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Purma Soniya
Research Associate, AICRP-
MSPE, Hyderabad Center,
Telangana, India

Dr. D Muthumanickam
Professor and Head, Remote
Sensing & GIS, TNAU, Tamil
Nadu, India

R Greeshma
Research Scholar, Department of
Agricultural Statistics, PJTAU,
Hyderabad, Telangana, India

Corresponding Author:
Purma Soniya
Research Associate, AICRP-
MSPE, Hyderabad Center,
Telangana, India

Soil fertility and soil quality index assessment in sugarcane-growing soils of Vellore District, Tamil Nadu

Purma Soniya, D Muthumanickam and R Greeshma

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Abstract

Soil fertility status with special reference to micronutrients and Sulphur in sugarcane-growing areas was assessed by analyzing 308 geo-referenced soil samples collected from 20 blocks of Vellore district, Tamil Nadu. Soil quality assessment of these samples revealed significant spatial variability in major soil properties and micronutrients. The results revealed that soil pH ranged from 6.35 to 8.65, electrical conductivity (EC) from 0.11 to 0.80 dS m⁻¹, organic carbon from 0.19 to 0.79 per cent. Soils were predominantly (96 percent) neutral to moderately alkaline with non-saline conditions and low (76 percent) to medium organic carbon. Free CaCO₃ content from 0.13 to 12.5 per cent. Nearly 100 per cent were non-saline in nature and 88.6 per cent were non-calcareous. Calcium carbonate and sulphur showed extreme heterogeneity. With respect to micronutrient availability, iron and copper were generally sufficient and the percentage of samples falling under the deficient category for DTPA-extractable Zn and Mn and hot water-soluble boron were 16, 12 and 38 per cent, respectively. Among which available zinc exhibited strong spatial variability with widespread deficiency-prone zones. Available boron showed moderate non-normal distributions. Highly variable CaCO₃, available sulphur, Zn and Cu were key factors controlling soil quality index variation. The computed Soil Quality Index (SQI) value of 0.45 for sugarcane-growing soils indicated that the soils of the study area are of medium quality. The study demonstrates that SQI serves as a reliable indicator for assessing soil suitability for sugarcane cultivation and provides a cost-effective and time-saving approach for soil quality evaluation. The results underscore the need for site-specific nutrient management to enhance soil fertility and agricultural sustainability.

Keywords: Soil quality index, available micronutrients, soil fertility, PCA

Introduction

India's agriculture, supported by diverse climatic and soil conditions, encompasses a wide range of crops such as rice, wheat, sugarcane, cotton, pulses, fruits and vegetables. Despite its significance, the sector faces persistent challenges including fragmented landholdings (Islam & Rahman, 2022) ^[14], water scarcity (Kulkarni *et al.*, 2023) ^[18], low levels of mechanization (Mehta *et al.*, 2023) ^[22], and increasing vulnerability to climate change (Hazarika *et al.*, 2024) ^[13]. Although government policies provide critical support through subsidies and price stabilization mechanisms, problems of low farm income and rising indebtedness continue. Consequently, the adoption of technological innovations and sustainable agricultural practices has become essential to improve productivity, reduce environmental impacts, and strengthen long-term resilience. Nevertheless, agriculture remains central to India's food security, rural livelihoods, and overall economic development (Pathak *et al.*, 2025) ^[23].

Soil testing does not conclude with laboratory results; rather, these results must be effectively interpreted in relation to the expected crop response and the precise fertilizer requirements needed to correct nutrient deficiencies (2021).

Sugarcane, *Saccharum officinarum*, Ganna (Hindi), Karumbu (Tamil) thrives in deep, fertile, well-drained soils, particularly rich loamy, alluvial, or black soils that retain moisture but don't become waterlogged, ideally with a slightly acidic to neutral pH (6.5-7.5). It can grow in various soils, including heavy clays or lighter soils, provided drainage and irrigation are good, but avoids overly saline, basic, or acidic conditions. Good soil structure for aeration and microbial activity is also crucial (TNAU agritech Portal).

India is the second largest producer of rice, wheat, cotton, sugarcane, farmed fish, sheep & goat meat, fruit, vegetables and tea. India ranks second in sugarcane production with 22.2% share next to Brazil in 2022 (FAOSTAT, 2025). The agriculture sector in India holds the record for the second-largest agricultural land in the world, generating employment for about half of the country's population. Food grain production in India touched around 330 Mt in 2022-23. (Pathak, H. *et. al*, 2025) ^[23]

In India, Tamil Nadu state (except Kanniyakumari and Nilgiris districts) being 4th position after UP, MH, Karnataka states had 0.15 million hectares area (2.64% of India sugar cane growing area) and producing 15.93 million tonnes (3.51%) at the rate of 1,05,000 kg/hectare yield of sugarcane completely under irrigated condition. In Tamilnadu state sugarcane crop stands in first position in productivity along with Maize, Oilseeds, Groundnut and Rice being in second position. Sugarcane crop having 108.4,132.5 and 122.2 in all India Index Numbers of Area, production and yield respectively of Principal Crops in the year 2024-25, indicating the trend in cultivated area of major crops in India relative to a base year and are using it to assess changes in cropping patterns and agricultural development. (DA&FW, 2021&2024). Since 1950s area (Mha), production (Mt), productivity (Kg/ha) of sugarcane in India improved from 1.71 to 5.74, 57.05 to 453.16 and 33422 to 78593 in 2023-24 (Pathak H. *et.al*, 2025) ^[23].

