



RESEARCH ARTICLE

Geographical Information System based spatial fertilizer recommendation mapping using soil test crop response equations and validation in paddy

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Abstract

The main barrier to greater crop output is unpredictability of soil nutrients. It's necessary to produce location-specific information on status of soil nutrients. This study aimed to develop and validate Geographical Information System (GIS)-based spatial fertilizer recommendation maps using Soil Test Crop Response (STCR) equations for improving rice yield and nutrient management in the command area. The nutrients used to achieve the intended yield are significantly reduced by STCR equation integrated with fertiliser recommendation maps. Gathered 59 composite soil samples in the Hosahalli village tank command area of Hassan district, Karnataka (India) and plotted the nutrient recommendations for desired yields in GIS platform. The interpolation technique was used to create the ready reckoner nutrient tables and nutrient recommendation maps for rice production. Executed a field experiment in farmer's fields of command area in kharif 2021 based on the recommended maps to achieve the targeted yields of 40, 50 and 60 q ha⁻¹ compared with farmer's practice at different organic carbon levels. The study area was acidic, normal EC, low in OC and available P, moderate in available N and K. STCR fertilizer recommendation for 60 q ha⁻¹ targeted yield has recorded higher grain and straw yields. The STCR fertilizer recommendation for 60 q ha⁻¹ target yield increased grain yield by 68 % (53.59 q ha⁻¹ compared to 31.89 q ha⁻¹) and straw yield by 48 % (80.36 q ha⁻¹ compared to 54.12 q ha⁻¹) over farmer practice while reducing fertilizer usage. The rice growth, yield and nutrient uptake were significantly impacted by the fertiliser recommendations for targeted yields. The farmer's precise target yield was achieved with far less fertiliser owing to the thematic nutrient recommendation maps.

Keywords: Arc-GIS; Geographical Information System; Geographical Positioning System; Soil Test Crop Response; targeted yield

Introduction

Nutritional security and economic growth have been spurred by the green revolution in the nation. From 51 m in 1950 to 314 m in 2021, food production increased quickly (1). To move these agricultural breakthroughs towards an evergreen revolution, it is imperative to integrate traditional knowledge with state-of-the-art technologies. Technological innovations such as the Global Positioning System (GPS) and GIS facilitate the mapping of soil fertility and provide quantitative support for policy and decision-making aimed at improving agricultural practices for balanced nutrition.

The methodical collecting of georeferenced samples and the creation of spatial data characterising the distribution of nutrients are made easier using GPS and GIS (2). Large amounts

of data regarding natural resources can be quickly accessed, retrieved and altered using the GIS. There are several global and national databases that demonstrate the systematic entry of data at an appropriate size for the planning and management of soil resources (3). Georeferenced maps can also be used to track changes in nutritional status over time by revisiting them with GPS. An important source of soil data utilised globally is the FAO soil map of the world (4).

The intense cultivation of high yielding varieties and hybrids, along with a reduction in the use of organic manures and crop residue recycling, has resulted in the depletion of native nutrients and the establishment of widespread shortages of both macro and micronutrients. Despite the intended increase in agricultural output in the country brought about by the soil

testing project, most farmers do not fertilise their crops based on the findings of soil tests due to a lack of knowledge. The STCR approach, which emphasises balanced nutrient treatments depending on crop demands, is one option in light of this (5).

Digital maps are accurate, potent instruments that allow one to associate a feature with any specific geographic place. The creation of management regions using thematic mapping provides instruments for increasing crop productivity (6). Reducing fertiliser costs and boosting farm profitability can be achieved with the aid of soil data. In addition to serving as an essential decision support tool for precision fertiliser management, the soil fertility maps made with the GIS platform will aid in identifying the pattern of nutrient depletion in the command area (7).

The novelty of this study lies in the integration of GIS-based spatial nutrient mapping with STCR equations for paddy yield optimization under varying organic carbon levels. This approach provides precise, location-specific fertilizer recommendations, enabling targeted nutrient management and efficient resource use.

