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RESEARCH ARTICLE

Soil fertility dynamics in the Northeastern agroclimatic zone of Tamil Nadu: a targeted analysis of Tiruvannamalai district

Suganthi Palanivel Koushika[1], Anbalagan Krishnaveni[2]*, Sellaperumal Pazhanivelan[3], Alagirisamy Bharani[1], Venugopal Arunkumar[2], Dhevagi Periyasamy[1] & Jayashree Ramaswamy[1]

[1]Department of Environmental Science, Tamil Nadu, Agricultural University, Coimbatore 641 003,Tamil Nadu, India

[2]Department of Crop Management, Tamil Nadu, Agricultural University, Vazhavachanur, Tiruvannamalai 606 753, Tamil Nadu, India

[3]Centre for Water and Geospatial Studies, Tamil Nadu, Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Email: krishnavenia@tnau.ac.in

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Abstract

Soil fertility degradation due to poor nutrient management is a growing concern in many farming areas. This study focuses on assessing the soil health of Tiruvannamalai district, Tamil Nadu, by examining key factors like pH, organic carbon (OC), electrical conductivity (EC) and the availability of essential nutrients (nitrogen, phosphorus, potassium) and micronutrients (zinc, iron, copper, manganese, boron). A systematic soil sampling method was employed, collecting 129 samples from 18 blocks using a 5 × 5 km grid at 0-15 cm depth. The results showed that the soils were primarily neutral to slightly alkaline, with pH values ranging from 7.15 to 7.41. Electrical conductivity was low (<0.26 dS/m), indicating minimal salinity. Organic carbon levels were also low, with more than half of the samples (53.06%) falling below optimal levels, ranging from 0.29% to 0.64%. The analysis revealed widespread nutrient deficiencies, with 65% of the soils low in nitrogen, 63.06% lacking phosphorus and 79.44% deficient in potassium. Additionally, significant micronutrient shortages were detected, with zinc (83.89%), iron (83.06%), copper (76.67%), manganese (88.89%) and boron (75.28%) all showing depletion. These results highlight the urgent need for improved soil management practices, including targeted fertilization and nutrient restoration efforts, to enhance soil fertility and ensure sustainable agricultural productivity in the region.

Keywords

available nutrients; mapping; nutrient index; organic carbon; soil fertility

Introduction

Soil is the primary medium for plant growth and its fertility is essential for sustainable farming (1). Fertile soil provides necessary nutrients, maintains good physical conditions and creates a healthy environment for plant growth, which is vital for achieving high crop yields and quality. This directly impacts food security and sustainable agriculture (2). Soil pH and electrical conductivity (EC) are important indicators of soil health and plant growth. Key nutrients such as nitrogen (N), phosphorus (P) and potassium (K) are crucial for plant health: nitrogen promotes leaf growth, phosphorus aids in root development and energy transfer and potassium enhances drought resistance and overall plant strength (3-5). Trace elements like iron, zinc and copper are crucial for various plant processes (6,7). Monitoring the availability of these nutrients allows farmers to use balanced fertilization methods, preventing deficiencies that could lower crop yields and quality (8). Organic carbon further enhances fertility by improving soil structure, water retention and nutrient-holding capacity and promoting beneficial microbial activity (9).

Soil surveys and testing are reliable for assessing soil fertility and developing balanced fertilizer management strategies to boost crop productivity and maintain soil health (10). Regular soil testing is crucial to identify nutrient imbalances and guide proper fertilization, ensuring that crops receive the right nutrients in the right amounts (11). Sustainable practices such as crop rotation, cover cropping and using organic materials can improve soil fertility over time, supporting long-term farming productivity and environmental health (12). Effective soil fertility management not only aids in food production but also promotes economic growth reduces poverty and ensures the sustainability of farming systems. This aligns with global efforts to achieve food security and protect the environment (13). The levels and distribution of micronutrients in soil are influenced by factors such as the original soil materials, organic matter content, pH levels, mineral content, soil formation processes, drainage, vegetation and both human activities and natural processes (14, 15). In Tamil Nadu, micronutrient levels are generally low due to intensive farming without replacing missing nutrients and limited use of organic manures (16). The Green Revolution significantly increased food production from 50.8 million tonnes in 1950 to 275.11 million in 2016-17 (17). Combining traditional knowledge with modern technologies like GPS and GIS can improve agricultural practices and ensure balanced nutrition (18). Understanding and incorporating the spatial variation of micronutrients is crucial for site-specific management, precision farming and sustainable agriculture (19). Poor soil management practices can harm soil quality and lead to the excessive use of chemical fertilizers and other pollutants. While chemical fertilizers might boost soil productivity in the short term, they can increase costs, create nutrient imbalances and cause environmental pollution. Analyzing the thresholds and applications of chemical fertilizers based on soil nutrient distribution is essential for efficiently using water and soil resources, determining plant needs and planning restoration programs. Accurate evaluation and creation of soil fertility maps are crucial.

Effective soil management is essential for boosting agricultural production, especially with the growing global population and the need to produce more food. Understanding the levels and patterns of soil properties is vital to creating effective, sustainable land management programs. Traditional methods for assessing soil fertility can be expensive and time-consuming. Therefore, many studies have been conducted to find better solutions for managing soil in ways that benefit agriculture and the environment (20). Creating large-area soil nutrient maps enhances our understanding of nutrient issues and their connections to climate, soil properties and genetics. Intermediate-scale maps help identify specific problem areas, while detailed maps for precision agriculture reveal the links between soil micronutrient content and availability.

In the Tiruvannamalai district of Tamil Nadu, India, a comprehensive soil resource inventory was conducted to evaluate electrical conductivity, pH, organic carbon and the availability of essential nutrients like nitrogen, phosphorus and potassium. Detailed fertility maps were created at the block level using GPS coordinates, providing valuable insights for better soil management and agricultural practices.