Materials and Methods

Description about study area

Vellore district, located in the northern part of Tamil Nadu, India, covers a total geographical area of 5920.18 km². The district is bounded by Chittoor district of Andhra Pradesh and Tiruvallur district to the north, Tiruvannamalai district to the south, Kancheepuram district to the east, and Dharmapuri district to the west. Geographically, the district lies between 12°15' and 13°15' North latitude and 78°20' and 79°50' East longitude. Administratively, Vellore district comprises twenty development blocks, namely Arakkonam, Kaveripakkam, Nemili, Arcot, Timiri, Gudiyattam, Katpadi, K.V. Kuppam, Peranambattu, Jolarpet, Kandili, Natrampalli, Tiruppathur, Alangayan, Madhanur, Anaicut, Kaniyambadi, Vellore, Sholinghur, and Walajapet. At present, the district consists of 743 panchayat villages.

According to the National Agricultural Research Project (NARP) agro-climatic classification, Vellore district falls under the North Eastern Zone. Under the ICAR agro-ecological regionalization, it belongs to the Eastern Coastal Plains, hot sub-humid to semi-arid eco-region. As per the Planning Commission's agro-climatic classification, the district is part of the East Coast Plains and Hills Region.

The climate of the district is predominantly hot and dry for most of the year, characterized as hot semi-arid, with temperatures ranging from 19.5°C (minimum) to 40.2°C (maximum). The district receives an average annual rainfall of about 936.2 mm.

Agriculture and its allied activities form the principal livelihood of the district's population. The soil resources of Vellore district are diverse, with red loam soils occupying the largest area (51.1% of the total geographical area), followed by clay and clay loam soils (33.8%), sandy and sandy loam soils (13.9%), and black cotton soils (1.1%). Thus, red loamy soils constitute the predominant soil group in the district. A total of fourteen soil series have been identified, of which the Mangalathupatty series (Mng) is the most extensive, covering an area of 127,342 ha.

The land-use pattern of the district indicates that, out of the total geographical area, the extent under forest, barren and uncultivable land, non-agricultural uses, cultivable waste, permanent pastures and grazing land, miscellaneous tree crops and groves, current fallow, other than current fallows, and net area sown is 100,102; 21,000; 85,900; 6,000; 4,000; 3,000; 56,600; 67,600; and 174,696 ha, respectively.

The major crops grown in the district are rice, ragi, cumbu, sorghum, groundnut, gingelly, cotton, sugarcane, banana, coconut and vegetables. The main wetland crop of the district is rice in black soil while groundnut in red soil. The rainfed crops are coconut, groundnut, redgram, horsegram, ragi, sorghum. Garden land crops are groundnut, sugarcane, vegetables, flowers and turmeric. In Vellore district rice, sorghum, cumbu and ragi are the main food crops and Cotton, Sugarcane and Groundnut are nonfood crops. Sugarcane is grown chiefly in December – May in the entire state.

Collection and processing of geo-referenced surface soil samples

A total of 309 surface soil samples were collected covering all the sugarcane growing fields (309) and in twenty blocks of Vellore district were collected randomly at 0-15 cm depth by adopting the standard procedures of soil sample collection. The Global Positioning System (GPS) data (Latitude °N and Longitude °E) were collected from each sampling sites distributed over entire Vellore district by using GPS - Garmin Etrex Vista HCX model. Each sampling area was thoroughly mixed and from the mixture, 1kg of the composite sample was taken for lab analysis. These composite samples were thoroughly cleaned to ensure that they contain no foreign substances like pebbles, roots and stones. The derived samples of each site were collected in a clean fabric bag and inscribed with the required information. Before, the samples were subjected to lab analyses the composite soil samples of each area were crushed to powder by using wooden hammer and sifted to get particles of 2-mm dimension.

Soil Sampling and Analysis

A total of 309 surface soil samples were analyzed for pH, EC, organic carbon (OC), CaCO₃, available sulphur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu) and hot water soluble boron (HWS-B) using standard laboratory procedures (Table. 1).

Table 1: Methods of soil analysis

S. No	Parameter	Method
1	Soil reaction (pH)	1:2.5 soil water suspension by EUTECH pH meter (Jackson,1973) ^[5]
2.	Soluble salts	1:2.5 soil water suspension by EUTECH conductivity bridge (Jackson,1973) ^[5]
3	Available Sulphur	Chesnin and Yien (1950) ^[4]
4	Available Zn, Fe, Cu & Mn	DTPA-TEA-CaCl ₂ extraction method (Lindsay and Norvell, 1978) ^[20]
5	Calcium carbonate	Titrimetric method (FAO, 1974)
6	Available Boron	Hot water soluble method (Berger and Troug, 1949) ^[38]

Statistical analysis

The database on the analysis of soil available micronutrient content was developed using Microsoft Excel. Descriptive statistics, the inter relationship between available micronutrients and soil properties were worked out through simple correlation analysis using SPSS 16.0. Soil quality index has been derived using Principal component analysis executed in SPSS 16.0 software.

Categorization of sample based on critical limits

The soil samples were categorized based on the critical limit of DTPA micronutrients. The deficiency per cent sample at each

category was assessed for all elements at block level by comparing with critical limits (Table 2). 3 percent of soils are slightly acidic in soil reaction where as 23 percent are neutral, 47 percent are slightly alkaline, 22 percent are moderately alkaline and only 5 percent are alkaline in condition. Soil are non-saline, non-calcareous (89 percent) in nature having predominantly low (76 percent) organic carbon content. Sugarcane growing soils contain sufficient available iron and copper, 38 percent of available boron deficiency, 18.5 percent of available Sulphur deficiency, 15.9 percent of available zinc deficiency and 12.34 percent of available manganese deficiency.

