SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V13I4P118

Volume 13 Issue 4, 155-165, April 2026

Original Article

Effects of Level-III Land Use/Land Cover on Spatial Distribution of Soil Chemical Properties and Soil Quality Index in a High-Rainfall Area in the Western Ghats, India

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Received: 14 January 2026 Revised: 15 February 2026 Accepted: 20 March 2026 Published: 28 April 2026

Abstract - *In humid tropical areas, the chemical properties of the soil depend much on the rainfall, changes in the land's shape, and biogeochemical processes. The current study represents the influence of Level-III Land Use and Land Cover (LULC) classes on the spatial variability of significant soil chemical properties in Puttur Taluk, situated on the eastern slopes of the Western Ghats in Karnataka, India. A total of 145 georeferenced soil samples (0-20 cm depth) were obtained from agricultural lands, forested regions, plantations, and habitation regions. The soil samples were analyzed for pH, Electrical Conductivity (EC), Organic Carbon (OC), Nitrogen (N), Phosphorus (P), Potassium (K), and Sulphur (S) contents. The spatial variability of soil chemical properties was presented using the Inverse Distance Weighted (IDW) interpolation technique in a GIS environment. Analysed data reveals that the soils are typically acidic in nature, with pH values ranging from 4.66 to 6.82. Even though there are some areas of high salinity, particularly in some of the plantation areas and settlements, the EC levels indicate that the soils are non-saline in general. The analysis of macronutrients depicted that there was a lot of variation in the macronutrient analysis results, which could be explained by both the inherent characteristics of the soil and variations in land use practices. Organic carbon and nitrogen levels were higher in mixed vegetation areas and forested areas and lower in agricultural and plantation areas. The Soil Quality Index (SQI) was determined using organic carbon, nitrogen, phosphorus, potassium, and sulphur, which showed that most of the villages had moderate fertility, according to the SQI values: 1.6-2.5. These soils are considered useful for agricultural purposes, provided there is balanced nutrient management, with special emphasis on phosphorus and potassium nutrition. The distribution of nutrients was balanced, and the soil pH was favorable in areas with high SQI values, including Bellipadi, Puttur, Kabaka, Kudippadi, and the surrounding forested areas. Lower SQI values appeared in areas such as parts of Munduru, Kuriya, and nearby degraded forest regions. This suggests a need for nutrient management and soil restoration. The results essentially emphasize the need for assessing soil fertility at the village level and the requirement for site-specific soil management practices for sustainable soil health in the Puttur taluk region.*

Keywords - *Western Ghats, Soil Quality Index (SQI), Soil Chemical Properties, Land Use/Land Cover*.

1. Introduction

Among the most important natural resources underpinning food production, ecological stability, and responsible land management, soil occupies a central position, particularly across tropical topography where steep gradients and intense rainfall drive complex pedological dynamics (FAO, 1976; Arnold et al., 1998; Lal, 2004). How land is used and how vegetation cover changes over time exerts considerable influence over key soil chemical indicators among them pH, Electrical Conductivity (EC), Organic Carbon (OC), and macro-nutrients through the interaction of plant communities, management authorities, and biogeochemical cycling (Jenny, 1980; Brady & Weil, 2008; Feller & Beare, 1997; Tiessen et al., 1994). When land-use changes occur, the resulting disturbance to vegetation structure, tillage systems, and nutrient rejuvenation can progressively erode soil fertility and increase susceptibility to degradation through nutrient depletion, erosion, and the loss of organic matter (Lal, 2001; Montgomery, 2007; Rakshit et al., 2021). Low soil fertility frequently increases land's vulnerability to degradation, including nutrient depletion, erosion, and loss of organic matter, which are significantly affected by changes in vegetation cover, cropping systems, and management practices (Lal, 2001; Montgomery, 2007;

Rakshit et al., 2021). Extensive prior research has reported the connection between land use and soil chemical quality in tropical regions, revealing significant differences in nutrient availability and organic matter pools across contrasting land-use systems. However, a persistent drawback of such studies is their dependency on broad LULC classifications and the absence of high-resolution spatial analyses that include GIS-based techniques along with composite soil quality indicators. The Western Ghats, though broadly tropical, represent an ecologically distinct context. Extremely high rainfall intensities, laterite-dominated soil profiles, and rugged terrain combine to accelerate leaching, regulate organic matter turnover, and generate sharp spatial gradients in soil nutrient distribution, all of which demand region-specific research frameworks rather than generalised approaches taken from other humid tropics. Within this ecologically significant setting, Puttur Taluk falls in the eastern slopes of the Western Ghats, receiving annual rainfall exceeding 4,000 mm and supporting a richly diversified fusion of land uses including natural forests, plantation agriculture, cultivated fields, and urban settlements (Gadgil & Guha, 1992; District Statistical Office, Dakshina Kannada, 2020; Prasad et al., 2014). Under these continuously humid tropical conditions, soils typically develop strong acidity alongside highly variable nutrient reserves, with forested and plantation-dominated areas generally retaining greater organic matter and nutrients than intensively farmed lands (Sanchez, 1976; Brady & Weil, 2008; Lal, 2004; Feller & Beare, 1997; Tiessen et al., 1994; NBSS & LUP, 1996; Sehgal, 1996; Rakshit et al., 2021).

EC acts as a stand-in for salt stress, and soil pH controls the availability of nutrients and the activity of soil microbial communities. Land management decisions and the nutrient cycle routes they support have a significant impact on the primary macronutrients, OC, N, P, K, and S. (Brady & Weil, 2008; Havlin et al., 2014; Lal, 2004; Rakshit et al., 2021; Srinivasan et al., 2024). In light of this, combining a fine-grained Level-III LULC classification with GIS-based spatial interpolation provides a reliable and spatially explicit framework for describing soil chemical variability and obtaining composite fertility metrics like the Soil Quality Index (SQI) (Arnold et al., 1998; McBratney et al., 2003; Rakshit et al., 2021).

Despite the Western Ghats' acknowledged ecological significance and Puttur Taluk's diverse land-use patterns, comprehensive spatial studies that combine Level-III LULC data with soil chemical characterization for systematic soil quality assessment are noticeably lacking. This gap constrains the capacity to grasp how fine-scale distinctions in land use influence soil fertility outcomes and hinders the creation of contextually appropriate land management solutions for high-rainfall tropical locations. Recent developments in remote sensing and geostatistical approaches have considerably expanded the capacity to quantify spatial variability of soil characteristics and their association with land use at smaller scales (McBratney et al., 2003; Srinivasan et al., 2024). High-resolution satellite data combined with enhanced interpolation and spatial modeling methodologies enable improved identification of micro-level LULC fluctuations and their effect on soil processes (Arnold et al., 1998; McBratney et al., 2003). Studies have progressively emphasized the role of micro-LULC dynamics, landscape connectivity, and ecosystem services in controlling soil fertility, nutrient cycling, and carbon storage in complex tropical environments (Karlen et al., 1997; Lal, 2004; Tiessen et al., 1994). In particular, landscape architecture and connectivity influence the transport of water, sediments, and nutrients, consequently changing spatial patterns of soil quality (Montgomery, 2007; Lal, 2004). Integrating these perspectives with soil quality assessment provides a more holistic understanding of land–soil interactions and supports sustainable land management strategies (Karlen et al., 1997).

2. Objectives of the Study

The objectives of the study are:

1. To map and analyze the spatial variation of major soil chemical properties like pH, Electrical Conductivity (EC), Organic Carbon (OC), nitrogen (N), phosphorus (P), potassium (K), and sulphur (S) in Puttur Taluk using GIS-based spatial interpolation techniques.
2. To evaluate the impact of Level-III LULC classes on the spatial variability of soil chemical properties in the high rainfall environment of the Western Ghats region.
3. To develop a composite Soil Quality Index (SQI) incorporating major soil fertility parameters and analyze the spatial variability of soil quality in different land use systems.
4. To identify land use-specific soil quality criteria for site-specific soil management and land use planning in Puttur Taluk.

3. Overview of the Study Area

Puttur Taluk, located in the southwestern coastal hinterlands of Karnataka, India, is an area that is studied in relation to the impact of climatic conditions, land use practices, and the geomorphological position of an area on soil, nutrient cycling, and soil moisture retention. The hydrological processes associated with the area`s major rainfall occur during the southwest monsoon, which contributes to a total annual precipitation that is both high and concentrated during the monsoon. As a result, the duration of moisture retention in the soil, chemical weathering, and the distribution of nutrients through leaching will be positively influenced by these factors. In comparison to the patterns of temperature, moisture retention in the soil will consistently hold temperatures that provide favourable conditions for the biological activity associated with the rapid breakdown of organic matter in the upper layers of the soil. Geologically, the soils of this study area are predominantly lateritic and are formed over ancient crystalline basement rocks. These geological features, along with a poor base status and a tendency toward weak acidities, result in soils with a high variability in soil fertility. The increase in organic matter and land management will have a measurable effect on the soil's ability to hold onto nutrients. Land uses of the taluk are made up of plantations, agroforestry, rugged areas with intact forests, and urban areas that are becoming populated.

