems to monocultures of high-water-demand crops like paddy and sugarcane, which are largely dependent on irrigation and chemical inputs, has occurred in Karnataka's Southern Dry Zone (SDZ), particularly in the Mandya district under the control of the Thonnur Kere distributary.

A vital part of the Cauvery Command Area, where guaranteed irrigation has made intensive farming methods possible, is the Thonnur Kere distributary. But these advantages have come at the expense of putting more strain on the health of the land. Ongoing monocropping, excessive fertilizer use, particularly of nitrogen and phosphorus and negligent irrigation practices, which frequently lead to nutrient leaching, waterlogging and salinization, are characteristics of the region's paddy and sugarcane ecosystems (2, 3). Particularly in rice-wheat or rice-sugarcane systems, excessive irrigation has been shown to reduce microbial diversity, hasten the loss of soil organic carbon and promote physical degradation such as compaction and crusting (4, 5).

The difference in nutrients in irrigated command zones is another major concern. Uneven fertilizer application that disregards spatial soil fertility variation leads to localized nutrient deficiencies and toxicities (6). These variations can affect agricultural productivity, reduce the efficiency of fertilizer use and cause nitrogen runoff and leaching that contaminates water bodies (7). In the paddy and sugarcane tracts surrounding Thonnur Lake, farmers usually apply fertilizer in the same amounts throughout fields, disregarding site-specific nutrition requirements. This causes nutrient mining in some areas and over-enrichment in others.

The biological health of the soil is significantly impacted by monocropping, particularly when the soil is irrigated. The diversity and activity of soil microbial communities, which are critical for preserving soil structure and nutrient cycling, are known to be reduced in long-term monoculture systems (8). While sugarcane's long development cycle and high biomass needs deplete the soil of nutrients, continuous flooding of paddy fields limits aerobic microbial activity. These factors work together to produce nutritional imbalances, reduced vulnerability to climatic stresses and lower activity of soil enzymes such as phosphatase and dehydrogenase (9).

To sustain agricultural productivity, a comprehensive assessment of soil quality and nutrient variability is desperately needed in the Thonnur Kere distributary zone. Such assessments involve evaluating key physical, chemical and biological indicators of soil health-including organic carbon content, bulk density, macro- and micronutrient status, pH, electrical conductivity and biological activity (10-12). Degradation hotspots may be identified and suitable soil management plans can be developed by comprehending these indicators in light of current management methods.

There is a dearth of localized information on the current state of the soil in the Thonnur Kere distributary region, that even though soil quality is crucial to agricultural viability. The majority of soil health programs in the region have prioritised fertilizer use and yield optimization, frequently ignoring long-term effects on soil characteristics. Therefore, to inform choices about sustainable land management, a thorough evaluation of the soil quality under the prevalent cropping systems of sugarcane and paddy is desperately needed. Site-specific suggestions to improve soil health and resource-use efficiency may be obtained by combining these findings with information on agricultural practices and irrigation patterns in the Thonnur Kere distributary (13).

In light of this, the study's objectives are to: (i) assess the soil's important physio-chemical and nutrient characteristics under these cropping systems; (ii) create a SQI using a few chosen indicators; and (iii) pinpoint areas of deterioration and possible remediation measures under the Thonnur Kere distributary that result from overwatering, uneven fertilizer application and extended monocropping. The project aims to offer the scientific foundation for sustainable land management techniques that may preserve and increase soil productivity, safeguard environmental quality and enhance livelihoods by gaining a better knowledge of the soil limits in this area.

Materials and Methods

Study area

The study area is Thonnur Kere distributary situated in the SDZ of Karnataka state, India (Fig. 1), covering 2150 ha of area (12.4875° north and 76.6422°) and is roughly 20 km from the town of Mandya and 10.3 km north of Pandavapura town. It is a part of the Cauvery command area receiving irrigation from Krishnaraja Sagara dam indirectly for irrigation SDZ, especially for crops like paddy and sugarcane, with the elevation varying from 603 m to 709 m above mean sea level. The area exhibits a dendritic to sub-parallel configuration of drainage patterns, resulting in distinct lowlands, midlands and upland relief characteristics.

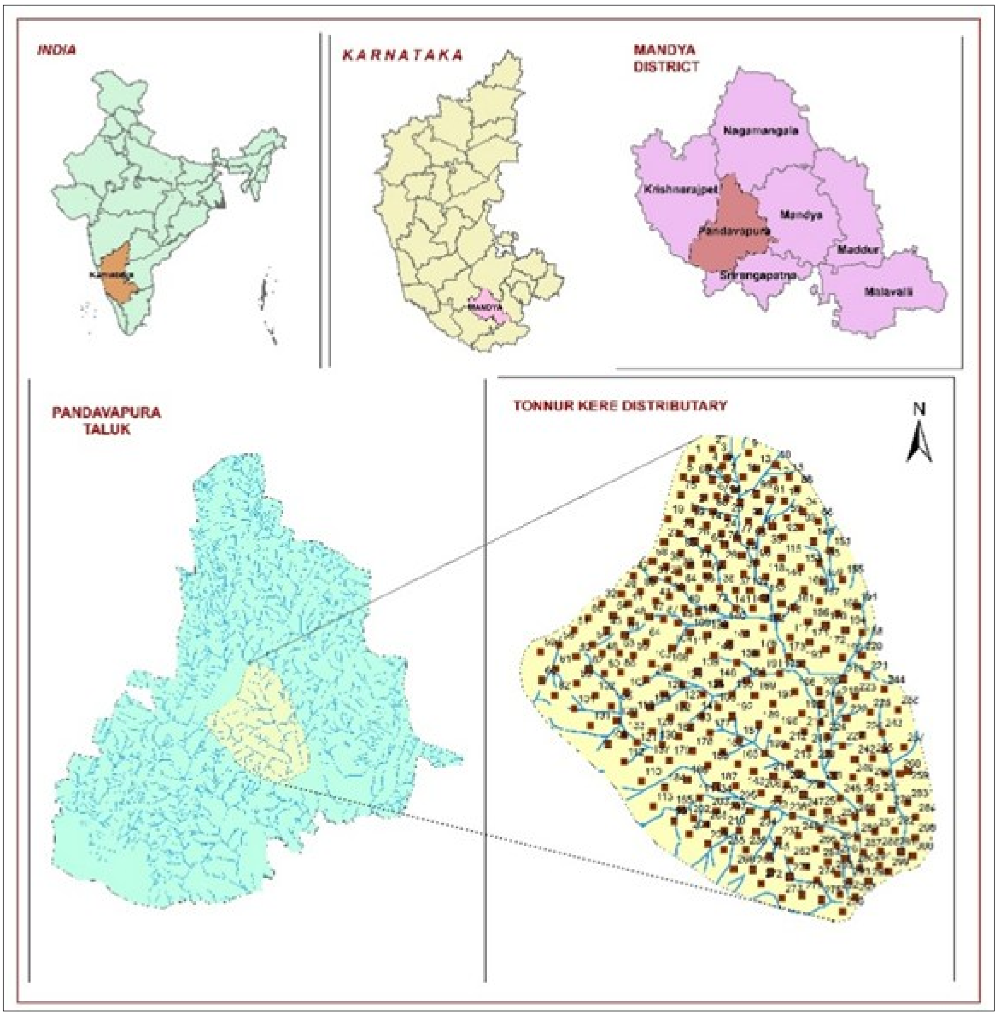


Fig. 1. Location map of the study area.