Table 2: Critical limits for the soil samples categorization into different fertility classes

Categories				
Soil Properties				
pH	Acidic	Neutral	Alkaline	
	< 6.5	6.6-7.3	> 7.4	
Electrical Conductivity (dS m ⁻¹)	Low	Medium	High	
	< 1.0	1.0-3.0	> 3.0	
Organic Carbon (%)	Low	Medium	High	
	< 0.5	0.5-0.75	> 0.75	
Free CaCO ₃ (%)	Non-Calcareous	slightly calcareous	Mod. Calcareous	Calcareous
	< 5	5-10	10-15	>15
Elements (mg kg ⁻¹)	Critical Limits			
	Deficient	Sufficient		
Zinc (Zn)	< 0.6	> 0.6		
Iron (Fe)	< 4.0	> 4.0		
Copper (Cu)	< 0.2	>0.2		
Manganese (Mn)	< 2.0	> 2.0		
Boron (B)	< 0.52	> 0.52		
Sulphur (S)	< 10	> 10		

Source: D.V. Ramana Reddy *et al* (2012) ^[24]

Soil Quality index values and fertility rating:

Each soil indicator was converted into a dimensionless Q-value (0–1) using appropriate linear scoring functions, wherein organic carbon (OC), sulphur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and boron (B) were treated under the “more-is-better” function, electrical conductivity (EC) and calcium carbonate (CaCO₃) under the “less-is-better” function, and soil pH under the “optimum-is-better” function with an optimum value (X_{opt}) of 6.8. The minimum, maximum, and mean values derived from the dataset were used for computing the Q-values. Indicator weights (W_i) were determined through Principal Component Analysis (PCA) performed in SPSS, where factor loadings were obtained from the Rotated Component Matrix and eigenvalues from the Total Variance Explained table.

$$W_i = \frac{|\text{Loading}| \times \text{Eigenvalue}}{\sum(|\text{Loading}| \times \text{Eigenvalue})}$$

The weights were calculated using the expression ensuring that the sum of all weights equaled 1. The Soil Quality Index (SQI) was then computed as the weighted summation of the individual indicator scores, expressed as

$$SQI = \sum(Q_i \times W_i)$$

The Soil Quality Index (SQI) values were categorized into five classes, namely poor (<0.40), fair (0.40–0.55), good (0.55–0.70), very good (0.70–0.85), and excellent (>0.85) (Table 3) suggested by Karlen *et al.* (1997) ^[16], Andrews *et al.* (2004) ^[37],

Masto *et al.* (2008) ^[21] and Ghaemi *et al.* (2014) ^[11].

Table 3: Classification of soil based on SQI values

S. No	SQI Value/ Range	Soil Quality Class	Interpretation
1	< 0.40	Poor	Severely degraded soil
2	0.40 – 0.55	Fair	Moderately degraded
3	0.55 – 0.70	Good	Moderately good soil
4	0.70 – 0.85	Very Good	High soil quality
5	0.85	Excellent	Very high soil quality

Results and Discussion

Micronutrients deficiencies are often noticed in the soils under intensive cropping system of many agriculturally progressive states in India. The imbalanced use of fertilizer nutrients, increased demand of high yielding varieties, intensive cropping, decrease in recycling of organic manures and micronutrient free high input agricultural activities leads to continuous mining of micronutrients in soils leading to declined crop productivity and soil heath. Hence, the present study was conducted to assess the soil health and quality indices of Sugarcane growing soils in Vellore district of Tamil Nadu. Basic details on the system of cultivation, crops cultivated and cropping system followed in the study area were also collected to understand the relationship between soil nutrient availability and management strategies adopted. The relationship between soil chemical properties and available micronutrients status was worked out by constructing correlation studies to know the major factor that governs the nutrient availability.

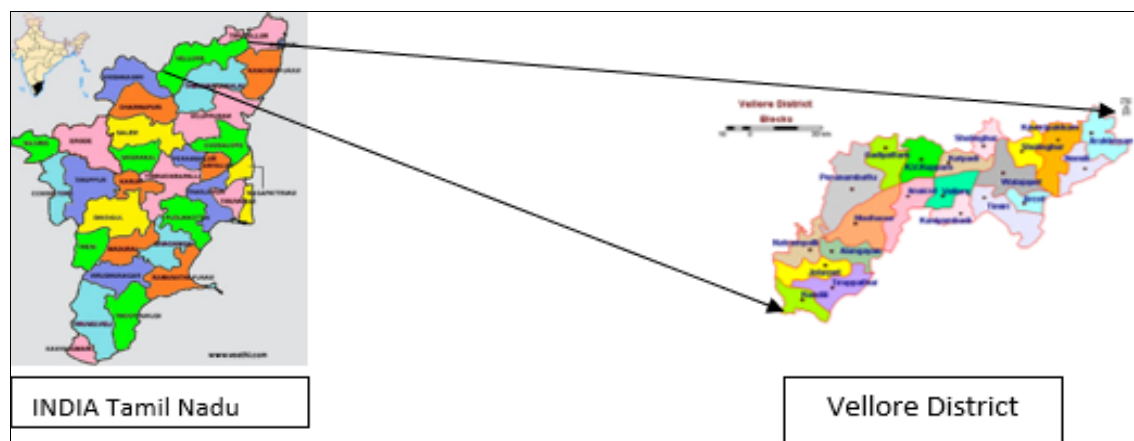


Fig 1: Location Site of the study

Three hundred and eight surface soil samples were collected from the sugarcane based cropping system of the study area. The sugarcane based cropping systems were adopted in all the blocks of Vellore district. The sugarcane-millets cropping system was adopted in Arakkonam, Kaveripakkam, Nemili, Timiri, Katpadi, Jolarpet, Natrampalli, Tiruppathur, Anaicut, Kaniyambadi, Sholinghur, Walajapet and Vellore blocks of Vellore district, the sugarcane-coconut system was followed in Arcot, Gudiyattam, Kandili, Peranambattu, and Madhanur blocks.

