PLANT SCIENCE TODAY
Vol 12(sp4): 01–14
https://doi.org/10.14719/pst.11700

eISSN 2348-1900

RESEARCH ARTICLE

Geostatistical analysis of soil fertility and land resource inventory - Guided nutrient management strategies for improving soil health and agricultural productivity in the Bankanahalli micro-watershed

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Received: 09 September 2025; Accepted: 25 November 2025; Available online: Version 1.0: 04 January 2026

Cite this article: Girish KS, Fathima PS, Yogananda SB, Ananthakumar MA, Thimmegowda P, Sathish A. Geostatistical analysis of soil fertility and land resource inventory - Guided nutrient management strategies for improving soil health and agricultural productivity in the Bankanahalli micro-watershed. Plant Science Today. 2025;12(sp4):01–14. https://doi.org/10.14719/pst.11700

Abstract

Soil fertility variability is an important factor that affects nutrient use efficiency and crop productivity in varied landscapes. This variability stands out in semi-arid regions. Here, using general fertilizer recommendations often causes nutrient imbalances, lowers soil health and results in lower crop yields. In this context, present study was conducted in Bankanahalli micro-watershed of Mandya district of Karnataka state to evaluate the spatial variability of soil physico-chemical properties and develop site-specific nutrient management strategies. A total of 45 gridbased soil samples were collected and analysed for pH, electrical conductivity (EC), organic carbon (OC), available nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O). Geostatistical approaches, including semivariogram modelling and kriging interpolation, were employed to generate spatial variability maps. Best-fitted semivariogram models were identified using RMSE, nugget/sill ratio and range values, highlighting strong to moderate spatial dependence across nutrients. The results revealed that soil pH ranged from slightly alkaline to strongly alkaline, while organic carbon (OC) content ranged from low to medium. Available nitrogen (N) and potassium (K_2O) were deficient, whereas phosphorus (P_2O_5) was relatively abundant across the study area. A correlation matrix and principal component analysis (PCA) biplot were developed to examine interrelationships among soil parameters. Spatial maps identified nutrient-deficient and nutrient-rich zones, while correlation and PCA analyses showed strong relationships of pH and EC with K_2O and OC with N availability. Based on these outputs, nutrient management strategies were developed under Low-High (L-M-H) and very low-very high (VL-L-M-H-VH) classification schemes, demonstrating significant potential for fertilizer savings and improved input efficiency. Integrating spatial variability analysis with land resource inventory (LRI)-based nutrient management strategies, along with green manuring and mulching, was effective in maintaining soil health and boosting crop productivity within the micro-watershed.

Keywords: micro-watershed; nutrient management strategies; ordinary kriging; principal component analysis; spatial variability mapping

Introduction

Soil fertility assessment forms the foundation for sustainable agricultural productivity, as it directly governs crop growth, nutrient availability and long-term soil health (1). However, soils in semi-arid regions are inherently heterogeneous in their physical and chemical properties, resulting in uneven nutrient distribution and reduced nutrient use efficiency when uniform fertilizer recommendations are applied (2). In this context, geostatistical assessment offers powerful tools to quantify spatial variability of soil properties, using semivariogram modelling and kriging interpolation to generate reliable maps that support site-specific management decisions (3, 4).

Soil fertility encompasses both the capacity of soil to supply essential nutrients and its physical-chemical environment that supports root growth. Variability in parameters such as soil pH, electrical conductivity (EC), organic carbon (OC) and available macronutrients (N, P_2O_5, K_2O) critically influence nutrient cycling and crop performance (5). Understanding this variability is essential in semi-arid zones, where soils are often low in nitrogen and potassium but enriched in phosphorus due to continuous imbalanced fertilization.

To address this, Land Resource Inventory (LRI)-based nutrient management strategies have emerged as a promising approach. LRI integrates soil survey, spatial mapping and landscape information to delineate management zones and recommend appropriate nutrient interventions (6). By incorporating practices such as green manuring, mulching and crop-specific fertilizer scheduling, LRI-based nutrient management promotes balanced nutrient application, reduces input wastage and enhances soil resilience (7).

The ultimate goal of these strategies is to enhance soil health and crop productivity through balanced and efficient nutrient management. Soil health goes beyond fertility, encompassing soil structure, biological activity and its ability to support ecosystem services. Nutrient-efficient practices restore soil organic matter, enhance microbial activity and improve nutrient-use efficiency, thereby contributing to sustainable productivity (8). Several studies have demonstrated that site-specific and integrated nutrient management practices significantly improve crop yields while reducing fertilizer costs and environmental risks (9, 10).

The present study was conducted in the Bankanahalli micro-watershed, situated in the semi-arid region (southern dry zone) of Karnataka, India, where soils are heterogeneous and farmers largely depend on rainfed agriculture. Blanket fertilizer recommendations in this region often lead to nutrient imbalances, reduced yields and soil degradation. Therefore, a geostatistical approach was employed to assess spatial variability of soil fertility parameters and develop LRI-based nutrient management strategies tailored to the micro-watershed. The outcomes aim to demonstrate how integrating geostatistics with LRI can serve as a practical pathway for enhancing soil health, saving fertilizers and maximizing crop productivity in smallholder farming systems.

The objectives of this study were to: (a) assess the spatial variability of key soil physico-chemical properties using geostatistics; (b) identify interrelationships among these properties using PCA; and (c) evaluate the efficacy of different LRI-based nutrient management strategies on soil health and maize productivity.

Materials and Methods

Study area

The present investigation was conducted in the Bankanahalli micro-watershed (4B3C3F1b), situated in Mandya Taluk of Mandya District, Karnataka state, India (Fig. 1). The watershed is part of the Dudda sub-watershed and covers approximately 489 ha. Geographically, it lies between 76°45′0″ to 76°46′30″ E longitude and 12°35′0″ to 12°36′0″ N latitude. The soils of the region are predominantly red sandy loams, derived from granite and gneiss parent material, with variable depth and fertility status. The climate is semi-arid tropical with moderate rainfall (633.91 mm), primarily received during the southwest monsoon. The watershed typifies the southern dry zone of Karnataka, characterized by predominantly rainfed agriculture. In this region, variability in soil fertility across the landscape is a key factor affecting nutrient use efficiency and overall crop productivity.

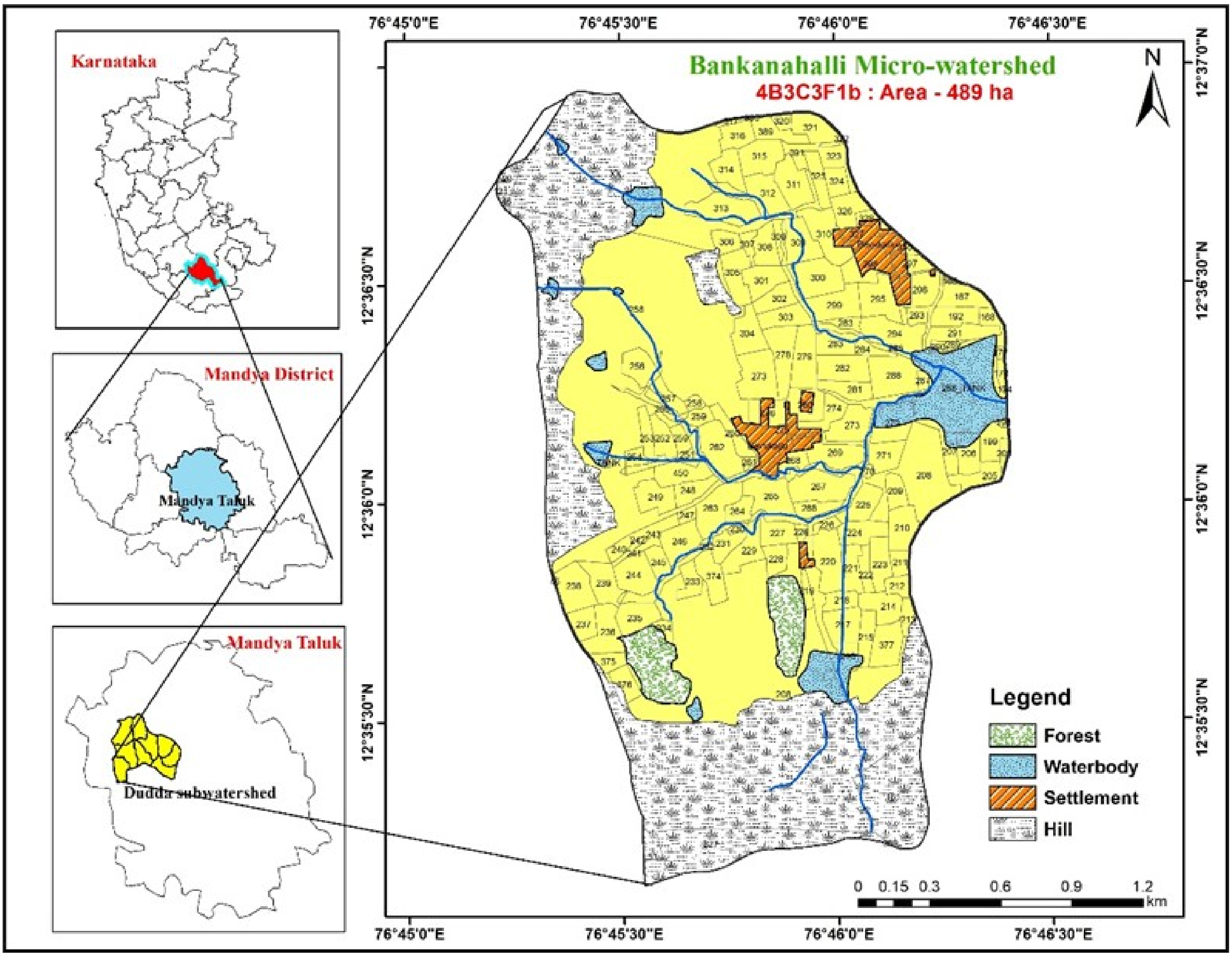

Fig. 1. Location map of the study area.