Despite the availability of soil testing, farmers often lack site-specific fertilizer recommendations due to variability in soil properties and organic carbon levels. The study aims to fill this gap by integrating GIS-based mapping with STCR equations for precision nutrient management in rice cultivation.

A successful fertiliser programme and crop yield depend on accurate soil test calibration and fertiliser adjustments (8). Establishing a connection between the estimated soil nutrient levels from a laboratory estimate and the field-level response of crops to fertilisation is the significance of fertiliser adjustment based on soil test value. Target yield approaches and variable-rate fertiliser application also minimise the need for fertiliser by avoiding over-application in areas where crop demand is met by nutrient availability. The Hosahalli village tank command area's soil fertility status was determined through a thorough soil survey. Thematic nutrient recommendation maps in rice crops were later validated through an experiment comparing farmer practices at various levels of organic carbon to the maps for various targeted yields (Eqn. 1).

Objectives of the study:

1. To develop GIS-based nutrient recommendation maps for paddy using STCR equations.
2. To validate the fertilizer recommendations in farmers' fields under different organic carbon levels.
3. To assess the impact of site-specific nutrient management on rice growth, yield and nutrient uptake.
4. To evaluate the potential for reducing fertilizer use while achieving targeted yields through spatial nutrient mapping.

Materials and Methods

Study area

With a size of 23.94 acres, the command area of the Hosahalli village tank is situated in the Hassan district's Alur Taluk. The study area is situated between latitudes 12° 55' 40.75" to 12° 56' 19.12" north and 75° 56' 56.40" to 75° 55' 45.72" east longitude.

From loamy sand to clay, the soil's texture varies. The Hosahalli village tank is around 9.5 km from Alur town and is located in Karnataka's Southern Transition Zone (Zone VII). The annual rainfall ranges from 612 mm to 1054 mm and the climate is hot, humid and sub-humid. The command area is located 953 m above mean sea level. Location map of the study area has been shown in Fig. 1.

Preparation of base map and delineation of study area

The study's satellite data came from the Karnataka State Remote Sensing Application Centre in Bengaluru. A tracing film was placed on top of the toposheet covering the study area. The micro-boundaries were removed along with important land features like rivers, roads, tanks and other features. Thus, various theme maps were made using a base map that featured the common terrain features mentioned earlier (Fig. 2).

Soil survey and sample collection

Cartosat-1 PAN 2.5 mts and resource at-2 LISS-IV MX-merged satellite imagery were used to demarcate the study area at a resolution of 1:5000 on a base map and a scale of 1:50000 on a toposheet. A total of 59 surface soil samples were taken at 40 m grid spacing. Soil samples were later examined for their physicochemical characteristics and nutritional content using standardised procedures. In the current experiment, used a GARMIN GPS 72 H GPS receiver in stand-alone mode to obtain data regarding the exact locations of the soil sampling sites and ground truth sites.

Soil sample analysis

After being allowed to air dry in the shade, the soil samples were ground into a powder using a pestle and mortar and filtered through a 2 mm sieve. Afterwards, soil samples underwent standard laboratory tests to determine organic carbon, electrical conductivity and soil reaction (9) and major nutrients (10) as cited in Table 1.

Methodology of mapping

To enhance image contrast and create photo products for a later assessment, the digital data was converted. The image was georeferenced with sub-pixel accuracy using a first-order polynomial transformation (Fig. 3, 4 & 5).

STCR fertilizer adjustment equations

The fertiliser recommendations developed using fertiliser adjustment equations from STCR can be displayed in the form of a spatial fertiliser recommendation map by linking the information with soil fertility maps. By using the kriging interpolation approach in the GIS framework, the fertiliser recommendation maps for various management zones in terms of nitrogen, phosphorous and potassium were created. For fertiliser recommendations, the Fertilizer Adjustment Equations created for the Southern Transitional Zone (Zone-VII) by AICRP on STCR, University of Agricultural Sciences, Bengaluru were used (11).