The study area experiences a semi-arid climate characterized by an average annual rainfall of 737 mm, a mean temperature of 36 °C, potential evapotranspiration (PET) of 1600 mm and relative humidity ranging from 45 % to 79 %. The soils in the area are classified as Alfisols and Inceptisols with some potential for Entisols in specific areas having a hyperthermic temperature regime. The predominant agriculture crops in the region are high-water-demanding crops such as paddy and sugarcane.

Soil sampling and analysis

A random soil sampling strategy was employed during January 2024 to ensure a broad understanding of soil quality across the study area. A total of 300 soil samples were collected at 0-20 cm depth from 3 different regions, i.e., upper, middle and tail end regions of the study area in major cropping systems viz., paddy and sugarcane, with corresponding global positioning system coordinates. The study area and location of soil samples are depicted in Fig. 1. The collected soil samples were pre-processed and subjected to laboratory analysis to determine physico-chemical properties for assessing soil quality. Standard protocols, as described by (14), were followed for measuring pH, electrical conductivity (EC), bulk density (BD) and maximum water-holding capacity (MWHC). Exchangeable cations (potassium (K), calcium (Ca), magnesium (Mg), sodium (Na)) and cation exchange capacity (CEC) were assessed (15). Available phosphorus (avail. P_2O_5) was assessed as per (16). Soil organic carbon (SOC), available Fe and Zn were measured following the procedures described earlier (17, 18).

Assessment of soil quality index (SQI)

Minimum data set

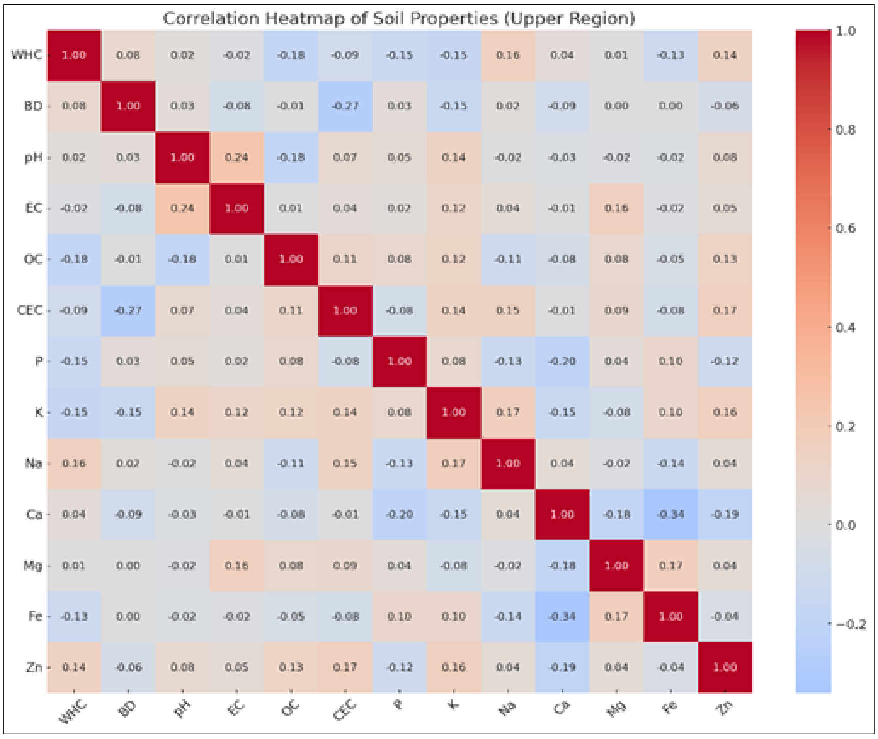
A multivariate statistics-based principal component analysis (PCA) technique described previously (10, 11) to select soil quality indicators and create minimum data set (MDS). It comprises variables that are uncorrelated to each other and the process reduces the multicollinearity of the dataset. In the present study, 12 soil attributes possessing pivotal roles in determining soil health and crop productivity were selected, which include soil reaction pH, EC, OC, avail. P_2O_5, K, Ca, Mg, Na, MWHC, BD, CEC, available iron (avail. Fe) and available zinc (avail. Zn). These critical parameters were selected due to their significant impact on soil fertility, root growth, soil porosity, structure and aggregate stability. The soils of the Cauvery command area are prone to soil salinity and alkalinity. Therefore, proxies for salinity, including pH, EC, calcium Ca, magnesium Mg and sodium Na were considered for the analysis. The dataset underwent PCA to distil and pinpoint the essential indicators for the MDS.

Principal components (PCs) with eigenvalues ≥1, representing at least 5 % of the variance, were retained for further analysis (10, 11). The careful selection process extended to indicators exhibiting high loadings, with threshold values within 10 % of the highest loading factor, making them suitable choices for inclusion in the MDS. Given that PCs inherently contain correlated variables, Pearson's correlation analysis was employed to identify and manage redundancy among attributes within each PC. Specifically, if multiple attributes with high loading factors (greater than the threshold) were present within a PC, those with significant correlations ($r > 0.6$) were scrutinized. In such cases, priority was given to the attribute with the highest factor loading. The procedure ensured that the comprised a refined selection of soil indicators, emphasizing their non-redundancy and significance in delineating soil quality dynamics. This selection and evaluation process is integral to the reliability and comprehensiveness of the SQI, as it ensures that only the most influential and non-redundant soil attributes contribute to the overall assessment. The steps followed for SQI calculation are presented in Fig. 2.

