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RESEARCH ARTICLE

Geospatial mapping of soil salinity and sodicity: Insights for crop suitability and management in Thanjavur District, Tamil Nadu

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Abstract

Soil characteristics significantly influence the sustainability of agriculture. Physico-chemical characteristics such as pH, electrical conductivity (EC) and exchangeable cations (calcium, magnesium, sodium and potassium) significantly influence soil salinity. Understanding the spatial distribution of salinity and sodicity is crucial for planning site-specific management strategies, especially in degraded lands. Thanjavur, often called the "Rice Bowl of Tamil Nadu," encounters challenges sustaining agriculture due to its varied soil characteristics. This study examines the spatial distribution of pH, EC and exchangeable cations across various blocks of Thanjavur district to understand their agricultural implications. Analysis reveals significant variability: The mean soil pH varied from slightly acidic (6.63 in Thanjavur) to alkaline (8.01 in Peravurani) and the mean EC ranged from 0.71 dS m^{-1} in Thanjavur to 8.26 dS m^{-1} in Sethubavachatram, indicating stark differences in salinity. The mean exchangeable calcium ranged from 6.49 Cmol (p^+) kg^{-1} (Papanasam) to 14.2 Cmol (p^+) kg^{-1} (Sethubavachatram) and mean exchangeable magnesium from 3.91 Cmol (p^+) kg^{-1} (Orathanadu) to 7.67 Cmol (p^+) kg^{-1} (Sethubavachatram). The mean exchangeable sodium levels span from 1.48 Cmol (p^+) kg^{-1} (Thanjavur) to 3.68 Cmol (p^+) kg^{-1} (Sethubavachatram) and mean exchangeable potassium from 0.12 Cmol (p^+) kg^{-1} (Thanjavur) to 0.37 Cmol (p^+) kg^{-1} (Sethubavachatram), Blocks like Sethubavachatram, Peravurani exhibits higher salinity, challenging salt-sensitive crops, while Thanjavur, Thiruppanandal and Thiruvidaimarudur are better suited for diverse crops. Using geospatial mapping, these findings offer a valuable resource for farmers, agronomists and policymakers, facilitating targeted interventions for sustainable agricultural development in Thanjavur district.

Keywords

spatial mapping; soil properties; salinity; Thanjavur

Introduction

Spatial mapping is indispensable for a district, as it offers a visual framework for analyzing socioeconomic, environmental and geographic characteristics, facilitating strategic planning and informed decision-making (1). Soil parameters exhibit significant spatial variability due to physical, chemical and biological processes acting at different scales. To find appropriate zones for agricultural land management, it is crucial to understand how soil qualities vary across gradual and continuous patterns. Comprehensive surveys incorporating geospatial techniques are necessary to characterize spatial variability effectively (2). Hence, spatial soil mapping is critical for environmental conservation and disaster management as it aids in monitoring land-use changes and mapping risk patterns around the region.

The most crucial concern regarding agriculture in the 21st century is soil salinization, which continuously expands in different regions (3). Soil salinization is the accumulation of soluble salts in the soil to a level beyond which it negatively impacts agricultural production potential and environmental health. To enable site-specific prediction and management of this issue, salinity mapping is crucial as it delineates the distribution patterns of salinity levels across degraded regions. Developing site-specific measures to reduce salinity, strengthen soil health and increase agricultural yield requires this information on salinity or sodicity mapping, specifically in degradation-prone areas like the country's coastal region. By directing the selection of salt-tolerant crops, proper irrigation strategies and soil management tactics appropriate for saline settings, salinity mapping aids in planning sustainable land use in affected regions (4).

Around one billion ha of earthland is globally affected by salt and salt-associated threats (5). In contrast, India covers 6.73 M ha of salt-affected soil, of which nearly 2.96 M ha of soils are dominated by saline soil (6). Soil salinity is prevalent in six districts of Tamil Nadu: Ramanathapuram, Cuddalore, Kanchipuram, Tirunelveli, Thanjavur and Pudukkottai districts. Thanjavur, a well-known district in the Cauvery Delta, depends on agriculture and related industries for their livelihood, making it a crucial area in Tamil Nadu's agricultural landscape. The district has a gross cropped area of about 2.69 lakh ha and a total land area of 3.39 lakh ha. Thanjavur has been called the Rice Bowl of Tamil Nadu and is essential in maintaining the state's food security. Tertiary and Alluvial formations dominate its topography, further enhancing its agricultural potential. The geological composition consists of Cretaceous, Tertiary and Alluvial deposits (7, 8). Though Thanjavur is not located directly on the coastline, it lies relatively close to the Bay of Bengal and is surrounded by coastal areas like Nagapattinam. The spatial mapping of soil parameters like pH, Electrical conductivity (EC), exchangeable cations *viz*., calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR) is crucial for Thanjavur district. Farmers, scientists and agricultural experts could alter the strategies to maximize sustainability and productivity by understanding the spatial distribution of key soil characteristics. At the same time, the mapping furnishes crucial information on soil fertility and health, enabling more efficient agricultural management (9). The metrics EC, ESP and SAR are essential when assessing the salinity and sodicity of the soil, which Thanjavur commonly experiences due to irrigation techniques and seawater intrusion from nearby coastlines.

Spatial soil mapping promotes sustainable land management practices by guiding decisions related to irrigation, amendments, fertilization and soil conservation (10, 11, 12). It aids in implementing region-specific techniques that preserve resources, enhance soil health and lessen environmental degradation by offering comprehensive insights into the variations in soil properties across various locations. This strategy also promotes precision agriculture, effectively minimizing waste and environmental impact by applying inputs like water, fertilizer and soil conditioners (13).

Hence, this study was conducted to map and evaluate the spatial distribution of soil quality (pH, EC, exchangeable cations: Ca, Mg, Na and K) across different blocks of Thanjavur by utilizing mapping programs in ArcGIS software. This method offered thorough insights into the regional variations in soil characteristics and its use in site-specific management strategies, enabling optimal agricultural performance and fostering long-term sustainability. The results are vital for enhancing crop yields and ensuring regional food security.

Materials and Methods

Study area

Thanjavur district (10.7877 °N and 79.2384 °E) is situated in the Cauvery Delta region on the eastern coast of Tamil Nadu. The district comprises eight taluks and 14 community development blocks, including Ammapettai, Budalur, Kumbakonam, Madukkur, Orathanadu, Papanasam, Pattukkottai, Peravurani, Thanjavur, Thiruppanandal, Sethubhavachatram, Thiruvaiyaru, Thiruvonam and Thiruvidaimarudur. Together, they cover an area of 3397 square km. The district receives water from two major river basins: the Agniyar River basin covers 35.2 % of the area, while the Cauvery River basin makes up 64.73 %. The district's agricultural activity depends on these basins for irrigation and water availability. The climatic profile shows a warm and humid tropical climate with an average yearly temperature of 32.9 °C (maximum) and 23.7 °C (minimum). The average annual rainfall of 1038.4 mm also reinforces rainfed and irrigated agriculture operations (7, 8).