The diversification that is found on the Level-III Land Use Land Cover (LULC) map representations (Figure 3) provides the tools necessary to assess changes between each type of landuse and chemical differences in soil. The combination of high amounts of rainfall, lateritic type soils, and a diversity of land usage in the same region makes the Puttur Taluk a perfect natural laboratory for the assessment of spatial patterns of soil quality in the Western Ghats.

However, despite the ecological importance of the Western Ghats and the diverse land use patterns prevailing in Puttur Taluk, there is a lack of detailed spatial studies that integrate Level III LULC classification with soil chemical properties to assess the soil qualities. This limits the understanding of the effects of diverse land use systems on soil fertility.

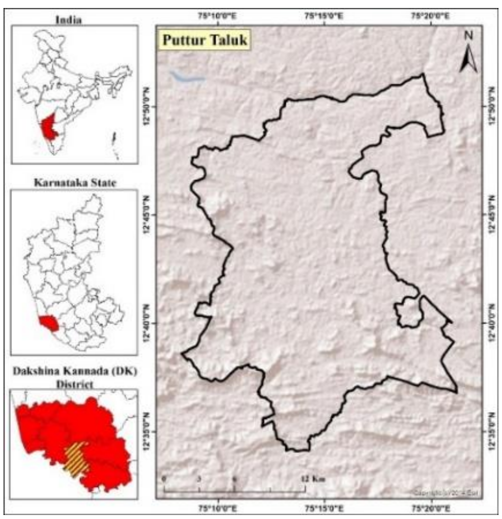


Fig. 1 Study area

4. Data and Methodology

4.1. Soil Sampling and Laboratory Analysis

Structured (spatially aware) soil sampling was carried out across the diverse land use systems of Puttur Taluk to capture spatial variability. To guarantee representative coverage of the main land use groups, such as forests, plantations, agricultural fields, and habitation areas, a stratified sample approach based on Level-III LULC categories was used. Land use heterogeneity, accessibility, and the requirement to represent spatial variability throughout Puttur Taluk's high rainfall terrain were taken into consideration for determining the number of sample locations. In order to reduce sampling bias and increase the dependability of spatial interpolation and soil quality assessment, surface soil samples (0–20 cm depth) were taken from 145 georeferenced locations. The number of samples from each land use class was proportionate to its spatial extent and variability. Sampling locations were carefully selected to ensure adequate representation of Level-III LULC classes (Figure 3), and geographic coordinates were recorded using a handheld GPS unit for subsequent spatial analysis (Figure 2).

Before performing laboratory analyses, the collected samples were air-dried, crushed, and sieved with a 2 mm mesh. Standard laboratory methods were used for the analysis of the soil's chemical characteristics. The soil reaction (pH) and Electrical Conductivity (EC) of a soil-water suspension were measured using calibrated electronic instrumentation. The organic carbon content of the sample was determined by using the Walkley-Black wet oxidation technique; available nitrogen was determined with the alkaline permanganate technique; available phosphorus was extracted with the Olsen method; potassium was determined by flame photometry; and sulfur was measured using turbidimetry. Quality assurance and processes are strictly followed during the testing process to ensure the accuracy of this data.

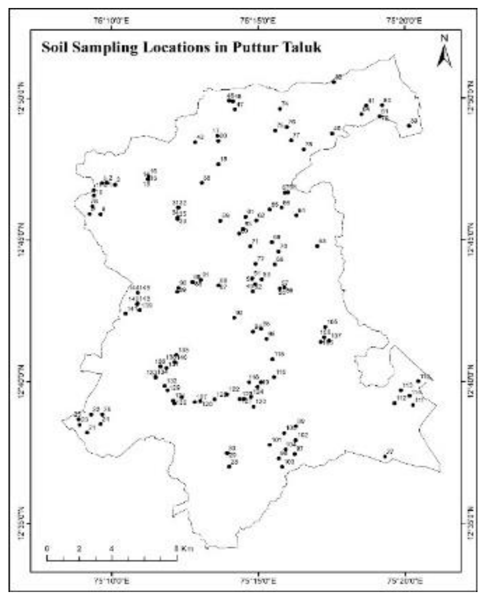


Fig. 2 Soil Sampling Locations in Puttur Taluk

4.2. Standards for Soil Testing

Table 1 represents the status of soil fertility based on soil nutrient standards and provides recommendations for proper nutrient management to keep the soil productive and support crop growth. Soil nutrient standards will help classify soils as low, medium, or high fertility, and influence fertilization practices as well as the productivity of crops grown on the soil being tested. Table 1 outlines the optimum range defined for each parameter regarding soil nutrient content, which can be used to evaluate whether or not soil nutrient levels will be adequate to produce healthy crops.

Table 1. Nutrients available in the soil

Nutrient	Low	Medium	High
Nitrogen (N)	<280 kg/ha	280-560 kg/ha	>560 kg/ha
Phosphorus (P)	<10 kg/ha	10-25 kg/ha	>25 kg/ha
Potassium (K)	< 110 kg/ha	110-280 kg/ha	>280 kg/ha
Sulfur (S)	<0.5 mg/kg	5 to 10 mg/kg	10 to 15 mg/kg
Organic Carbon	<0.5%	0.5-0.75%	>0.75%

Source: Ministry of Agriculture and Farmers Welfare, et al, 2024

4.3. Spatial Interpolation and GIS Analysis

In the present study, a Geographic Information System (GIS) framework is used to analyze and map the soil chemical properties of point-based soil observations through the interpolation of these properties using Inverse Distance Weighted (IDW) methods to create continuous spatial distribution maps for each parameter. The IDW method was selected because it best accommodates irregularly spaced samples while capturing the local variability of these soil properties. We created classified raster layers that classify the soil parameters according to standard thresholds for the purposes of comparison and interpretation of the data, based on the respective land uses. In order to observe differences in soil chemical parameters that are specific to land use, we performed spatial overlays of the soil property maps with the Level-III LULC map (Figure 3).

Each soil parameter was classified into three categories- Low, Medium, and High-based upon the established agronomic thresholds reported in Table 2. Soil fertility was classified using the standards set forth by the Soil Health Card (ICAR, 2015). Each class was given a score of either 1, 2, or 3 as follows.

Table 2. Classification of soil fertility levels based on key nutrient parameters

Parameter	Low (Score = 1)	Medium (Score = 2)	High (Score = 3)
OC (%)	<0.5	0.5- 0.75	>0.75
N (kg/ha)	< 280	280 – 560	> 560
P (kg/ha)	<10	10 – 25	>25
K (kg/ha)	< 110	110 – 280	>280
S (mg/kg)	<0.5	05 – 10	> 10

Each sample's individual parameter value was converted into its corresponding score based on the above table.

4.4. Soil Quality Index (SQI) Development

Equation 1 gives an average score ranging from 1.0 to 3.0, reflecting overall soil quality.

$$SQI = \frac{\sum Property\ Score}{Total\ Number\ of\ Properties} \quad (1)$$

$$SQI = \frac{OC\ score + N\ score + P\ score + K\ score + S\ score}{5}$$

This formula gives an average score ranging from 1.0 to 3.0, reflecting overall soil quality. Table 3 gives the Soil Quality Index (SQI) Range and Interpretation for Agricultural Suitability (ICAR, 2015).

Table 3. Soil Quality Index (SQI) Range (ICAR, 2015)

SQI Range	Interpretation	Meaning
1.0 – 1.5	Low Soil Quality	Soils with severe nutrient deficiencies are potentially limiting productivity.
1.6 – 2.5	Medium Soil Quality	Soils are moderately suitable for crop cultivation; they may require fertilization or amendments.
2.6 – 3.0	High Soil Quality	Nutrient-rich soils with high agricultural potential.

Soil Fertility Classifications were established using a Soil Rating Chart published by ICAR (Indian Council of Agriculture Research) as well as from TNAU (Tamil Nadu Agricultural University), which provides an accepted standard for determining soil quality by providing a reliable evaluation based on relevant chemical properties measured and displayed in Table 4.

Table 4. Soil Quality Assessment Matrix

Macro Nutrient Property	Soil Quality with Score		
	Low (1)	Medium (2)	High (3)
Organic Carbon (%)	< 0.5	0.5–0.75	> 0.75
N: Nitrogen (kg/ha)	< 280	280–560	> 560
P: Phosphorus (kg/ha)	< 10	10–25	> 25
K: Potassium (kg/ha)	< 110	110–280	> 280
Sulphur (mg/kg)	< 10	10–20	> 20

4.5. Statistical Analysis

Soils in the study area were analyzed with statistical analyses in order to determine the average values and the variability of soil chemical characteristics throughout the entire area. Soil chemical properties were also examined to improve understanding of the relationships between each property and the different types of land use that occurred in the study area. The combination of both statistical summaries and graphical representations of the data allowed for a complete interpretation of soil chemical characteristics with regard to different management practices.