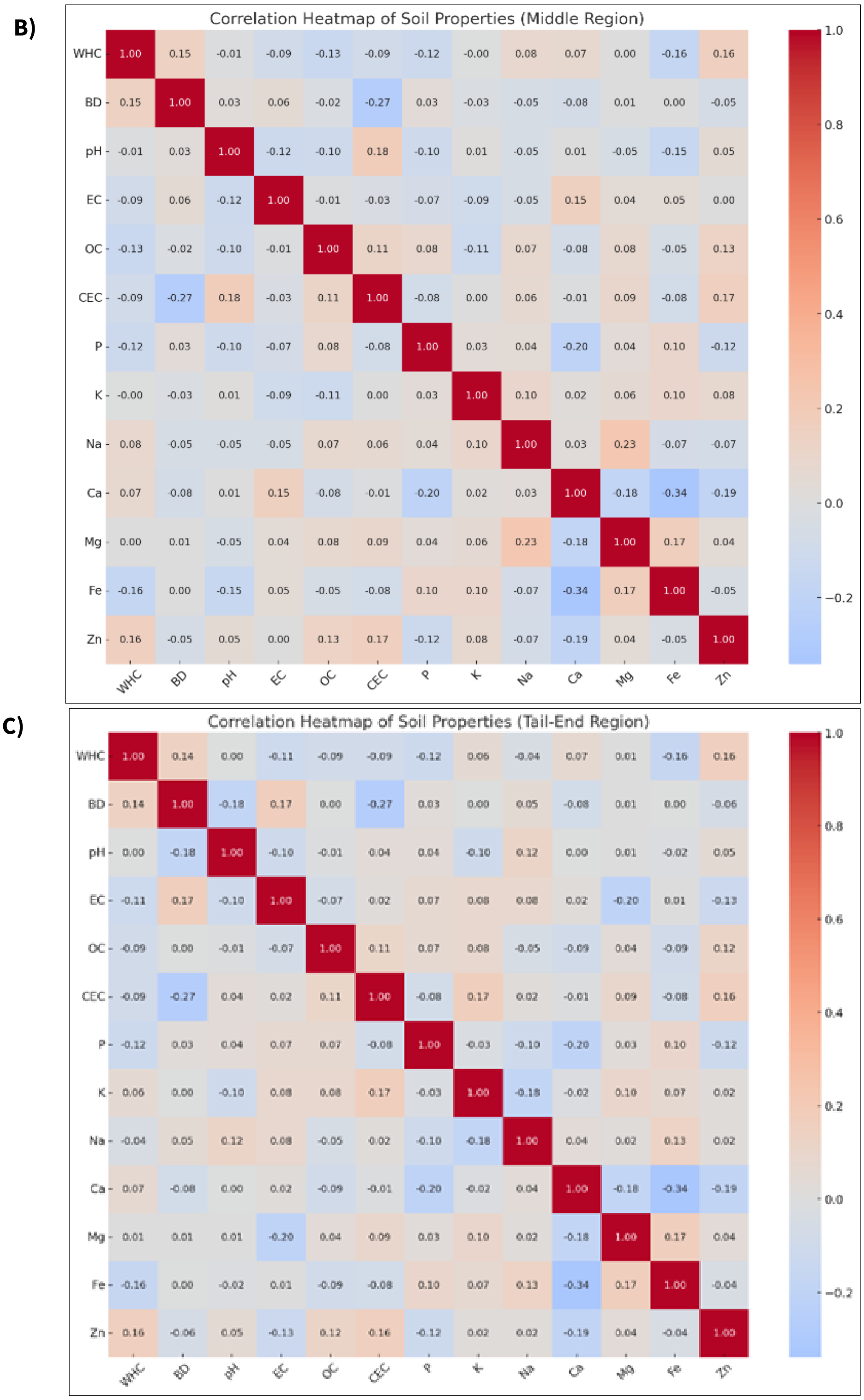
Scoring of indicators

Soil properties scores were assigned based on the 'more is better', 'less is better' and 'optimum range' functions. The classification of soil quality parameters into "more is better", "less is better" and "optimum range" is based on various agronomic principles (19). Parameters like OC, CEC, avail. P_2O_5, exchangeable cations (Ca, Mg, K), avail. Fe, avail. Zn and MWHC, fall under the "more is better" criterion because higher levels of these parameters enhance soil structure, nutrient retention and overall soil fertility. Conversely, parameters such as BD, exchangeable Na is classified as "less is

A)



	WHC	BD	pH	EC	OC	CEC	P	K	Na	Ca	Mg	Fe	Zn
WHC	1.00	0.08	0.02	-0.02	-0.18	-0.09	-0.15	-0.15	0.16	0.04	0.01	-0.13	0.14
BD	0.08	1.00	0.03	-0.08	-0.01	-0.27	0.03	-0.15	0.02	-0.09	0.00	0.00	-0.06
pH	0.02	0.03	1.00	0.24	-0.18	0.07	0.05	0.14	-0.02	-0.03	-0.02	-0.02	0.08
EC	-0.02	-0.08	0.24	1.00	0.01	0.04	0.02	0.12	0.04	-0.01	0.16	-0.02	0.05
OC	-0.18	-0.01	-0.18	0.01	1.00	0.11	0.08	0.12	-0.11	-0.08	0.08	-0.05	0.13
CEC	-0.09	-0.27	0.07	0.04	0.11	1.00	-0.08	0.14	0.15	-0.01	0.09	-0.08	0.17
P	-0.15	0.03	0.05	0.02	0.08	-0.08	1.00	0.08	-0.13	-0.20	0.04	0.10	-0.12
K	-0.15	-0.15	0.14	0.12	0.12	0.14	0.08	1.00	0.17	-0.15	-0.08	0.10	0.16
Na	0.16	0.02	-0.02	0.04	-0.11	0.15	-0.13	0.17	1.00	0.04	-0.02	-0.14	0.04
Ca	0.04	-0.09	-0.03	-0.01	-0.08	-0.01	-0.20	-0.15	0.04	1.00	-0.18	-0.34	-0.19
Mg	0.01	0.00	-0.02	0.16	0.08	0.09	0.04	-0.08	-0.02	-0.18	1.00	0.17	0.04
Fe	-0.13	0.00	-0.02	-0.02	-0.05	-0.08	0.10	0.10	-0.14	-0.34	0.17	1.00	-0.04
Zn	0.14	-0.06	0.08	0.05	0.13	0.17	-0.12	0.16	0.04	-0.19	0.04	-0.04	1.00



	WHC	BD	pH	EC	OC	CEC	P	K	Na	Ca	Mg	Fe	Zn
WHC	1.00	0.15	-0.01	-0.09	-0.13	-0.09	-0.12	-0.00	0.08	0.07	0.00	-0.16	0.16
BD	0.15	1.00	0.03	0.06	-0.02	-0.27	0.03	-0.03	-0.05	-0.08	0.01	0.00	-0.05
pH	-0.01	0.03	1.00	-0.12	-0.10	0.18	-0.10	0.01	-0.05	0.01	-0.05	-0.15	0.05
EC	-0.09	0.06	-0.12	1.00	-0.01	-0.03	-0.07	-0.09	-0.05	0.15	0.04	0.05	0.00
OC	-0.13	-0.02	-0.10	-0.01	1.00	0.11	0.08	-0.11	0.07	-0.08	0.08	-0.05	0.13
CEC	-0.09	-0.27	0.18	-0.03	0.11	1.00	-0.08	0.00	0.06	-0.01	0.09	-0.08	0.17
P	-0.12	0.03	-0.10	-0.07	0.08	-0.08	1.00	0.03	0.04	-0.20	0.04	0.10	-0.12
K	-0.00	-0.03	0.01	-0.09	-0.11	0.00	0.03	1.00	0.10	0.02	0.06	0.10	0.08
Na	0.08	-0.05	-0.05	-0.05	0.07	0.06	0.04	0.10	1.00	0.03	0.23	-0.07	-0.07
Ca	0.07	-0.08	0.01	0.15	-0.08	-0.01	-0.20	0.02	0.03	1.00	-0.18	-0.34	-0.19
Mg	0.00	0.01	-0.05	0.04	0.08	0.09	0.04	0.06	0.23	-0.18	1.00	0.17	0.04
Fe	-0.16	0.00	-0.15	0.05	-0.05	-0.08	0.10	0.10	-0.07	-0.34	0.17	1.00	-0.05
Zn	0.16	-0.05	0.05	0.00	0.13	0.17	-0.12	0.08	-0.07	-0.19	0.04	-0.05	1.00

	WHC	BD	pH	EC	OC	CEC	P	K	Na	Ca	Mg	Fe	Zn
WHC	1.00	0.14	0.00	-0.11	-0.09	-0.09	-0.12	0.06	-0.04	0.07	0.01	-0.16	0.16
BD	0.14	1.00	-0.18	0.17	0.00	-0.27	0.03	0.00	0.05	-0.08	0.01	0.00	-0.06
pH	0.00	-0.18	1.00	-0.10	-0.01	0.04	0.04	-0.10	0.12	0.00	0.01	-0.02	0.05
EC	-0.11	0.17	-0.10	1.00	-0.07	0.02	0.07	0.08	0.08	0.02	-0.20	0.01	-0.13
OC	-0.09	0.00	-0.01	-0.07	1.00	0.11	0.07	0.08	-0.05	-0.09	0.04	-0.09	0.12
CEC	-0.09	-0.27	0.04	0.02	0.11	1.00	-0.08	0.17	0.02	-0.01	0.09	-0.08	0.16
P	-0.12	0.03	0.04	0.07	0.07	-0.08	1.00	-0.03	-0.10	-0.20	0.03	0.10	-0.12
K	0.06	0.00	-0.10	0.08	0.08	0.17	-0.03	1.00	-0.18	-0.02	0.10	0.07	0.02
Na	-0.04	0.05	0.12	0.08	-0.05	0.02	-0.10	-0.18	1.00	0.04	0.02	0.13	0.02
Ca	0.07	-0.08	0.00	0.02	-0.09	-0.01	-0.20	-0.02	0.04	1.00	-0.18	-0.34	-0.19
Mg	0.01	0.01	0.01	-0.20	0.04	0.09	0.03	0.10	0.02	-0.18	1.00	0.17	0.04
Fe	-0.16	0.00	-0.02	0.01	-0.09	-0.08	0.10	0.07	0.13	-0.34	0.17	1.00	-0.04
Zn	0.16	-0.06	0.05	-0.13	0.12	0.16	-0.12	0.02	0.02	-0.19	0.04	-0.04	1.00