Georeferenced soil sampling

Soil samples were randomly collected from various blocks of Thanjavur in January and February of 2024. The study covered all 14 blocks of Thanjavur district and 12 to 15 soil samples were collected from each block to reflect the various locales. The sampling point's geographic coordinates were noted using a handheld GPS device (Fig. 1-2). Using a soil auger, 194 soil samples were taken between 0 and 15 cm, representing the root zone and topsoil characteristics. They were then placed in plastic bags, marked with the location and brought to the laboratory for examination. In the laboratory, the samples were allowed to air dry at room temperature before being sieved through a 2-mm mesh and stored for subsequent analysis. The parameters evaluated included soil pH, electrical conductivity (EC) (dS m^{-1}), exchangeable calcium (Cmol (p^+) kg^{-1}, exchangeable magnesium (Cmol (p^+) kg^{-1}), exchangeable sodium (Cmol (p^+) kg^{-1}), exchangeable potassium (Cmol (p^+) kg^{-1}) content and Cation Exchange Capacity (Cmol (p^+) kg^{-1}). The derived parameters, such as Exchangeable Sodium Percentage (ESP) and Sodium Adsorption Ratio (SAR) were determined for salinity characterization.

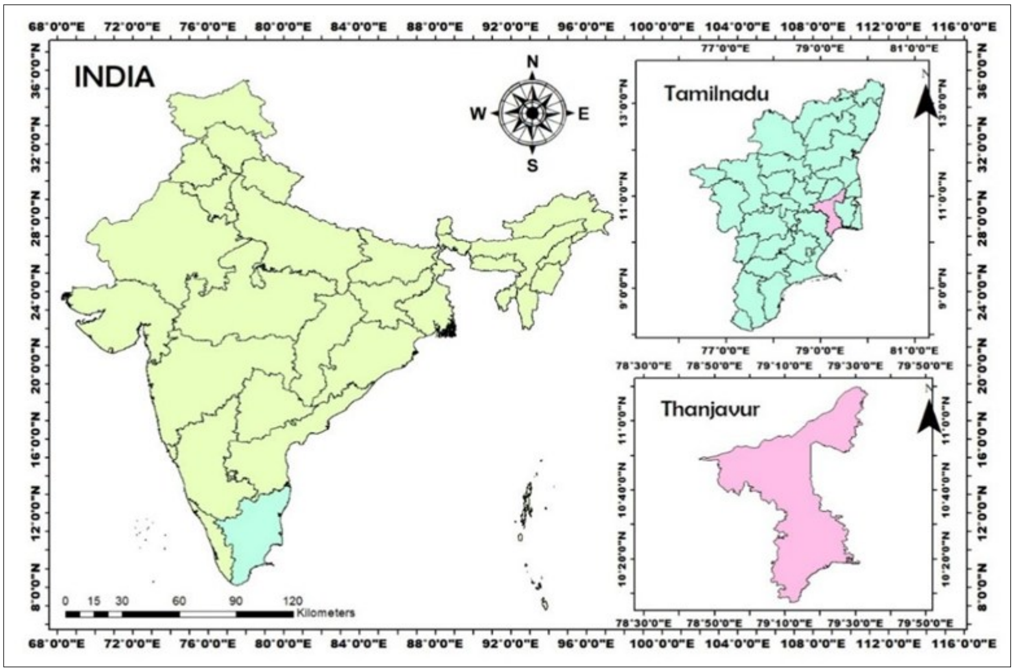

Fig. 1. Study area map illustrating the precise location of Thanjavur district, Tamil Nadu, India (Developed using ArcGIS Software).

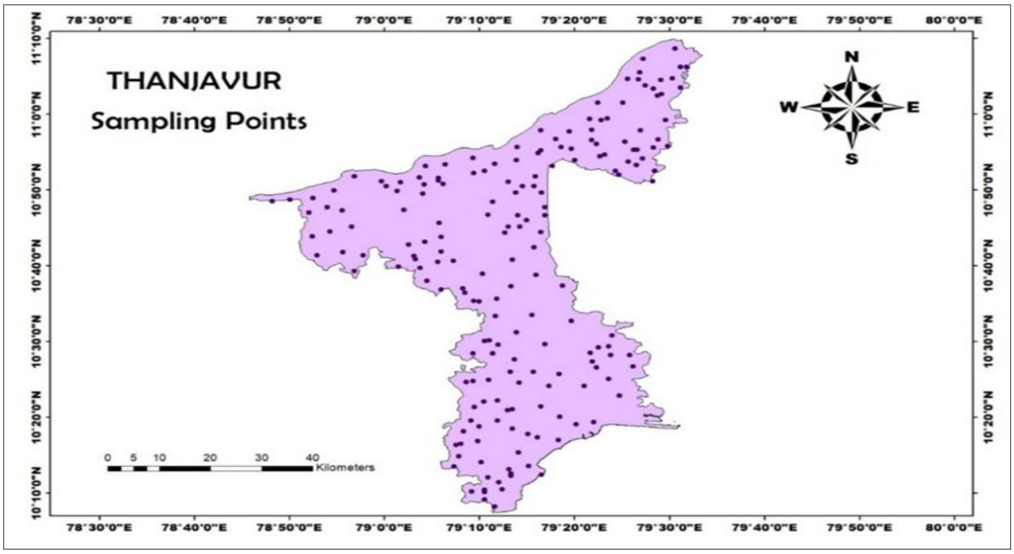

Fig. 2. Sampling locations showing the precise positions of sample collection across various blocks of Thanjavur district (Mapped using ArcGIS Software).

Soil reaction (pH) & Electrical conductivity (EC)

The pH and EC of the soil were determined using a 1:2.5 soil-to-water suspension, a standard method for assessing soil acidity or alkalinity, which influences nutrient availability and microbial activity. The pH was measured using a calibrated pH meter (EUTECH) and the conductivity was recorded using an electrical conductivity meter (ELICO CM 180) (14).

Exchangeable cations

The calcium and magnesium content was analyzed using the versenate titration method and sodium and potassium by flame photometry and expressed in Cmol (p^+) kg^{-1} (14, 15). CEC was analyzed using sodium acetate (pH > 8.2) and ammonium acetate extraction (pH < 8.2) methods.

Exchangeable sodium percentage

Exchangeable sodium percentage (ESP) is, accordingly, the amount of adsorbed sodium on the soil exchange complex expressed in percent of the cation exchange capacity, as given in Equation 1 (16, 17).

$$ESP = \frac{\text{Exchangeable sodium (Na)}}{CEC} \times 100 \qquad \text{(Eqn. 1)}$$

Where soils are classified based on pH, EC and ESP as follows

Sodic: pH > 8.5, EC < 4 dS m^{-1} and ESP > 15

Slightly Saline: pH < 8.5, EC 2 - 4 dS m^{-1} and ESP < 15

Moderately saline: pH < 8.5, EC 4 - 8 dS m^{-1} and ESP < 15

Strongly Saline: pH < 8.5, EC 8 - 16 dS m^{-1} and ESP < 15

Very Strongly Saline: pH < 8.5, EC > 16 dS m^{-1} and ESP < 15

Sodium adsorption ratio

According to the US Salinity Laboratory, the exchangeable sodium percentage of the soils is quantitatively related to the soil solution's sodium adsorption ratio (SAR), which effectively

$$SAR = \frac{\text{Exchangeable Sodium (Na)}}{\sqrt{\frac{Ca + Mg}{2}}} \quad \text{(Eqn. 2)}$$

characterizes the soil sodicity issue (16). The following equation defines the sodium adsorption ratio, or SAR, in Equation 2:

Geospatial mapping

This ArcGIS Geostatistical Analyst tool created a series of thematic maps that visually represent spatial variations in soil salinity characters across Thanjavur. ArcMap 10.8, developed by (18), is used as geographic information system (GIS) software for spatial data analysis and map creation. The interpolation method, called Inverse Distance Weighting (IDW), was applied to achieve accurate spatial representation. It is a deterministic spatial interpolation method that assumes that the variable of interest is more similar to nearby points than those far away. This method is beneficial when the mapped phenomenon is expected to change gradually and is influenced by nearby features. By giving closer points more weight and farther points less, this method guarantees that values of a particular variable at unmeasured locations are calculated using the values at nearby measured sites.