Soil properties

The cropping system showed wide variation in soil properties and the soil reaction of soil samples ranged from 6.35 to 8.65 indicating slightly acidic to alkaline nature of soil (Table 1). The highest mean soil pH was found in sugarcane-millets cropping system (8.18) in Natrampalli block while the lowest was noticed (7.23) in sugarcane-coconut cropping system of Gudiyattam block. The increase in pH of soils could be due to increased calcium carbonate content which produces more OH ions upon hydrolysis and created an alkaline effect (Somasundaram *et al.* 2009) ^[32]. The EC ranged from 0.11 to 0.80 dS m⁻¹ with an overall mean of 0.29 dS m⁻¹ representing low in salt concentration. The highest mean EC was noticed in sugarcane-millet (0.34 dS m⁻¹) system in Arakkonam and Natrampalli block while the lowest mean electrical conductivity was observed in the soils of K.V.Kuppam block (0.24 dS m⁻¹) in the sugarcane-coconut cropping system. The low salinity in these soils is evident due to enhanced leaching losses and reduced accumulation of salts in the root zone which contributed to a decline in EC values (Duhan and Singh 2002) ^[6].

The organic carbon content varied from 0.19 to 0.79 percent indicating low to high in organic carbon status. The highest mean organic carbon content was observed in soils under sugarcane-coconut (0.49 percent) in K.V.Kuppam block soils while the lowest in sugarcane-millet system (0.36 percent) at Natrampalli block. The low organic carbon content might be due to over depletion under these cropping systems and could be explained by increased carbon input through the addition of root biomass and crop residues (Sidhu and Beri 1989) ^[30]. The

overall free CaCO₃ content in these soils ranged from non-calcareous to moderately calcareous and the values varied from 0.13 to 12.5 per cent. The highest mean free CaCO₃ content recorded in sugarcane-coconut system (4.0%) in Kaniyambadi block while the lowest free CaCO₃ found in sugarcane-coconut (1.3%) in Kandili block.

The analysis of surface soil samples collected from sugarcane based cropping system of different blocks of Vellore district showed sufficient availability of sulphur. The highest mean available sulphur content in sugarcane based cropping system, found in sugarcane-cotton system (65.9 mg kg⁻¹) in Alangayan block while the lowest in sugarcane-coconut system (11.1 mg kg⁻¹) at Kandili block.

The range values varied from 4.0 - 102.0, 2.2 - 46.7, 0.7 - 59.4, 0.2 - 9.5, 0.3 - 8.2 and 0.1 - 2.1 for S, Fe, Mn, Zn, Cu and B respectively (Table 5). The deficient mean values of Zn was noticed in Tiruppathur block of Vellore district. The overall mean available zinc content was 1.62 mg kg⁻¹ indicating medium in zinc availability in sugarcane based cropping system. The highest (9.5 mg kg⁻¹) and lowest (0.2 mg kg⁻¹) available zinc found in sugarcane-millets system in Walajapet and Tiruppathur blocks respectively. The DTPA Fe content of the soils was sufficient and among the various sugarcane based systems, the highest mean DTPA Fe availability recorded in sugarcane-millets system (46.7 mg kg⁻¹) of Gudiyattam block and the lowest under sugarcane-coconut system (2.2 mg kg⁻¹) at Madhanur block. The DTPA-Cu availability showed an overall mean of 2.32 mg kg⁻¹ indicating sufficient in Cu availability in sugarcane based cropping systems adopted in these regions. The highest (8.2 mg kg⁻¹) is noticed in Tirupathur (sugarcane-millets cropping system) and lowest (0.4 mg kg⁻¹) DTPA Cu content noticed in sugarcane-millets system in Sholinghur and Walajapet block. The DTPA-Mn status of the soils, observed to be sufficient in sugarcane based cropping systems and the highest (59.4 mg kg⁻¹) and the lowest (0.7 mg kg⁻¹) available Mn registered in the soils under sugarcane-millets system in Gudiyattam and Walajapet blocks respectively. The available boron was highest (1.98 mg kg⁻¹) and lowest (0.1 mg kg⁻¹) available boron content was recorded respectively in kaveripakkam and Walajapet blocks respectively.

Table 4: Soil properties of sugarcane based growing soils in different blocks of Vellore district (n= 308)