**Correlation is significant at the 0.01 level, * Correlation is significant at the 0.05 level

Fig. 2. Correlation heatmap for the A) upper, B) middle and C) tail end region showing correlation between various soil properties. Strong positive correlations are shown in dark red, while strong negative correlations are shown in dark blue.

better” because high levels of BD and Na can degrade soil structure and reduce permeability. Parameters like EC and pH are classified under the “optimum range” criterion, as both high and low extremes can adversely affect nutrient availability and plant growth.

Linear scoring (LS) was used for transforming soil data into dimensionless units. The indicator scores were assigned based on the ‘more is better’ and ‘less is better’ criteria using linear scoring equations (Eqn. 1 and 2) as described by (20):

Formula (if more is better):

$$Score = \frac{X - Xmin}{\mathrm{Xmax} - \mathrm{Xmin}} \qquad \text{Eqn.}$$

Formula (if less is better):

$$Score = \frac{Xmax - X}{\mathrm{Xmax} - \mathrm{Xmin}} \qquad \text{Eqn. 2}$$

LS is the linearly normalized score for the X soil attribute, X is the observed value of the soil property, Xmin is the minimum observed value of the X soil property and Xmax is the maximum observed value of the X soil property.

These scoring equations standardize the soil property values, transforming them into a dimensionless score between 0 and 1. The ‘more is better’ scoring approach infers that higher values of the soil attribute are desirable, while the ‘less is better’ scoring approach suggests that lower values are desirable.

Development of soil quality indices

To compute SQI using the LS method, the weightage of variables was determined through PCA, employing communality as a basis. The communality of each factor elucidated a specific percentage of the variation within the MDS. The weight values assigned to individual indicators were derived from the ratio of the communality of each quality indicator to the sum of all indicator communalities included in the MDS, following the methodology proposed by (21). Then, each indicator’s linear and non-linear scores were multiplied by the weightage factor obtained through communalities, to obtain LS-SQI (Eqn. 3).

$$LS - SQI = \sum_{i=1}^{n} (Wi * LSi) \qquad \text{Eqn. 3}$$

LS-SQI is developed using linear scoring, LSi is the linear score of the ith soil attribute and Wi is the communality-based weight of the ith soil attribute.

Sensitivity index

The SQIs were compared and evaluated using the sensitivity index (SI) formulated by Eqn. 4.

$$SI = \frac{\text{SQI (max)}}{\text{SQI (min)}} \qquad \text{Eqn. 4}$$

The maximum and minimum values of each SQI scenario are denoted by SQI (max) and SQI (min). SI illustrates the sensitivity of soil quality indicators to management practices and environmental factors. An elevated SI value indicates heightened susceptibility to both natural and man-made processes. The calculated SQI is classified based on the grades given in Table 1.

Table 1. Soil quality index grade classes

Index	**Soil quality grades**				
	Very high (I)	**High (II)**	**Moderate (III)**	**Low (IV)**	**Very low (V)**
SQI-LS	>0.547	0.49-0.547	0.433-0.49	0.381-0.433	<0.381

Results and Discussion

Descriptive statistics of soil properties

Descriptive statistics of soil properties in upper, middle and tail end regions of Thonnur Kere distributary are presented in Tables 2, 3 and 4 respectively. Every feature in the top, middle and tail zones has the highest coefficient of variation, except for K and pH. The soil's pH exhibited an increasing trend from the upper to the lower portions. With a mean pH of 7.03 and a range of 6.12 to 7.98, the top part exhibited circumstances that were slightly acidic to neutral. The middle zone showed pH values between 7.15 and 8.97 (mean 8.03), but the tail-end soils had continuously alkaline conditions with a narrow range of 8.12 to 8.97 and a higher mean of 8.64. The pH rise downstream is explained by accumulated salts, insufficient leaching and limited carbonate flushing in semi-arid conditions (22). High pH reduces the availability of micronutrients, particularly for Zn and Fe. From the head of the directive to its tail, EC measurement of soluble salts, rose. The upper region had EC values between 0.13 and 0.87 dS m^{-1} (mean 0.55 dS m^{-1}), whereas the middle region ranged from 0.21 to 1.18 dS m^{-1} (mean 0.76 dS m^{-1}). The tail-end region showed EC values as high as 1.99 dS m^{-1}, with a mean of 1.12 dS m^{-1}, indicating the onset of salinity. This trend reflects the accumulation of salts due to inadequate leaching and high evaporation rates, especially in the tail region (23). OC declined progressively down the canal command. In the upper region, OC ranged from 0.51 % to 1.48 % with a mean of 1.04 %, indicating good OC content. The middle region showed a range of 0.28 % to 1.25 % (mean 0.81 %), while the tail-end soils were considerably lower, with OC ranging from 0.20 % to 0.92 % and a mean of just 0.50 %. This indicates lower biomass returns and faster decomposition in tail-end areas, possibly due to poor residue management and nutrient stress (24).

Table 2. Descriptive statistics of soil properties in the upper region

	pH	**EC**	**OC**	**CEC**	**Ca**	**Mg**	**K**	**Na**	**P**	**Fe**	**Zn**	**WHC**	**BD**
		(dS m^{-1})	**(%)**	**(c mol (p^{+}) kg^{-1})**					**(kg ha^{-1})**	**(mg kg^{-1})**		**(%)**	**(g cm^{-3})**
Minimum	6.12	0.13	0.51	11.79	7.14	1.72	0.30	0.31	15.25	21.74	0.25	23.23	0.90
Maximum	7.98	0.87	1.48	21.37	10.41	2.79	0.35	0.44	31.21	44.53	1.19	46.30	1.25
Mean	7.03	0.55	1.04	16.98	8.86	2.19	0.32	0.37	23.41	32.22	0.70	34.11	1.08
SD	0.46	0.21	0.29	2.93	0.89	0.34	0.01	0.04	4.94	6.93	0.28	6.66	0.11
CV	6.59	37.80	27.62	17.27	10.01	15.48	4.01	9.87	21.08	21.50	40.73	19.53	9.80
Kurtosis	-0.70	-0.99	-0.98	-1.29	-0.93	-1.36	-0.57	-1.25	-1.29	-1.20	-1.27	-1.06	-1.19
Skewness	0.49	-0.44	-0.28	-0.16	-0.13	0.26	0.04	0.12	-0.01	0.23	0.14	0.26	-0.11