Statistical analysis

Statistical analysis was conducted using R software (version 4.3.3) and GRAPES KAU to evaluate the spatial variability of soil parameters, including pH, electrical conductivity (EC), exchangeable cations *viz.,* calcium (Ca), magnesium (Mg), sodium (Na) and potassium (K), across all blocks of Thanjavur. Parallel coordinate plots were developed to visualize the multivariate relationships among these parameters, offering a comprehensive overview of soil characteristics across the various blocks. Regression analysis was conducted using the GRAPES KAU tool to identify relationships between dependent and independent soil parameters. Box plots were generated using the `ggplot2` package in R to evaluate the distribution of calcium content across blocks and the mean calcium and magnesium levels, providing insights into soil nutrient variability. These analyses provided critical insights into soil salinity characterization, nutrient dynamics and variability, contributing to informed soil management strategies for sustainable agriculture.

Results

The pH of most soils across the blocks of Thanjavur district stayed within a range of 6.65 to 8.00, which is generally suitable for agricultural growth. Near-neutral to slightly alkaline conditions were found in the majority of areas. Only a few blocks (Sethubavachatram, Peravurani, Orathanadu) exhibited high salinity or alkalinity issues (Fig. 3). The lowest pH was recorded with Thanjavur and Thiruppanandal, with mean values of 6.63 and 6.82, respectively, suggesting slightly acidic to neutral soils. In contrast, Peravurani and Sethubavachatram were slightly alkaline, with pH values averaging 8.01 and 7.96, respectively. The rest of the blocks other than these, including Thiruvonam, Pattukottai, Madukkur, Thiruvidaimarudur and Kumbakonam, had mean pH values close to neutral, ranging from 7.03 to 7.78.

Electrical conductivity (EC) varied significantly among blocks, indicating differences in salinity level (Fig. 4). Sethubavachatram recorded the highest EC (4.12-12.6 dS m^{-1}, mean 8.26 dS m^{-1}), indicating severe salinity. Peravurani (mean 3.97 dS m^{-1}) and Madukkur (mean 2.78 dS m^{-1}) also exhibited elevated salinity. Moderate EC levels were observed in Thiruvonam (1.29 dS m^{-1}), Pattukottai (1.75 dS m^{-1}), Thiruvidaimarudur (1.37 dS m^{-1}) and Kumbakonam (1.54 dS m^{-1}). Blocks such as Thiruppanandal (0.94 dS m^{-1}), Papanasam (1.39 dS m^{-1}) and Thanjavur (0.71 dS m^{-1}) exhibited relatively low salinity.

The exchangeable calcium and magnesium levels across the blocks were moderate to low, with minimal variation (Fig. 7-8). The coastal line blocks like Sethubavachatram and Peravurani exhibited the highest exchangeable calcium concentrations, with 14.3 and 13.0 Cmol (p^+) kg^{-1} of mean values, respectively. Madukkur, Thiruvonam and Pattukottai showed moderate levels of exchangeable calcium, with mean values between 10.2, 9.04 and 8.98 Cmol (p^+) kg^{-1}, respectively.

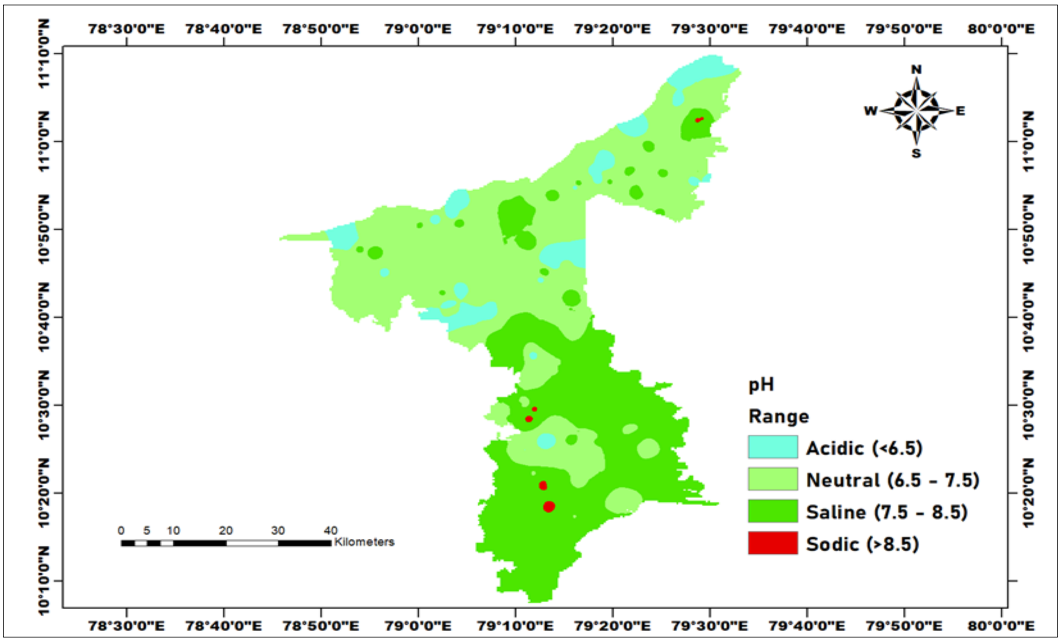

Fig. 3. Spatial distribution of soil pH in Thanjavur district, created using the IDW (inverse distance weighting) interpolation method in ArcGIS.