Materials and Methods

Tamil Nadu is divided into seven different farming zones. One is the northeastern zone, split into six areas, including the coastal and Northern plain. The Northern plain covers the districts of Thiruvallur, Vellore, Kancheepuram, Thiruvannamalai, Villupuram, parts of Cuddalore, Perambalur and Ariyalur. A significant part of the region is hilly, with many mountains and small hills. The Eastern Ghats, a range of hills including the Javadis, Shevaroys, Kalrayans, Pachamalais and Kollimalais, stretch between the Palar and Cauvery rivers and connect to the Nilgiri hills. The central plateau lies between the Eastern and Western Ghats, with the Palghat gap separating the Nilgiris from the Annamalai hills to the west. The Western Ghats include the highest mountains in southern India. The Nilgiris, located north of the Palghat Gap, covers an area of about 2950 square kilometres. Some backwaters are along the coast near Cuddalore, Marakkanam and Pichavaram. The main crops in this area are rice, millet, pulses, sugarcane and cashew. The region receives an average annual rainfall of 1039.8 mm. The weather patterns are as follows: Winter season (January-February): 31.3 mm and Summer (March-May): 102.9 mm. The district is divided into three revenue divisions: Tiruvannamalai, Arni and Cheyyar, with 12 taluks. It has 18 development blocks. It is located between 11°55' and 13°15' N latitude and 78°20' and 79°50' E longitude.

Agriculture is the main occupation, with about 56% of the population working in this sector. Tiruvannamalai is known for its rice production, especially from the Arni region, which is exported across Tamil Nadu, other parts of India and even abroad. The district also grows millets like Thinai, Samai and Varagu, along with Seetha and Jackfruit in the Jawadhu hills and banana plantations are common in the Padavedu region. The land is primarily used for cultivating paddy, groundnut, vegetables and sugarcane. The soil is mainly red loamy, with some areas having ferruginous loamy, sandy loamy and black series loam. The district receives significant rainfall during the southwest and northeast monsoon seasons.

A ground survey was conducted and geo-referenced soil samples were collected to map the distribution of soil micronutrient levels. Samples were randomly collected from agricultural land using a 5×5-kilometer grid. 129 samples, taken from 0-15 cm depth and marked with GPS coordinates, were gathered from eighteen blocks throughout the Tiruvannamalai district. The soil samples were air-dried, crushed using a wooden pestle and mortar and sieved through a 2-mm mesh (0.2 mm mesh for organic carbon). Each sample was labelled and stored correctly. These samples underwent analysis for 12 chemical parameters, which included pH and electrical conductivity (EC); organic carbon; available nitrogen (N), phosphorus (P), potassium (K); available micronutrients like zinc (Zn), iron (Fe), copper (Cu), manganese (Mn) and boron (B) (22-25). The analytical results of each soil sample were categorized as low, medium and high for organic carbon and macronutrients and as deficient, moderate and sufficient for available sulfur and micronutrients based on the critical limits used in Tamil Nadu.

The percentage of samples in each category and the nutrient index values (NIV) were calculated using the following formula given as equation 1.

$$\text{Percent sample category} = \frac{\text{Number of samples in the low or medium or high category}}{\text{Total number of samples}} \times 100 \quad \text{(Eqn. 1)}$$

$$\text{Nutrient index value (NIV)} = \frac{(P_H \times 3) + (P_M \times 2) + (P_L \times 1)}{100} \quad \text{(Eqn. 2)}$$

In equation 2, P_L, P_M and P_H represent the percentage of soil samples falling in the low, medium and high nutrient status categories, weighing one, two and three, respectively (26). The index values are rated into various categories: low (<1.67), medium (1.67-2.33) and high (>2.33) for organic carbon and available N, P and K; and very low (<1.33), low (1.33-1.66), marginal (1.66-2.00), adequate (2.00-2.33), high (2.33-2.66) and very high (>2.66) for available micronutrients (27). Ordinary kriging, a statistical analysis method, was used to estimate soil properties across the district. Kriging considers spatial relationships between sample points to predict values at unmeasured locations. Each block's micronutrient deficiency degree was calculated and presented as a percentage. Thematic maps showing the levels of different available micronutrients were then created using ArcGIS (28).