5. Results and Discussion

5.1. Spatial Distribution of Soil Reaction and Electrical Conductivity

Table 5 contains all the results of the soil chemical tests conducted across the study area, while Figure 5 shows the map of the entire Puttur Taluk. According to Figure 6, which shows the spatial distribution of the soil pH throughout Puttur Taluk, soils have moderate to slight acidity, which is influenced by high levels of rainfall, lateritic parent materials, and extensive leaching of base cations over a long time. The forested areas appear to be relatively stable with respect to pH due to constant addition of organic materials and little disturbance from soil tillage. In contrast, both agricultural and plantation areas have variable soil reactions, most likely related to frequent application of fertilisers, cropping intensity, and management practices. The Electrical Conductivity (EC) values for the study area (Figure 7) are generally in the non-saline range, indicating no widespread salinity problems. However, there are localised areas of higher EC levels in plantation and habitation, indicating anthropogenic influences such as fertilizer residues and domestic wastewater. The relatively low EC values can be attributed to the high rainfall regime.

Table 5. Laboratory analytical results based on soil samples

ID	Longitude(X)	Latitude(Y)	P^H	EC	OC	N	P	K	S
1	75.1639	12.7836	6.47	0.91	1.74	490	23.33	194.66	178.05
2	75.1642	12.7835	5.8	0.53	2.35	610	23.85	278.54	16.26
3	75.1686	12.7825	5.11	1.48	1.79	490	25.9	358.85	25.68
4	75.1613	12.7834	6.12	1.05	2.32	600	14.1	134.51	17.12
5	75.1613	12.7832	4.84	1.35	1.9	539	65.13	400.85	13.7
6	75.1573	12.7676	6.9	0.62	1.7	485	21.28	109.65	11.13
7	75.1558	12.7698	6.33	1.20	2.1	560	30.77	366.58	17.12
8	75.1558	12.7698	4.82	0.40	1.97	542	26.67	87.14	54.78
9	75.1567	12.7698	4.92	0.42	1.88	519	42.31	149.74	35.95
10	75.1567	12.7762	5.7	0.41	1.88	519	57.18	436.8	39.38
11	75.1566	12.7792	6.1	0.65	2.08	558	86.66	216.72	46.22
12	75.1876	12.7854	5.59	0.53	2.01	550	20.51	228.26	20.54
13	75.1875	12.7857	4.67	1.02	1.83	510	3.85	47.94	65.91
14	75.1876	12.7858	5.68	1.13	1.97	530	143.58	39.54	51.36
15	75.1877	12.7873	5.71	0.33	1.92	524	26.92	91.28	34.24
16	75.1876	12.7874	5.65	1.54	1.88	519	28.2	71.23	16.26
17	75.2268	12.8112	5.49	1.51	0.91	314	22.82	54.32	11.98
18	75.2273	12.7945	5.14	0.40	1.72	485	7.44	154.45	18.83
19	175.215	12.8099	5.49	3.00	2.02	557	39.23	177.52	43.66
20	75.2272	12.8082	5.77	0.44	2.97	538	11.03	35.5	31.67
21	75.146	12.6443	5.76	1.44	1.52	442	12.82	85.12	17.12
22	75.1468	12.6443	5.52	0.55	1.7	480	4.36	70.34	15.41
23	75.1484	12.6454	5.12	0.21	0.53	195	14.36	71.79	21.4
24	75.1475	12.6453	5.82	0.53	1.97	530	12.31	33.6	27.39
25	75.1479	12.6445	5.74	2.33	1.92	524	37.18	49.39	5.14
26	75.1613	12.6474	5.64	0.52	1.88	519	8.46	52.53	20.54
27	75.3219	12.6224	6.2	1.74	0.91	314	3.33	154.45	6.85
28	75.2334	12.6166	5.65	0.63	1.5	438	8.97	67.09	26.54
29	75.2323	12.6245	4.92	0.33	1.81	504	5.38	85.9	21.4
30	75.232	12.6245	6.06	0.60	1.63	466	18.72	31.7	6.85
31	75.2049	12.7689	5.64	0.40	1.68	476	12.56	43.68	37.66
32	75.2044	12.7689	5.94	0.91	0.62	252	0.51	15.12	13.7
33	75.2043	12.7628	5.49	0.75	1.74	490	44.36	129.14	15.41
34	75.2042	12.7632	5.84	0.91	1.63	467	50.51	211.9	22.26
35	75.2042	12.7622	5.46	0.49	1.56	452	10.51	157.92	23.97
36	75.4021	12.712	5.94	1.27	1.27	390	24.36	120.4	0.86
37	75.4025	12.7111	5.79	0.67	0.47	185	1.03	354.37	21.4
38	75.218	12.7835	5.93	0.75	0.53	195	5.38	448	5.14
39	75.3424	12.8086	5.87	0.44	0.69	266	1.79	143.7	15.41

40	75.3112	12.8059	6	0.57	1.5	450	13.85	110.88	13.7
41	75.3231	12.8038	5.66	0.41	1.72	482	33.33	161.62	24.82
42	75.2142	12.8074	5.72	0.53	1.68	476	79.23	218.62	47.08
43	75.4125	12.8451	5.88	0.54	1.4	430	32.05	89.94	15.41
44	75.4125	12.8045	5.74	0.61	1.7	480	61.54	177.52	35.1
45	75.4511	12.8321	6.21	0.56	1.83	510	3.33	87.92	30.82
46	75.2335	12.8318	6.08	0.51	0.91	314	11.79	86.24	61.63
47	75.2368	12.8317	6.1	0.55	1.38	414	11.03	168	6.85
48	75.2356	12.8314	5.84	0.48	1.43	423.7	19.74	201.6	41.09
49	75.2482	12.7239	5.5	0.36	1.26	395	6.41	170.13	15.41
50	75.2483	12.7239	4.9	0.33	2.1	550	10	178.08	34.24
51	75.2465	12.7274	4.49	0.36	1.65	475	5.13	265.22	26.54
52	75.2469	12.7196	4.55	0.30	1.7	480	6.92	69.22	31.67
53	75.2484	12.7267	5.07	0.30	1.43	435	8.2	83.33	35.1
54	75.2648	12.722	5.23	0.45	1.59	460	16.15	68.77	23.97
55	75.2648	12.722	5.66	0.59	1.27	396	5.9	81.42	23.97
56	75.2648	12.722	3.66	0.43	2.2	560	88.2	384.38	38.52
57	75.2623	12.7214	5.39	0.49	1.34	425	10.51	178.08	49.65
58	75.2594	12.7355	5.96	0.70	2.2	560	0.26	156.35	22.26
59	75.2285	12.7612	5.88	0.29	2.2	560	0.26	75.94	59.06
60	75.2392	12.7537	5.93	0.35	1.23	390	0.26	280	29.96
61	75.2428	12.7635	5.66	0.35	2.19	585	2.82	48.94	10.27
62	75.2489	12.7614	5.87	0.33	2.17	580	16.15	329.28	22.26
63	75.2835	12.7463	5.88	0.34	1.54	447	2.82	212.58	14.55
64	75.2718	12.7643	5.92	0.50	2.13	572	18.46	189.28	10.27
65	75.2565	12.7678	5.69	0.37	2.15	575	6.15	99.46	22.26
66	75.2632	12.7689	5.53	0.29	2.13	572	8.46	38.42	14.55
67	75.2652	12.7777	5.66	0.37	1.6	461	3.85	56.45	16.26
68	75.2668	12.778	5.64	0.36	1.9	523	14.61	62.16	11.13
69	75.2577	12.7487	5.36	0.23	1.63	466	5.64	425.6	59.06
70	75.2615	12.7431	5.48	0.44	1.8	504	6.41	174.38	1.71
71	75.2455	12.7461	5.33	0.62	1.9	523	5.9	414.4	4.28
72	75.2485	12.7359	5.94	0.49	2.01	550	3.08	448	17.12
73	7502474	12.7238	5.01	0.33	2.1	557	5.64	436.8	2.57
74	75.2624	12.827	5.27	0.96	2.4	640	2.82	96.32	11.13
75	75.2597	12.8142	5.21	0.36	2.1	580	17.95	39.87	8.56
76	75.2662	12.8163	4.87	0.43	2.4	640	23.08	90.27	19.69
77	75.2688	12.8084	5.58	0.50	2.4	640	17.69	105.95	29.96
78	75.2759	12.8031	5.72	0.40	1.9	523	10.26	448	28.25
79	75.3191	12.8225	5.93	0.41	2.2	585	23.08	85.34	13.7
80	75.3186	12.8237	5.33	0.36	2.4	640	6.92	448	17.12
81	75.3191	12.8225	6.03	0.48	2.4	640	8.2	179.65	29.1
82	75.2929	12.8427	5.31	0.22	2.1	580	6.92	161.95	28.25
83	7.5E+07	12.8314	5.4	0.34	2.1	580	15.38	87.7	5.99
84	75.3086	12.8238	5.49	0.31	1.8	514	15.13	95.65	15.49
85	75.2131	12.7252	5.05	0.32	2.01	550	17.95	157.7	19.69
86	75.2124	12.7252	5.37	0.25	2.06	552	23.08	236.77	29.96
87	75.2274	12.7231	5.35	0.32	1.56	447	17.69	154.9	28.25
88	75.2274	12.7231	4.74	0.50	2.3	635	10.26	66.75	13.7
89	75.204	12.7194	5.34	0.27	2.3	635	10.26	66.75	13.7
90	75.2045	12.7217	5.48	0.27	2.03	552	23.08	55.66	19.69
91	75.2172	12.7265	5.55	0.62	2.3	614	17.69	200.48	29.96
92	75.2363	12.7042	5.21	0.60	1.7	480	10.26	336	28.25