S. No.	Name of the block	No. of Samples	Cropping system	Soil properties							
				pH		EC (dS m ⁻¹)		OC (%)		CaCO ₃ (%)	
				Range	Mean	Range	Mean	Range	Mean	Range	Mean
1	Arakkonam	7	Sugarcane-millet	6.54-8.56	7.61	0.11-0.58	0.34	0.25-0.62	0.4	0.5-10.4	3.0
2	Kaveripakkam	28	Sugarcane-millet	6.57-8.65	7.67	0.15-0.80	0.31	0.19-0.55	0.4	1.3-11.9	3.9
3	Nemili	4	Sugarcane-millet	7.62-8.17	7.87	0.18-0.32	0.27	0.36-0.53	0.4	1.4-2.5	2.1
4	Arcot	28	Sugarcane-coconut	6.38-8.43	7.55	0.16-0.47	0.28	0.19-0.58	0.40	1.1-11.9	2.8
5	Timiri	27	Sugarcane-millet	6.35-8.56	7.53	0.12-0.46	0.31	0.24-0.69	0.44	0.5-10.3	2.8
6	Gudiyattam	18	Sugarcane-coconut	6.55-7.68	7.23	0.13-0.52	0.29	0.24-0.78	0.45	1.0-3.6	1.9
7	Katpadi	8	Sugarcane-millet	7.16-7.93	7.55	0.18-0.35	0.27	0.27-0.54	0.44	1.3-5.9	2.6
8	K.V.Kuppam	9	Sugarcane-coconut	6.47-7.86	7.37	0.16-0.45	0.24	0.39-0.79	0.49	1.4-9.5	3.2
9	Peranambattu	22	Sugarcane-coconut	6.46-7.91	7.30	0.16-0.52	0.27	0.26-0.63	0.41	1.1-3.0	1.8
10	Jolarpet	8	Sugarcane-millet	6.48-8.35	7.40	0.16-0.42	0.28	0.27-0.51	0.39	1.5-9.5	3.1
11	Kandili	4	Sugarcane-coconut	6.98-7.56	7.30	0.15-0.49	0.33	0.27-0.59	0.40	1.0-1.8	1.3
12	Natrampalli	2	Sugarcane- millets	8.12-8.24	8.18	0.29-0.38	0.34	0.31-0.40	0.36	2.5-5.1	3.8
13	Tiruppathur	11	Sugarcane-millet	6.52-8.24	7.40	0.15-0.47	0.28	0.28-0.52	0.41	1.3-9.6	3.1
14	Alangayan	11	Sugarcane-cotton	6.91-7.78	7.50	0.15-0.42	0.29	0.27-0.76	0.45	1.3-4.3	2.3
15	Madhanur	19	Sugarcane-coconut	6.38-8.48	7.55	0.17-0.49	0.29	0.25-0.56	0.41	1.1-12.5	2.7
16	Anaicut	26	Sugarcane-millet	6.47-8.41	7.58	0.11-0.56	0.28	0.24-0.59	0.41	0.1-11.9	2.9
17	Kaniyambadi	7	Sugarcane-millet	7.63-8.36	7.88	0.11-0.58	0.25	0.27-0.64	0.47	1.4-8.6	4.0
18	Vellore	3	Sugarcane-millet	7.54-7.79	7.64	0.24-0.33	0.29	0.37-0.51	0.44	2.0-3.1	2.7
19	Sholinghur	35	Sugarcane-millet	6.81-8.49	7.62	0.12-0.55	0.28	0.19-0.76	0.44	0.4-11.3	3.0
20	Walajapet	31	Sugarcane-millet	6.48-8.57	7.63	0.16-0.59	0.29	0.27-0.55	0.43	1.0-11.4	2.8
	District	308		6.35-8.65	7.57	0.11-0.80	0.29	0.19-0.79	0.42	0.1-12.5	2.8

Table 5: Micronutrients and sulphur availability of sugarcane based growing soils of different blocks of Vellore district (n=308)

S. No.	Name of the block	No. of Samples	S (mgkg ⁻¹)		Fe (mgkg ⁻¹)		Mn (mgkg ⁻¹)		Zn (mgkg ⁻¹)		Cu (mgkg ⁻¹)		B (mgkg ⁻¹)	
			Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
1	Arakkonam	7	9.36-41.9	23.5	6.3-10.43	8.01	1.2-12.7	5.23	0.7-2.8	1.29	1.0-7.2	2.8	0.83-2.6	1.43
2	Kaveripakkam	28	7.9-45.1	19.9	4.9-27.12	15.0	1.9-44.6	19.1	0.3-5.9	1.37	0.3-2.9	1.4	0.27-1.98	0.79
3	Nemili	4	39.5-52.4	45.9	6.34-18.63	11.4	3.18-30.3	17.5	0.7-1.9	1.2	0.9-1.5	1.2	0.44-0.82	0.60
4	Arcot	28	7.6-36.8	17.3	3.69-44.2	23.2	13.5-40.4	30.1	0.3-3.7	1.5	0.8-3.9	2.2	0.12-1.3	0.52
5	Timiri	27	15.6-18.7	17.3	2.4-26.9	10.2	8.4-40.9	27.9	0.6-4.6	1.4	1.1-4.8	2.2	0.10-1.4	0.54
6	Gudiyattam	18	6.2-57.1	22.5	6.5-46.7	22.7	19.5-59.4	44.3	1.1-7.3	2.7	1.0-3.1	1.8	0.19-1.2	0.70
7	Katpadi	8	5.5-25.2	15.3	11.3-22.1	16.5	2.6-9.9	5.3	1.0-3.3	2.1	2.3-4.8	3.1	0.45-1.13	0.77
8	K.V.Kuppam	9	5.7-19.2	13.0	4.5-22.6	15.9	2.8-22.0	7.8	0.4-2.6	1.3	1.1-5.5	3.0	0.18-1.0	0.56
9	Peranambattu	22	8.1-76.6	21.2	5.3-31.5	22.5	12.0-44.9	29.4	0.7-5.0	2.0	0.9-2.7	1.4	0.31-1.5	0.74
10	Jolarpet	8	8.5-36.2	18.4	16.1-29.5	21.4	2.1-13.04	7.62	0.4-2.0	0.9	2.5-5.6	4.0	0.10-0.7	0.28
11	Kandili	4	10.0-13.9	11.1	8.6-20.2	13.4	10.3-18.8	15.2	0.4-1.6	1.1	1.0-4.6	2.9	0.16-0.5	0.38
12	Natrampalli	2	1.88-6.36	4.12	20.4-20.7	20.6	10.2-14.2	12.2	0.94-1.0	0.97	1.8-2.0	1.91	0.9-1.24	1.06
13	Tiruppathur	11	12.2-102.0	43.1	6.8-19.3	14.4	7.9-17.4	13.3	0.2-0.6	0.3	1.3-8.2	2.9	0.1-2.1	0.48
14	Alangayan	11	7.4-100.8	65.9	7.9-28.3	18.7	11.0-19.6	15.7	1.0-2.9	2.0	1.3-6.6	3.1	0.10-0.76	0.37
15	Madhanur	19	4.0-41.5	12.3	2.2-29.01	11.0	11.3-51.7	44.7	0.3-4.2	0.9	0.5-4.3	1.75	0.20-2.1	1.14
16	Anaicut	26	7.0-54.7	25.4	15.4-42.0	28.6	42.7-52.9	46.9	0.2-3.5	1.0	1.0-5.1	2.4	0.59-1.8	1.05
17	Kaniyambadi	7	13.1-26.5	18.7	9.95-37.4	20.3	4.6-35.9	21.5	1.6-2.4	1.94	2.0-5.2	3.4	0.11-0.6	0.32
18	Vellore	3	31.3-39.7	35.2	11.4-25.6	20.0	3.0-6.5	4.6	1.8-4.9	3.2	1.2-1.6	1.34	0.97-1.5	1.3
19	Sholinghur	35	5.4-72.1	15.6	6.8-39.2	21.8	2.3-40.5	19.7	0.4-4.9	1.4	0.4-5.0	2.0	0.10-1.1	0.43
20	Walajapet	31	5.01-35.6	16.4	3.3-16.7	8.3	0.7-8.45	4.8	0.2-9.5	3.8	0.4-2.7	1.6	0.10-1.4	0.63
	District	308	4.0-102.0	23.1	2.2-46.7	17.2	0.7-59.4	19.6	0.2-9.5	1.6	0.3-8.2	2.3	0.10-2.1	0.70