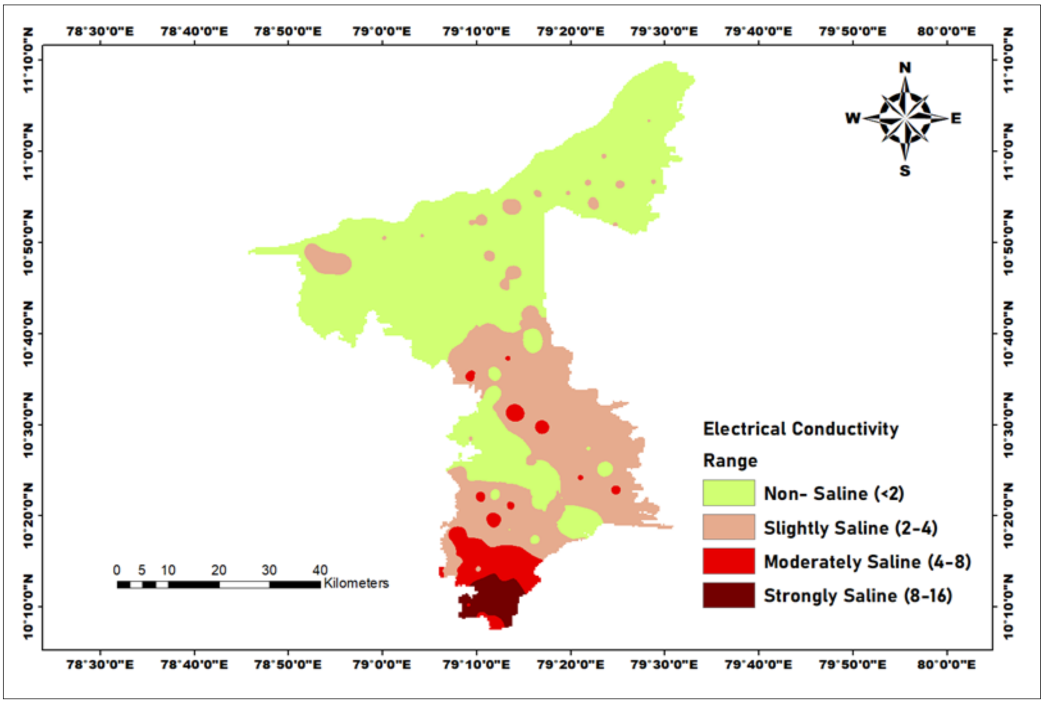

Fig. 4. Spatial distribution of soil electrical conductivity (dS m^{-1}) across Thanjavur district, generated using the IDW (inverse distance weighting) interpolation method in ArcGIS.

Exchangeable magnesium content was relatively high with Sethubavachatram (7.67 Cmol (p^+) kg^{-1}) and low with Orathanadu (3.91 Cmol (p^+) kg^{-1}).

The exchangeable sodium concentrations varied significantly, reflecting the degree of sodicity in each block (Fig. 5). Highest exchangeable sodium content was found with coastline blocks: Sethubavachatram 3.68 Cmol (p^+) kg^{-1}, followed by the Orathanadu block and Peravurani with a mean of 3.53 and 3.33 Cmol (p^+) kg^{-1} respectively, while moderate exchangeable sodium content was observed in Ammapettai, Thiruvonam and Thiruvaiyaru with mean values of 2.49, 2.48 and 2.26 Cmol (p^+) kg^{-1}, respectively. The lower exchangeable sodium content was recorded with Thiruppanandal and Thanjavur, with mean values of 1.64 and 1.48 Cmol (p^+) kg^{-1}, respectively.

The exchangeable potassium content across the various blocks was moderate. However, variations were evident (Fig. 6). This follows the same trend of Sodium: Sethubavachatram, Peravurani and Orathnadu recorded the highest exchangeable potassium levels, with mean of 0.37, 0.35 and 0.26 Cmol (p^+) kg^{-1}, respectively. Followed by Madukkur, with a mean of 0.25 Cmol (p^+) kg^{-1}. The lower exchangeable potassium levels were recorded in Thiruppanandal and Thanjavur, averaging 0.13 and 0.12 Cmol (p^+) kg^{-1}, respectively.

The Exchangeable Sodium Percentage (ESP) and Sodium Adsorption Ratio (SAR) values (Fig. 9) showed notable sodicity problems across the blocks, especially in Orathnadu, which had the highest ESP of a maximum of 23.5 with 33.3 % of the area under high ESP. Followed by Ammapettai and Pattukkottai with ESP of more than 15 of about 21.4 % area (Table 2). SAR showed slight sodicity, with mean SAR values of

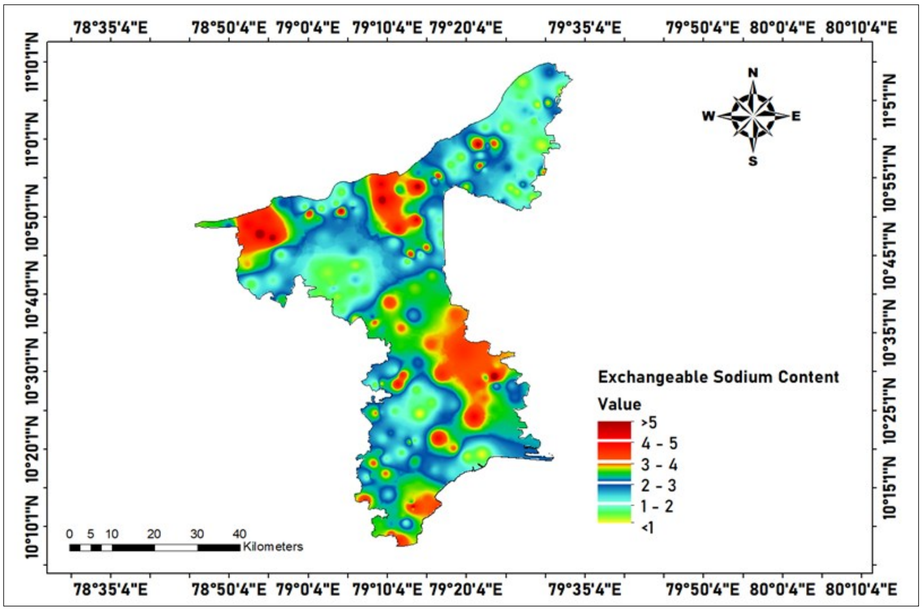

Fig. 5. Spatial distribution of soil exchangeable sodium content (Cmol (p^+) kg^{-1}) across Thanjavur district, generated using IDW (Inverse Distance Weighting) interpolation method in ArcGIS.

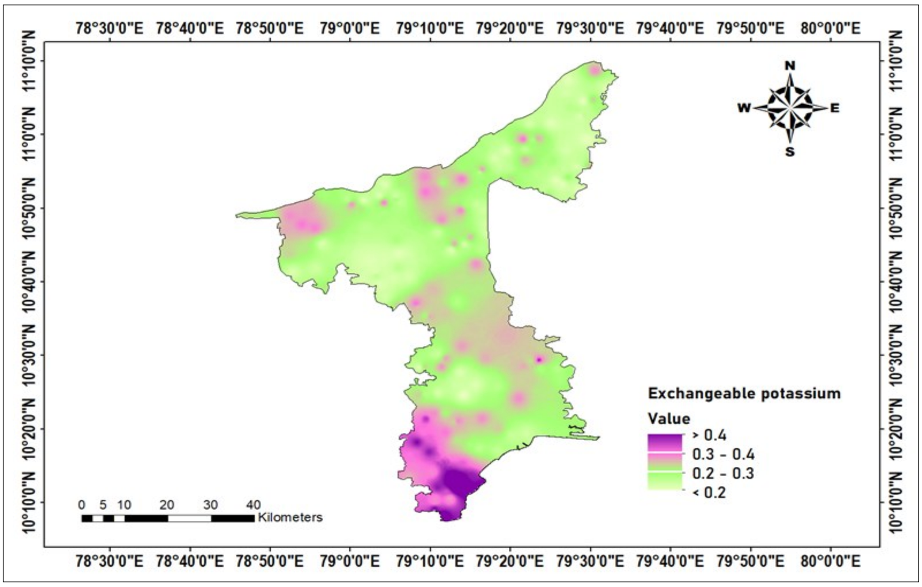

Fig. 6. Spatial distribution of exchangeable potassium (Cmol (p+) kg-1) content in Thanjavur district, Tamil Nadu, created using IDW (inverse distance weighting) interpolation in ArcGIS.