93	75.2413	12.7564	5.75	0.44	2.03	552	23.08	127.57	13.7
94	75.247	12.6959	5.45	0.37	1.38	414	37.69	57.34	0.86
95	75.2515	12.6977	5.31	0.32	0.89	309	46.15	157.14	1.71
96	75.2547	12.6917	5.61	0.32	1.23	380	30.26	91.62	1.71
97	75.265	12.6266	5.72	0.45	0.78	285	35.13	97.1	29.96
98	75.2615	12.6215	5.97	0.45	1.2	376	10.26	57.9	0.86
99	75.2646	12.6363	5.59	0.40	1.79	499	46.15	41.89	8.56
100	75.2646	12.6363	5.99	0.63	1.99	542	7.95	54.99	17.12
101	75.2625	12.6264	5.25	0.33	1.5	438	16.41	448	23.11
102	75.265	12.6266	5.62	0.36	2.06	557	11.03	448	16.26
103	75.2645	12.6265	5.47	0.52	1.98	528	11.03	448	18.83
104	75.2655	12.6267	5.46	0.40	1.94	533	8.97	119.84	4.28
105	75.2865	12.6936	5.5	0.36	2.1	560	13.59	122.08	9.42
106	75.2855	12.6899	5.57	0.29	2.3	613	30.26	33.6	1.71
107	75.2876	12.6922	5.5	0.33	2.3	613	50.25	560	21.4
108	75.2875	12.6926	5.2	0.26	2.6	680	80	616	22.26
109	75.2875	12.3926	5.66	0.46	2.4	623	17.95	109.31	16.26
110	75.3434	12.6652	5.95	0.42	2.3	613	57.18	162.29	33.38
111	75.3373	12.6588	5.85	0.36	1.47	433.2	10	451.36	9.42
112	75.3334	12.6574	5.55	0.43	1.9	647.7	28.97	160.61	2.57
113	75.3319	12.6574	5.3	0.39	2.32	613.3	3.85	53.98	0
114	75.3359	12.6583	4.8	0.55	1.47	433.2	15.64	104.72	7.7
115	75.2579	12.6798	5.3	0.46	0.87	305	45.9	51.3	0
116	75.2589	12.6693	5.13	0.27	1.41	423.7	15.38	51.07	5.99
117	75.2514	12.6663	5.67	0.41	1.59	428	53.84	83.44	29.96
118	75.2448	12.6663	5.58	0.49	1.45	425.5	10.26	189.62	71.05
119	75.2494	12.6634	4.8	0.21	1.47	433.2	22.31	189.84	3.42
120	75.2472	12.6519	5.29	0.57	1.38	400	10.77	208.1	2.57
121	75.2394	12.6564	4.74	0.26	1.27	375	19.49	183.46	65.06
122	75.2321	12.6591	5.1	0.44	2.59	671.5	26.15	72.58	1.71
123	75.2418	12.6564	5.4	0.33	2.97	670	2.56	61.82	28.25
124	75.2458	12.6577	5.89	0.79	1.24	370	13.08	34.94	13.7
125	75.225	12.6562	5.76	0.48	2.62	673	19.74	40.32	13.7
126	75.2168	12.6551	5.2	0.20	1.61	428	15.38	136.86	19.69
127	75.2139	12.6546	5.15	0.28	1.91	648	29.23	65.86	29.96
128	75.2064	12.6574	5.45	0.39	1.93	650	0.26	48.72	28.25
129	75.1984	12.6615	5.32	0.33	1.9	647	26.92	32.93	13.7
130	75.2022	12.6539	5.33	0.37	2.01	550	10.26	82.1	5.99
131	75.2015	12.6555	5.32	0.35	2.06	552	25.64	80.53	29.96
132	75.1967	12.6642	4.75	0.35	1.56	447	54.36	143.25	71.05
133	75.1915	12.6691	4.88	0.27	2.3	635	190.25	42.78	65.8
134	75.1916	12.6694	5.58	0.59	2.3	635	125.38	39.31	15.5
135	75.2034	12.6823	5	1.41	2.03	552	189.48	45.81	17.4
136	75.1943	12.6756	4.65	0.25	2.3	614	189.48	45.81	18.4
137	75.1977	12.6747	5.6	0.45	1.7	480	8.46	117.49	13.9
138	75.2023	12.6781	4.87	0.24	2.03	552	4.62	128.58	23.2
139	75.1825	12.7086	5.5	0.44	1.38	414	13.59	345.63	16.64
140	75.2026	12.678	5.59	0.46	0.89	309	22.56	329.06	18.8
141	75.1745	12.7066	4.95	0.33	1.23	380	11.28	209.33	23.1
142	75.1812	12.7122	5.96	1.18	0.91	314	5.64	256.03	16.2
143	75.1814	12.7126	5.42	0.54	1.38	414	5.13	437.7	18.32
144	75.1815	12.7189	4.7	0.35	1.43	423.7	0	526.51	9.42
145	75.1815	12.7189	4.68	0.64	1.26	395	5.64	255.36	2.57

5.2. Spatial Variability of Organic Carbon and Macronutrients

Figure 8 shows that OC concentrations are greater in areas of mixed and forest vegetation than in most cultivated crops and plantations. The patterns described indicate that litter accumulation, reduced soil disturbance, and more humid and stable microclimates are conducive to the accumulation of organic matter in Tropical Soils. The low abundance of OC in extensively managed lands suggests that there could be a negative effect from the continuous cultivation of land and reduced organic material from agricultural activities.

Figure 9 clearly exhibits the correlation between OC spatial patterns and the availability of N. While OC levels are variable due to many factors, the availability of nitrogen will also have strong correlations with organic matter variations within tropical soils. Forest and plantation systems generally preserve higher nitrogen levels, while agricultural lands display pronounced spatial heterogeneity, reflecting differences in fertilizer application and crop intake.

Available phosphorus (P) and potassium (K) distributions (Figures 10 and 11) indicate moderate to high variability across land use classes. While lower concentrations in forest soils indicate natural cycle mechanisms, higher phosphorus levels in cultivated and plantation regions indicate external fertilizer inputs. Both parent material and management techniques affect potassium availability; regions that receive frequent fertilization have greater amounts. The distribution of sulfur (S) in Figure 12 indicates comparatively greater concentrations in plantation and forest regions, which are probably related to air deposition under humid circumstances and organic matter mineralization. Crop loss and restricted sulfur replenishment may be the cause of lower sulfur availability in cultivated areas.

Table 6. Level – III land use land cover distribution, 2019

Sl No	LEVEL III LULC	Area in Km^2
1	Mixed Vegetation	148.81
2	Agricultural Plantation	83.49
3	Tree Groves	80.67
4	Habitation	31.19
5	Evergreen / Semievergreen Dense Forest	25.95
6	Land with scrub	14.72
7	Habituation with Vegetation	12.51
8	Kharif crop	5.37
9	Evergreen / Semievergreen Open Forest	3.77
10	Kharif + Rabi (Double Crop)	3.12
11	River / Stream	3.54
12	Forest Plantations	2.64
13	Scrub Forest	2.31
14	Barren Rocky / Stony Waste / Sheet Rock Area	1.91
		420.00

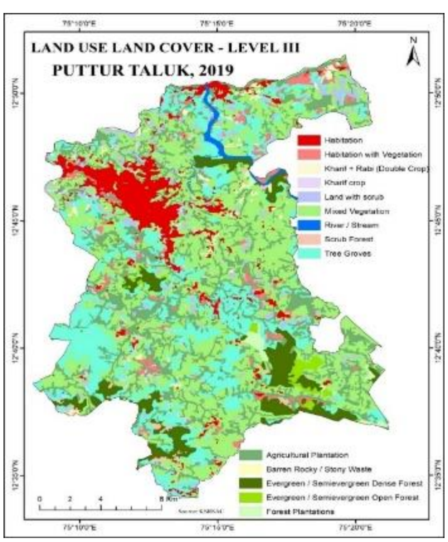


Fig. 3 Level – III Land Use Land Cover of Puttur Taluk, 2019

5.3. Level-III Land Use/Land Cover (LULC) Classification

In order to maintain land-use-specific study of soil chemical characteristics and to comprehend the intricate land-use complexity within Puttur Taluk, Level-III Land Use/Land Cover (LULC) categorization was implemented. LULC Level III has greater thematic resolution than coarse LULC levels. LULC Level III identifies differences in forest types, plantation systems, agricultural practices, and habitation areas, all of which greatly influence soil processes.