Fertilizer adjustment equations for the study area for paddy:

$$FN = 5.343807 T - 0.690865 SN (KMnO_4-N) - 0.00125 OM$$

$$FP_2O_5 = 1.89835 T - 0.660225 SP_2O_5 (Brays P_2O_5) - 0.0017 OM$$

$$FK_2O = 4.055729 T - 1.023547 SK_2O (NH_4OAc K_2O) - 0.00328 OM$$

Table 1. Soil chemical properties and nutrient status of command area of Hosahalli village tank

Sl. No.	Grid point	pH	EC (dS m ⁻¹)	Organic Carbon (%)	Available nitrogen (kg ha ⁻¹)	Available phosphorus (kg ha ⁻¹)	Available potassium (kg ha ⁻¹)
1	0	5.50	0.158	0.99	476.67	5.00	519.48
2	1	4.70	0.238	0.45	489.22	22.57	426.00
3	2	4.80	0.079	0.54	388.86	10.26	115.44
4	3	4.85	0.174	0.57	376.32	5.39	430.92
5	4	4.65	0.114	0.84	401.41	10.77	213.84
6	5	4.38	0.327	0.42	363.78	19.49	41.52
7	6	4.55	0.329	0.69	765.18	23.34	652.56
8	7	4.68	0.171	0.75	551.94	12.57	313.80
9	8	4.50	0.321	0.90	338.69	33.86	246.96
10	9	5.80	0.474	0.81	363.78	21.16	271.44
11	10	4.60	0.196	0.42	363.78	17.18	64.56
12	11	5.80	0.298	0.99	451.58	43.09	270.00
13	12	4.90	0.206	0.84	338.69	8.98	235.44
14	13	5.00	0.203	0.63	376.32	16.29	374.28
15	14	4.50	0.264	0.36	401.41	7.05	320.76
16	15	4.70	0.153	1.02	338.69	7.82	166.20
17	16	4.60	0.126	0.36	288.51	4.49	255.00
18	17	4.60	0.120	0.66	363.78	5.51	371.52
19	18	4.50	0.120	0.81	401.41	7.82	293.04
20	19	4.60	0.112	0.87	464.13	5.51	177.72
21	20	4.50	0.230	0.45	351.23	16.16	406.20
22	21	4.20	0.225	0.48	426.50	13.08	143.04
23	22	4.60	0.371	0.42	426.50	3.46	478.32
24	23	4.50	0.202	0.81	326.14	5.90	268.44
25	24	4.60	0.119	0.66	376.32	8.85	147.84
26	25	4.90	0.036	0.48	326.14	3.72	300.00
27	26	4.20	0.244	0.33	338.69	11.67	245.76
28	27	4.10	0.251	0.51	376.32	3.08	220.80
29	28	5.20	0.139	0.45	388.86	10.64	146.52
30	29	4.10	0.263	0.54	426.50	11.16	230.76
31	30	4.50	0.071	0.39	401.41	3.98	281.52
32	31	4.40	0.150	0.75	351.23	9.87	374.52
33	32	4.10	0.193	0.42	351.23	3.72	236.76
34	33	4.40	0.098	0.36	288.51	7.57	111.36
35	34	5.10	0.137	0.39	338.69	5.90	219.24
36	35	4.50	0.054	0.39	313.60	11.29	364.56
37	36	5.20	0.047	0.39	363.78	2.69	300.36
38	37	5.40	0.068	0.48	401.41	1.92	316.20
39	38	4.70	0.061	0.42	439.04	5.77	285.00
40	39	4.80	0.197	0.48	250.88	3.85	130.44
41	40	5.65	0.078	0.42	439.04	2.18	151.56
42	41	5.49	0.046	0.45	175.62	1.15	291.48
43	42	5.59	0.037	0.48	250.88	2.08	276.00
44	43	5.00	0.052	0.30	351.23	5.13	196.20
45	44	5.36	0.151	0.57	200.70	4.49	204.96
46	45	4.98	0.061	0.36	238.34	9.62	195.00
47	46	4.78	0.050	0.51	301.06	5.13	264.48
48	47	5.15	0.052	0.51	351.23	4.62	239.28
49	48	5.18	0.095	0.45	388.86	20.90	378.84
50	49	5.50	0.075	0.48	376.32	1.80	143.04
51	50	4.80	0.072	0.42	313.60	7.31	242.28
52	51	4.33	0.204	0.39	263.42	11.41	360.48
53	52	5.12	0.181	0.66	275.97	2.18	222.72
54	53	4.80	0.177	0.72	213.25	11.67	200.76
55	54	5.02	0.053	0.60	200.70	5.26	207.24
56	55	4.82	0.128	0.54	639.74	10.13	228.48
57	56	4.98	0.110	0.54	514.30	3.08	278.52
58	57	5.65	0.096	0.63	401.41	3.33	219.24
59	58	4.90	0.094	0.39	351.23	2.05	156.48
Mean		4.84	0.155	0.56	369.73	9.25	261.44
SD		0.43	0.094	0.18	98.40	7.85	109.36
CV (%)		8.94	60.48	33.03	26.61	84.85	41.83