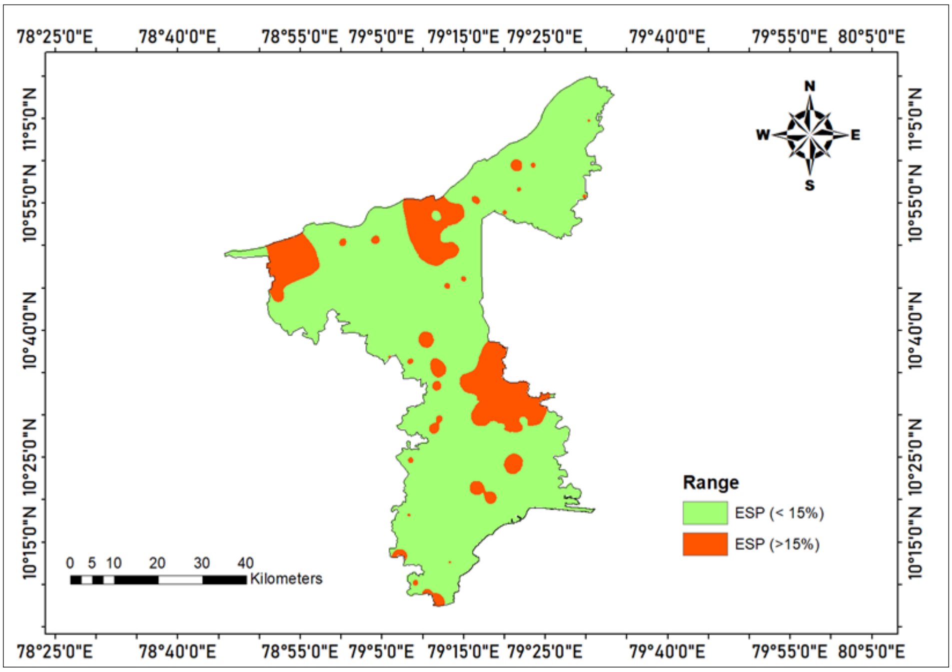

Fig. 7. Spatial distribution of exchangeable sodium percentage (ESP) across Thanjavur district, Tamil Nadu, generated using inverse distance weighted (IDW) interpolation in ArcGIS.

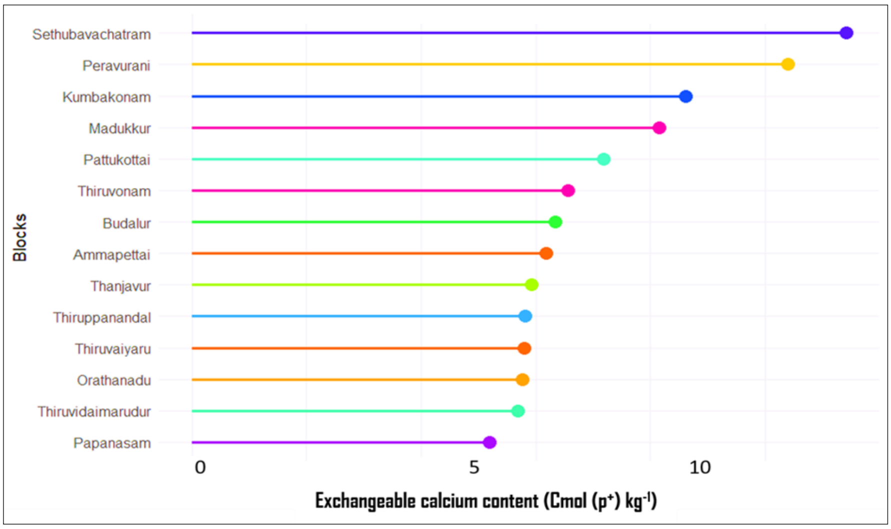

Fig. 8. Exchangeable calcium content across various blocks of Thanjavur (R Software version 4.3.3).

1.71, whereas Thiruppanandal and Thanjavur exhibited comparatively lowest levels of sodicity, with mean SAR values of 0.98 and 0.92, respectively.

There were notable differences in the average soil salinity and sodicity between the various blocks of Thanjavur (Table 1). The higher salinity was found in Sethubavachatram, which had an average EC of 8.26 ds m^{-1} while higher sodicity with ESP of 23.5 was recorded in Orathanadu. With an average EC of 0.71 dS m^{-1} and SAR of 0.92, Thanjavur, on the other hand, had the lowest salinity and sodicity hazards. High EC and ESP values were trending in most areas, suggesting possible salinity hazards or sodicity-induced soil degradation. While magnesium concentrations were generally low, most blocks had moderate to higher potassium and calcium levels. These findings highlight the need for tailored soil management practices to mitigate salinity and sodicity effects and improve agricultural productivity.

Discussion

Sethubavachatram and Peravurani blocks, located along the coastal line, exhibit the highest pH values (7.5-8.5), indicating

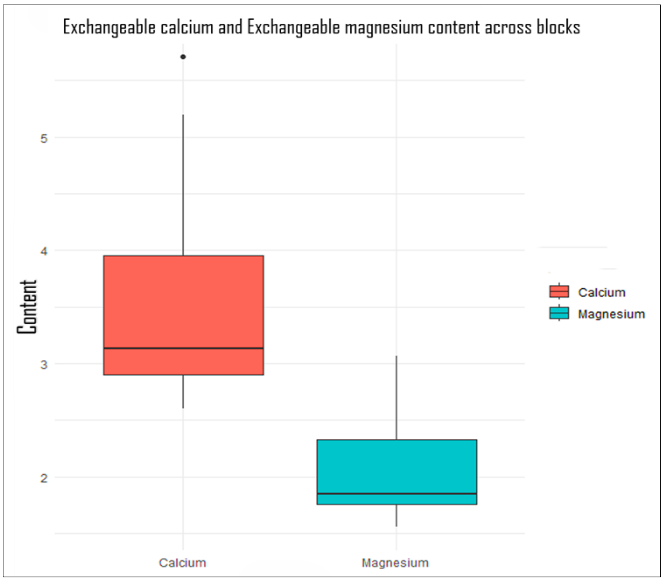

Fig. 9. Boxplot contrasts the exchangeable Ca and exchangeable Mg content in each block. Exchangeable Ca content is wider with an interquartile range (IQR) of roughly 3 to 4 and a median of about 3.5. An outlier exceeding 5 indicates that certain blocks have a high concentration. Exchangeable Mg concentrations are less variable among blocks, showing a median near 2 and a narrower IQR (R Software version 4.3.3).