Level-III LULC classification was performed using high-resolution satellite imagery to capture fine-scale land use variations such as plantations, mixed cropping, built-up areas, and forest types, which are often generalized in coarser classification schemes. The classification accuracy was evaluated using ground truth data and standard accuracy assessment metrics, including overall accuracy and kappa coefficient, to ensure the reliability of the LULC map.

The LULC map shows a heterogeneous mosaic of land use classes created by plantation agriculture, forest areas, agricultural land, and an expanding human population. LULC's major land use is that of plantations (e.g., arecanut, coconut, rubber, mixed crops), which cover a significant portion of the area. This is indicative of the area's economic reliance on the cultivation of plantations or perennials over the long term. The distribution of natural forest cover is limited and restricted to low human impact and also higher elevations, where there has been minimal or no human development.

Agricultural land is typically found in the form of gentle slopes or valleys that are subjected to intensive agricultural cultivation and nutrient management. Therefore, agricultural lands are highly prone to erosion and run-off, so they require careful management.

In contrast to agricultural land (which is relatively small and spatially dispersed) and human settlements (which are large but sporadically distributed), there are areas that have been developed and are now subject to increased anthropogenic disturbance (e.g., waste disposal, new construction, reconfigured drainage). These human alterations can locally affect soil chemistry by introducing contaminants into soils.

The spatial distribution of the Level III LULC classes provides an important framework for understanding how to relate the distribution of soils with different chemical characteristics and the distribution of soils with different SQI values across the entire taluk. Therefore, when LULC class maps and soil property maps were combined to conduct a comparative analysis of LULC class and soils under high rainfall, land use types with a variety of responses will be present due to the effects of LULC on soil properties.
In order to support targeted soil management and land-use planning strategies in the Puttur Taluk region, this thorough categorization serves as a crucial input for evaluating the impact of land use in regulating soil chemical variability.

5.4. Spatial Interpolation of Soil Samples

The Inverse Distance Weighting (IDW) approach was chosen because it is easy to use, works well with irregularly spaced soil sample data, and maintains local spatial variability—a crucial feature in varied environments like the Western Ghats. A geostatistical method called spatial interpolation uses inspection from sampled sites to calculate values of a variable at unsampled places. Due to time, financial, and accessibility limitations, it is frequently not feasible to directly quantify soil parameters at every site in soil research. Interpolation allows for the creation of continuous surfaces from separate soil samples, allowing for the mapping and spatial analysis of soil attributes over an area. In accordance with recognized SQI development frameworks documented in the literature, indicator weighting was carried out to represent the relative significance of each parameter in affecting soil fertility and plant growth. To make sure that no one soil characteristic significantly dominated the index, a sensitivity analysis was carried out to assess the impact of specific indicators on the total SQI values. One of the most popular deterministic interpolation techniques is Inverse Distance Weighting (IDW). IDW makes the assumption that a known data point's influence diminishes with distance, so that sites nearer a sample point have more similar values than those farther away. To evaluate the stability and usefulness of the index in depicting soil quality conditions, the calculated SQI values were cross-validated with observed soil fertility status and land use patterns. The IDW illustration and examples are given in Figure 4.

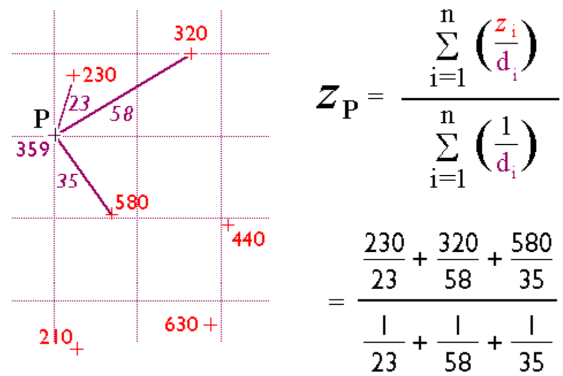


Fig. 4 Illustration of IDW Interpolation Technique

Source: https://www.e-education.psu.edu/natureofgeoinfo/c7_p9.html

Where,

- Z_P = estimated value at location *P*
- Z_i = observed value at sample point *i.*
- d_i = distance between point *P* and sample point *i.*

In this study, IDW interpolation was used to soil chemical properties collected from different sampling points (Table 5) using Longitude_X and Latitude_Y across Puttur Taluk. By using IDW, Soil pH, organic carbon, and nutrient content were incorporated into prepared maps. These interpolated maps help visualize the spatial variance of soil properties, point out nutrient-rich and nutrient-deficient zones, and provide insights into the effect of Land Use and Land Cover (LULC) on soil fertility.

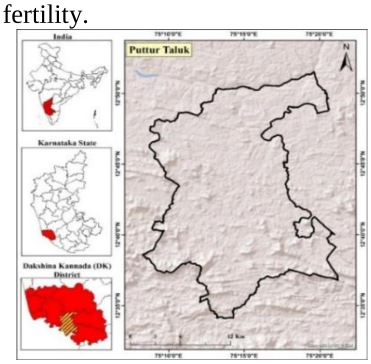


Fig. 5 Study area

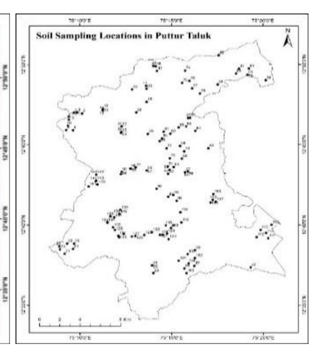


Fig. 6 Soil Sampling Locations in Puttur Taluk

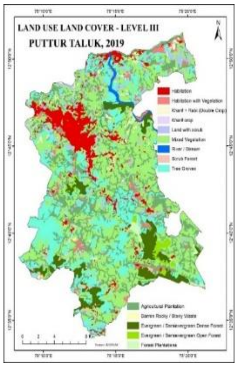
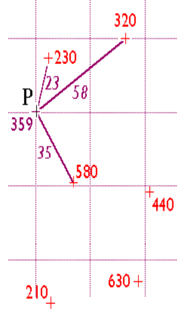


Fig. 7 Level – III Land Use Land Cover of Puttur Taluk, 2019



$$Z_P = \frac{\sum_{i=1}^{n}\left(\frac{z_i}{d_i}\right)}{\sum_{i=1}^{n}\left(\frac{1}{d_i}\right)} = \frac{\frac{230}{23}+\frac{320}{58}+\frac{580}{35}}{\frac{1}{23}+\frac{1}{58}+\frac{1}{35}}$$

Fig. 8 Illustration of IDW Interpolation Technique

Source: https://www.e-education.psu.edu/natureofgeoinfo/c7_p9.html

Where,

- Z_P = estimated value at location *P*
- Z_i = observed value at sample point *i.*
- d_i = distance between point *P* and sample point *i.*