Descriptive statistics

The descriptive statistics of major soil properties for 308 samples are presented in Table 6. The results indicate wide spatial variability among the measured parameters, reflecting heterogeneity of soil conditions in the study area. Soil pH ranged from 6.35 to 8.65 with a mean of 7.54, indicating predominantly neutral to moderately alkaline soil reaction. The low standard error (0.03) and moderate standard deviation (0.46) suggest relatively stable pH distribution. The skewness (-0.17) and kurtosis (0.34) values indicate near-normal distribution of pH. Electrical conductivity (EC) varied from 0.11 to 0.80 dS m⁻¹ with a mean of 0.28 dS m⁻¹, indicating mostly non-saline conditions. However, the distribution was moderately right-skewed (1.05) with leptokurtic behavior (2.10), showing localized salt accumulation in some soils.

Organic carbon (OC) ranged from 0.19 to 0.79%, with a mean value of 0.42%, indicating low to medium organic matter status. The slight positive skewness (0.48) and moderate kurtosis (0.78) suggest marginal departure from normal distribution. Calcium carbonate (CaCO₃) content exhibited high variability, ranging from 0.13 to 12.50% with a mean of 2.70%. The distribution was strongly right-skewed (2.30) and highly leptokurtic (4.50), confirming the presence of both non-calcareous and strongly calcareous soils, which significantly influence soil quality and SQI values. Available sulphur content ranged widely from 1.88 to 102.03 mg kg⁻¹ with a mean of 21.26 mg kg⁻¹, showing very high variability (SD = 16.21). The strong positive skewness (2.52) and high kurtosis (7.79) indicate heterogeneous sulphur distribution, likely controlled by calcareousness and organic matter content.

Among micronutrients, iron (Fe) ranged from 2.20 to 46.74 mg kg⁻¹ with a mean of 17.62 mg kg⁻¹, showing near-normal distribution. Manganese (Mn) varied from 0.66 to 59.38 mg kg⁻¹ with a mean of 23.99 mg kg⁻¹, with slight skewness and platykurtic distribution. Zinc (Zn) displayed wide variation (0.16–9.48 mg kg⁻¹, mean 1.70 mg kg⁻¹) with strong positive skewness (2.81) and very high kurtosis (8.68), indicating pronounced spatial heterogeneity and widespread deficiency-prone zones. Copper (Cu) ranged from 0.32 to 8.22 mg kg⁻¹ with a mean of 2.12 mg kg⁻¹, showing moderate skewness and

leptokurtic distribution. Hot water soluble boron (HWSB) varied from 0.10 to 2.62 mg kg⁻¹ with a mean of 0.68 mg kg⁻¹. The positive skewness (0.98) and kurtosis (1.61) indicate uneven boron distribution influenced by soil moisture regime and micronutrient interactions. Overall, the observed variability and non-normal distribution of several parameters, particularly CaCO₃, sulphur, Zn and Cu, emphasize their dominant role in controlling SQI variation and soil fertility status in the study area.

Table 6: Descriptive statistics of the soils of sugarcane growing soils in Vellore district

N=308	Range	Mean	Std. Error	Std. Deviation	Skewness	Kurtosis
pH	6.35-8.65	7.54	0.03	0.46	-0.17	0.34
EC (dSm ⁻¹)	0.11-0.8	0.28	0.01	0.10	1.05	2.10
OC (%)	0.19-0.79	0.42	0.01	0.10	0.48	0.78
CaCO ₃ (%)	0.13-12.5	2.70	0.15	2.56	2.30	4.50
Sulphur (mgkg ⁻¹)	1.88- 102.03	21.26	0.92	16.21	2.52	7.79
Fe (mgkg ⁻¹)	2.2-46.74	17.62	0.55	9.71	0.54	-0.17
Mn (mgkg ⁻¹)	0.66-59.38	23.99	0.94	16.43	0.25	-1.28
Zn (mgkg ⁻¹)	0.16-9.48	1.70	0.10	1.69	2.81	8.68
Cu (mgkg ⁻¹)	0.32-8.22	2.12	0.07	1.15	1.63	4.14
HWSB (mgkg ⁻¹)	0.1-2.62	0.68	0.02	0.41	0.98	1.61