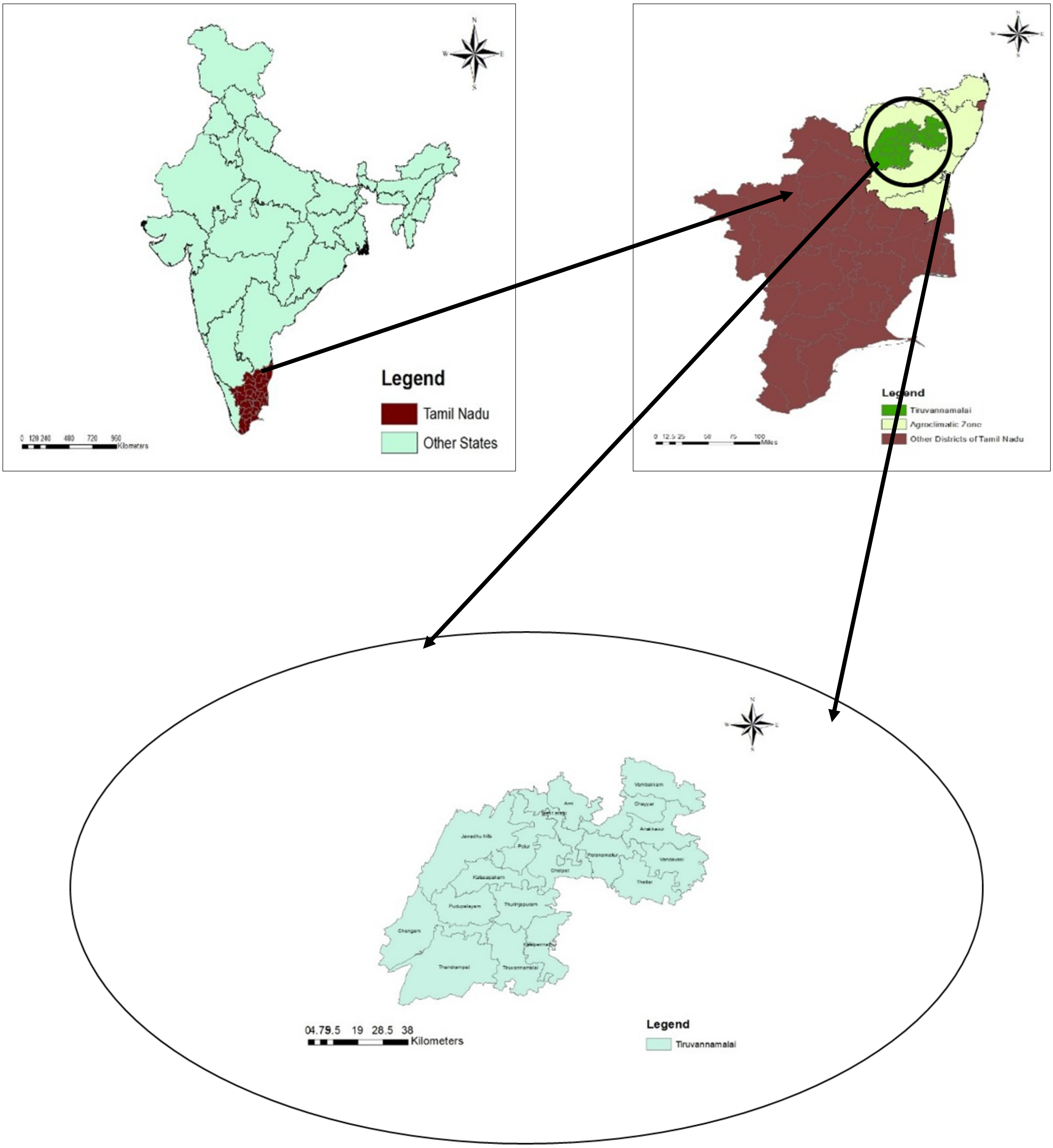

Fig. 1. Study area map.

Results and Discussion

This study aims to evaluate soil's chemical properties, available nitrogen, phosphorus, potassium and micronutrient levels and the overall fertility status in the Tiruvannamalai district in the North Western zone of Tamil Nadu. The study also seeks to create thematic maps to represent these findings visually. The soil analysis from various blocks in the Tiruvannamalai district reveals significant insights into soil fertility parameters.

Soil chemical properties

The pH values range from 7.15 to 7.41, indicating that the soils are predominantly neutral to slightly alkaline. This range is comparatively similar to Krishnagiri (7.28 to 8.15) and somewhat lower than the highly alkaline soils in Salem (5.09 to 9.51) and Tiruchirappalli (7.63 to 10.17) (29,30). The Electrical Conductivity (EC) values are consistently low, all below 0.26 Ds/m, suggesting minimal salinity issues, matching the non-saline classification found in both Salem (mean EC 0.31 dS/m) and Krishnagiri (0.02 to 0.17 dS/m) (31) as well as Tiruchirappalli (0.16 to 0.72 dS/m) (30). This suggests that salinity is not a significant concern in these districts.

Organic Carbon (OC) content varies between 0.29% and 0.64%, which points to a low to moderate presence of organic matter in the soil, which is lower compared to the moderate OC content of Krishnagiri soils (mean 0.41%) (31). However, the organic carbon content in Salem is slightly higher, with mean values reaching up to 0.60% (29), while Tiruchirappalli reports low to medium OC content, similar to Tiruvannamalai (30). The lower OC levels in Tiruvannamalai may reflect reduced organic matter input and rapid decomposition, a consistent challenge across these districts. Fig. 2. represents the spatial distribution of available organic carbon across the district.

Nutrient levels

As mentioned in Table 1, the nitrogen levels span from 154.35 to 194.61 kg/ha, highlighting moderate nitrogen availability across the blocks. Tiruchirappalli district soils have very low available nitrogen, ranging from 162.8 to 229.9 kg/ha (30). Similarly, Salem soils exhibit low nitrogen levels, with 92.5% of samples classified as low, with an overall mean of 200 kg/ha (29). Krishnagiri district shows slightly better results, with nitrogen values ranging from 143 to 312 kg/ha but with a mean of 238 kg/ha (31). Thus, while Tiruvannamalai is moderate in nitrogen, it still falls within the low -to-moderate range of other districts. Fig. 3. displays the levels of available nitrogen in the soil samples.

Phosphorus content shows variability, ranging from 24.65 to 33.90 kg/ha, indicating differences in available phosphorus. In Tiruchirappalli, available phosphorus is in the medium-to-high range, between 11.95 and 32.85 kg/ha (30).

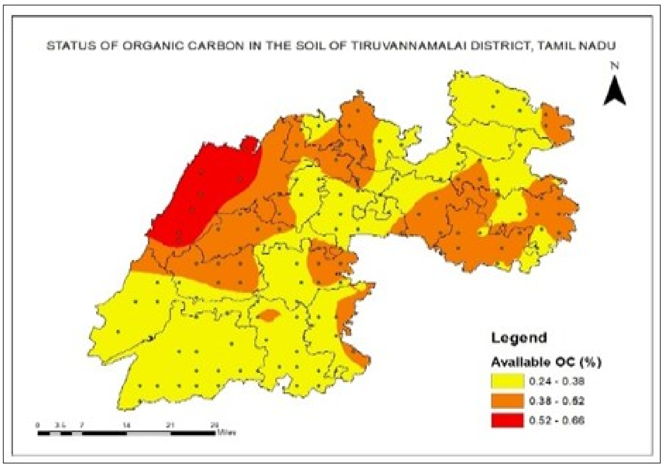

Fig. 2. Available organic carbon.