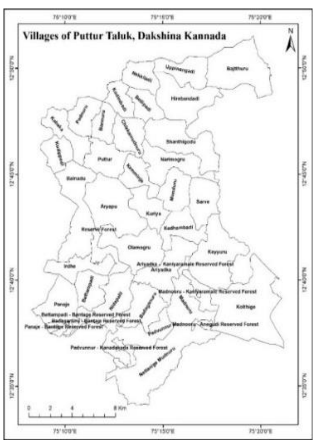


Fig. 9 Village map of Puttur Taluk

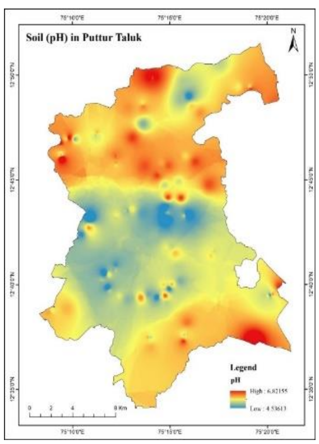


Fig. 10 Spatial Distribution of Soil - pH in Puttur Taluk

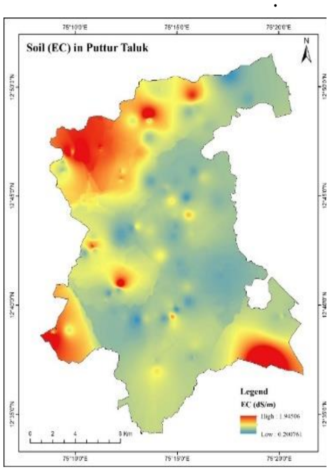


Fig. 11 Spatial Distribution of Soil - EC in Puttur Taluk

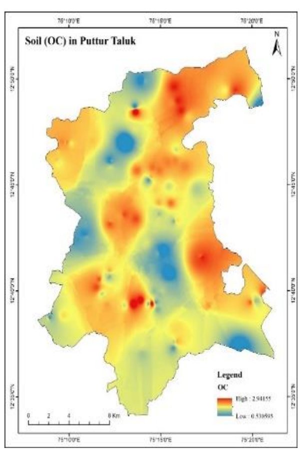


Fig. 12 Spatial Distribution of Soil Organic Carbon (%) in Puttur Taluk

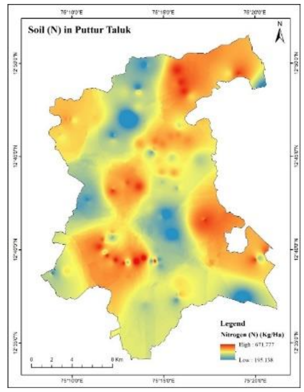


Fig. 13 Spatial Distribution of Soil Nitrogen (N) in Puttur Taluk

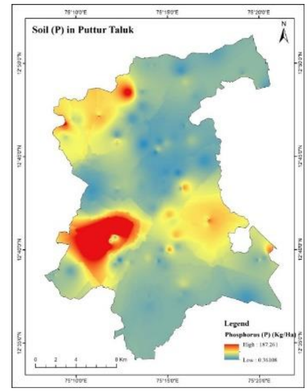


Fig. 14 Spatial Distribution of Soil Phosphorus (P) in Puttur Taluk

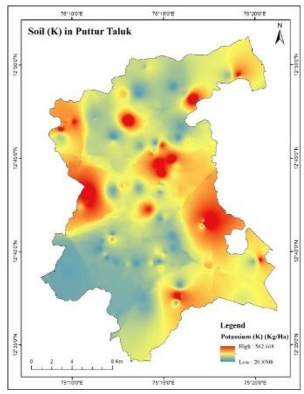


Fig. 15 Spatial Distribution of Soil Potassium (K) in Puttur Taluk

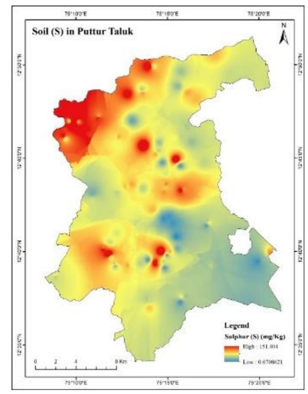


Fig. 16 Spatial Distribution of Soil Sulphur (S) in Puttur Taluk

5.5. Influence of Land Use/Land Cover on Soil Properties

The relationship between soils and land use is very clear for Puttur Taluk. In terms of organic carbon levels and balance of nutrients, there is much more organic carbon and balanced nutrients in Forest soils than in other land uses, because there is a constant flow of litter into the soil, little to no disturbance, and because there is a well-defined cycle of nutrients (movement back into the plant). The soils are able to maintain good chemical properties despite receiving a lot of rainfall. Soils from Plantation areas have organic carbon and nitrogen levels between those found in Forest soils and those in Agricultural soils, but in some cases, nutrient levels (enrichment or depletion) are specific to the crops grown and the fertilization practices that are used. Agricultural soils are often highly variable in terms of N, P, and K; this is due to differences in cropping systems used and the intensity of management practices. Some Agricultural soils in high rainfall areas will also have some nutrient imbalance(s). Settlement zones are limited in extent within Puttur Taluk, but there are some very distinct chemical properties for these areas, including localized elevated electrical conductivity and somewhat variable nutrient levels as a result of human-induced inputs and different drainage patterns. Land use and management practices are the primary drivers of the spatial variation of soil chemistry across Puttur Taluk.

5.6. Soil Quality Index (SQI)

The Soil Quality Index (SQI) is calculated by combining five factors: organic carbon, nitrogen, phosphorus, potassium, and sulphur (shown in Table 7). The selected soil quality indicators (pH, EC, OC, N, P, K, and S) were chosen based on their ecological relevance, sensitivity to land use changes, and their established use in tropical soil quality assessment studies. This score represents how well soil functions through its distribution across Puttur Taluk (shown in Figure 17). The majority of soils qualify as medium to high quality; however, due to the effects of severe rainfall and lateritic soils, this is not always the case. The computed Soil Quality Index (SQI) values were interpreted based on established classification frameworks and benchmarked against regional soil fertility standards and comparable studies from tropical regions to ensure consistency and broader applicability of the results. Forested areas tend to have high SQI values due to their continued organic inputs and effective nutrient cycling. Areas designated for tree plantations range from moderate to high SQI values because the trees provide year-round cover and because of proper nutrient management. Large fluctuations exist in agricultural areas because there are areas of lower SQI due to nutrient loss and organic matter reduction.

Reclined SQI values are primarily evidenced in agricultural and settlement areas because of continual land use, continual disturbance to the soil, and insufficient replacement of nutrients. Combining multiple soil indicators into one composite value makes it easier to identify locations that should receive priority for soil improvement and for developing land management strategies for use in those locations.

Table 7. Soil Quality Index of Puttur Taluk

ID	Longitude X	Latitude Y	Soil Quality Ratings					SQI	Quality
			OC	N	P	K	S		
1	75.16386	12.78355	3	2	2	2	3	2.4	Medium
2	75.16421	12.78354	3	3	2	2	2	2.4	Medium
3	75.16858	12.78245	3	2	3	3	3	2.8	High
4	75.16127	12.78342	3	3	2	2	2	2.4	Medium
5	75.16126	12.78323	3	2	3	3	2	2.6	High
6	75.15727	12.76761	3	2	2	1	2	2	Medium
7	75.15582	12.76975	3	2	3	3	2	2.6	High
8	75.15582	12.76975	3	2	3	1	3	2.4	Medium
9	75.15675	12.76977	3	2	3	2	3	2.6	High
10	75.15668	12.77620	3	2	3	3	3	2.8	High
11	75.15657	12.77920	3	2	3	2	3	2.6	High
12	75.18763	12.78545	3	2	2	2	3	2.4	Medium
13	75.18745	12.78571	3	2	1	1	3	2	Medium
14	75.18756	12.78578	3	2	3	1	3	2.4	Medium
15	75.18769	12.78729	3	2	3	1	3	2.4	Medium
16	75.18758	12.78743	3	2	3	1	2	2.2	Medium
17	75.22680	12.81117	3	2	2	1	2	2	Medium
18	75.22730	12.79449	3	2	1	2	2	2	Medium
19	75.21527	12.80990	3	2	3	2	3	2.6	High
20	75.22719	12.80823	3	2	2	1	3	2.2	Medium
21	75.14600	12.64426	3	2	2	1	2	2	Medium
22	75.14678	12.64432	3	2	1	1	2	1.8	Medium
23	75.14842	12.64535	2	1	2	1	3	1.8	Medium
24	75.14754	12.64527	3	2	2	1	3	2.2	Medium
25	75.14789	12.64448	3	2	3	1	1	2	Medium
26	75.16129	12.64741	3	2	1	1	3	2	Medium
27	75.32190	12.62238	3	2	1	2	1	1.8	Medium
28	75.23335	12.61655	3	2	1	1	3	2	Medium
29	75.23235	12.62454	3	2	1	1	3	2	Medium
30	75.23200	12.62454	3	2	2	1	1	1.8	Medium
31	75.20485	12.76894	3	2	2	1	3	2.2	Medium
32	75.20436	12.76894	2	1	1	1	2	1.4	Low
33	75.20433	12.76284	3	2	3	2	2	2.4	Medium
34	75.20423	12.76321	3	2	3	2	3	2.6	High