Soil Quality index

Soil indicators were transformed into dimensionless Q-values using linear scoring functions based on more-is-better, less-is-better and optimum-is-better criteria, with dataset-specific minimum and maximum values. The computed Soil Quality Index (SQI) for the study area was 0.455, indicating moderate soil quality. Among the indicators, pH and CaCO₃ contributed the highest weight to SQI, while micronutrient deficiencies, particularly Zn and S, reduced overall soil quality. The Soil

Quality Index (SQI) was computed as a weighted linear combination of the selected soil indicators, resulting in an overall SQI value of 0.455. The SQI values were interpreted using a widely accepted classification system that categorizes soil quality into five classes: very high (>0.80), high (0.60–0.80), moderate (0.40–0.60), low (0.20–0.40), and very low (<0.20). Based on this classification, the soils of the study area fall under the moderate soil quality category. (Rajendran A, 2019, M. Shanmuganathan 2016, 2017 & 2019) [25, 27, 28, 29]

Table 7: Computation of Soil Quality Index

Rotated Component Matrix					Factor loading		Eigen Value	product	SUM	W	Qi	SQI
Parameter	Component											
	1	2	3	4								
pH	0.834	-	-	-	PC1	0.834	1.755	1.464	9.124	0.160	0.68	0.11
EC (dSm ⁻¹)	0.328	-	0.405	-	PC3	0.405	1.208	0.489	9.124	0.054	0.75	0.04
OC (%)	-0.273	-0.137	-0.285	0.593	PC4	0.593	1.036	0.614	9.124	0.067	0.39	0.03
CaCO ₃ (%)	0.849	-	-	-	PC1	0.849	1.755	1.490	9.124	0.163	0.79	0.13
Sulphur (mgkg ⁻¹)	-0.201	-	-0.119	-0.735	PC4	0.735	1.036	0.761	9.124	0.083	0.19	0.02
Fe (mgkg ⁻¹)	-	0.704	-0.122	-0.209	PC2	0.704	1.42	1.000	9.124	0.110	0.35	0.04
Mn (mgkg ⁻¹)	-0.188	0.702	0.242	0.186	PC2	0.702	1.42	0.997	9.124	0.109	0.40	0.04
Zn (mgkg ⁻¹)	-0.14	-0.526	0.101	-	PC2	0.526	1.42	0.747	9.124	0.082	0.17	0.01
Cu (mgkg ⁻¹)	-	0.267	-0.667	0.146	PC3	0.667	1.208	0.806	9.124	0.088	0.23	0.02
HWSB (mgkg ⁻¹)	-	0.252	0.626	0.342	PC3	0.626	1.208	0.756	9.124	0.083	0.23	0.02
SQI												0.45
Class Medium/moderate												

This moderate soil quality status reflects the combined influence of multiple soil properties, among which pH and CaCO₃ exhibited the highest weighting factors, demonstrating their dominant role in regulating soil chemical conditions and overall soil health. In contrast, relatively low Q-values for sulphur (0.194) and zinc (0.166), indicate deficiencies of these essential nutrients, which significantly constrained the composite soil quality score. Although parameters such as electrical conductivity and organic carbon contributed moderately to the index, the limited availability of sulphur and micronutrients emerged as the major limiting factors affecting soil productivity in the study area. These findings suggest that while the soils are reasonably suitable for agricultural production, targeted nutrient management strategies, particularly the application of sulphur-

and micronutrient-enriched fertilizers, are essential for improving soil fertility, enhancing crop productivity, and ensuring long-term soil sustainability.

Overall scenario of soil properties and micronutrient availability in soils of sugarcane based cropping system in Vellore district

Totally, 309 soil samples were collected and analyzed for available sulphur and micronutrients besides assessing soil chemical properties. The results revealed that soils of various blocks of sugarcane growing soils of Vellore district were mostly slightly alkaline (47%) in soil reaction and low in salt content. About seventy six per cent of the soils were low in organic carbon status and 89 per cent of soils are non -

calcareous nature in free CaCO₃ in soil.

Among the micronutrients, Boron appears to be a most crucial element and to be managed in the soils of Vellore district. About 38 per cent of soils samples were B deficient. Next to B, Zn deficiency was noticed to an extent of 15.9 per cent in the soils which indicated the necessity of Zn nutrition in that locality.

Among secondary nutrients fertility status of Sulphur, is also low having 18 percent of deficiency DTPA Mn deficiency recorded 12 percent and iron and copper fertility status is high. Hence, managing B, Zn, S and Mn deficiencies in various blocks of Vellore district is essential to achieve optimum productivity

of crops.

Relationships between soil properties and micronutrients availability in different blocks of district

The evaluation of soil quality through the Soil Quality Index (SQI) and correlation analysis provides a comprehensive understanding of soil fertility dynamics in the study area. The SQI values reflected the combined influence of key physico-chemical and micronutrient parameters, while correlation analysis explained the underlying interactions responsible for the observed soil quality status.