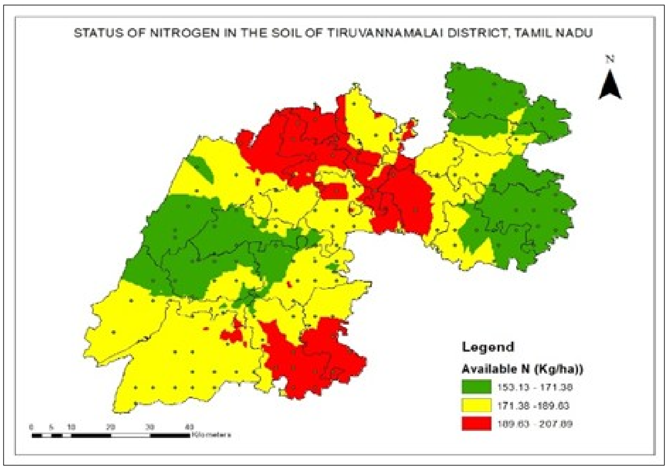

Fig. 3. Available nitrogen.

Table 1. Mean values of EC, pH, available organic carbon, nitrogen, phosphorous and potassium in different blocks of Tiruvannamalai districts.

Blocks	pH	EC (dS/m)	OC (%)	N (Kg/ha)	P (Kg/ha)	K (Kg/ha)
Anakkavur	7.38	0.22	0.34	**174.26**	**29.81**	**169.52**
Arni	7.28	0.14	0.37	161.78	27.20	174.60
Chengam	7.35	0.16	0.31	176.75	32.85	188.20
Chetpet	7.32	0.15	0.32	189.56	29.00	169.90
Cheyyar	7.19	0.19	0.34	191.46	33.30	179.10
Jawadhu hills	7.23	0.26	0.64	165.84	24.65	163.80
Kalasapakam	7.29	0.19	0.34	186.89	32.65	167.15
Keelpennathur	7.41	0.14	0.31	180.66	26.90	160.55
Peranamallur	7.33	0.15	0.37	187.08	27.65	170.70
Polur	7.32	0.15	0.33	179.92	28.15	210.55
Pudupalayam	7.28	0.12	0.38	159.95	25.45	166.15
Thandrampet	7.27	0.17	0.34	174.42	30.52	183.35
Thellar	7.15	0.14	0.39	168.88	26.05	182.30
Thurinjapuram	7.39	0.13	0.33	171.66	26.60	167.65
Tiruvannamalai	7.28	0.13	0.29	194.61	26.20	197.85
Vandavasi	7.24	0.15	0.38	154.35	25.85	203.65
Vembakkam	7.40	0.15	0.30	160.99	33.90	165.55
West arani	7.34	0.16	0.32	191.17	29.25	163.00
Total	131.45	3.05	6.39	3170.19	515.98	3183.57

Salem district also has moderate to high phosphorus levels, with a mean of 20.65 kg/ha, while Krishnagiri shows a high phosphorus status, ranging from 10.4 to 51.6 kg/ha (29,31). Thus, Tiruvannamalai falls within the medium range, indicating that some blocks could benefit from phosphorus supplementation. Fig. 4. illustrates the distribution of available phosphorus in different blocks.

Potassium levels are also varied, with values between 160.55 and 210.55 kg/ha, reflecting a range of potassium availability in the Tiruvannamalai district. Tiruchirappalli soils are generally medium to high in potassium, ranging from 155.4 to 362.9 kg/ha(30). Salem district reports potassium levels ranging from 75 to 599 kg/ha, but most soils are in the medium category (29). In Krishnagiri, potassium content varies from 108 to 301 kg/ha, generally falling into the medium category (31). Thus, Tiruvannamalai's potassium levels align with the medium status observed in other districts, though some blocks may require attention. Fig. 5. shows the spatial variation in available potassium across the district. Overall data suggest that while there are areas with adequate fertility, certain blocks may require targeted interventions to optimize soil health and productivity.

Micronutrient analysis

The micronutrient analysis of soil samples from various blocks in the Tiruvannamalai district reveals considerable variability in the availability of essential nutrients. In Table 2, DTPA-extractable zinc (Zn) concentrations range from 0.49 to 1.16 mg/kg, with an overall total of 13.47 mg/kg, indicating differing zinc levels across the blocks. Trichy soils have adequate zinc levels, while Salem soils show a broader range from 0.01 to 8.77 mg/kg, with a mean of 0.90 mg/kg (29). Tiruvannamalais' zinc levels are similar to Salem's, suggesting sufficient availability, though monitoring for deficiencies is essential. Fig. 6. indicates the levels of available zinc in the soil samples. Iron (Fe) levels, measured as DTPA-extractable Fe, range from 4.67 to 6.32 mg/kg, totalling 101.80 mg/kg, suggesting a generally adequate iron availability. Salem displays a much broader range of 0.42 to 44 mg/kg, with a mean of 13.29 mg/kg (29). Tiruvannamalais' lower iron levels than Salem may necessitate additional iron applications for crops with high iron requirements. Fig. 7. represents the distribution of available iron in the soils. Copper (Cu) content varies between 0.57 and 1.12 mg/kg, amounting to 14.33 mg/kg, indicating moderate variability in copper levels. Salem ranges from 0.04 to 8.14 mg/kg, averaging 2.01 mg/kg (29). The copper levels in Tiruvannamalai are lower than those in Salem, suggesting that copper supplementation could be necessary to maintain optimal crop health. Fig. 8. displays the levels of available copper in different areas.