35	75.20421	12.76215	3	2	2	2	3	2.4	Medium
36	75.40212	12.71200	3	2	2	2	1	2	Medium
37	75.40252	12.71110	1	1	1	3	3	1.8	Medium
38	75.21800	12.78345	2	1	1	3	1	1.6	Medium
39	75.34241	12.80855	2	1	1	2	2	1.6	Medium
40	75.31120	12.80588	3	2	2	2	2	2.2	Medium
41	75.32311	12.80379	3	2	3	2	3	2.6	High
42	75.21418	12.80739	3	2	3	2	3	2.6	High
43	75.41251	12.84512	3	2	3	1	2	2.2	Medium
44	75.41254	12.80451	3	2	3	2	3	2.6	High
45	75.45110	12.83210	3	2	1	1	3	2	Medium
46	75.23350	12.83184	3	2	2	1	3	2.2	Medium
47	75.23679	12.83171	3	2	2	2	1	2	Medium
48	75.23559	12.83140	3	2	2	2	3	2.4	Medium
49	75.24824	12.72386	3	2	1	2	2	2	Medium
50	75.24825	12.72385	3	2	2	2	3	2.4	Medium
51	75.24653	12.72738	3	2	1	2	3	2.2	Medium
52	75.24693	12.71959	3	2	1	1	3	2	Medium
53	75.24835	12.72670	3	2	1	1	3	2	Medium
54	75.26482	12.72196	3	2	2	1	3	2.2	Medium
55	75.26482	12.72196	3	2	1	1	3	2	Medium
56	75.26482	12.72197	3	2	3	3	3	2.8	High
57	75.26228	12.72138	3	2	2	2	3	2.4	Medium
58	75.25939	12.73552	3	2	1	2	3	2.2	Medium
59	75.22855	12.76120	3	2	1	1	3	2	Medium
60	75.23917	12.75371	3	2	1	2	3	2.2	Medium
61	75.24277	12.76351	3	3	1	1	2	2	Medium
62	75.24888	12.76138	3	3	2	3	3	2.8	High
63	75.28345	12.74625	3	2	1	2	2	2	Medium
64	75.27176	12.76431	3	3	2	2	2	2.4	Medium
65	75.25647	12.76781	3	3	1	1	3	2.2	Medium
66	75.26323	12.76889	3	3	1	1	2	2	Medium
67	75.26518	12.77768	3	2	1	1	2	1.8	Medium
68	75.26683	12.77798	3	2	2	1	2	2	Medium
69	75.25768	12.74865	3	2	1	3	3	2.4	Medium
70	75.26147	12.74311	3	2	1	2	1	1.8	Medium
71	75.24554	12.74608	3	2	1	3	1	2	Medium
72	75.24847	12.73591	3	2	1	3	2	2.2	Medium
73	75.02474	12.72383	3	2	1	3	1	2	Medium
74	75.26243	12.82697	3	3	1	1	2	2	Medium
75	75.25967	12.81418	3	3	2	1	1	2	Medium
76	75.26620	12.81634	3	3	2	1	2	2.2	Medium
77	75.26876	12.80843	3	3	2	1	3	2.4	Medium
78	75.27587	12.80315	3	2	2	3	3	2.6	High
79	75.31912	12.82248	3	3	2	1	2	2.2	Medium
80	75.31865	12.82375	3	3	1	3	2	2.4	Medium
81	75.31912	12.82248	3	3	1	2	3	2.4	Medium
82	75.29293	12.84267	3	3	1	2	3	2.4	Medium
83	75.31329	12.83144	3	3	2	1	1	2	Medium
84	75.30864	12.82384	3	2	2	1	2	2	Medium
85	75.21310	12.72515	3	2	2	2	2	2.2	Medium
86	75.21243	12.72518	3	2	2	2	3	2.4	Medium
87	75.22740	12.72312	3	2	2	2	3	2.4	Medium

88	75.22740	12.72312	3	3	2	1	2	2.2	Medium
89	75.20396	12.71940	3	3	2	1	2	2.2	Medium
90	75.20454	12.72175	3	2	2	1	2	2	Medium
91	75.21723	12.72652	3	3	2	2	3	2.6	High
92	75.23635	12.70420	3	2	2	3	3	2.6	High
93	75.24135	12.75640	3	2	2	2	2	2.2	Medium
94	75.24699	12.69594	3	2	3	1	1	2	Medium
95	75.25151	12.69774	3	2	3	2	1	2.2	Medium
96	75.25465	12.69169	3	2	3	1	1	2	Medium
97	75.26498	12.62664	3	2	3	1	3	2.4	Medium
98	75.26155	12.62151	3	2	2	1	1	1.8	Medium
99	75.26458	12.63635	3	2	3	1	1	2	Medium
100	75.26460	12.63635	3	2	1	1	2	1.8	Medium
101	75.26249	12.62637	3	2	2	3	3	2.6	High
102	75.26498	12.62664	3	2	2	3	2	2.4	Medium
103	75.26451	12.62654	3	2	2	3	2	2.4	Medium
104	75.26549	12.62665	3	2	1	2	1	1.8	Medium
105	75.28649	12.69359	3	2	2	2	1	2	Medium
106	75.28546	12.68990	3	3	3	1	1	2.2	Medium
107	75.28763	12.69215	3	3	3	3	3	3	High
108	75.28746	12.69262	3	3	3	3	3	3	High
109	75.28746	12.39262	3	3	2	1	2	2.2	Medium
110	75.34343	12.66521	3	3	3	2	3	2.8	High
111	75.33727	12.65876	3	2	2	3	1	2.2	Medium
112	75.33338	12.65744	3	3	3	2	1	2.4	Medium
113	75.33193	12.65736	3	3	1	1	1	1.8	Medium
114	75.33585	12.65829	3	2	2	1	1	1.8	Medium
115	75.25794	12.67984	3	2	3	1	1	2	Medium
116	75.25886	12.66927	3	2	2	1	1	1.8	Medium
117	75.25138	12.66634	3	2	3	1	3	2.4	Medium
118	75.24476	12.66627	3	2	2	2	3	2.4	Medium
119	75.24940	12.66344	3	2	2	2	1	2	Medium
120	75.24724	12.65188	3	2	2	2	1	2	Medium
121	75.23937	12.65639	3	2	2	2	3	2.4	Medium
122	75.23212	12.65913	3	3	3	1	1	2.2	Medium
123	75.24182	12.65645	3	3	1	1	3	2.2	Medium
124	75.24579	12.65771	3	2	2	1	2	2	Medium
125	75.22502	12.65616	3	3	2	1	2	2.2	Medium
126	75.21682	12.65515	3	2	2	2	2	2.2	Medium
127	75.21389	12.65456	3	3	3	1	3	2.6	High
128	75.20637	12.65735	3	3	1	1	3	2.2	Medium
129	75.19843	12.66152	3	3	3	1	2	2.4	Medium
130	75.20222	12.65394	3	2	2	1	1	1.8	Medium
131	75.20149	12.65548	3	2	3	1	3	2.4	Medium
132	75.19671	12.66415	3	2	3	2	3	2.6	High
133	75.19153	12.66907	3	3	3	1	3	2.6	High
134	75.19158	12.66938	3	3	3	1	2	2.4	Medium
135	75.20340	12.68233	3	2	3	1	2	2.2	Medium
136	75.19430	12.67559	3	3	3	1	2	2.4	Medium
137	75.19775	12.67466	3	2	1	2	2	2	Medium
138	75.20231	12.67811	3	2	1	2	3	2.2	Medium
139	75.18254	12.70863	3	2	2	3	2	2.4	Medium
140	75.20257	12.67798	3	2	2	3	2	2.4	Medium

141	75.17446	12.70659	3	2	2	2	3	2.4	Medium
142	75.18117	12.71220	3	2	1	2	2	2	Medium
143	75.18144	12.71258	3	2	1	3	2	2.2	Medium
144	75.18149	12.71893	3	2	1	3	1	2	Medium
145	75.18150	12.71890	3	2	1	2	1	1.8	Medium

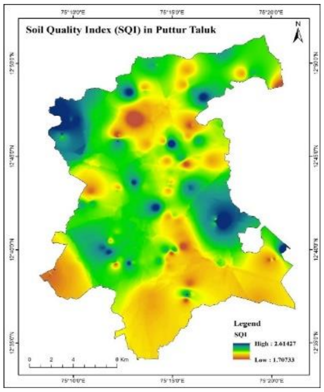


Fig. 17 Spatial Distribution of Soil Quality Index (SQI) in Puttur Taluk

The data on Soil Quality Index (SQI) from Puttur Taluk is shown in Table 8, where it was found that there is much variation in SQIs between villages, with minimums of 1.49 in Puttur to 2.26 in Kabaka and maximums of 2.12 in Padvunnur-Kanadakada Reserved Forest and 2.97 in Keyyuru. The mean SQI was from 1.96 (Chikkamudnuru) to 2.46 (Kabaka), indicating that the different villages had different potential for usefulness of the soil. Villages that had dense vegetation habitat and were protected from human disturbances, such as Reserve Forest Villages and Bantaje RF, had a high average SQI with low standard deviations (0.01-0.05), indicating that they had a more consistent SQI. Conversely, many of the villages that have high cultivation rates, i.e., Puttur and Keyyuru, have a larger dispersion in their SQIs (up to 1.07) and high standard deviations (0.11), indicating that they are more heterogeneous and have the greatest local variations due to anthropogenic activities. Overall, the SQI study indicates that land-use patterns, vegetation cover, and management practices affect the spatial variability of soil health in Puttur Taluk.