Soil sampling and analysis

Soil sampling was carried out in the Bankanahalli micro-watershed using a systematic grid approach (320 x 320 m) to capture the spatial variability of soil properties. A total of 45 geo-referenced surface soil samples (0-15 cm depth) were collected using a stainless-steel auger at the intersections of the predetermined grid points. The geographical coordinates of each sampling location were recorded using a handheld GPS device to facilitate spatial analysis and preparation of thematic maps. The collected samples were air-dried in shade, gently crushed and passed through a 2 mm sieve before laboratory analysis. The collected soil samples were analyzed for key physico-chemical properties following standard procedures. Soil pH and electrical conductivity (EC) were measured 1:2.5 soil-water suspension using a digital pH meter and conductivity bridge, respectively (11). Organic carbon (OC) was estimated by the Walkley and Black's wet oxidation method (12). Available nitrogen (N) was determined using the alkaline $KMnO_4$ method (13), while available phosphorus (P_2O_5) was extracted by the Olsen method for neutral to alkaline soils or Bray's method for acidic soils (14). Available potassium (K_2O) was extracted with neutral normal ammonium acetate and measured using a flame photometer (15).

Spatial variability assessment

The spatial variability of soil properties (pH, EC, OC, N, P_2O_5 and K_2O) was assessed using a geostatistical approach. Experimental semivariogram models were developed to quantify the spatial dependence and suitable theoretical models were fitted based on the lowest RMSE (Root mean square error), nugget, P- sill (Partial sill) and major range. The best fitted semivariogram models were then used for ordinary kriging interpolation in ArcGIS 10.5 to generate range maps. These range maps provided a visual representation of nutrient distribution and delineated zones of low, medium and high fertility status, which formed the basis for site-specific nutrient management.

PCA analysis and correlation matrix analysis

To explore relationships among soil properties, Principal Component Analysis (PCA) was performed using R studio on standardized data of pH, EC, OC, available N, P_2O_5 and K_2O. Principal Component Analysis (PCA) reduced the dataset's dimensionality and identified the key factors contributing to spatial variation in soil fertility. A biplot was constructed to visualize soil variables (loadings) and sampling points (scores) in a two-dimensional space, helping to interpret correlations, clustering of soil samples and dominant factors influencing nutrient distribution.

Additionally, a correlation matrix was created to measure the pairwise linear relationships among soil properties. Pearson's correlation coefficients were computed and the results were represented both numerically and through a correlation heat map. This helped in identifying significant positive or negative associations among soil properties (e.g., OC-N, pH, EC and K_2O relationship), which complemented the PCA findings.

Field experiment on nutrient management strategies

Results from the PCA biplot and correlation matrix analysis revealed the main soil fertility factors and how nutrients relate to each other. A field experiment was conducted in the Bankanahalli micro-watershed to assess the effects of different nutrient management strategies on soil health and crop productivity. The treatments were designed considering the spatial variability of nutrients and their associations, with the aim of developing a best-fit nutrient management plan for enhancing crop productivity and nutrient use efficiency.

The experiment was laid out in a randomized block design (RCBD) with 12 treatments and 3 replications. The treatments included: T_1: UAS Package of practices, T_2: LRI based NMP-I i.e. L, M, H approach, T_3: LRI based NMP-II i.e. VL, L, M, H, VH approach, T_4 GM (Sunhemp) fb Maize with T_2, T_5: GM (Sunhemp) fb Maize with T_3, T_6: Maize + Green gram intercrop with T_2, T_7:Maize + Green gram intercrop with T_3, T_8: Maize + mulching (Green leaf/crop residue) with T_2, T_9: Maize + mulching (Green leaf/crop residue) with T_3,T_{10}: GM (Sunhemp) fb Maize + mulching (Green leaf/crop residue) with T_2, T_{11}: GM (Sunhemp) fb Maize + mulching (Green leaf/crop residue) with T_3, T_{12}: Absolute control.

In this study, Nutrient Management Plans (NMP-I and NMP-II) were developed based on soil nutrient categories. NMP-I used a Low-Medium-High (L-M-H) approach, while NMP-II employed a Very Low-Low-Medium-High-Very High (VL-L-M-H-VH) approach. Fertilizers were applied according to these categories, using the threshold values listed in Table 1. To evaluate best nutrient management plan for crop productivity, Growth parameters like dry matter production, RGR, CGR, AGR were computed. Grain and straw yield, nutrient uptake were recorded at harvest. Change in pH, EC, OC due to different nutrient management strategies were recorded.

Results

Assessment of spatial variability

Semivariogram modelling and kriging interpolation

The semivariogram parameters for soil properties are presented in Table 2, showing the best-fit model, RMSE, nugget, partial sill and range. Model selection was based on the lowest root mean square error (RMSE) value (16), which reflected diverse spatial structures among different soil nutrients. Recent studies have shown that the nugget-to-sill ratio is a reliable indicator of spatial dependence, while the range parameter defines the effective distance of spatial autocorrelation (17, 18).

Table 1. Thresholds for categorization of nutrients and Fertilizer requirement multiplication factors for different nutrient availability levels

Nutrient	VL	L	M	H	VH
Nitrogen (N (Kg ha^{-1}))	<140	140-280	280-560	560-700	>700
Phosphorus (P_2O_5, (Kg ha^{-1}))	<11.45	11.45-22.90	22.91-57.25	57.26-91.60	>91.60
Potassium (K_2O, (Kg ha^{-1}))	<72.3	72.3-144.6	144.7-337.4	337.5-674.8	>674.8
Multiplication factors for different nutrient availability levels of N, P_2O_5, K_2O	RDF × 1.67	RDF × 1.33	RDF × 1.00	RDF × 0.67	RDF × 0.33

(Source: DSS for crop based nutrient management and soil health, Sujala-III, Watershed Development Department, GoK, Bengaluru)

Table 2. Semivariogram model parameters for soil fertility attributes in Bankanahalli micro watershed

Nutrient	Model	RMSE	Nugget (a)	P Sill (b)	Sill (a+b)	Nugget/sill ratio (%) [(a/a+b)]100	Spatial class	Range (m)
Soil reaction (pH)	Exponential	0.562	0	0.351	0.351	0	Strong	651.26
Electrical conductivity (EC)	Gaussian	0.074	0.0006	0.0104	0.011	5.45	Strong	638.68
Organic carbon (OC)	Spherical	0.204	0.00019	0.0519	0.05209	0.36	Strong	638.68
Nitrogen (N)	Exponential	80.27	0	22592.1	22592.1	0	Strong	2062.08
Phosphorus (P_2O_5)	Spherical	15.85	119.09	166.43	285.52	41.71	moderate	706.46
Potassium (K_2O)	Circular	56.63	1851.4	2894.2	4745.6	39.01	moderate	1288.06

Nugget/sill ratio (%) = [$a/(a+b)$] × 100. Strong =% nugget <25%; moderate =% nugget 25-75%; random =% nugget >75% (48).

The fitted semivariogram models indicated that soil properties exhibited moderate to strong spatial dependence across the watershed. Soil reaction (pH) followed an exponential model with zero nugget and a range of 651.26 m, suggesting a continuous and predictable pattern of spatial variability. EC and OC were best explained by Gaussian and spherical models respectively, with short ranges (638.68 m), indicating localized variability influenced by land use and management practices (19). Nitrogen variability extended over a longer range (2062 m) under the exponential model, showing broader-scale heterogeneity, while phosphorus followed a spherical model with moderate nugget to sill ratio, reflecting patchy distribution due to fixation and fertilization practices. Potassium exhibited a circular model with a high sill value and long range (1288 m), suggesting strong structural control by parent material and soil texture. Similar results were reported (20, 21). Overall, the nugget-to-sill ratios showed that most soil parameters had a strong level of spatial dependence, justifying the use of kriging interpolation to create accurate nutrient distribution maps.

Spatial heterogeneity of soil properties across Bankanahalli micro-watershed

To visualize nutrient distribution across the Bankanahalli micro-watershed, spatial variability maps were produced using ordinary kriging based on semivariogram modelling. These maps classified pH, EC, OC, N, P_2O_5 and K_2O into fertility zones ranging from low to high and facilitated the identification of target areas for site-specific nutrient management.

The spatial variability map of soil reaction (pH) in the Bankanahalli micro-watershed (Fig. 2) revealed a wide range from slightly acidic (6.32) to moderately alkaline (8.64). Central and southern pockets showed neutral to slightly alkaline conditions (pH 6.5-7.5), while the northern and north-eastern zones exhibited higher alkalinity (pH > 8.0). Such heterogeneity reflects topographic influence, land use and soil management practices, which play a critical role in nutrient availability and crop response (22, 23). The spatial distribution of electrical conductivity (EC) in the Bankanahalli micro-watershed shows considerable variability