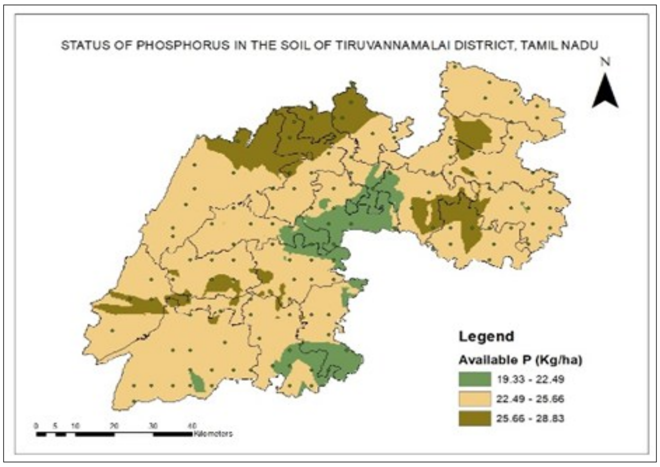

Fig. 4. Available phosphorus.

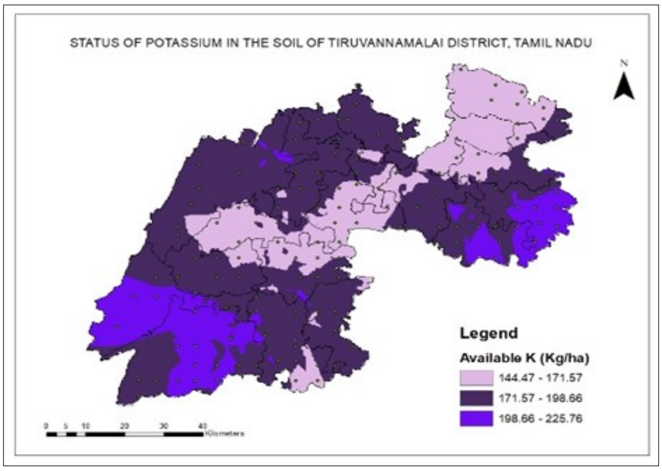

Fig. 5. Available potassium.

Table 2. Mean values of Available micronutrients in different blocks of Tiruvannamalai district

Blocks	DTPA - Zn	DTPA - Fe	DTPA - Cu	DTPA - Mn	DTPA - B
Anakkavur	0.92	5.74	0.74	1.90	0.72
Arni	1.01	6.14	1.12	1.64	0.68
Chengam	0.71	5.74	0.63	2.26	0.66
Chetpet	0.62	5.81	0.67	1.29	0.47
Cheyyar	0.90	5.61	0.57	1.79	0.65
Jawadhu hills	0.95	5.45	0.84	2.28	0.49
Kalasapakam	0.78	5.75	0.63	1.84	0.56
Keelpennathur	0.58	5.38	1.12	1.49	0.56
Peranamallur	0.67	4.67	0.63	2.12	0.59
Polur	1.16	5.17	0.78	1.12	0.44
Pudupalayam	0.60	5.36	1.08	1.59	0.46
Thandrampet	0.78	5.87	0.69	1.95	0.78
Thellar	0.52	6.32	0.82	1.26	0.35
Thurinjapuram	0.59	5.59	0.89	1.35	0.59
Tiruvannamalai	0.61	6.02	0.90	0.95	0.45
Vandavasi	0.49	6.25	0.78	0.85	0.39
Vembakkam	0.76	5.20	0.70	1.79	0.60
West arani	0.85	5.72	0.74	1.88	0.78
Total	13.47	101.80	14.33	29.33	10.22

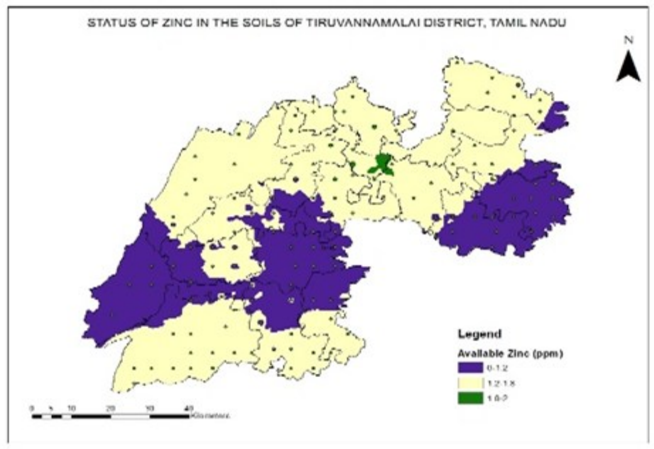

Fig. 6. Available zinc.

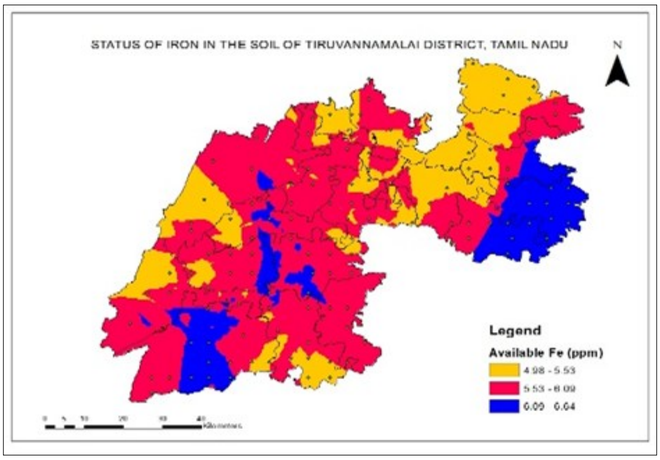

Fig. 7. Available iron.

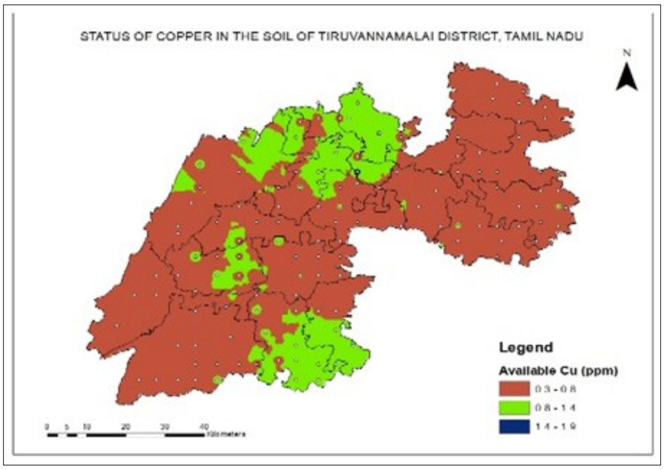

Fig. 8. Available copper.