Table 1. Soil Quality and Salinity Indicators (Max, Min and Mean Values) in Thanjavur district blocks

Blocks		pH	EC	Ca	Mg	Na	K	ESP	SAR
	Units		dS m^{-1}		Cmol (p^+) kg^{-1}				
Thiruvonam	Minimum	6.48	0.15	3.75	3.45	0.74	0.08	3.66	0.45
	Maximum	8.77	2.56	14.0	8.58	4.87	0.32	19.01	2.64
	Mean	7.57	1.30	9.04	5.68	2.48	0.18	10.3	1.35
Pattukottai	Minimum	5.26	0.75	4.05	2.69	0.48	0.06	2.26	0.25
	Maximum	8.95	2.68	15.5	8.42	4.91	0.32	18.1	2.93
	Mean	7.54	1.75	8.98	5.15	2.26	0.17	9.68	1.32
Madukkur	Minimum	6.85	1.11	5.90	3.73	2.09	0.15	8.73	0.99
	Maximum	8.25	4.25	15.4	8.47	6.04	0.39	21.6	2.99
	Mean	7.78	2.78	10.2	5.88	3.13	0.25	12.3	1.61
Peravurani	Minimum	7.58	2.14	6.45	3.76	2.83	0.32	9.82	1.46
	Maximum	8.46	5.36	17.9	9.47	4.18	0.40	15.9	1.71
	Mean	8.01	3.97	13.0	7.03	3.33	0.35	9.08	1.16
Sethubava chatram	Minimum	7.64	4.12	3.40	2.24	2.48	0.30	8.68	0.96
	Maximum	8.45	12.6	21.6	11.4	5.61	0.49	18.5	2.79
	Mean	7.96	8.26	14.27	7.67	3.68	0.37	11.9	1.60
Thiruppanandal	Minimum	5.15	0.15	4.20	2.64	0.48	0.06	2.51	0.32
	Maximum	8.67	2.12	10.9	6.00	3.78	0.25	15.7	2.12
	Mean	6.82	0.94	7.27	4.17	1.64	0.13	7.51	0.98
Thiruvidai marudur	Minimum	5.99	0.56	3.90	2.59	0.61	0.07	2.93	0.32
	Maximum	8.11	2.24	10.5	5.90	3.87	0.26	15.9	2.27
	Mean	7.03	1.37	7.11	4.20	1.77	0.14	8.08	1.09
Kumbakonam	Minimum	5.14	0.17	5.88	3.82	0.74	0.08	3.67	0.45
	Maximum	8.17	2.65	18.6	10.20	5.39	0.35	21.9	3.46
	Mean	7.18	1.54	10.8	6.27	2.37	0.20	9.49	1.51
Papanasam	Minimum	5.14	0.17	5.88	3.82	0.74	0.08	3.67	0.45
	Maximum	8.17	2.65	18.63	10.20	5.39	0.35	21.9	3.46
	Mean	7.04	1.39	6.49	4.37	2.37	0.19	10.5	1.51
Thiruvaiyaru	Minimum	5.58	0.17	3.13	2.38	0.74	0.08	3.77	0.45
	Maximum	8.26	2.87	10.8	7.21	5.26	0.34	23.0	4.43
	Mean	6.98	1.23	7.25	4.44	2.26	0.18	9.90	1.38
Ammapettai	Minimum	5.77	0.14	5.75	3.52	0.65	0.07	2.94	0.33
	Maximum	8.32	2.68	14.0	7.65	5.09	0.33	20.6	3.23
	Mean	6.91	1.30	7.73	4.51	2.49	0.18	10.7	1.47
Thanjavur	Minimum	5.89	0.12	3.08	4.68	0.71	0.07	2.78	0.29
	Maximum	7.65	1.11	15.9	5.34	3.65	0.25	15.3	2.07
	Mean	6.63	0.71	7.39	4.47	1.48	0.12	6.91	0.92
Budalur	Minimum	5.59	0.58	3.85	2.71	1.03	0.09	4.19	0.45
	Maximum	7.88	2.65	13.4	7.48	5.29	0.34	20.5	3.18
	Mean	7.17	1.54	7.93	4.75	2.92	0.23	12.3	1.71
Orathanadu	Minimum	6.19	1.14	3.38	2.00	2.23	0.16	9.40	1.12
	Maximum	8.34	3.65	13.4	7.01	5.37	0.35	23.5	3.11
	Mean	7.76	1.91	7.20	3.91	3.53	0.26	13.9	2.23

Table 2. Distribution of saline and sodic soil based on pH, EC and ESP across different blocks of Thanjavur district

District	pH				EC (dS m^{-1})				ESP	
	Acidic (<6.5)	Neutral (6.5 - 7.5)	Saline (7.5 - 8.5)	Sodic (>8.5)	Non-Saline (0 - 2)	Slightly saline (2 -4)	Moderately saline (4-8)	Strongly saline (8-16)	(< 15)	(> 15)
	Percentage									
Thiruvonam	-	50.0	25.0	25.0	75.0	25.0	-	-	83.3	16.7
Pattukottai	7.10	42.9	28.6	21.4	64.2	35.8	-	-	78.6	21.4
Madukkur	-	16.7	83.3	-	16.7	66.6	16.7	-	100	-
Peravurani	-	-	92.3	7.70	-	53.8	46.2	-	100	-
Sethubavachatram	-	-	93.3	6.70	-	-	53.3	46.7	100	-
Thiruppanandal	40.0	40.0	13.3	6.70	93.3	6.70	-	-	100	-
Thiruvidaimarudur	20.0	60.0	20.0	-	80.0	20.0	-	-	100	-
Kumbakonam	8.30	58.3	33.3	-	66.6	33.3	-	-	100	-
Papanasam	28.6	50.0	21.4	-	78.6	21.4	-	-	100	-
Thiruvaiyaru	21.4	57.1	21.4	-	78.6	21.4	-	-	100	-
Ammapettai	28.6	57.1	14.3	-	78.6	21.4	-	-	78.6	21.4
Thanjavur	42.9	50.0	7.10	-	100	-	-	-	100	-
Budalur	14.3	57.1	28.6	-	78.6	21.4	-	-	92.9	7.20
Orathanadu	6.70	20.0	66.7	6.70	66.6	33.3	-	-	66.7	33.3

mild alkalinity. In contrast, blocks such as Thanjavur, Thiruppanandal and Ammapettai, located farther inland, display slightly acidic to neutral pH levels. These variations highlight the diverse soil conditions across the regions, with some areas requiring interventions to optimize soil health and crop productivity. To address the high pH problem in soils (>8.5), incorporating gypsum and reducing pH by replacing sodium ions with calcium ions and improving the soil structure is recommended. In addition, under chemical reaction, sulfur in gypsum turns into sulphuric acid, which helps reduce pH and neutrality. Organic amendments are recommended, as their decomposition releases organic acids that would reduce pH to neutralize alkalinity while improving soil structure. Further, proper drainage systems with good-quality irrigation water could reduce salt accumulation and maintain soil quality (19). Moreover, crop selection should align with soil pH conditions. Salt-tolerant crops such as cotton, maize, millets and sorghum are suitable crop choices in high-pH soils (20).

The electrical conductivity (EC) across various blocks reveals notable variations, with Sethubavachatram and Peravurani exhibiting very high EC values. This might be due to seawater intrusion contaminating groundwater with high salt concentrations. Salt sediments accumulate on the soil surface when water evaporates, raising EC. Conversely, blocks such as Thanjavur and Thiruppanandal registered low EC values, suggesting favourable conditions for general agricultural activities with minimal salinity-related challenges. Adopting salt-tolerant crops and using leaching techniques to eliminate excess salts from the soil profile are advised to control high EC levels (21) effectively.

Furthermore, adding organic mulch can enhance soil structure, decrease water evaporation and eventually lessen the accumulation of salts that induce soil salinity (22). The survey indicated that coconut is well-suited for these conditions due to its high salt tolerance (23). Traditional crops like paddy, banana and sugarcane can be grown successfully in regions with low EC and minimal salinity stress, supporting high agricultural productivity (24).