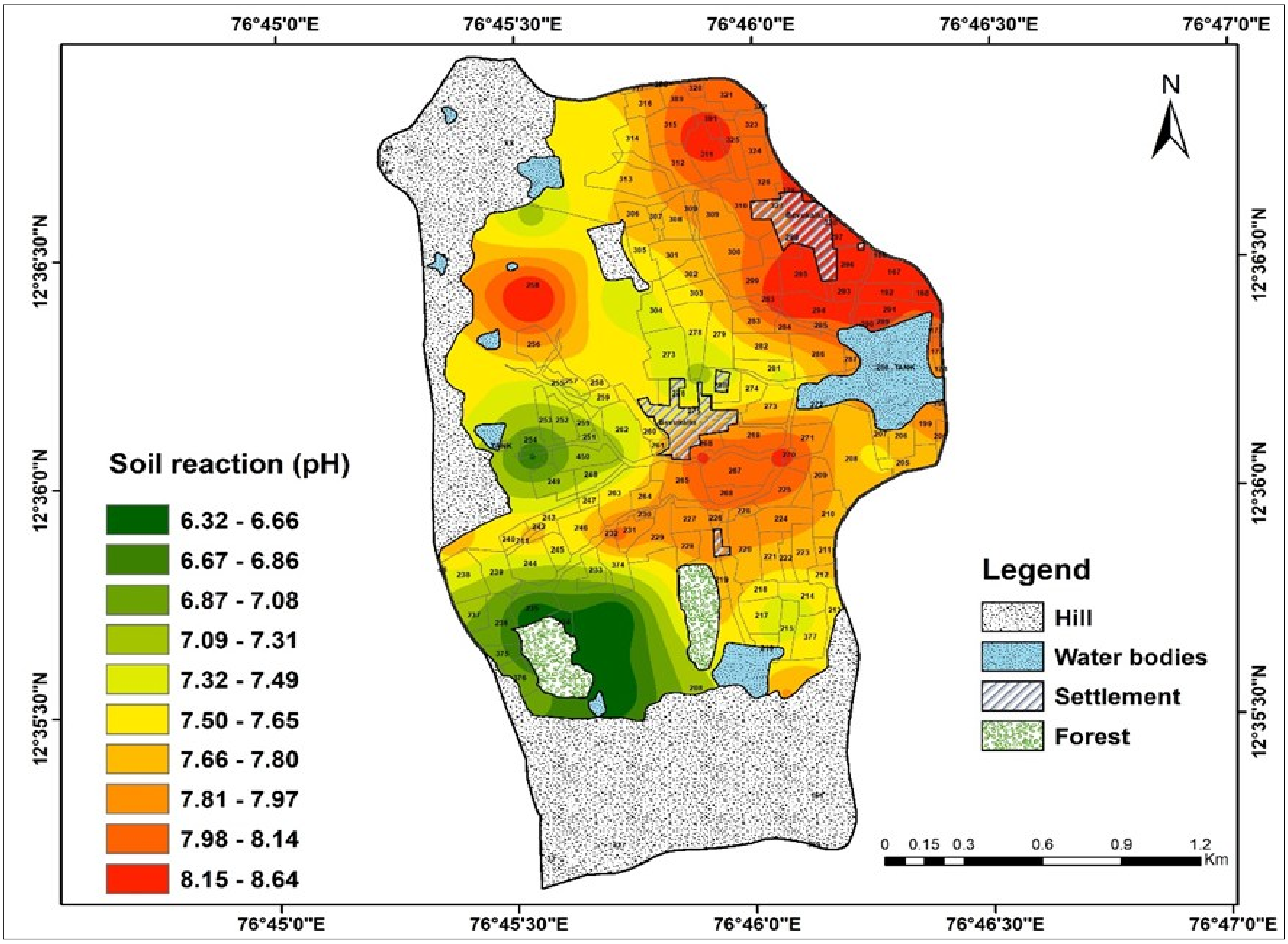

Fig. 2. Spatial distribution of soil reaction (pH).

ranging from 0.015 to 0.461 dS m^{-1} (Fig. 3). The majority of the area falls under low EC classes (0.015-0.132 dS m^{-1}), particularly concentrated in the southern and southwestern zones, indicating normal salt levels suitable for crop growth. In contrast, higher EC values (0.285-0.461 dS m^{-1}) are localized in the north-eastern and central parts of the watershed, reflecting moderate salt accumulation, likely due to irrigation return flows, reduced drainage, or soil texture effects.

The spatial variability of organic carbon (OC) in the Bankanahalli micro-watershed ranged from 0.06 to 0.84 % (Fig. 4), reflecting distinct fertility gradients. The northwestern and northeastern parts of the watershed exhibited very low to low OC levels (0.06-0.25 %), likely due to intensive cultivation, residue removal and low biomass return to the soil. In contrast, higher organic carbon (OC) content (0.51-0.84 %) was observed in the central and southern regions, as well as in a few isolated pockets of the watershed. This enrichment can be attributed to forest cover, settlement areas with the addition of organic waste and reduced soil erosion. Overall, the watershed shows a moderate to low level of organic matter, highlighting the importance of organic matter enrichment practices such as green manuring, crop residue recycling and the application of farmyard manure (FYM) or compost to maintain soil fertility and improve nutrient use efficiency (24, 25).

The nitrogen variability map (Fig. 5) reveals that the northern and eastern hill-forest regions of the micro-watershed have low available nitrogen (119.17-205.05 kg ha^{-1}), while the central and southern cultivated areas show medium to high nitrogen levels (271.93-392.35 kg ha^{-1}). Pockets in the southern fields record very high nitrogen availability (443.14-567.62 kg ha^{-1}), likely due to continuous fertilizer application. This indicates that while some regions require nitrogen supplementation, others need judicious application to prevent nutrient imbalance and losses (26). The available phosphorus status in the micro-watershed ranged from 16.42 to 84.17 kg ha^{-1} (Fig. 6). The northern and northeastern regions (hill-forest areas) recorded the lowest phosphorus availability (16.42-26.02 kg ha^{-1}), while the southern and central cultivated zones showed very high accumulation (46.48-84.17 kg ha^{-1}). This pattern reflects higher fertilizer usage and possible phosphorus build up in intensively farmed areas, whereas hilly and less-cultivated zones remain phosphorus deficient, indicating the need for balanced and site-specific phosphorus management. Overall, phosphorus showed strong spatial variability, with low to moderate availability in uplands and very high levels in southern cultivated fields, necessitating rational input management to avoid further imbalance (27). The available potassium status in the micro-watershed ranged from 24.24 to 236.88 kg ha^{-1} (Fig. 7). The southern and southwestern hilly-forest regions recorded the lowest potassium availability (24.24-62.13 kg ha^{-1}), whereas the central to eastern cultivated zones showed very high accumulation (157.60-236.88 kg ha^{-1}). This spatial pattern indicates potassium depletion in upland areas due to leaching and erosion. Conversely, higher K levels in intensively cultivated zones may result from repeated fertilizer applications and low crop uptake. These findings emphasize the importance of site-specific potassium management to address deficiencies and prevent nutrient mining.

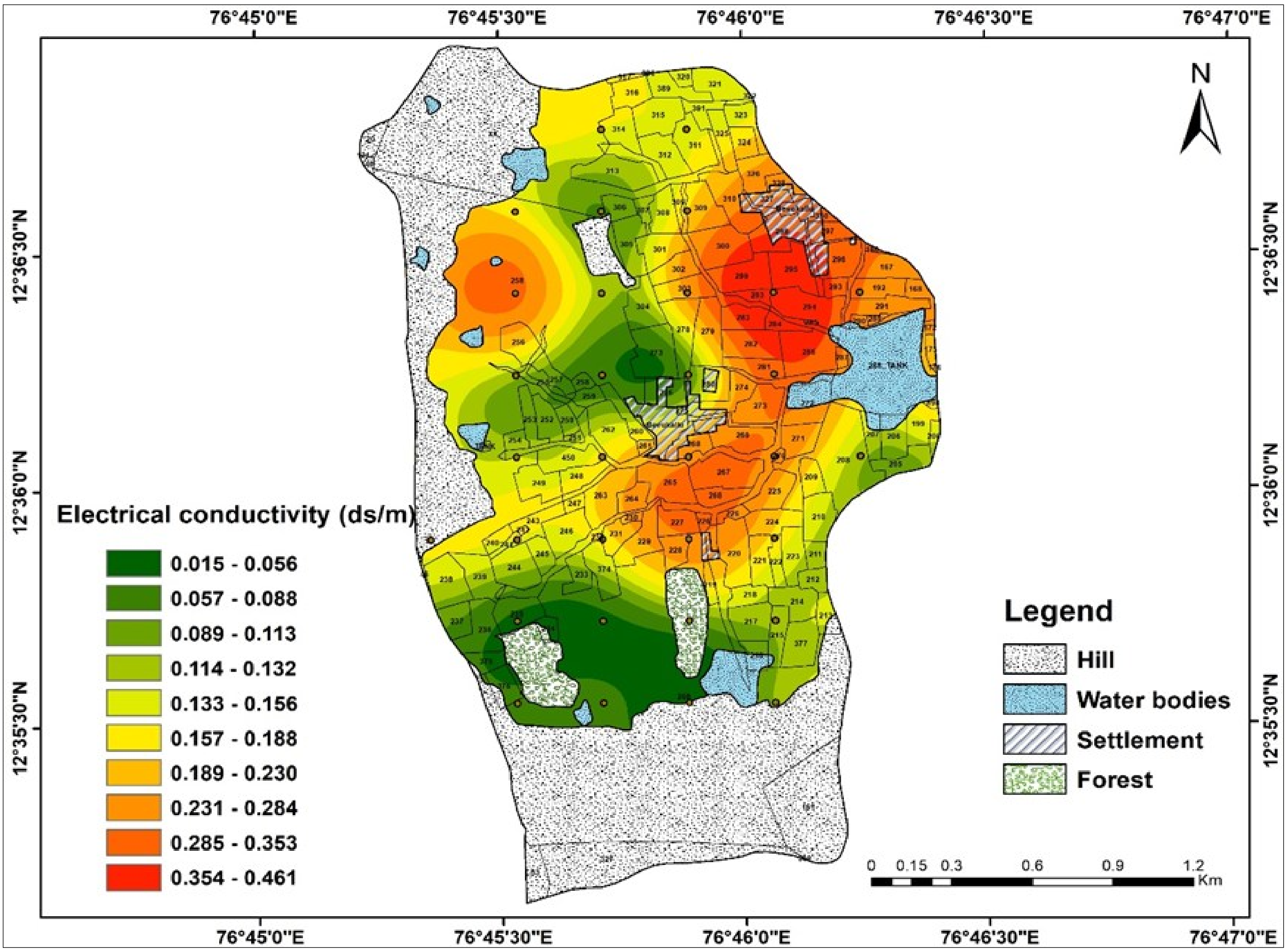

Fig. 3. Spatial distribution of electrical conductivity.