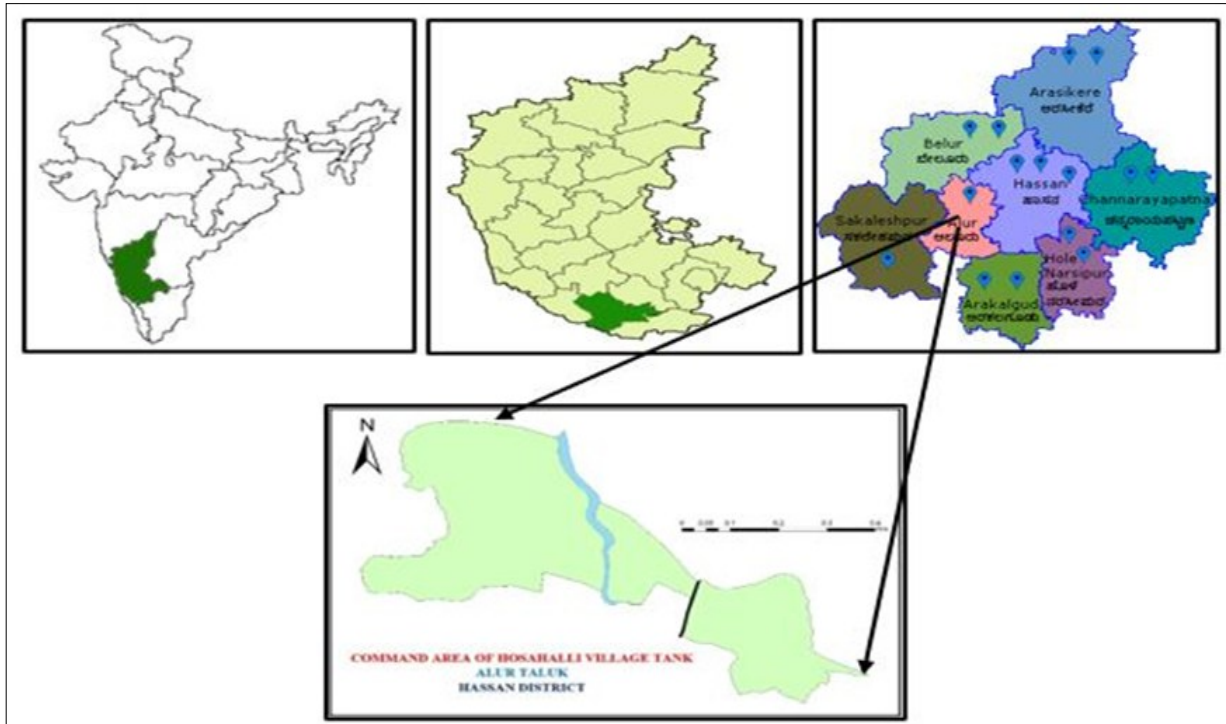


Fig. 1. Location map of Hosahalli village tank command area.