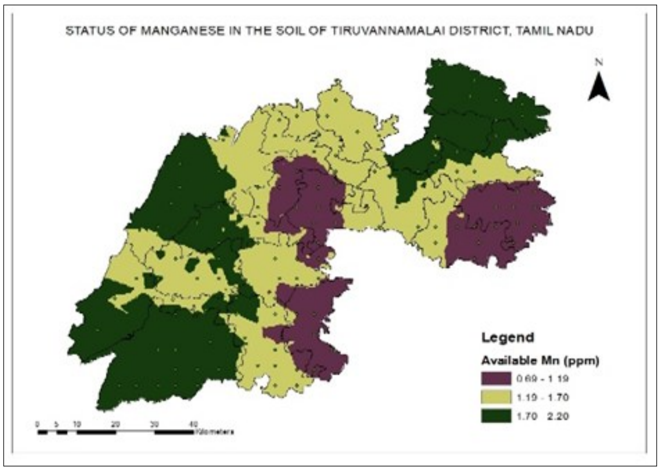

Fig. 9. Available manganese.

Manganese (Mn) levels, extracted as DTPA-Mn, range from 0.85 to 2.28 mg/kg, with an overall total of 29.33 mg/kg, reflecting differences in manganese availability. Salem has a much higher range of 0.50 to 75.2 mg/kg, with a mean of 16.78 mg/kg (29). Tiruvannamalai's lower manganese levels than Salem's highlight the need for careful monitoring to prevent deficiencies. Fig. 9. illustrates manganese variation across the district. Boron (B) levels range from 0.35 to 0.78 mg/kg, totalling 10.22 mg/kg, showing that boron availability is generally lower than other micronutrients. Salem ranges from 0.01 to 4.0 mg/kg, with a mean of 1.10 mg/kg (29). While adequate, the boron levels in Tiruvannamalai may require periodic assessment and management, particularly for crops sensitive to boron deficiency. Fig. 10. shows the spread of boron in the soil. This comprehensive analysis highlights the variability in micronutrient levels across the blocks. This can inform targeted soil management and fertilization practices to address specific nutrient deficiencies and enhance overall soil fertility.

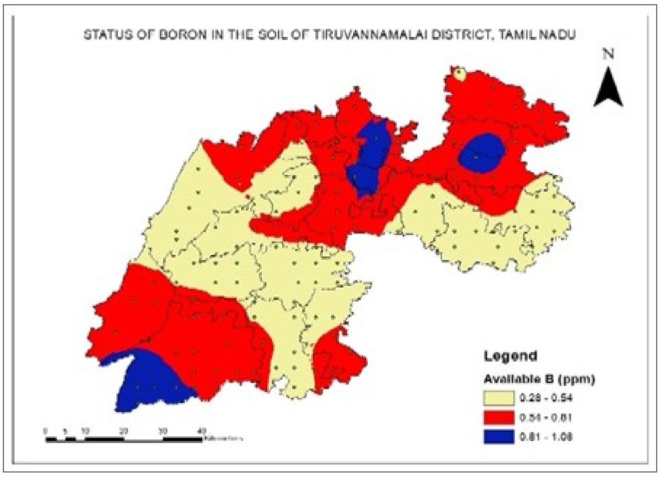

Fig. 10. Available boron.

Soil fertility assessment

In Table 3, the fertility assessment of 129 soil samples from the Tiruvannamalai district indicates a generally low fertility status across various nutrients. Organic Carbon (OC) levels are predominantly low, with 53.06% of samples falling into the low category, 34.17% in the medium category and only 12.78% in the high category, resulting in a nutrient index value 1.60. Comparatively, in the Chithamur block of Kanchipuram district, 76.84% of samples are categorized as low, 19.03% as medium and 4.13% as high, resulting in a nutrient index 1.27 (32). In Achyutadaspur village, Odisha, 79.2% of samples fall in the low category and 20.8% in the medium category (33). In Kelapur block, Maharashtra, organic carbon shows a higher fertility rate, with only 11.8% of samples being low, 28.2% medium and 60.0% high, leading to a nutrient index of 2.48 (34). Nitrogen (N) is similarly deficient, with 65.00% of samples categorized as low, 29.44% as medium and 5.56% as high, leading to a nutrient index value of 1.41. Chithamur block exhibits even lower nitrogen availability, where 83.78% of samples are low, 10.77% medium and 5.46% high, giving a nutrient index value of 1.22 (32). Achyutadaspur shows that 96% of the area is low in nitrogen and 4% medium (33), while Kelapur records 100% nitrogen deficiency across all samples, resulting in a nutrient index of 1.00 (34).

Table 3. Nutrient Status and Fertility Rating Based on Nutrient Index Values in the soils of Tiruvannamalai district

Parameters	Percent sample category of Tiruvannamalai district (Total no. of samples - 129)			Nutrient index value	Fertility rating
	Low	Medium	High		
OC (%)	53.06	34.17	12.78	1.60	Low
N (Kg/ha)	65.00	29.44	5.56	1.41	Low
P (Kg/ha)	63.06	33.61	3.33	1.40	Low
K (Kg/ha)	79.44	12.78	7.78	1.28	Low
ZN (mg/Kg)	83.89	8.61	7.50	1.24	Low
FE (mg/Kg)	83.06	8.89	8.06	1.25	Low
CU (mg/Kg)	76.67	16.94	6.39	1.30	Low
MN (mg/Kg)	88.89	5.83	5.28	1.16	Low
B (mg/Kg)	75.28	21.11	3.61	1.28	Low