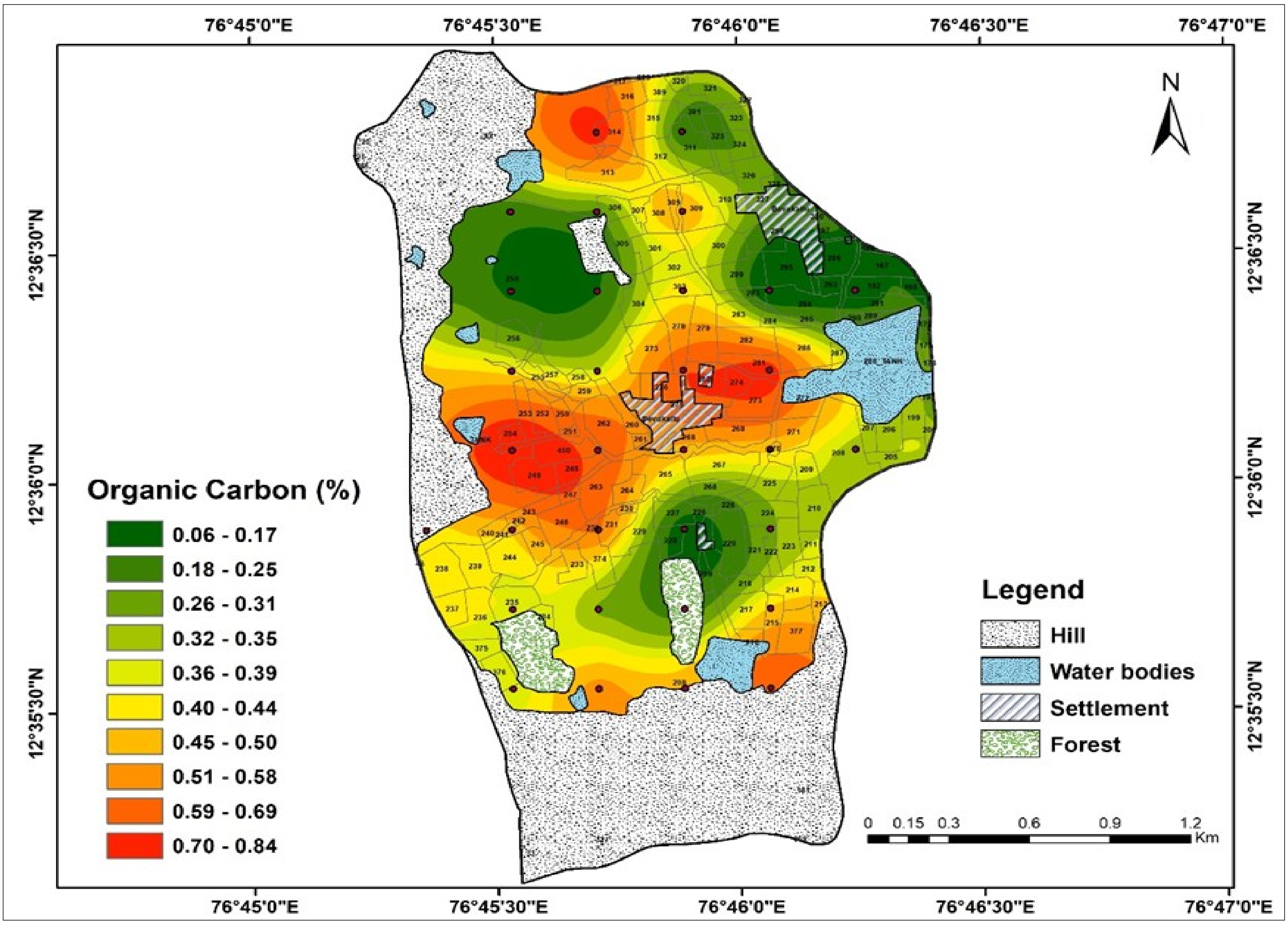

Fig. 4. Spatial distribution of organic carbon.

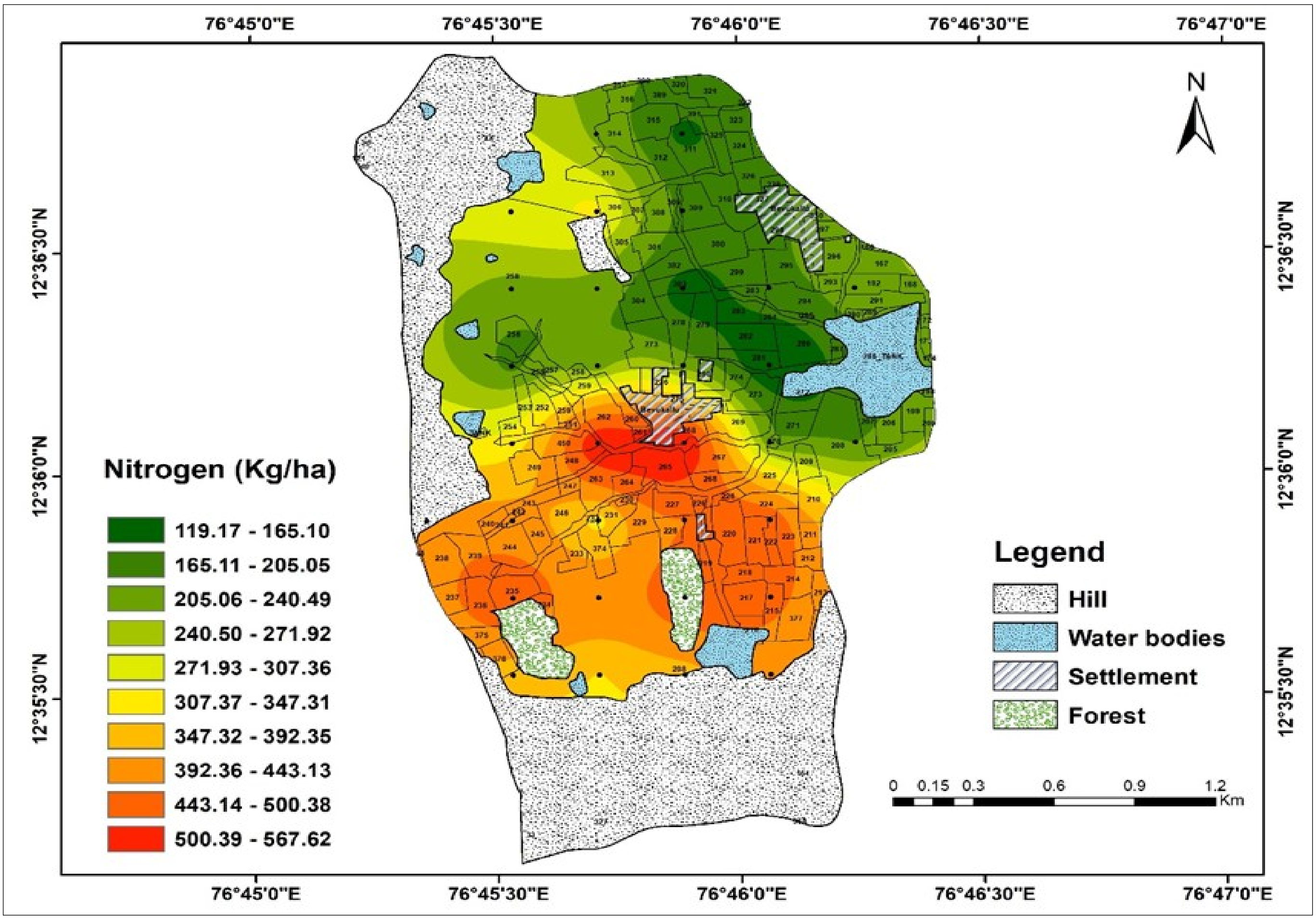

Fig. 5. Spatial distribution of nitrogen in Bankanahalli micro-watershed.