Table 3. Descriptive statistics of soil properties in the middle region

	pH	**EC**	**OC**	**CEC**	**Ca**	**Mg**	**K**	**Na**	**P**	**Fe**	**Zn**	**WHC**	**BD**
		(dS m^{-1})	**(%)**	**(c mol (p^{+}) kg^{-1})**					**(kg ha^{-1})**	**(mg kg^{-1})**		**(%)**	**(g cm^{-3})**
Minimum	7.15	0.21	0.28	11.98	7.28	1.79	0.22	0.50	16.06	10.65	0.16	30.30	1.05
Maximum	8.97	1.18	1.25	21.73	10.61	2.91	0.30	0.69	32.86	21.82	0.76	46.97	1.46
Mean	8.03	0.76	0.81	17.27	9.03	2.28	0.26	0.60	24.66	15.79	0.44	38.99	1.26
SD	0.42	0.28	0.29	2.98	0.90	0.35	0.02	0.05	5.20	3.39	0.18	4.96	0.12
CV	5.18	36.15	35.50	17.27	10.01	15.48	7.58	8.49	21.08	21.50	40.73	12.73	9.80
Kurtosis	-0.60	-1.10	-0.98	-1.29	-0.93	-1.36	-0.94	-0.96	-1.29	-1.20	-1.27	-1.28	-1.19
Skewness	0.10	-0.28	-0.28	-0.16	-0.13	0.26	-0.22	0.04	-0.01	0.23	0.14	-0.02	-0.11

Table 4. Descriptive statistics of soil properties in tail end region

	pH	**EC**	**OC**	**CEC**	**Ca**	**Mg**	**K**	**Na**	**P**	**Fe**	**Zn**	**WHC**	**BD**
		(dS m^{-1})	**(%)**	**(c mol (p^{+}) kg^{-1})**					**(kg ha^{-1})**	**(mg kg^{-1})**		**(%)**	**(g cm^{-3})**
Minimum	8.12	0.21	0.20	12.15	7.83	1.93	0.18	0.60	21.74	8.91	0.35	42.08	1.17
Maximum	8.97	1.99	0.92	22.00	11.41	3.14	0.23	0.80	44.50	18.26	1.65	64.36	1.63
Mean	8.64	1.12	0.50	17.53	9.71	2.46	0.20	0.71	33.38	13.21	0.97	53.37	1.40
SD	0.15	0.51	0.26	3.02	0.97	0.38	0.01	0.06	7.04	2.84	0.39	6.75	0.14
CV	1.79	45.88	51.58	17.22	10.01	15.48	7.29	8.07	21.08	21.50	40.73	12.66	9.80
Kurtosis	2.27	-1.12	-1.11	-1.29	-0.93	-1.36	-1.45	-1.08	-1.29	-1.20	-1.27	-1.29	-1.19
Skewness	-1.21	0.00	-0.10	-0.17	-0.13	0.26	-0.14	-0.13	-0.01	0.23	0.14	-0.03	-0.11

CEC remained fairly stable across regions. The upper region ranged from 11.79 to 21.37 c mol (p$^+$) kg^{-1} (mean 16.98), the middle ranged from 11.98 to 21.73 c mol (p$^+$) kg^{-1} (mean 17.27) and the tail-end from 12.15 to 22.00 c mol (p$^+$) kg^{-1} (mean 17.53). These values indicate moderate to high nutrient holding capacity, likely due to the presence of clay minerals and consistent texture across the command (25). Exchan. cations (Ca, Mg, K, Na) followed a similar trend, which increased from the upper region to the tail end via the middle region. Ca content was 8.86, 9.03 and 9.71 c mol (p$^+$) kg^{-1} in the upper, middle and tail end, respectively. Mg content was increased from a mean of 2.19 in the upper to 2.28 in the middle and 2.46 c mol (p$^+$) kg^{-1} in the tail-end region. K content increased from a mean of 0.32 in the upper to 0.26 in the middle and 0.23 c mol (p$^+$) kg^{-1} in the tail-end region, indicating a possible depletion due to crop uptake and poor replenishment. Na increased downstream, with means of 0.37, 0.60 and 0.71 c mol (p$^+$) kg^{-1} in the upper, middle and tail regions, respectively. This poses a sodicity threat, especially in the tail, where Na ranged from 0.60 to 0.80 mg kg^{-1}.

Available P increased from 15.25 to 31.21 kg ha^{-1} in the upper (mean 23.41), to 16.06 to 32.86 (mean 24.66) in the middle and finally 21.74 to 44.50 (mean 33.38 kg ha^{-1}) in the tail region. While this suggests high phosphorus availability, it may also reflect low uptake due to salinity or pH-induced fixation. Fe levels were highest in the upper region (21.74 to 44.53 mg kg^{-1}, mean 32.22) and decreased to 10.65-21.82 mg kg^{-1} (mean 15.79) in the middle and 8.91-18.26 (mean 13.21) in the tail. Zn varied across regions, with the lowest mean mg kg^{-1} (0.44 mg kg^{-1}) in the middle, compared to 0.70 in the upper and 0.97 in the tail-end. Despite slightly higher Zn in the tail, its bioavailability is compromised by high pH, leading to potential deficiencies (26).

Physical properties, viz., WHC and BD showed a consistent increase downstream, indicating heavier textures or compaction in the lower regions. In the upper region, WHC ranged from 23.23 % - 46.30 %, with a mean of 34.11 %. whereas in the middle region, WHC ranged from 30.30 % - -46.97 % (mean 38.99 %) and in the tail region it ranged from 42.08 % - 64.36 % (mean 53.37 %). BD also increased from 0.90 to 1.25 g cm^{-3} (mean 1.08) in the upper, to 1.05-1.46 (mean 1.26) in the middle and 1.17-1.63 (mean 1.40) in the tail. This indicates soil compaction and structural degradation, especially in the tail-end, which can hinder root growth and infiltration (27).

Correlation matrix

Pearson Correlation matrix was calculated to construct MDS, presented in Tables 5, 6 and 7 (Fig. 2), showing the relationships among various soil physicochemical properties and nutrient parameters in the upper, middle and tail end region of the study area respectively.

The strongest positive association (0.24) in the top area is seen between pH and EC, suggesting that electrical conductivity tends to increase with pH. Positive correlations between Zn and CEC (0.17) and Na and K (0.17) follow, indicating that these parameters have moderate relationships. Fe and Ca have the largest negative association (-0.34), indicating that reduced iron concentration is linked to greater Ca levels. Important interactions between nutrients and soil physical properties are highlighted by other noteworthy negative correlations, such as those between CEC and BD (-0.27) and Ca and P (-0.20).

The strongest positive association between Mg and Na (0.23*) is seen in the middle region; this might be because of similar soil, management and fertilizer usage. favourable correlations between pH and CEC (0.18*) and Fe and Mg (0.17*) follow, indicating somewhat favourable relationships between these parameters. Conversely, there is a substantial inverse association between the amounts of iron and calcium, as indicated by the greatest negative correlation (-0.34**) between the 2. Important interactions between soil chemical and physical parameters are shown by other noteworthy negative correlations, such as Ca and P (-0.20*) and CEC and BD (-0.27**). (Note: * significant at 0.05 level of significance and ** significant at 0.01 of level of significance)

The largest positive correlation (0.17) between Fe and Mg is seen in the tail end area, indicating that these 2 elements tend to rise together, maybe as a result of comparable availability in particular soil types. Positive correlations between Zn and WHC (0.16) and CEC and K (0.17) follow, suggesting that these parameters have minor relationships with one another. Conversely, Fe and Ca had the strongest negative correlation (-0.34**), suggesting a significant inverse link that may be the result of antagonistic interactions in soil chemistry. Other notable negative relationships include Mg and EC (-0.20*) and CEC and BD (-0.2**), reflecting the impact of bulk density and electrical conductivity on nutrient holding capacity.