The exchangeable sodium levels across blocks reveal significant variation where blocks like Orathanadu, Sethubavachatram, Peravurani and Madukkur display higher exchangeable sodium concentrations, which pose a risk of sodicity and soil degradation. The higher sodium levels may result from irrigation with saline or poor-quality water. High exchangeable sodium concentrations can degrade soil structure, reduce water infiltration due to soil compaction and impair plant growth by causing nutrient imbalances or ion toxicity. High quantities of monovalent cations are known to break down the bindings between soil particles, leading to soil aggregates' dissolution. This highlights the relative percentage of sodium ions in the exchange complex, which is crucial (25). To mitigate high sodium, it is recommended to apply gypsum, which facilitates sodium displacement from soil exchange sites by replacing it with calcium ions and enhances soil permeability through soil aggregation (19). Additionally, deep tillage can improve soil aeration, allowing for better water infiltration and facilitating salt leaching (26, 20). In regions with high sodium concentrations, salt-tolerant crops such as sorghum, maize, barley, millet and cotton are suitable crop choices to ensure sustainable agricultural practices (27).

On the contrary, blocks like Thanjavur, Thiruppanandal and Thiruvidaimarudur exhibit low exchangeable sodium levels, indicating favourable conditions for diverse crop cultivation without the challenges of sodium-induced salinity stress. Low exchangeable potassium levels in blocks like Thiruppanandal and Thanjavur may restrict plant development and lower crop yields, potentially due to high clay content causing potassium fixation. Potash-based fertilizers should be applied specifically in regions with low potassium concentrations to restore soil potassium levels and ensure ideal crop growth (28). Growing crops like paddy, sugarcane and oilseeds in low-potassium locations is recommended bolstered by suitable potassium supplementation to get sustainable yields (29).

Sethubavachatram and Peravurani exhibit the highest exchangeable calcium concentrations. This may result from salt accumulation caused by seawater intrusion into groundwater or the overuse of fertilizers and amendments like gypsum. These factors can alter soil properties, such as cation exchange capacity and pH while contributing to water hardness (30). While these higher calcium levels could help in the flocculation of soil particles that improve soil structure, they also raise the risk of nutrient imbalances due to specific ion toxicity, particularly deficiencies in ions like magnesium and potassium (31). In contrast, blocks such as Thiruppanandal and Papanasam registered with the lowest calcium, potentially limiting plant growth as it helps in cell division, elongation and enzymatic activities, which get inhibited under deficiency. In addition, its deficiency in soil results in poor soil structure and limits soil fertility. Regular monitoring is necessary to detect and treat nutrient imbalances, especially magnesium and potassium, which can be counteracted by higher calcium levels (32). Gypsum treatment can improve the soil structure and calcium availability in regions with low calcium concentrations, improving crop yield and soil health (33). Sugarcane, coconut and groundnut are well-suited for areas with high calcium levels due to their adaptability to such conditions. To maximize calcium availability and guarantee sustainable agricultural practices, crops like rice, vegetables and legumes should be grown in low-calcium locations in addition to the proper soil amendments.

The assessment of exchangeable magnesium (Mg) levels across blocks reveals significant disparities. Coastal blocks such as Sethubavachatram and Peravurani exhibit the highest magnesium levels. This can lead to nutrient imbalances, such as reduced calcium and potassium availability and negatively affect plant nutrient uptake. Blocks like Thanjavur and Orathanadu show low magnesium concentrations, possibly due to high potassium or calcium. Magnesium deficiencies in crops, which can negatively affect photosynthesis, might result in stunted growth and chlorosis, affecting overall plant health. To balance the magnesium-to-calcium ratio and prevent possible nutrient antagonism, it is advised to employ calcium-based soil amendments, such as lime, to control high magnesium levels (34, 35). Dolomite lime is a valuable technique for increasing the amount of magnesium in low-magnesium soils and enhancing soil fertility, which ensures sufficient magnesium availability for plant growth. In areas with low magnesium, cultivating pulses, vegetables and fruits is recommended. It should be combined with appropriate soil amendments or management practices to replenish magnesium and sustain agricultural productivity (36).

Significant variation in exchangeable calcium levels across the blocks is indicated by the more extensive Inter Quartile Range (IQR) when comparing the levels of exchangeable calcium and exchangeable magnesium in the various blocks of Thanjavur (Fig. 9). Additionally, the existence of an outlier above the top whisker indicates that the exchangeable calcium concentration in one block (Sethubavachatram) is very high (14.27 Cmol (p^+) kg^{-1}. This might be due to localized factors like natural buildup, excessive calcium inputs, seawater intrusion, evaporation and deposition in the soil surface (33). The variations in the spatial distribution of exchangeable calcium could be attributed to variations in the soil's composition, farming methods, or block-specific environmental variables. The exchangeable magnesium concentration, on the other hand, shows more constant levels throughout the blocks with a smaller IQR and a lower mean of about 3.91 Cmol (p^+) kg^{-1}(Orathanadu). Unlike the calcium data, the exchangeable magnesium data shows no outliers, indicating a consistent magnesium availability across the study area. Due to this constancy, the blocks are less likely to experience exchangeable magnesium deficits, which lessens the need for focused interventions to address variability.

The parallel coordinate plot (Fig. 10) illustrates the spatial variability of soil parameters, including EC, pH and exchangeable cations (Ca, Mg, Na and K) across various blocks of Thanjavur. The data normalization (0-1 scale) offers insights into the patterns and connections between these vital soil health indicators by ensuring comparability among parameters. Sethubavachatram and Peravurani exhibit the highest EC (8.26 and 3.97 dS m^{-1}) among the blocks, indicating serious salinity issues. Quick solutions like gypsum application, leaching with high-quality irrigation water, or planting salt-tolerant crops are recommended to address this. Additionally, understanding the nature of the salinity and following the region's salinity characterization (Table 2) will aid in appropriate interventions. Conversely, Thiruvaiyaru regularly displays lower normalized values for all criteria, indicating low soil fertility that calls for thorough fertilizer management strategies. With reasonable levels in all metrics, blocks such as Thanjavur and Papanasam show balanced trends, suggesting stable soil conditions that may be sustained with consistent monitoring. Variability in potassium and sodium levels in Kumbakonam highlights regional imbalances that may be resolved with focused nutrient management. Salinity control and nutrient management are crucial concerns in Sethubavachattra and Peravurani because of their continuously low magnesium levels and relatively high sodium levels.

The scatter plot (Fig. 11) illustrates the strong positive relationship between pH (independent variable) and exchangeable sodium (dependent) across various sampling points in the Thanjavur district. The regression analysis shows a statistically significant *P-value* of less than 0.0001, indicating a strong connection. Moreover, with a regression coefficient of 11.586, the dependent variable (exchangeable sodium) rises by an average of 11.586 units for every unit increase in pH. The significance was confirmed by the high t-value (11.443) and very significant *P-value* (<0.0001), which support this strong positive connection. To analyze the relationship between pH and potassium content, the expected value of the dependent variable at pH zero is represented by the model's intercept, which is 5.675. With a *P-value* of less than 0.0001, this intercept is statistically significant. According to the regression coefficient, the dependent variable (exchangeable potassium) increases by an average of 1.159 units for every unit increase in pH. A high t-value (11.443) and a highly significant *P-value* (<0.0001) verify the dependability of the substantial positive

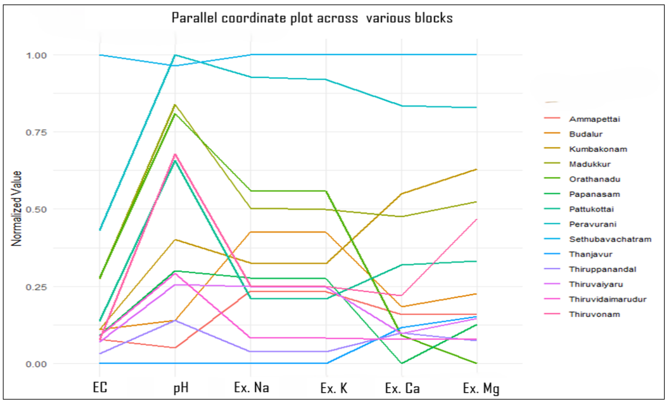

Fig. 10. Parallel coordinate plot depicts the trend of normalized values pH, EC (Electrical Conductivity), exchangeable Ca, Mg, Na and K across various blocks in Thanjavur district. Each line represents a block, with distinct colors corresponding to different blocks (R Software version 4.3.3).