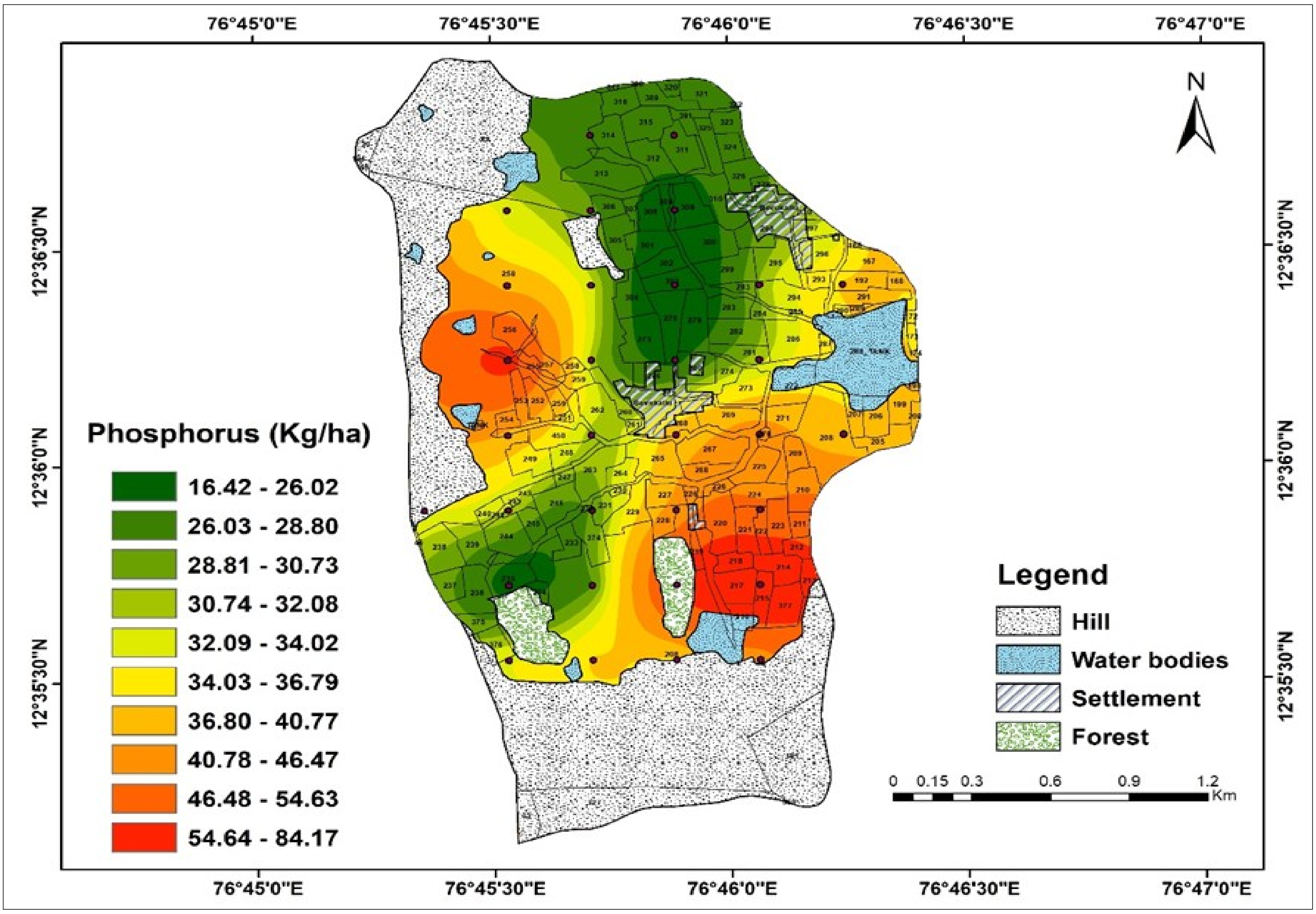

Fig. 6. Spatial distribution of phosphorus in Bankanahalli micro-watershed.

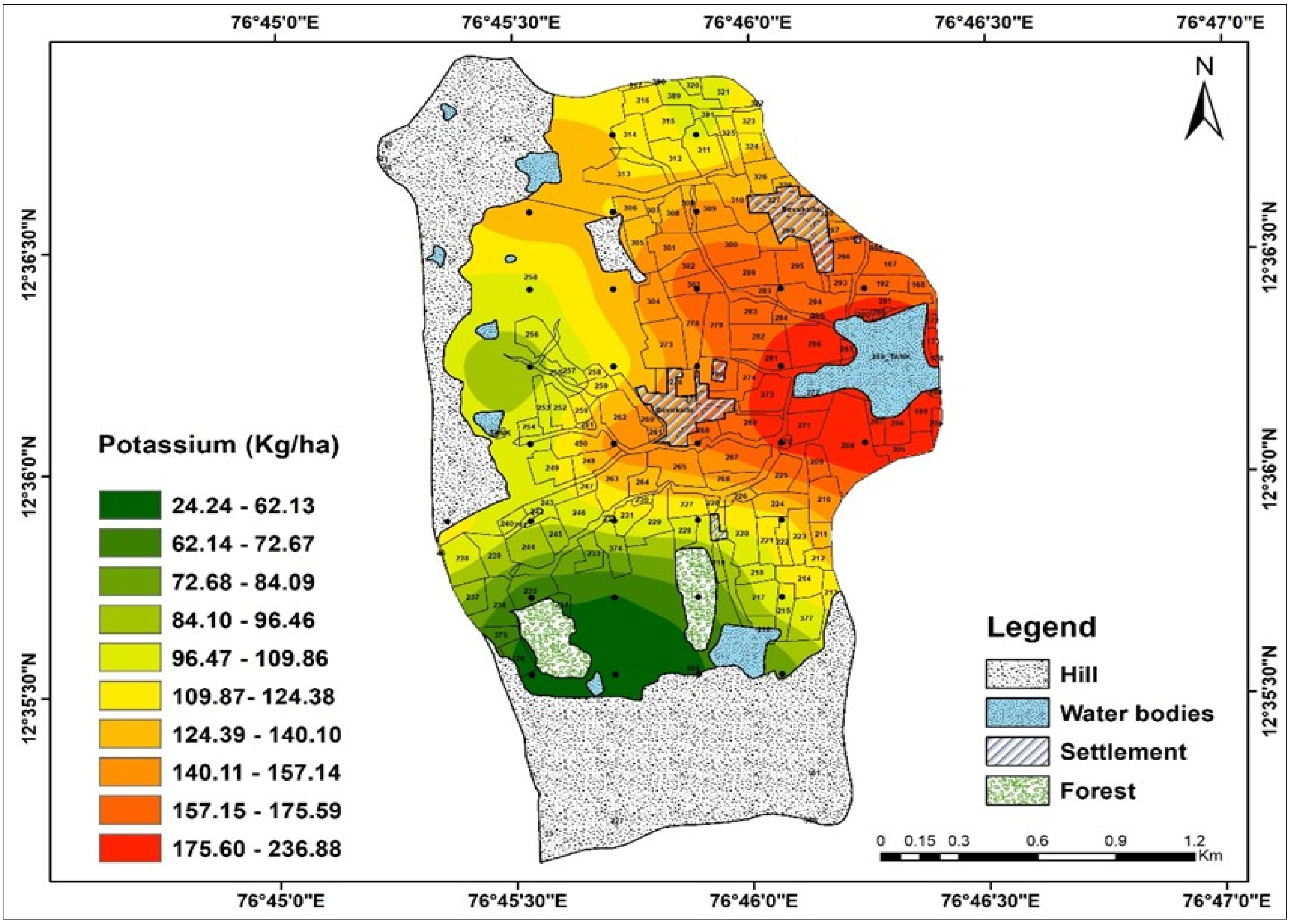

Fig. 7. Spatial distribution of potassium in Bankanahalli micro-watershed.

Visualization of soil property interactions using principal component analysis (PCA)

To understand the interrelationships among soil physico-chemical properties and nutrient availability, a PCA biplot (Fig. 8) was constructed, providing a multivariate perspective of soil variability across the micro-watershed. This approach reduces dimensionality while retaining maximum variability, thereby highlighting the most influential factors governing soil fertility (28- 30). The biplot provides a clear visual representation of how soil properties are interrelated and how they vary spatially across the micro-watershed. Such analysis is crucial for identifying nutrient linkages and prioritizing site-specific management practices.

The principal component analysis (PCA) biplot clearly distinguished the relationships among soil properties and sampling sites within the micro-watershed (Fig. 8). Organic carbon (OC) and available nitrogen (N) vectors were closely aligned, indicating a strong positive correlation, which reflects the role of organic matter in contributing to soil N availability. Available phosphorus (P_2O_5) vector was oriented separately and strongly associated with a cluster of samples *viz.,* 7, 8, 12, 13, 19), suggesting localized P enrichment, likely due to imbalanced fertilizer application practices as reported by (31). Potassium (K_2O) loaded prominently on PC1 and was linked with samples 22, 25 and 30, showing spatial variability in K status across the watershed.

Soil reaction (pH) and electrical conductivity (EC) vectors were positively correlated and associated with samples 23, 26 and 27, indicating areas with alkaline and slightly saline tendencies, a pattern consistent with findings of (32). In the PCA biplot, soil pH and electrical conductivity (EC) vectors were positioned close to each other and showed a positive relationship with available potassium (K_2O), indicating that these variables are firmly connected and likely affected by similar soil formation or management factors. Higher soil pH in alkaline soils is often linked with enhanced K availability due to increased release from exchange sites and mineral reserves (33). Similarly, elevated EC reflects higher soluble salt concentrations, including potassium ions, making EC a useful proxy for K_2O status in soils (34). The observed association suggests that in the studied micro-watershed, areas with relatively higher pH and EC also tend to show higher available K_2O, possibly due to the release of exchangeable K from clay minerals under alkaline conditions. However, this also highlights the risk of nutrient imbalance because higher pH and EC can reduce the availability of other essential nutrients like phosphorus and micronutrients (35). Thus, while K_2O availability appears to increase with pH and EC, balanced fertilizer application and soil amendments such as organic matter incorporation are necessary to mitigate secondary nutrient limitations.

These results highlight the need of site-specific nutrient management strategies rather than blanket recommendations and organic inputs like green manuring or mulching that are meant for enhancing both soil health and crop productivity through enhancing fertilizer use efficiency and buffering the soil properties for maintaining long-term soil quality in the micro-watershed (36).

Experimental results

The experiment was conducted to evaluate the efficiency of different nutrient management strategies, including green manuring, mulching, intercropping and LRI-based fertilizer plans (L, M, H/VL, L, M, H, VH approaches). These practices were assessed for their role in improving soil health and sustaining crop productivity in Bankanahalli micro-watershed. The results highlight comparative impacts of each strategy on soil properties and crop performance.