Table 5. Results of PCA for soil properties in the upper reach of Thonnur Kere distributary

Upper	**PC_1**	**PC_2**	**PC_3**	**PC_4**	**PC_5**	**PC_6**
WHC (%)	-0.071	**0.677**	-0.309	0.041	0.068	-0.165
BD (g cm^{-3})	0.047	0.062	**-0.763**	-0.003	0.106	-0.015
pH	0.008	0.038	-0.076	**0.784**	-0.084	0.184
EC (dS m^{-1})	-0.045	-0.074	0.144	**0.75**	0.079	-0.196
OC (%)	-0.116	**-0.434**	0.089	-0.201	**0.712**	-0.063
CEC {c mol (p$^+$) kg^{-1}}	-0.017	0.131	**0.693**	0.06	0.243	0.017
Avail. P_2O_5	0.239	**-0.546**	-0.215	0.155	0.017	0.162
exchn. K	0.286	-0.062	0.292	0.206	0.236	**0.648**
exchn. Na	0.018	**0.586**	0.174	0.012	0.012	0.329
exchn. Ca	**-0.764**	0.036	0.135	-0.031	-0.289	-0.023
exchn. Mg	0.357	0.022	0.175	0.163	0.147	**-0.709**
avail. Fe	**0.785**	-0.136	0.048	-0.092	-0.239	-0.085
avail. Zn	0.129	0.333	0.042	0.118	**0.694**	0.063
Eigen values	**1.77**	**1.64**	**1.35**	**1.25**	**1.12**	**1.05**
% Variance	13.61	12.59	10.41	9.61	8.59	8.05
Communalities	13.61	26.19	36.60	46.21	54.8	**62.85**
WF	0.22	0.20	0.17	0.15	0.14	0.13
HF	0.785	0.677	0.693	0.784	0.712	0.709
10 % of HF	0.706	0.609	0.623	0.705	0.64	0.638

*Note: WF- Weightage factor, HF-Highest factor (>0.4), bold values are the highest loading factors in each component and underlined bold values are selected as MDS

Table 6. Results of PCA for soil properties in the middle reach of Thonnur Kere distributary

Middle	PC1	PC2	PC3	PC4	PC5	PC6
WHC (%)	-0.286	**-0.538**	**0.451**	0.225	-0.153	-0.122
BD (g cm^{-3})	0.071	**-0.724**	0.044	-0.059	-0.005	0.055
pH	-0.140	0.205	0.219	-0.254	**-0.494**	-0.177
EC (dS m^{-1})	-0.073	0.026	0.082	-0.069	**0.815**	0.033
OC (%)	0.072	0.146	0.041	0.193	0.004	**0.774**
CEC {c mol (p$^+$) kg^{-1}}	-0.049	**0.690**	0.312	0.102	-0.154	0.108
avail. P_2O_5	0.344	-0.103	**-0.522**	0.122	-0.262	0.247
exchn. K	0.139	0.103	0.009	0.294	-0.150	**-0.603**
exchn. Na	-0.189	0.039	-0.129	**0.807**	-0.089	0.005
exchn. Ca	**-0.781**	0.091	-0.150	-0.022	0.244	-0.154
exchn. Mg	0.317	0.064	0.163	**0.629**	0.175	-0.013
avail. Fe	**0.743**	0.027	-0.114	0.087	0.256	-0.254
avail. Zn	0.198	0.053	**0.783**	0.001	-0.072	0.150
Eigen values	**1.68**	**1.52**	**1.30**	**1.25**	**1.18**	**1.12**
% Variance	12.89	11.66	10.02	9.58	9.11	8.59
Cumunalities	12.89	24.54	34.57	44.15	53.26	**61.85**
WF	0.21	0.19	0.16	0.15	0.15	0.14
HF	-0.781	-0.724	0.783	0.807	0.815	0.774
10 % of HF	0.702	0.651	0.751	0.726	0.733	0.696

*Note: WF- Weightage factor, HF-Highest factor (>0.4), bold values are the highest loading factors in each component and underlined bold values are selected as MDS

Table 7. Results of PCA for soil properties in the tail end region of Thonnur Kere distributary

Tail	PC1	PC2	PC3	PC4	PC5	PC6
WHC (%)	-0.058	-0.298	**0.698**	0.045	0.032	-0.178
BD (g cm^{-3})	0.009	**-0.713**	0.112	0.322	0.108	0.193
pH	0.012	0.197	-0.032	**-0.629**	0.044	0.059
EC (dS m^{-1})	-0.263	-0.097	-0.338	**0.474**	-0.005	**0.521**
OC (%)	-0.115	0.086	-0.183	0.022	**0.711**	-0.138
CEC {c mol (p$^+$) kg^{-1}}	0.003	**0.744**	0.047	0.166	0.262	0.132
avail. P_2O_5	0.137	-0.251	**-0.626**	-0.087	0.184	-0.263
exchn. K	0.171	0.314	0.093	**0.672**	0.030	-0.203
exchn. Na	0.096	0.008	0.101	-0.287	-0.062	**0.775**
exchn. Ca	**-0.632**	0.184	0.188	-0.025	**-0.435**	-0.052
exchn. Mg	**0.652**	0.130	0.160	-0.003	-0.029	-0.187
avail. Fe	**0.728**	-0.045	-0.235	0.063	-0.174	0.239
avail. Zn	0.136	0.106	**0.463**	-0.099	**0.627**	0.110
Eigen values	**1.63**	**1.58**	**1.36**	**1.31**	**1.14**	**1.09**
% Variance	12.53	12.17	10.43	10.05	8.74	8.33
Cumunalities	12.53	24.69	35.12	45.17	53.91	**62.24**
WF	0.20	0.19	0.17	0.14	0.14	0.13
HF	0.728	0.744	0.698	0.672	0.711	0.775
10 % of HF	0.655	0.670	0.628	0.605	0.640	0.698

Note: WF- Weightage factor, HF-Highest factor (>0.4), bold values are the highest loading factors in each component and underlined bold values are selected as MDS

PCA and MDS

To create a minimal data collection and determine the most important indications, PCA was used. PCA is a powerful statistical technique that improves interpretability by decreasing the dimensionality of large datasets while maintaining the most significant variance (28). In agricultural and environmental research, it is widely utilised to identify critical factors affecting crop output, soil properties and ecosystem health (29). Table 4-6 displays the PCA results for 13 indicators of soil quality.

Each PC was evaluated using the maximum loading factor (HF > 0.4) and those that were 10 % greater than the highest factor value in each component were considered for the MDS selection.

PCA was used to identify important indicators of soil quality for the upper reach of the research region from a larger dataset (Table 5). Six PCs were found to account for 62.85 % of the variance, with eigenvalues greater than 1 ranging from 1.05 to 1.77 (Table 5). PC6 was responsible for 8.05 % of the variance, whereas PC1 to PC6 accounted for 13.61 %. The cumulative variance demonstrated a reasonable approximation of the overall dataset variability across these components.

Among the 6 PCs extracted, the most influential variables were avail. Fe, avail. Ca in PC1 explaining 13.61 % variance (0.785 and 0.764), WHC in PC2 accounting 12.59 % variance (0.677), CEC and BD in PC3 showing 10.41 % variance (0.763 and 0.693), pH, EC in PC4 presenting 9.61 % variance (0.784 and 0.75), OC and Zn in PC5 explaining 8.59 % variance (0.712 and 0.694 %) and exchan. Mg and K in PC6 presenting 8.59 % variance (0.709 and 0.648). These variables were selected for the MDS based on their high loading values and correlation between them (<0.6), indicating their significant contribution to soil variability (3, 21). From PC1, PC3, PC4, PC5 and PC6, 2 soil quality indicators (Ca, CEC, EC, Zn and K) were selected for MDS, considering their correlation values are below the threshold (<0.6) and fell within 10 % threshold of the highest weighted factor.