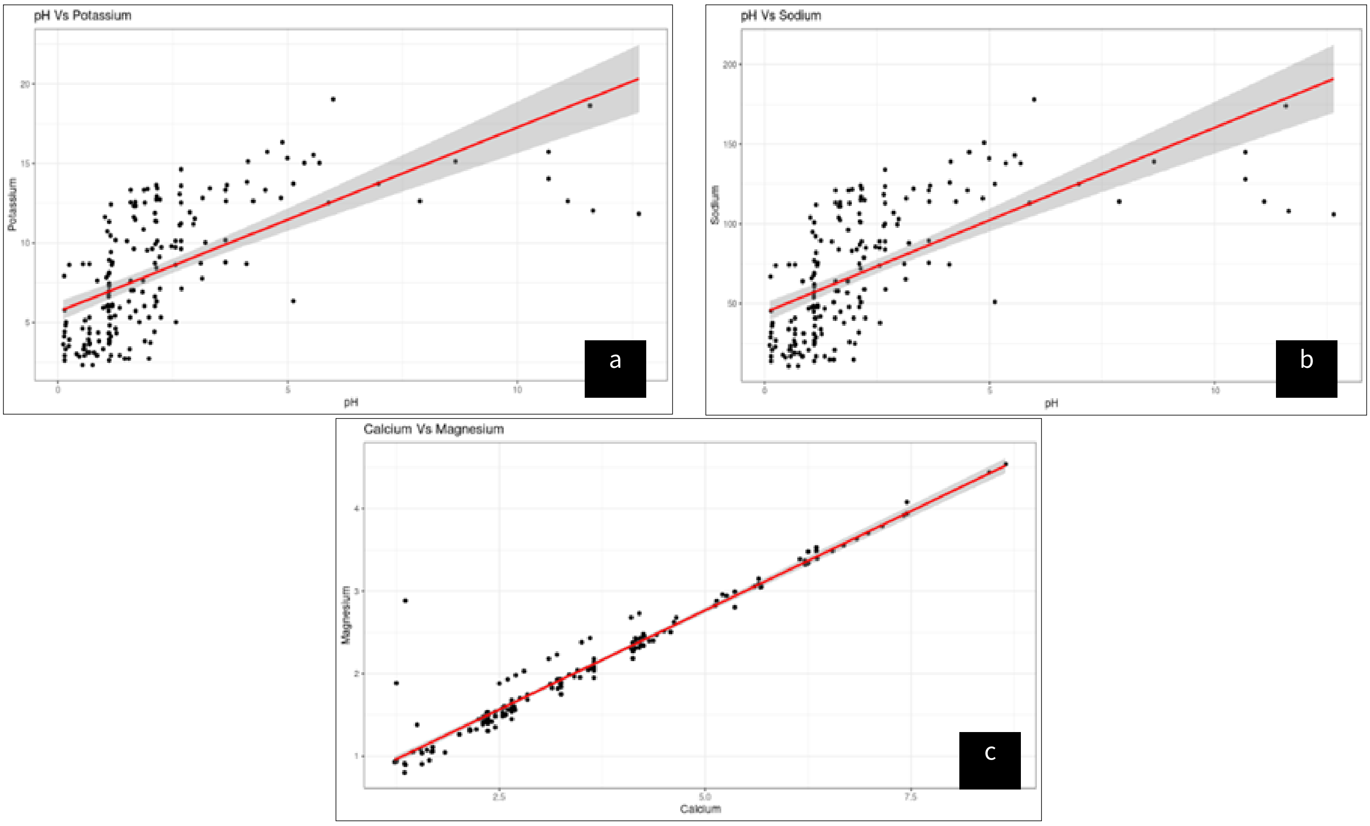

Fig. 11. Scatter plot with regression line depicting the relationship between (a) pH and exchangeable sodium content (b) pH and exchangeable potassium content (c) exchangeable calcium and magnesium content across different blocks of Thanjavur (GRAPES KAU).

connection between pH and potassium. The regression shows a strong positive correlation between calcium and magnesium across the sampling points in various blocks of Thanjavur. The expected value of the dependent variable, when calcium is zero, is represented by the intercept, which is 0.363. With a statistically significant *P-value* of less than 0.0001, this intercept does not result from chance. The dependent variable increases by an average of 0.481 units for every unit increase in calcium, according to the regression coefficient for calcium, which is 0.481. An extremely high t-value (55.710) and a highly significant *P-value* (<0.0001) support this strong positive connection, demonstrating the significance of calcium as a predictor in the model.

Conclusion

In conclusion, the geospatial analysis of soil properties for salinity characterization across various blocks in Thanjavur reveals significant variations in pH, EC and exchangeable cations viz., Ca, Mg, Na and K, each influencing agricultural productivity. High sodic-prone blocks like Orathanadu and saline-prone blocks such as Sethubavachatram and Peravurani require specific concern as they lie along coastal-line where immediate remediation with soil amendments (gypsum, organic matter) and salt-tolerant crops (sorghum, paddy, coconut) should be followed to mitigate alkalinity and salinity stress. Contrarily, certain blocks that fall with neutral to slightly acidic condition with balanced nutrients, like Thanjavur, offer favourable conditions for cultivating a wider range of crops with minimal restrictions on sustainable agricultural production. To maintain ideal nutrient ratios, it is essential to carry out focused soil interventions, such as modifying irrigation techniques (with good quality irrigation water), applying balanced fertilizer and choosing the right crop species. These specialized methods will successfully treat specific soil nutrient issues while enhancing soil health and fostering sustainable agricultural productivity.

Further thrusts

The study provides valuable insights into spatial distribution and soil salinity. Still, it has limitations, including geospatial resolution constraints, lack of seasonal and long-term data and exclusion of microbial influence and groundwater salinity impact. Socioeconomic factors and site-specific validation of management strategies are also missing. Future research should focus on dynamic soil monitoring, integrating microbial and organic amendments, precision agriculture and climate impact assessments. Comprehensive groundwater-soil management plans, farmer-centric advising systems and sustainable policy frameworks will help increase agricultural resilience in areas prone to salinity.

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Authors' contributions

SS carried out the experiment, work plan, methodology, analysis and observations, statistical analysis and wrote the draft manuscript; SM carried out work plan, conceptualization, methodology, supervision and coordinated the work; MB contributed by imposing the experiment, laboratory analysis, reviewing and editing; SK helped in editing, summarizing and revising the manuscript; CV editing, summarizing and revising the manuscript; TR helped in editing, summarizing and revising the manuscript.

Compliance with ethical standards

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