Effect of different nutrient management strategies on soil properties and crop performance in Bankanahalli micro-watershed

The data represented in Table 3 shows that, the initial soil pH of the experimental site was alkaline, ranging from 8.32 - 8.42 across treatments. A slight reduction in pH was observed after crop harvest, with the maximum decrease recorded in T_{11} (8.42 to 8.13) and T_{10} (8.36 to 8.08), while other treatments exhibited only

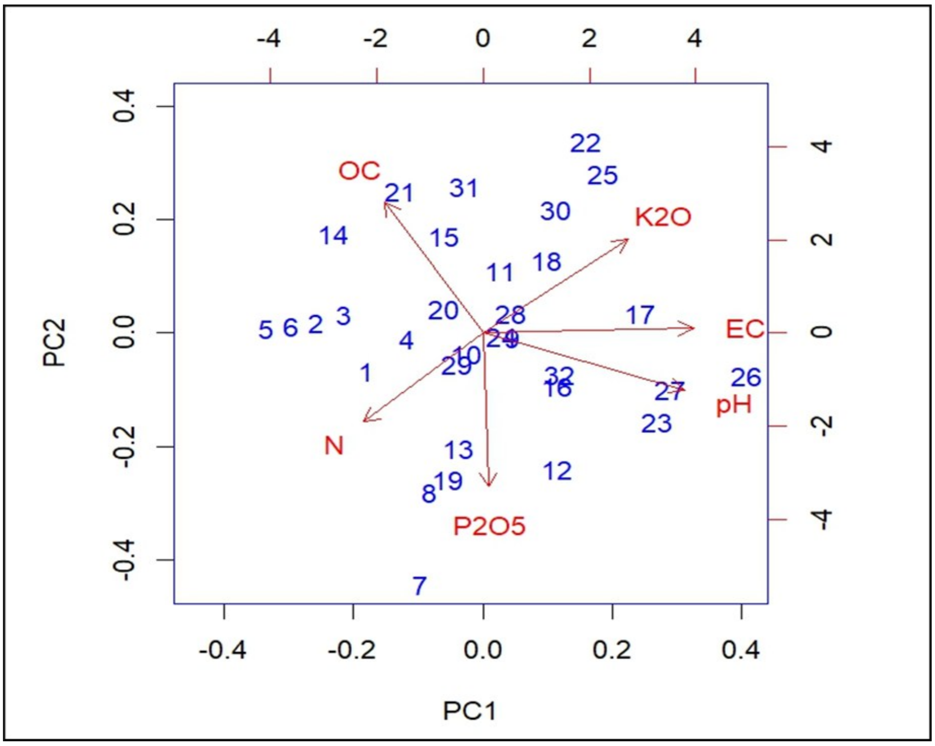

Fig. 8. Biplot depicting variability and associations among soil fertility parameters.

Table 3. Effect of different nutrient management strategies on soil properties, total dry matter production, yield and harvest index of maize in Bankanahalli micro-watershed

Treatments	pH (Before)	pH (After)	EC (dSm^{-1}) (Before)	EC (dSm^{-1}) (After)	OC (%) (Before)	OC (%) (After)	Total dry matter production (gm plant^{-1})	Grain yield (Kg ha^{-1})	Stover yield (Kg ha^{-1})	Harvest index
T_1	8.32	8.30	0.48	0.47	0.51	0.51	313.78	5703	6361	0.473
T_2	8.38	8.36	0.51	0.50	0.50	0.51	321.83	5967	6574	0.476
T_3	8.40	8.38	0.49	0.48	0.52	0.53	326.75	6012	6581	0.477
T_4	8.37	8.12	0.44	0.41	0.51	0.57	384.26	7736	8222	0.482
T_5	8.35	8.09	0.48	0.45	0.52	0.58	391.03	7885	8438	0.483
T_6	8.36	8.28	0.47	0.45	0.52	0.55	(340.79 + 16.73)*	(6470 + 683)*	(7132 + 1420)*	0.455*
T_7	8.42	8.33	0.46	0.44	0.53	0.56	(346.55 + 17.36)*	(6571 + 710)*	(7246 + 1477)*	0.454*
T_8	8.33	8.21	0.51	0.49	0.50	0.54	375.14	7287	7941	0.478
T_9	8.41	8.29	0.49	0.47	0.53	0.57	376.47	7355	8028	0.478
T_{10}	8.36	8.08	0.48	0.44	0.51	0.57	399.89	8463	8975	0.484
T_{11}	8.42	8.13	0.47	0.42	0.50	0.58	407.81	8573	9089	0.484
T_{12}	8.40	8.41	0.45	0.45	0.52	0.50	222.72	2974	3445	0.464
S.Em±	0.09	0.29	0.02	0.02	0.01	0.01	11.21	469.06	274.38	0.01
C.D.	NS	NS	NS	0.05	NS	0.04	32.87	1375.79	804.78	NS

*System observation (Maize and Green gram)

marginal changes. Electrical conductivity (EC) values remained within safe limits (<0.5 dS m^{-1}) throughout, with the greatest reduction noted in T_{11} (0.47 to 0.42 dS m^{-1}) and T_{10} (0.48 to 0.44 dS m^{-1}). Soil organic carbon (OC) content increased under nutrient management practices that included organic amendments. The highest increase was observed in T_{11}(0.50 to 0.58 %) and T_{10} (0.51 to 0.57 %), followed by T_5 (0.52 to 0.58 %) and T_4 (0.51 to 0.57 %), while no appreciable change was recorded in T_{12}.

Total dry matter production differed significantly among treatments, with T_{11} (407.81 g plant^{-1}) and T_{10} (399.89 g plant^{-1}) recording the highest values, followed by T_5 (391.03 g plant^{-1}) and T_4(384.26 g plant^{-1}). Grain yield also reflected a similar trend, wherein T_{11} (8573 kg ha^{-1}) and T_{10} (8463 kg ha^{-1}) significantly outperformed other treatments. These were followed by T_5 (7885 kg ha^{-1}), T_4 (7736 kg ha^{-1}), T_9 (7355 kg ha^{-1}) and T_8 (7287 kg ha^{-1}). Intercropping treatments, T_6 (6470 + 683 kg ha^{-1}) and T_7 (6571 + 710 kg ha^{-1}), recorded moderate yields, whereas the lowest grain yield was recorded in T_{12} (2974 kg ha^{-1}).

A similar trend was observed in stover yield, with T_{11} (9089 kg ha^{-1}) and T_{10} (8975 kg ha^{-1}) being superior, followed by T_5 (8438 kg ha^{-1}), T_4 (8222 kg ha^{-1}) and T_9 (8028 kg ha^{-1}). Intercropping treatments (T_6 and T_7) recorded comparatively higher stover contribution from greengram in addition to maize biomass. Harvest index (HI) remained statistically non-significant, ranging from 0.454 to 0.484, with the highest values observed in T_{11} and T_{10} (0.484 each).

Overall, the results indicated that T_{11} and T_{10} were the most effective treatments, as they not only enhanced soil organic carbon and reduced pH and EC but also produced the highest dry matter, grain and stover yields.

Influence of nutrient management strategies on nutrient status of Bankanahalli micro-watershed

The initial nutrient status of the soil indicated medium fertility, with available nitrogen ranging from 139.45 to 163.66 kg ha^{-1}, phosphorus from 47.23 to 61.13 kg ha^{-1} P_2O_5 and potassium from 140.28 to 172.87 kg ha^{-1} K_2O across treatments. Considerable variation was observed in nutrient inputs due to different management strategies. The maximum nutrient addition was recorded in T_{11} [GM (Sunhemp) followed by maize + mulching with LRI-based NMP-II; 297.24:71.33:141.77 kg ha^{-1} N: P_2O_5: K_2O], followed by T_{10} [GM + mulching with LRI-based NMP-I; 270.75:86.99:138.96 kg ha^{-1}], whereas T_{12} (absolute control) received no nutrient addition (Table 4).

Table 4. Effect of nutrient management strategies on nutrient input, uptake and post-harvest soil fertility in maize field of Bankanahalli micro-watershed

Treatments	Initial Nutrient Status			Total nutrients added			Total uptake by crop			Total available nutrients after harvest		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
T_1	158.95	48.03	172.87	137.50	65.00	62.50	108.41	25.44	108.39	172.52	82.83	117.92
T_2	151.07	50.41	146.77	170.50	65.00	68.00	127.72	28.35	117.89	178.37	82.44	92.09
T_3	147.03	48.42	147.13	193.17	65.00	68.00	131.52	30.42	120.81	191.72	78.60	89.24
T_4	153.80	51.57	163.23	273.45	82.08	140.94	185.10	45.07	164.40	217.37	82.39	117.40
T_5	152.39	55.90	153.93	274.23	82.26	141.52	193.75	47.95	173.08	209.18	83.88	101.87
T_6	144.76	55.06	172.08	170.50	54.00	62.50	160.59*	34.25*	158.19*	142.08	70.76	72.54
T_7	144.51	56.99	141.72	181.83	54.00	70.75	167.91*	35.54*	165.00*	145.67	71.39	47.12
T_8	150.94	57.29	140.28	170.50	54.00	70.75	165.60	37.85	152.86	140.48	68.61	47.90
T_9	152.28	53.36	172.65	181.83	59.50	62.50	170.89	40.54	156.67	147.39	67.62	66.79
T_{10}	146.36	47.23	155.98	270.75	86.99	138.96	213.18	52.66	188.91	181.77	75.37	83.25
T_{11}	139.45	61.13	153.63	297.24	71.33	141.77	219.09	54.62	193.31	194.20	71.87	80.25
T_{12}	163.66	55.92	170.34	0.00	0.00	0.00	53.70	10.77	48.43	101.14	42.77	112.03
S.Em±	-	-	-	-	-	-	10.50	2.49	7.40	11.39	4.67	12.23
C.D.	-	-	-	-	-	-	30.80	7.32	21.70	33.41	13.71	35.87

Note: * System uptake of nutrients

Total nutrients applied = Nutrients applied through FYM (7.5 t ha^{-1}) + Green manuring (102.95, 103.73, 100.25, 104.08 kg ha^{-1} Nitrogen & 22.58, 22.76, 21.99, 22.83 kg ha^{-1} Phosphorus & 75.69, 76.27, 73.71, 76.52 kg ha^{-1} Potassium was supplied through in-situ green manuring of sunhemp in T_4, T_5, T_{10} & T_{11} treatments respectively on dry weight basis) + Through fertilizers (Urea, SSP and MOP)

Crop nutrient uptake differed significantly among treatments. The highest uptake of nitrogen (219.09 kg ha^{-1}), phosphorus (54.62 kg ha^{-1}) and potassium (193.31 kg ha^{-1}) was obtained in T_{11}, which was closely followed by T_{10} (213.18:52.66:188.91 kg ha^{-1} N:P:K). These were significantly superior to the green manuring alone treatments, T_5 (193.75:47.95:173.08 kg ha^{-1}) and T_4 (185.10:45.07:164.40 kg ha^{-1}). Intercropping treatments, T_6 (160.59:34.25:158.19 kg ha^{-1}) and T_7 (167.91:35.54:165.00 kg ha^{-1}), also improved nutrient uptake but remained lower than the combined GM + mulching systems. The lowest uptake was recorded in the absolute control (T_{12}; 53.70:10.77:48.43 kg ha^{-1}), highlighting the necessity of nutrient supplementation.