Similarly, the PCA was employed to identify key soil quality indicators in the middle reach, resulting in 6 PCs with eigenvalues greater than 1 ranging from 1.12 to 1.68, collectively explaining 62.85 % of the total variance (Table 6). The variance explained by each component ranged from 12.89 % (PC1) to 8.59% (PC6), providing a reasonable representation of overall data variability. The most influential variables identified were avail. Ca and Fe in PC1 (0.781 and 0.743), BD and CEC in PC2 (0.724 and 0.690), Zn in PC3 (0.783), K in PC4 (0.807), EC in PC5 (0.815) and OC in PC6 (0.774). These variables were selected for the MDS based on their high factor loadings and low inter-correlation values (<0.6), indicating they contribute uniquely to soil variability (10, 11, 24). Additionally, from PC1 and PC2, 2 indicators each (Ca, Fe, BD and OC) were retained in the MDS since their loading values fell within 10 % of the highest weighted factor and met the correlation threshold, ensuring minimal redundancy among selected indicators.

Likewise, PCA was applied to determine key soil quality indicators in the tail end region of the study area (Table 7), extracting 6 PCs with eigenvalues greater than one, ranging from 1.09 to 1.63 and together accounting for 62.24 % of the total variance (Table 7). The variance explained by individual components ranged from 12.53 % (PC1) to 8.33 % (PC6), effectively capturing the variability in the dataset. The dominant variables identified were avail. Fe in PC1 (0.728), BD and CEC in PC2 (0.713 and 0.744), WHC in PC3 (0.698), pH and exchn. K in PC4 (0.629 and 0.672), OC in PC5 (0.711) and exchn. Na in PC6 (0.775). These variables were selected for inclusion in the MDS due to their high factor loadings and low inter-correlation values (<0.6), confirming their independent contributions to soil quality variation (10, 11, 24). Furthermore, from PC2 and PC4, 2 indicators each (BD, CEC, pH and exchn. K) were retained in the MDS since their loadings were within 10 % of the highest factor and met the correlation threshold, minimizing redundancy and enhancing the robustness of the selection.

Assessment of SQI

The soil quality indicators selected for the MDS were classified into 3 categories: "more is better" (including OC, CEC, exchn. Ca, Mg and K, avail. Fe and Zn and WHC), "less is better" (Na and BD) and "optimum range" (pH and EC).

The scores for these indicators were calculated using a LS method, as described in Eqn. 1 and 2. Following this, the SQI was computed by applying the respective weights from Tables 5, 6 and 7 for soil quality indicators of upper, middle and tail end region of study area along with the indicator scores, resulting in 3 index values SQI-U (based on LS; Eqn. 5), SQI-M (based on LS; Eqn. 6) and SQI-T (based on LS; Eqn. 7). If more than 1 soil quality indicator is selected from a single PC, the weightage factor for that component is distributed equally among the selected indicators by dividing the component's total weight by the number of indicators chosen from it.

SQI-U = (LS_Ca * 0.11) + (LS_Fe * 0.11) + (LS_WHC * 0.20) + (LS_BD * 0.085) + (LS_CEC * 0.085) +(LS_pH * 0.075) + (LS_EC * 0.075) + (LS_OC * 0.07) + (LS_Zn * 0.07) + (LS_K * 0.065) + (LS_Mg * 0.065) Eqn. (5)

SQI-M = (LS_Ca * 0.105) + (LS_Fe * 0.105) + (LS_BD * 0.095) + (LS_CEC * 0.095) (LS_Zn * 0.16) + (LS_Na * 0.15) + (LS_EC * 0.15) + (LS_OC * 0.14) Eqn. (6)

SQI-T = (LS_Fe * 0.20) + (LS_BD * 0.095) + (LS_CEC * 0.095) + (LS_WHC * 0.17) + (LS_pH * 0.07) + (LS_K* 0.07) + (LS_OC * 0.14) + (LS_Na * 0.13) Eqn.(7)

The SQI values for the selected sites are in Grade I (>0.547) indicating a "very high" soil quality class, with SQI scores ranging from 0.68 to 0.78, reflecting highly favorable soil conditions for sustainable crop production Table 8. The SI, recorded for 3 of the regions, ranged from 1.00 to a maximum of 1.15, suggesting that the SQI is moderately responsive to changes in soil parameters within this grade. This high sensitivity indicates the robustness of the scoring approach in effectively distinguishing soil quality within high-performing areas. These results confirm that the selected indicators and scoring method are suitable for assessing soil health in the upper category of soil quality.

Table 8. Soil quality index and sensitivity index

Study area	Grade	SQI class	SQI	SI
Upper	I (>0.547)	Very high	0.74	1.08
Middle	I (>0.547)	Very high	0.68	1.00
Tail end	I (>0.547)	Very high	0.78	1.15

Descriptive statistics

The descriptive statistics reveal notable spatial variations in soil physicochemical properties across the upper, middle and tail-end regions of the command area, indicating the cumulative effects of irrigation intensity, land management and landscape position.

Soil pH progressively increased from the upper region to the tail-end region, reflecting increasing alkalinity downstream. This trend may be attributed to the accumulation of basic cations through long-term irrigation and poor drainage, which restricts leaching of salts (30). EC exhibited a similar trend in the upper region to the tail-end, suggesting salt accumulation due to inadequate drainage and evapotranspiration exceeding precipitation (31). Such conditions are common in canal command areas and may lead to secondary salinization if not managed effectively. OC levels were highest in the upper region and decreased substantially in the tail-end region. This decline may be attributed to reduced organic matter inputs, increased decomposition under irrigated conditions and residue removal practices (32). The higher OC in the upper region could also be due to intensive cropping or the inclusion of green manures.

CEC remained fairly consistent across regions, indicating moderate nutrient retention capacity of soils throughout the command. However, a slightly greater CEC in the tail-end could be associated with increased clay content and base saturation (22). Ca and Mg exhibited significant variation among exchan. cations, but Na levels increased from the upper region to the tail-end. Elevated Na levels indicate sodicity, which can reduce infiltration and aeration and degrade soil structure. The K content remained low but rather stable across all sites, suggesting the need for exogenous supplementation. Zn and P concentrations are higher at the tail-end region, which might be due to nutrient buildup from surface runoff or limited absorption under more alkaline conditions. On the other hand, because increasing EC and pH reduces Fe availability and solubility, Fe decreased downstream (26). The WHC of the tail-end region increased dramatically from the upper to the lower, most likely as a result of greater clay or compaction levels. Although higher WHC might increase water retention, it can also reduce drainage and aeration if the soil structure is inadequate. Across the gradient, BD rose, indicating compaction from ongoing irrigation and mechanical activities, especially in tail-end locations. Water flow and root penetration are negatively impacted by high BD. These patterns show that to preserve productivity and ecological balance in the SDZ's irrigated paddy and sugarcane ecosystems, region-specific soil and nutrient management interventions are required.

Correlation matrix

Based on the correlation data provided (Fig. 2) for the upper, middle and tail-end regions, several notable relationships between soil properties can be observed.