Table 8. Village-wise Statistics of Soil Quality Index

S. N	Village Name	Descriptive Statistics of SQI				
		MIN	MAX	RANGE	MEAN	STDEV
1	Ariyadka	1.80	2.45	0.64	2.16	0.11
2	Aryapu	2.01	2.60	0.59	2.24	0.09
3	Badaganuru	1.93	2.39	0.46	2.15	0.08
4	Olamogru	2.00	2.60	0.59	2.24	0.10
5	Balnadu	1.90	2.48	0.58	2.22	0.12
6	Bettampadi	2.07	2.60	0.52	2.32	0.08
7	Irdhe	2.00	2.41	0.40	2.28	0.08
8	Kedhambadi	2.00	2.51	0.51	2.32	0.12
9	Kemminje	2.00	2.31	0.31	2.17	0.06
10	Keyyuru	2.11	2.97	0.87	2.41	0.11
11	Kolthige	1.80	2.79	0.99	2.09	0.13
12	Kuriya	2.01	2.44	0.43	2.20	0.06
13	Madnuru	1.82	2.15	0.33	2.04	0.04
14	Munduru	1.81	2.50	0.69	2.20	0.11
15	Narimogru	2.00	2.79	0.79	2.20	0.12
16	Nettanige Mudnuru	1.81	2.54	0.72	2.07	0.05
17	Nidapalli	1.80	2.59	0.78	2.27	0.07
18	Padvunnur	1.86	2.24	0.37	2.05	0.07
19	Panaje	1.84	2.29	0.45	2.05	0.08
20	Puttur	1.49	2.56	1.07	2.22	0.12
21	Sarve	2.00	2.46	0.46	2.26	0.12
22	Shanthigodu	1.81	2.34	0.53	2.11	0.07
23	Bajtthuru	1.68	2.40	0.72	2.21	0.09
24	Bellipadi	2.00	2.26	0.26	2.10	0.04
25	Chikkamudnuru	1.60	2.23	0.63	1.96	0.11
26	Hirebandadi	2.00	2.60	0.60	2.24	0.12
27	Kabaka	2.26	2.79	0.53	2.46	0.09

28	Kodimbadi	2.01	2.60	0.59	2.30	0.12
29	Kudippadi	2.04	2.79	0.75	2.44	0.09
30	Nekkiladi	2.05	2.39	0.34	2.18	0.02
31	Uppinangadi	2.00	2.36	0.36	2.18	0.07
32	Reserve Forest	2.16	2.18	0.02	2.17	0.01
33	Bettampadi - Bantage RF	2.12	2.28	0.16	2.22	0.05
34	Badaganuru - Bantaje RF	2.13	2.22	0.09	2.18	0.02
35	Padvunnur - Kanadakada RF	1.98	2.12	0.14	2.04	0.03
36	Madnooru - Anegudi RF	2.06	2.13	0.07	2.09	0.01
37	Ariyadka - Kaniyaramale RF	1.95	2.29	0.34	2.13	0.09
38	Bannuru	1.99	2.30	0.31	2.20	0.07
39	Padnuru	2.22	2.58	0.36	2.36	0.07
40	Panaje - Bantage Reserved Forest	1.98	2.23	0.25	2.05	0.05
41	Madnooru - Kaniyaramale RF	2.03	2.25	0.21	2.11	0.06

5.7. Management Implications

There is a correlation between land use, soil chemical characteristics, and soil quality that establishes the necessity for specific soil management plans related to each land-use type for high rainfall-related laterite soils. The addition of organic matter through residue management, green manuring, and organic fertilizers will help to improve the amount of nutrient holding capacity and reduce leaching loss in agricultural areas. Implementation of balanced and site-specific nutrient management will help resolve nutritional deficiencies and improve fertilizer use efficiency. The combination of nutrient management practices (both organic and inorganic) and minimizing soil disturbance will assist in managing plantation crops. A suitable waste management and drainage system will be necessary to address localized degradation of volatile chemical soils in the inhabited and peri-urban areas. The combination of Level-III LULC classification, GIS-based soil mapping, and analysis of SQI permits complete coverage of the land-use planning process, and therefore establishes quantifiable soil quality restrictions at a more detailed spatial level for the long-term preservation of soil fertility and ecologically sustainable development in the Western Ghats area.

6. Conclusion

The soil chemical property changes caused by land use are significant across 145 georeferenced soil samples from Puttur Taluk, which show soil conditions to be mostly acidic with a pH range of 4.66 to 6.82. Electrical conductivity suggests that the majority of the area has non-saline conditions. There are localized areas in some villages that show areas of salinity. Major macronutrient spatial variability is high, and this is due to a combination of natural and anthropogenic factors, which include: Organic Carbon, Nitrogen, Phosphorus, Potassium, and Sulphur.

The majority of villages in the SQI (Soil Quality Index) show moderate soil fertility values (SQI 1.6 – 2.5). These soils should be managed through general agronomic practices, ensuring that any phosphorus and potassium supplementation added is done at the appropriate rate to ensure the sustainability of the soil. Villages that have SQI values, maximum ranges of pH, and balanced nutrient availability include Kabaka, Puttur, Kudippadi, Bellipadi, and adjacent forest locations. Such locations should be advantageous to high-value or high-yield crops. Kuriya, portions of Munduru, and adjacent open spaces have SQI values that are low. The soils are highly acidic, low in phosphorus and organic matter, necessitating soil conservation of these soil sites and/or phosphorus supplementation.

Overall, the patterns of soil quality seen across Puttur Taluk are consistent with the findings of several worldwide studies, which indicate that land use has a significant impact on the accumulation, cycling, and depletion of nutrients within the soil system. The findings are given credence and placed into a well-established scientific discourse by this convergence with the broader LULC–SQI literature. However, the study adds much more than just confirmation. The Western Ghats are an ecologically complex, hydrologically intense, and geologically old terrain whose lateritic soils react to land-use stresses in ways that are not completely represented in research done elsewhere. Engaging that complexity through a Level-III LULC classification —

one sensitive enough to distinguish forest types, plantation systems, and agricultural practices — and grounding the analysis in GIS-based spatial mapping produces a granularity of understanding that coarser international studies, however rigorous, cannot replicate for this region.

Although various researchers have worked extensively in exploring the effect of land use on soils, there is still little information available regarding how Level-III LULC classification affects soil chemical variability in high rainfall tropical regions. Most of the existing literature is based on large-scale land use classification, which does not consider local variability in soils. In this context, it is clear that the application of Level-III LULC classification is an important contribution to the field of land use classification in exploring spatial soil quality assessment.

In conclusion, the findings highlight the need for soil mapping on the village level and the need to implement site-specific soil management practices for improving agricultural productivity and maintaining an ecological balance for sustainable land use in Puttur Taluk.

Study Limitations and Future Research Directions

The experiment is centered on the surface soil features, which are of the utmost importance to the land management practices and can be directly applied to the agricultural productivity and ecosystem operation. Future research can build on this basis by undertaking further evaluation to deeper layers of soil in order to further explain the vertical distribution of nutrients and the processes in the sub-surface, especially regarding root growth and water flow.

The Soil Quality Index (SQI) produced during the research incorporates central chemical indicators, which are generally acknowledged to measure the fertility of the soil as well as the effects of land-use. Although chemical indicators provide vital data on the condition of soil, additional research may provide benefits to this framework, requiring the integration of chosen physical and biological parameters, which will simplify a more comprehensive evaluation of soil functioning under various management regimes.

In complex landscapes, the generated spatial patterns of interpolation techniques are useful for emphasizing regional trends in soil quality. Future research will be able to significantly enhance spatial forecasting and resolution, especially in complicated and steep topography, as remote sensing, digital soil mapping, and data-based modeling techniques develop.

Overall, the research's methodology and findings offer a strong scientific basis for evaluating the region's soil quality. The results can help with planning for sustainable land management and serve as a model for comparable high-rainfall regions. Long-term improved soil resource planning and environmental sustainability in the Western Ghats would be made possible by the further development of these findings through ongoing study.

Data Availability

The raw data underlying the results presented in this study are available from the corresponding author upon request.

Acknowledgements

We would like to express our gratitude to everyone who helped us throughout the process of completing this research work, including our teachers, students, families, reviewers, and friends.

Contributions

Prasad Pujar: conceptualization, data curation, formal data analysis, visualization, writing—original draft, and editing. Sowmya N J and Sandeep J Nayak: conceptualization, investigation, validation, writing.

Competing Interests

The authors declare no competing interests.

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