Phosphorus (P) follows this trend, with 63.06% of samples in the low category, 33.61% in the medium category and 3.33% in the high category, giving a nutrient index value of 1.40. Chithamur block reveals a divided result where phosphorus in acidic soils is low (78.10%) but high in alkaline soils, with a nutrient index value of 2.65 (32). In Achyutadaspur, phosphorus is medium in 82.4% of samples and high in 17.6% (33), while in Kelapur, phosphorus is low in 37.6% of samples, medium in 35.9% and high in 26.5%, resulting in a nutrient index of 1.89 (34). Potassium (K) is critically low in 79.44% of samples, medium in 12.78% and high in 7.78%, with a nutrient index value 1.28. In Chithamur, potassium is similarly deficient, with 98.53% of samples classified as low and only 1.33% high, with a nutrient index of 1.03 (32). In Achyutadaspur, 27.2% of samples show low potassium, 64% medium and 8.8% high (33), whereas Kelapur has abundant potassium, with 87.3% of samples being high, 11.7% medium and only 1.0% low, giving a nutrient index of 2.86 (34). The nutrient analysis reveals that zinc (Zn) is low in 83.89% of samples, medium in 8.61% and high in 7.50%, with a nutrient index value of 1.24. Comparatively, in Achyutadaspur, 79.2% of the area is low in zinc, while 20.8% is medium (33). Kelapur reports zinc deficiency in 69.9% of samples, with 30.1% being sufficient (34). Iron (Fe) levels are low in 83.06% of samples, medium in 8.89% and high in 8.06%, yielding a nutrient index value 1.25. Comparatively, in Kelapur block, 27.9% of samples are deficient in iron, while 72.1% are sufficient (34). Copper (Cu) is low in 76.67% of samples, medium in 16.94% and high in 6.39%, with a nutrient index value 1.30. In Kelapur, copper is sufficient in 99.9% of samples, with only 0.1% showing deficiency(34). Manganese (Mn) is low in 88.89% of samples, medium in 5.83% and high in 5.28%, resulting in a nutrient index value 1.16. In Kelapur, manganese levels are sufficient in 99.5% of samples, with only 0.5% showing deficiency (34). Boron (B) levels are low in 75.28% of samples, medium in 21.11% and high in 3.61%, with a nutrient index value of 1.28. Comparatively, in Achyutadaspur, boron is deficient in 92.6% of the area and only 7.4% of samples are in the medium category (33).

Tiruvannamalai district has significant nutrient deficiencies, particularly in nitrogen, potassium and essential micronutrients like zinc, iron and manganese. In contrast, Chithamur shows similar deficiencies but has higher phosphorus levels in alkaline soils. Achyutadaspur and Kelapur also reflect these patterns, with Achyutadaspur showing severe shortages in nitrogen and boron. Meanwhile, Kelapur has better potassium and micronutrient levels like copper and manganese but still struggles with nitrogen and zinc deficiencies.

Descriptive statistics

Electrical conductivity: The soil samples from the Tiruvannamalai district have an average EC value of 0.1628 dS/m, indicating low salinity, which is good for plant growth, as shown in Table 4. The EC values are quite consistent, with only small variations, as demonstrated by the low standard deviation (0.0754) and standard error (0.0066). The data is strongly skewed to the right (skewness of 3.4906), meaning most samples have EC values lower than the average, with a few higher values affecting the mean. The high kurtosis (17.9348) suggests extreme EC values are more common than usual. The EC values range from 0.08 to 0.67 dS/m, with most values being on the lower side, as indicated by the median value of 0.14 dS/m.

pH: As mentioned in Table 4, the average pH of the soils in this district is 7.3732, which is neutral to slightly alkaline and generally suitable for most crops. The pH values are relatively stable, with a low standard deviation (0.3215) and standard error (0.0282). The slight positive skew (skewness of 0.8574) suggests more samples with pH values slightly above the average. The kurtosis of 5.6448 indicates that most pH values are concentrated around the average, with some outliers. The pH values range from 6.11 (slightly acidic) to 8.9 (moderately alkaline), with the median at 7.34, showing that most soils are near neutral.

Available OC: The soil's average organic carbon content is 0.4188%, indicating a moderate level of organic matter, which is crucial for soil fertility. The variation in organic carbon levels is not too wide, as reflected by the standard deviation (0.0997) and standard error (0.0087) in Table 4. The data has a moderate positive skew (skewness of 0.8168), meaning more samples have lower organic carbon content, with fewer having higher levels.

Table 4. Descriptive statistics of EC, pH and Available OC

	EC	pH	Available OC
Mean	0.16	7.37	0.41
Standard Error	0.006	0.02	0.008
Median	0.14	7.34	0.41
Mode	0.12	7.3	0.45
Standard Deviation	0.07	0.32	0.09
Sample Variance	0.0056	0.10	0.009
Kurtosis	17.93	5.64	1.68
Skewness	3.49	0.85	0.81
Range	0.59	2.79	0.58
Minimum	0.08	6.11	0.13
Maximum	0.67	8.9	0.71
Sum	21.17	958.51	54.45
Count	129	129	129
Largest (1)	0.67	8.9	0.71
Smallest (1)	0.08	6.11	0.13
Confidence Level (95.0%)	0.013	0.05	0.017

The kurtosis of 1.6832 suggests a broader range of values than normal. The organic carbon content ranges from 0.13% to 0.71%, with most soils having levels close to the median value of 0.41%, essential for maintaining soil health.

***Available N*:** Table 5 shows that the soil samples have an average nitrogen content of 178.43 kg/ha, a moderate level needed for plant growth. The standard deviation of 35.94 kg/ha means some variation in nitrogen levels among the samples. The data is slightly negatively skewed, meaning more samples have nitrogen levels above the average. The kurtosis value indicates that the nitrogen distribution is close to normal, ranging from 58.8 to 270.3 kg/ha and a median of 182.05 kg/ha.