In the upper region, the strongest positive correlation is between pH and EC, indicating that as pH increases, electrical conductivity also tends to increase, possibly due to higher solubility of salts in alkaline conditions supports findings by (33), who reported that alkaline conditions often coincide with increased soluble salts due to limited leaching in canal-irrigated areas. The strongest negative correlation is between Ca and Fe, suggesting that an increase in Ca may inhibit Fe availability or mobility, a trend commonly seen due to antagonistic ionic interactions in calcareous soils. The consistently strong negative correlation between Ca and Fe across all regions aligns with observations by (21), who explained that high Ca levels in soil, particularly in calcareous conditions, can precipitate iron as insoluble hydroxides, reducing its bioavailability. In the middle region, the highest positive correlation is observed between CEC and pH, which implies that increased pH may enhance the soil's capacity to hold and exchn. cations, often due to the deprotonation of functional groups on clay and organic matter surfaces. The strongest negative correlation again involves Ca and Fe, reaffirming the antagonistic relationship between these 2 nutrients. In the tail-end region, the strongest positive correlation is found between CEC and K, suggesting that soils with higher exchange capacity tend to retain more potassium, which is essential for crop productivity.

PCA, scoring and SQI

PCA was conducted for the upper, middle and tail-end regions of the Thonnur Kere distributary to identify key soil quality indicators and understand regional variability. The PCA reduced the dataset to 6 PCs for each region, cumulatively explaining over 60 % of the total variance.

In the upper region, avail. Fe, WHC, CEC, pH, OC and exchn. Mg were selected as part of the MDS. The dominance of Fe and CEC suggests higher nutrient availability and retention in this region, possibly due to less leaching and greater organic matter (22, 34). High WHC and OC values imply better soil structure and fertility, which is often observed in upstream irrigated lands receiving early and consistent water supply (35, 36). Notably, exchn. Ca showed a strong negative loading, indicating an inverse relationship with Fe, possibly due to ionic competition in cation exchange complexes or differential solubility under specific pH conditions (37). High pH and EC influence the chemical balance's role in nutrient dynamics in well-managed irrigated soils (38, 39). In the middle region, dominant contributors included exchn. Ca, BD, avail. Zn, exchn. Na, EC and OC. The negative loading of Ca and BD suggests possible base cation depletion and structural degradation, which are most likely caused by intensive farming and intermediate water delivery (35). The presence of EC and Na suggests that salinity-related stress buildup is there in this region, possibly as a result of poor irrigation or drainage (40). The substantial Zn and OC loading supports recent studies that found that the presence of OC enhanced Zn mobility, indicating the significance of organic matter in micronutrient availability (26, 41). These patterns can be a sign of transitional soil conditions, where base saturation is being affected by leaching but organic residues are still building. Significant loadings were seen in the tail-end region for available Fe, CEC, WHC, exchn. K, OC and exchn. Na. Fe, OC and WHC are often found in different places, which suggests their general importance in assessing soil health in irrigated agriculture (1, 10, 11). Nonetheless, the tail-end area showed unusually high Na, suggesting possible sodicity problems exacerbated by insufficient leaching and low-quality water downstream (26, 38). The significant impact of K and CEC also points to nutrient buildup or redistribution, which is frequently seen in tail-end areas where soluble salts and small particles settle (42, 43). The appearance of exchn. Mg and EC with moderate loadings support these physicochemical constraints affecting productivity in tail soils.

The PCA comparatively reveals that Fe, CEC and OC are consistently critical across all regions, aligning with previous studies emphasizing their roles in nutrient cycling, structural stability and microbial activity (44). These spatial differences in soil quality indicators underscore the importance of region-specific sustainable land management practices. For example, incorporating organic matter and gypsum amendments may help mitigate sodicity in tail-end areas (23), while conservation tillage may benefit the middle region by reducing compaction (45).

SQI assessment

The SQI assessment for the Thonnur Kere distributary revealed that all 3 regions-upper, middle and tail-end fall within Grade I classification. These high scores reflect favorable edaphic conditions supporting sustainable crop production throughout the command area. In the tail-end region, the highest SQI was primarily influenced by elevated avail. Fe and WHC, indicating improved micronutrient availability and water retention capacity. These properties likely result from fine-textured alluvial deposits and consistent irrigation. Moreover, the inclusion of low exchn. Na (scored under “less is better”) and high CEC imply a well-buffered soil system capable of sustaining long-term fertility CEC and WHC are the critical indicators of soil quality in irrigated landscapes (1, 10, 11). The higher SI in this region suggests that the SQI is more responsive to changes in soil properties here, likely due to variable management practices or topographic influence on erosion and runoff (37, 46). In the upper region, the SQI was significantly contributed by WHC and avail. Fe, supported by relatively balanced contributions from exchn. Ca, BD, CEC and pH. The moderately high OC and exchn. cations also point to good soil structure and nutrient-holding capacity (46). The middle reach, with the lowest SQI, still falls within the very high quality class. However, the marginally reduced score might be attributed to lower WHC and BD, coupled with relatively lower OC and a noticeable influence of exchn. Na (0.15), which is categorized under "less is better". Elevated Na can impair soil structure and permeability, leading to decreased aeration and root proliferation (47). Furthermore, the lower SI in this region may imply a more stable but less responsive soil environment.

Recommendations

The recommended management practices or amendments based on SQI in different regions of the study area. The present management techniques seem to be successful in encouraging the buildup of organic matter and preserving the availability of micronutrients at the research area's tail-end. Given how sensitive the area is to outside changes, these practices ought to be maintained, paying special attention to recurring management actions. In addition, it is advised to regularly check salt (Na) levels to prevent the onset of sodicity, which may jeopardise crop output and soil health in the long run (48). By encouraging the use of organic amendments like compost and green manure, it is necessary to stabilise the SQI in the upper reach and lessen geographic variability. Microbial activity, nutrient availability and soil structure can all be improved by these additions. It is also advised to utilize conservation -focused techniques like cover crops and contour farming to reduce nutrient runoff and stop soil erosion, which will promote productive and sustainable land use in this area. The middle reach of the research area shows indications of a little buildup of Na, which should be controlled by applying supplements based on gypsum or by switching up the irrigation water sources. Potential sodicity concerns can be reduced with the use of these tactics (23). Furthermore, as stressed by (35), increasing microbial activity and soil structural integrity requires raising soil organic carbon levels through crop rotation and residue retention (33, 49). It is anticipated that these integrated management techniques would improve the middle reach's overall soil resilience and quality.

Conclusion

The overall evaluation of soil quality across the Thonnur Kere distributary revealed consistently high SQI values in the upper, middle and tail-end regions, indicating "very high" soil quality (Grade I, SQI > 0.547) suitable for sustainable agricultural production. Despite the prevalence of intensive monocropping systems such as rice and sugarcane, the soils remain functionally resilient-likely supported by efficient irrigation that maintains favourable moisture and enhances microbial and nutrient activity. The tail-end region showed the highest SQI (0.78), potentially due to better water retention and reduced agrochemical buildup. Key soil quality indicators identified through PCA, including OC, micronutrients (Fe, Zn), cation exchange capacity and WHC, underscore the importance of maintaining biological and chemical balance. While the middle region exhibited slightly lower SQI (0.68), possibly due to salt accumulation and reduced organic matter, all areas demonstrated strong soil health. The high SI in the tail-end area (SI = 1.15) further validated the robustness of the SQI model (50). To sustain productivity and prevent long-term degradation, the study recommends site-specific management practices such as crop rotation, organic amendments and integrated nutrient management, alongside ongoing monitoring to maintain soil functionality in these intensively farmed irrigated ecosystems.

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Authors' contributions

S carried out the research work, soil collection, laboratory analysis, statistical analysis and drafted the manuscript. CS supervised during whole process of research work framing, coordination and conductance. GG guided to frame study, supported during analysis and drafted the manuscript. DV guided during research work, designing and manuscript preparation. HS guided design of the study. All authors read and approved the final manuscript.

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During the preparation of this work, the author used AI tools (ChatGPT and Quillbot) to rephrase the sentences and standardize the paragraphs. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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