The residual nutrient status after harvest reflected the cumulative effect of the management practices. Available nitrogen was maximum in T_4 (217.37 kg ha^{-1}), followed by T_{11} (194.20 kg ha^{-1}) and T_{10} (181.77 kg ha^{-1}). Available phosphorus ranged from 42.77 to 83.88 kg ha^{-1}, with higher values in T_5 (83.88 kg ha^{-1}) and T_1 (82.83 kg ha^{-1}). Similarly, available potassium was highest in T_1(117.92 kg ha^{-1}) and T_4(117.40 kg ha^{-1}), whereas the intercropping and mulching treatments, particularly T_7 (47.12 kg ha^{-1}) and T_8 (47.90 kg ha^{-1}), showed relatively lower values due to higher crop extraction.

Overall, the combined practice of green manuring followed by maize with mulching under LRI-based nutrient management plan (T_{11} and T_{10}) was found to be most efficient, as it recorded the highest nutrient uptake while sustaining higher post-harvest nutrient availability, thereby demonstrating their effectiveness in enhancing nutrient use efficiency and maintaining soil fertility.

Effect of nutrient management strategies on growth rate indices of maize

The growth analysis parameters such as Absolute Growth Rate (AGR), Crop Growth Rate (CGR) and Relative Growth Rate (RGR) were significantly influenced by different nutrient management strategies (Fig. 9-11).

Absolute Growth Rate (AGR): Among the treatments, maximum AGR was recorded under T_{11} (5.71, 3.59 and 3.81 g plant^{-1} day^{-1} at 30-60 DAS, 60-90 DAS and harvest, respectively), closely followed by T_{10} (5.59, 3.54, 3.71) and T_5 (5.42, 3.47, 3.66) (Fig. 9). Incorporation of green manuring and mulching in conjunction with LRI-based nutrient management (T_{11} and T_{10}) consistently improved AGR compared to sole LRI-based nutrient management (T_2 and T_3). In contrast, the lowest AGR was observed in the absolute control (T_{12}: 3.75, 0.95, 2.37). The improvement in AGR under integrated strategies can be attributed to better nutrient synchrony, enhanced soil organic matter and favourable soil environment for root growth (37, 38).

Crop Growth Rate (CGR): CGR followed a similar trend, where T_{11} (31.69, 19.92, 21.18 g m^{-2} day^{-1}) recorded the highest values, followed by T_{10} (31.07, 19.69, 20.59), while the lowest was in T_{12} (20.84, 5.29, 13.16) (Fig. 10). The results clearly indicate that integration of organic inputs such as green manure and mulching with site-specific nutrient management not only enhanced early and mid-season biomass accumulation but also sustained growth till maturity. The higher CGR under T_{11} and T_{10} treatments reflects increased leaf area expansion, photosynthetic efficiency and prolonged assimilate partitioning (39).

Relative Growth Rate (RGR): RGR values did not differ significantly across treatments, except during the 60-90 DAS period. Marginally higher RGR was noticed under T_{11} (0.0367, 0.00661, 0.00476 g g^{-1} day^{-1}) and T_{10} (0.0366, 0.00665, 0.00470), while control (T_{12}) recorded irregular trends with lower mid-season RGR (0.00311) but a relatively higher value at harvest (0.00558) (Fig. 11), possibly due to delayed maturity and poor biomass partitioning.

Overall, treatments T_{11} (GM + mulching + LRI-based NMP-II) and T_{10} (GM + mulching + LRI-based NMP-I) outperformed other nutrient management strategies across AGR and CGR, emphasizing the synergistic effect of organic and inorganic inputs in improving crop growth dynamics. These findings corroborate earlier reports where integrated nutrient management enhanced growth rate indices and crop productivity in maize (40, 41).

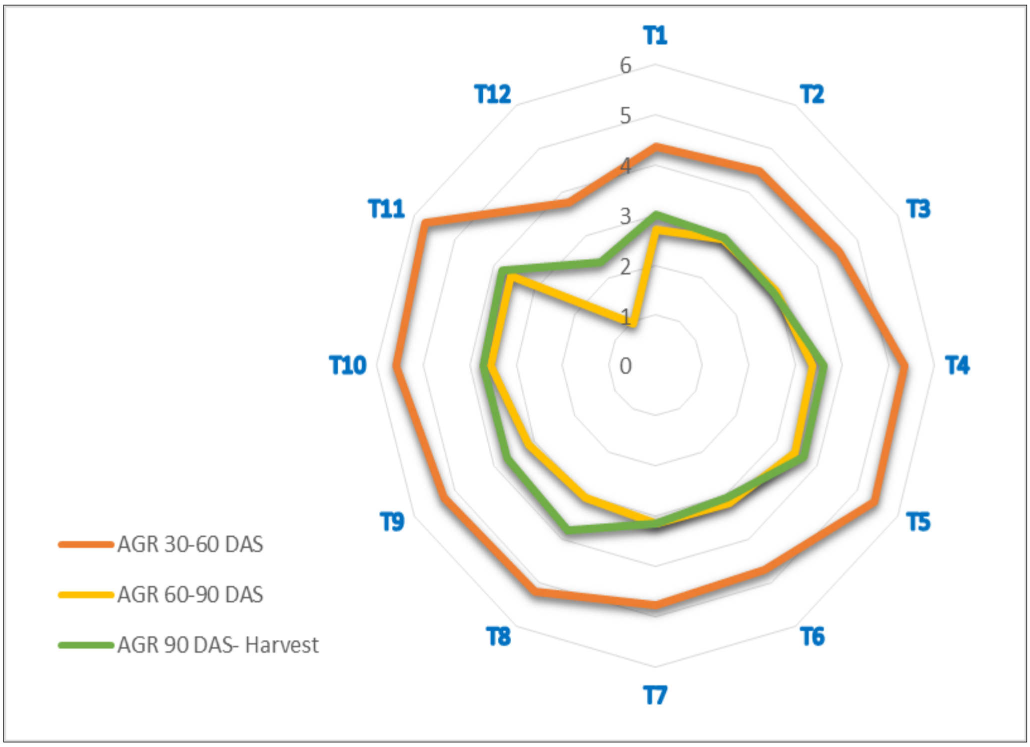

Fig. 9. Effect of nutrient management strategies on absolute growth rate (AGR) at different growth stages of maize.

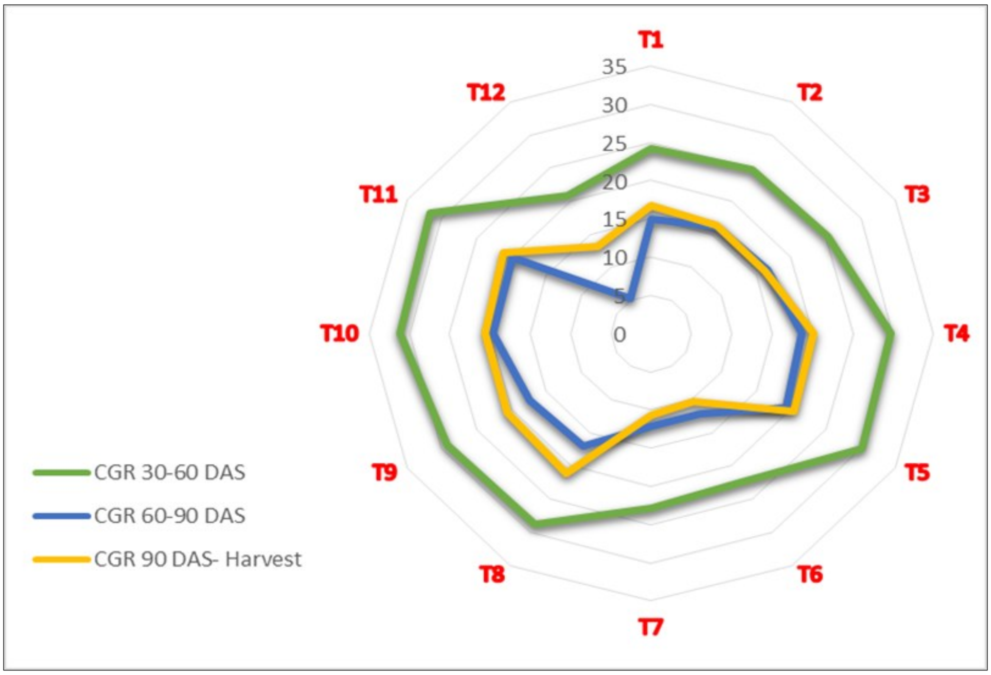

Fig. 10. Effect of nutrient management strategies on crop growth rate (CGR) at different growth stages of maize.