Table 8: Correlation between soil properties, available sulphur and micronutrients status of different blocks of Vellore District

Parameters	pH	EC	OC	CaCO ₃	Sulphur	Fe	Mn	Zn	Cu	HWSB
pH	1	.194**	-0.098	.542**	-0.062	-0.023	-0.098	-0.042	-0.053	0.009
EC	.194**	1	-0.074	.145*	-0.002	-0.057	0.006	0.008	-0.04	0.084
OC	-0.098	-0.074	1	-.180**	-0.047	-0.067	0.018	0.06	0.066	0.001
CaCO ₃	.542**	.145*	-.180**	1	-.115*	-0.015	-0.086	-0.038	-0.047	-0.017
Sulphur	-0.062	-0.002	-0.047	-.115*	1	0.077	-0.052	-0.013	0.047	-0.101
Fe	-0.023	-0.057	-0.067	-0.015	0.077	1	.280**	-.117*	0.088	-0.002
Mn	-0.098	0.006	0.018	-0.086	-0.052	.280**	1	-.127*	0.029	.192**
Zn	-0.042	0.008	0.06	-0.038	-0.013	-.117*	-.127*	1	-0.057	-0.045
Cu	-0.053	-0.04	0.066	-0.047	0.047	0.088	0.029	-0.057	1	-0.072
HWSB	0.009	0.084	0.001	-0.017	-0.101	-0.002	.192**	-0.045	-0.072	1

** . Correlation is significant at the 0.01 level (2-tailed).

* . Correlation is significant at the 0.05 level (2-tailed).

Correlation results revealed that soil pH and CaCO₃ are the dominant regulators of soil behavior. The highly significant positive correlation between pH and CaCO₃ ($r = 0.542$, $p < 0.01$), similar studies reported by Lin *et al.* 2017^[19] along with the significant association of EC with both pH and CaCO₃, confirms that alkalinity and calcareousness strongly influence salinity development and nutrient solubility. These properties exert major control over SQI values, as elevated pH and CaCO₃ reduce the availability of several essential nutrients, thereby lowering overall soil quality scores in many locations.

The significant negative relationship between organic carbon and CaCO₃ ($r = -0.180$, $p < 0.01$) (Xiaolu Dou, 2024)^[5] explains the generally low organic matter content observed in calcareous soils, which contributes to reduced biological activity and nutrient buffering capacity, negatively affecting SQI. Likewise, the significant negative correlation between CaCO₃ and sulphur ($r = -0.115$, $p < 0.05$) indicates sulphur fixation under alkaline conditions, further constraining soil fertility and lowering soil quality ratings.

Micronutrient interactions also played a crucial role in SQI variation. The highly significant positive correlation between Fe and Mn ($r = 0.280$, $p < 0.01$) as reported by Sirous Shakeri & Mahboub Saffari, 2020^[26], reflects their common geochemical behavior, while the significant negative correlations of both Fe and Mn with Zn indicate strong antagonistic effects that limit zinc availability in calcareous environments. These micronutrient imbalances are key contributors to the moderate and low SQI classes observed in several sampling locations. In addition, the positive association between HWSB and Mn ($r = 0.192$, $p < 0.01$) suggests that boron availability is influenced by manganese dynamics, further affecting soil quality status.

Overall, the integrated interpretation demonstrates that soil quality in the study area is primarily constrained by high pH, elevated CaCO₃ content, low organic carbon, and micronutrient antagonism, which together govern nutrient availability and SQI distribution. The predominance of moderate to low SQI classes highlights the need for management practices focused on

organic matter enrichment, sulphur supplementation, and balanced micronutrient application to improve soil health and sustain crop productivity.

Conclusion

Soil properties and nutrient availability varied with crops and cropping system. The increase in pH of soils could be due to increased calcium carbonate content which produces more OH ions upon hydrolysis and created an alkaline effect (Somasundaram *et al.* 2009)^[32]. The low salinity in these soils is evident due to enhanced leaching losses and reduced accumulation of salts in the root zone which contributed to a decline in EC values (Duhan and Singh 2002)^[6]. The low organic carbon content might be due to over depletion under sugarcane cropping systems and could be explained by increased carbon input through the addition of root biomass and crop residues (Sidhu and Beri 1989)^[30]. Almost all the soils grown with sugarcane based cropping system showed sufficient availability of Fe and Cu. This highest values of iron might be due to better supply of Fe and Cu under maintenance of optimum moisture in the soils. But the very low organic carbon content of the soils indicates that corrective measures would be required to avoid B, Zn and Sulphur deficiency in near future and similar observations have been made by Katyal and Datta (2004)^[17] and Anil Sood *et al.* (2009)^[2]. The Cu availability in sole crop of sugarcane cropping systems is sufficient in considering its mean value due to increase in finer fractions of the soil lead to increased surface area for ion exchange thus contributing to higher Cu availability. Higher availability of all nutrients in the soils under sugarcane cropping systems might be due to higher organic carbon content through the addition of crop residues (Balwinder Kumar *et al.* 2008)^[3].

Sugarcane, the main source of income for the farmers of Vellore district in order to evaluate the quality of soil, using newly formulated SQI. The total SQI value of all the samples investigated in this study ranged from 0.45. This range suggests that all the soil samples chosen in this study are moderate in

quality and suitable for the cultivation sugarcane with mitigating some constrains.

Unlike cereal crops mechanization remains underutilized in sugarcane crop (Srinivasa Rao, Ch, 2024) ^[33]. Increasing mechanization does not necessarily entail high capital investment. Critical is selecting context-specific power sources based on scale, function, and resource availability. With over 80% of Indian farmers categorized as small or marginal, affordability remains a key constraint. In states such as Punjab and Haryana, the deployment of Custom Hiring Services (CHS) has proven effective in bridging this gap (Yukiko, 2024) ^[35].

India generates about 750 Mt of agricultural waste annually, much of which can be recycled as soil amendments to improve nutrient balance, carbon sequestration, and overall soil and ecosystem health, while residues like sugarcane bagasse support energy generation. Adoption of circular economy strategies could unlock nearly USD 500 billion in economic value for India by 2030 through resource efficiency, product life extension, and waste valorization (Accenture, 2015; Fiksel *et al.*, 2021) ^[36, 7].

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