***Available P* :** The average phosphorus content in the soil is 28.81 kg/ha, as shown in Table 5, which is a moderate level essential for root development. The 8.88 kg/ha standard deviation suggests that phosphorus levels vary moderately among the samples. The data has a slight positive skew, meaning most samples have phosphorus levels below average. The negative kurtosis value indicates a flatter distribution, with phosphorus levels ranging from 7 to 51 kg/ha and a median of 28.5 kg/ha.

***Available K* :** According to Table 5, the average potassium content is 28.87 kg/ha, a moderate level necessary for plant health. The standard deviation of 8.86 kg/ha shows that potassium levels have a moderate spread among the samples. The data is slightly positively skewed, meaning more samples have potassium levels below average. The negative kurtosis suggests a slightly flatter distribution, with potassium levels ranging from 7 to 51 kg/ha and a median of 29 kg/ha.

***Available S* :** Table 6 indicates that the average sulfur content is 12.17 ppm, which is important for plant protein synthesis. The standard deviation of 4.91 ppm shows significant variation in sulfur levels across the samples. The positive skewness suggests that most samples have sulfur levels below the average, ranging from 6 to 24.18 ppm and a median of 11.34 ppm.

***Available Zn* :** Table 6 shows that the average zinc content is 0.76 ppm, a micronutrient crucial for plant enzyme activation. The standard deviation of 0.46 ppm indicates moderate variability in zinc levels. The data has a strong positive skew, meaning most samples have zinc levels below the average, ranging from 0.12 to 2.82 ppm and a median of 0.65 ppm.

***Available Fe* :** The average iron content is 5.89 ppm, as detailed in Table 6, essential for plant chlorophyll synthesis. The standard deviation of 1.76 ppm suggests some variation in iron levels. The data is highly positively skewed, meaning most samples have lower iron levels with a few very high values. Iron levels range from 0.35 to 17.68 ppm, with a median of 5.77 ppm.

Table 5. Descriptive statistics of Available N, P and K

	Available N	Available P	Available K
Mean	178.43	28.81	28.86
Standard Error	3.15	0.77	0.77
Median	182.05	28.5	29
Mode	120	25	25
Standard Deviation	35.94	8.87	8.86
Sample Variance	1291.74	78.79	78.58
Kurtosis	0.43	-0.31	-0.32
Skewness	-0.41	0.15	0.13
Range	211.5	44	44
Minimum	58.8	7	7
Maximum	270.3	51	51
Sum	23196.2	3745.4	3781.4
Count	129	129	129
Largest (1)	270.3	51	51
Smallest (1)	58.8	7	7
Confidence Level (95.0%)	6.23	1.54	1.53

***Available Cu*:** According to Table 6, the average copper content is 0.83 ppm, which is necessary for photosynthesis and respiration in plants. The standard deviation of 0.48 ppm shows some variability in copper levels. The data has an extreme positive skew, meaning most samples have lower copper levels, with a few higher values skewing the average. Copper levels range from 0.31 to 4.53 ppm, with a median of 0.74 ppm

***Available Mn*:** Table 6 shows that the average manganese content is 1.56 ppm, essential for photosynthesis and nitrogen metabolism. The standard deviation of 0.76 ppm indicates moderate variability in manganese levels. The data is almost symmetric, with manganese levels ranging from 0.12 to 4.13 ppm and a median of 1.63 ppm.

***Available B*:** According to Table 6, the average boron content is 0.60 ppm, important for plant cell wall formation. The standard deviation of 0.39 ppm indicates moderate variability in boron levels. The data is strongly positively skewed, meaning most samples have lower boron levels with a few higher values. Boron levels range from 0.21 to 2.69 ppm, with a median of 0.49 ppm.

Table 6. Descriptive statistics on Available S, Zn, Fe, Cu, Mn and B

	Available S	Available Zn	Available Fe	Available Cu	Available Mn	Available B
Mean	12.17	0.76	5.89	0.82	1.56	0.60
Standard Error	0.42	0.04	0.15	0.04	0.06	0.03
Median	11.34	0.65	5.77	0.74	1.63	0.49
Mode	6.5	0.58	7.2	0.82	1.85	0.34
S D	4.91	0.46	1.76	0.48	0.75	0.39
Sample Variance	24.12	0.21	3.10	0.23	0.57	0.15
Kurtosis	-0.23	4.78	17.89	29.30	0.02	6.98
Skewness	0.72	1.92	2.72	4.53	-0.05	2.20
Range	18.18	2.7	17.33	4.22	4.01	2.48
Minimum	6	0.12	0.35	0.31	0.12	0.21
Maximum	24.18	2.82	17.68	4.53	4.13	2.69
Sum	1594.35	99.87	771.9	108.7	204.46	79.09
Count	129	129	129	129	129	129
Largest (1)	24.18	2.82	17.68	4.53	4.13	2.69
Smallest (1)	6	0.12	0.35	0.31	0.12	0.21
Confidence Level (95.0%)	0.84	0.08	0.30	0.08	0.13	0.06

Conclusion

The soil in Tiruvannamalai district shows a mix of neutral to slightly alkaline pH levels, with low electrical conductivity indicating minimal salinity issues. However, organic carbon content is low to moderate, reflecting limited organic matter in the soil. Nutrient levels, including nitrogen, phosphorus and potassium, vary across the district, with some areas having adequate levels while others fall short. Micronutrient analysis reveals significant variability, with many samples showing low levels of essential nutrients like zinc, iron, copper, manganese and boron. These deficiencies suggest that the overall soil fertility is low, which could impact agricultural productivity.

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Authors' contributions

SPK conducted the fieldwork, performed the soil analysis, interpreted the data and drafted the manuscript. AK conceived the study, coordinated the research and provided critical revisions to the manuscript. SP contributed to the statistical analysis and participated in the study design. AB assisted with data collection and performed laboratory analysis. VA supported the data interpretation and manuscript review. DP contributed to the preparation of GIS maps and data visualization. JR participated in the literature review and manuscript editing. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no competing interests related to this research.

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