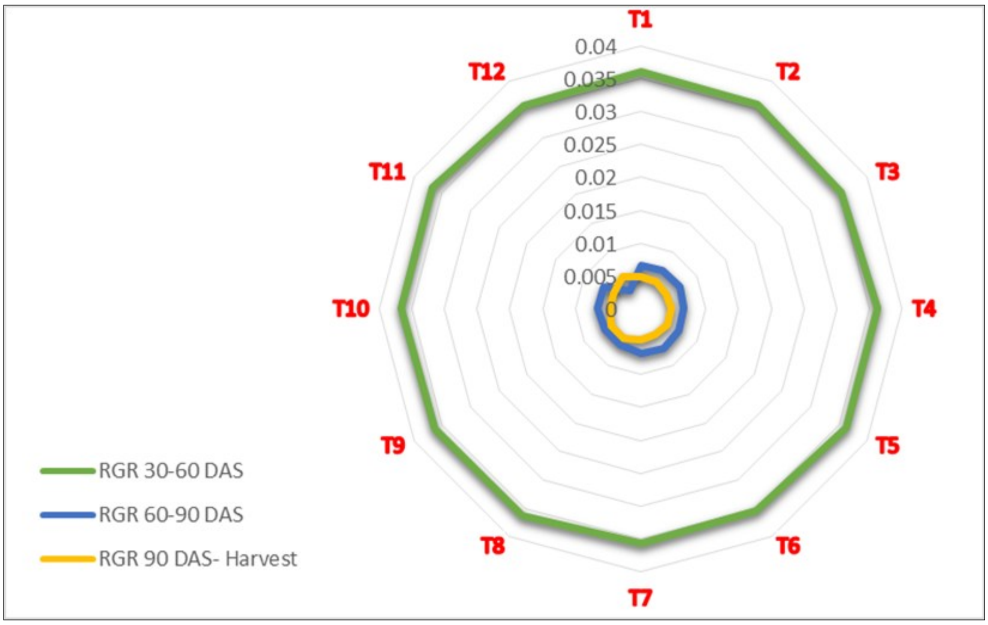

Fig. 11. Effect of nutrient management strategies on relative growth rate (RGR) at different growth stages of maize.

Discussion

Spatial dependence of soil properties

The semivariogram analysis revealed distinct spatial structures across soil parameters. Soil pH and EC fitted exponential models, while OC and available N were explained by Gaussian and spherical models, respectively. Phosphorus (P_2O_5) exhibited localized variation with shorter ranges, whereas nitrogen and potassium showed broader ranges, indicating that N and K variability are influenced by large-scale processes such as organic matter distribution and crop uptake and majorly, these soils were, derived from granite and gneiss parent material, with variable depth and fertility status, while P hotspots likely result from fertilizer application and fixation under alkaline conditions (42). Nugget-to-sill ratios suggested moderate to strong spatial dependence, reflecting both pedogenic controls and management influences (43).

Spatial variability in soil fertility

The fertility maps indicated neutral to moderately alkaline soils, typical of semi-arid landscapes dominated by basic parent materials. Alkalinity has critical implications for P fixation and micronutrient solubility (44). Low EC confirmed non-saline conditions, while low-to-medium organic carbon pointed to rapid decomposition and limited organic inputs. Nitrogen was largely deficient due to high crop demand and losses via leaching, volatilization and denitrification, a common feature in tropical soils. In contrast, phosphorus was enriched in pockets due to imbalanced fertilizer use, while potassium variability reflected crop removal patterns and parent material differences. These patterns suggest strong interaction of natural soil heterogeneity with management practices.

Interrelationships among soil properties

The PCA Biplot (Fig. 8) provided a multivariate view of soil property interactions. Soil pH showed strong association with K_2O and EC, suggesting that in alkaline soils, increased exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}) contribute to ionic balance and conductivity. This also reflects the influence of weathering processes where base saturation governs both pH and K dynamics. OC clustered with N, highlighting that organic matter is the main reservoir of N through mineralization (45). Conversely, the weak negative association of pH with P_2O_5 indicated P fixation under alkaline conditions due to the formation of calcium phosphates, thereby reducing its availability despite high total P content. Further illustrate these relationships, a correlation matrix comprising histograms, scatter plots and pairwise correlation coefficients were developed (Fig. 12). The histograms on the diagonal show the frequency distribution of individual soil parameters, while the scatter plots with fitted regression lines illustrate their bivariate associations. The visualization clearly depicts the positive association of OC with available N, as well as the influence of soil reaction (pH) on K and EC, these interrelationships suggest that improving soil OC would not only enhance N but also buffer soil pH, indirectly improving availability of other nutrients. The correlation analysis supported these results, with strong OC-N correlation confirming the role of SOM in N supply and moderate pH-K_2O correlation reflecting soil mineralogy and cation exchange processes.

Management implications

The results highlight that blanket fertilizer recommendations are unsuitable for this micro-watershed. Nitrogen and potassium deficiencies, coupled with localized P surpluses, demand site-specific interventions. Variable-rate fertilizer application guided by nutrient maps can optimize inputs and improve efficiency, while balanced NPK application is essential to prevent further nutrient imbalances (46, 47). Incorporating green manures and crop residues can improve OC and N supply, while diversifying cropping systems with legumes will enhance biological N fixation. Potassium supplementation is critical in K-deficient zones to sustain productivity. Collectively, an integrated nutrient management approach combining organic inputs, precision fertilization and diversification will ensure long-term soil health and yield sustainability in the Bankanahalli micro-watershed.

Conclusion

The study revealed significant spatial variability in soil physico-chemical properties and macronutrients (N, P_2O_5, K_2O) within the Bankanahalli micro-watershed using semivariogram modelling, kriging interpolation and spatial nutrient mapping. Phosphorus showed localized enrichment, while nitrogen and potassium were largely deficient. Correlation and PCA analyses highlighted strong linkages among pH, EC and K_2O, indicating their collective role in nutrient dynamics. These results underscore the need for site-specific nutrient management over uniform fertilizer use. Integrating spatial variability with land resource inventory enables precision fertilizer recommendations and when combined with practices like green manuring, intercropping and mulching, promotes efficient nutrient use, improved soil health and sustainable crop productivity. The nutrient management plans like T_{11}: GM + Mulching + LRI-based NMP-II recorded higher grain yield (8573 kg ha^{-1}) and stover yield (9089 kg ha^{-1}) and also showed positive impact on balancing the soil pH, EC and OC. Finally, the recommendation is to adopt the similar geostatistics-LRI integrated frameworks for developing site-specific nutrient management plans in semi-arid regions to enhance agricultural sustainability and productivity.

Acknowledgements

The authors are grateful to Watershed Development Department, Government of Karnataka, World Bank funded program REWARD, UAS, GKVK, Bengaluru for technical support during initial period of data collection and also non-technical staff of field unit, College of Agriculture, V. C. Farm, Mandya for their vast help for crop production and Mr. Puttaswami, Farmer, Bankanahalli, who helped me in land renting for experimentation in the micro-watershed.

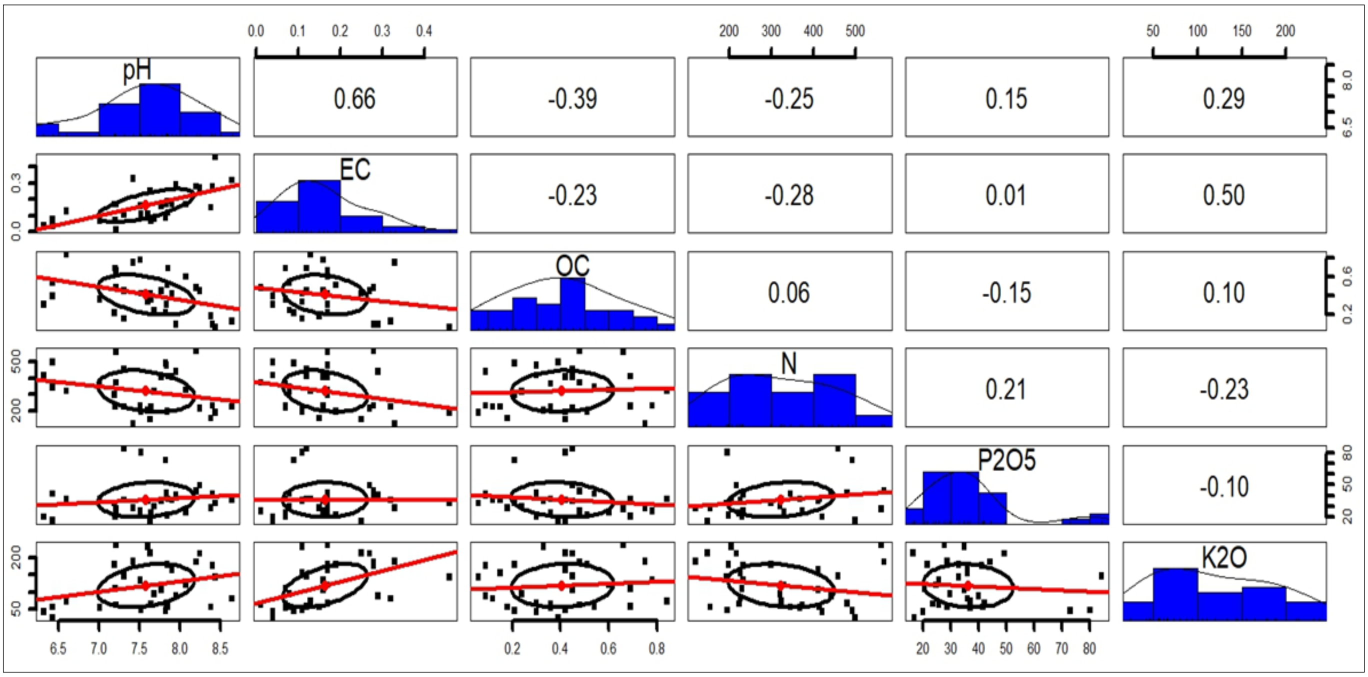

Fig. 12. Correlation matrix showing relationships among soil physico-chemical properties and available nutrients in the Bankanahalli micro-watershed.

Authors' contributions

FPS, YSB, AMA and SA designed and conceived the study idea. GKS completed the experiments. GKS, TP and AMA analysed the data and performed visualizations and statistical data analysis. FPS comprehensively reviewed the manuscript. FPS, YSB, AMA and TP provided the resources and supervision. All authors made valuable revisions, edited the manuscript and approved the final version.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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