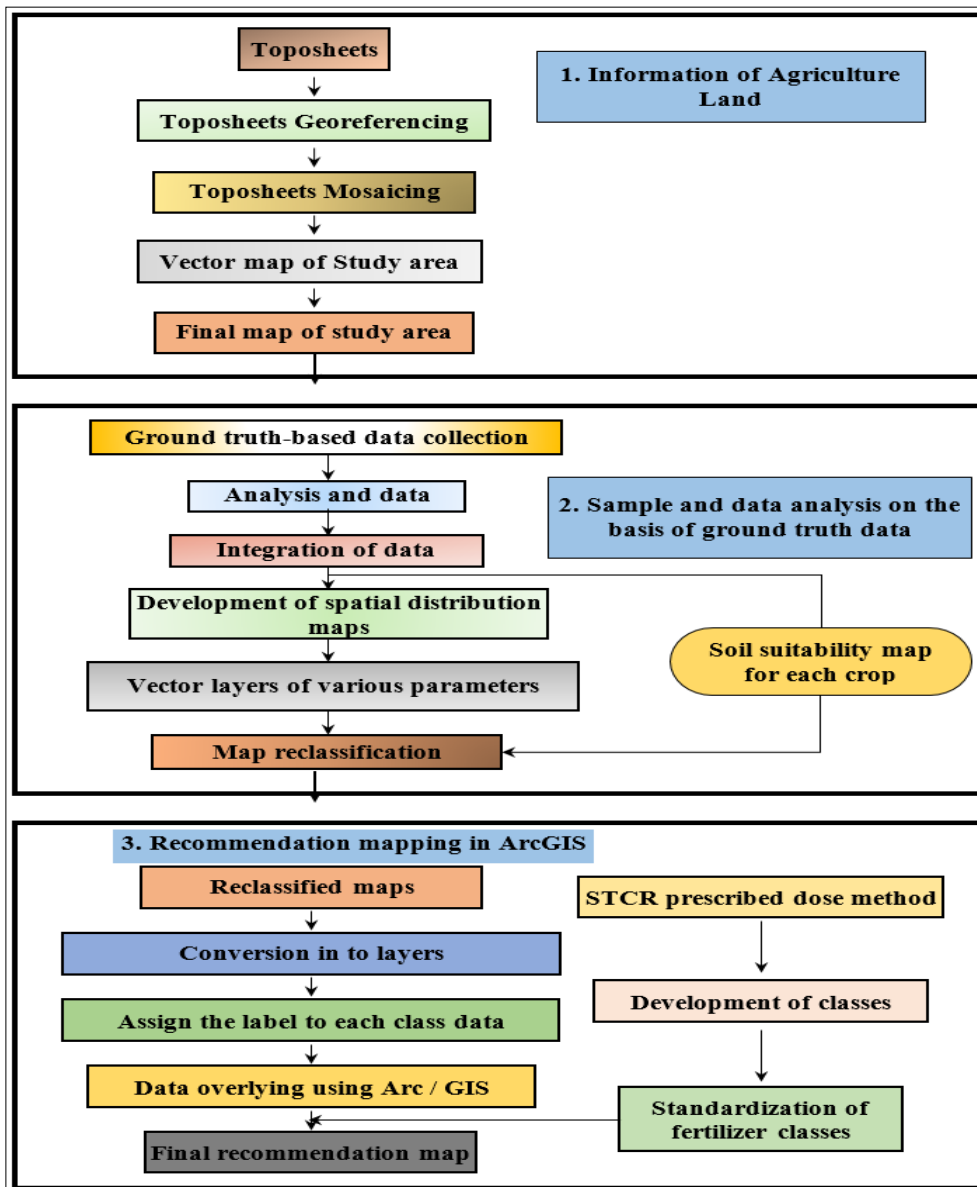


Fig. 2. The conceptual flow of research methodology.

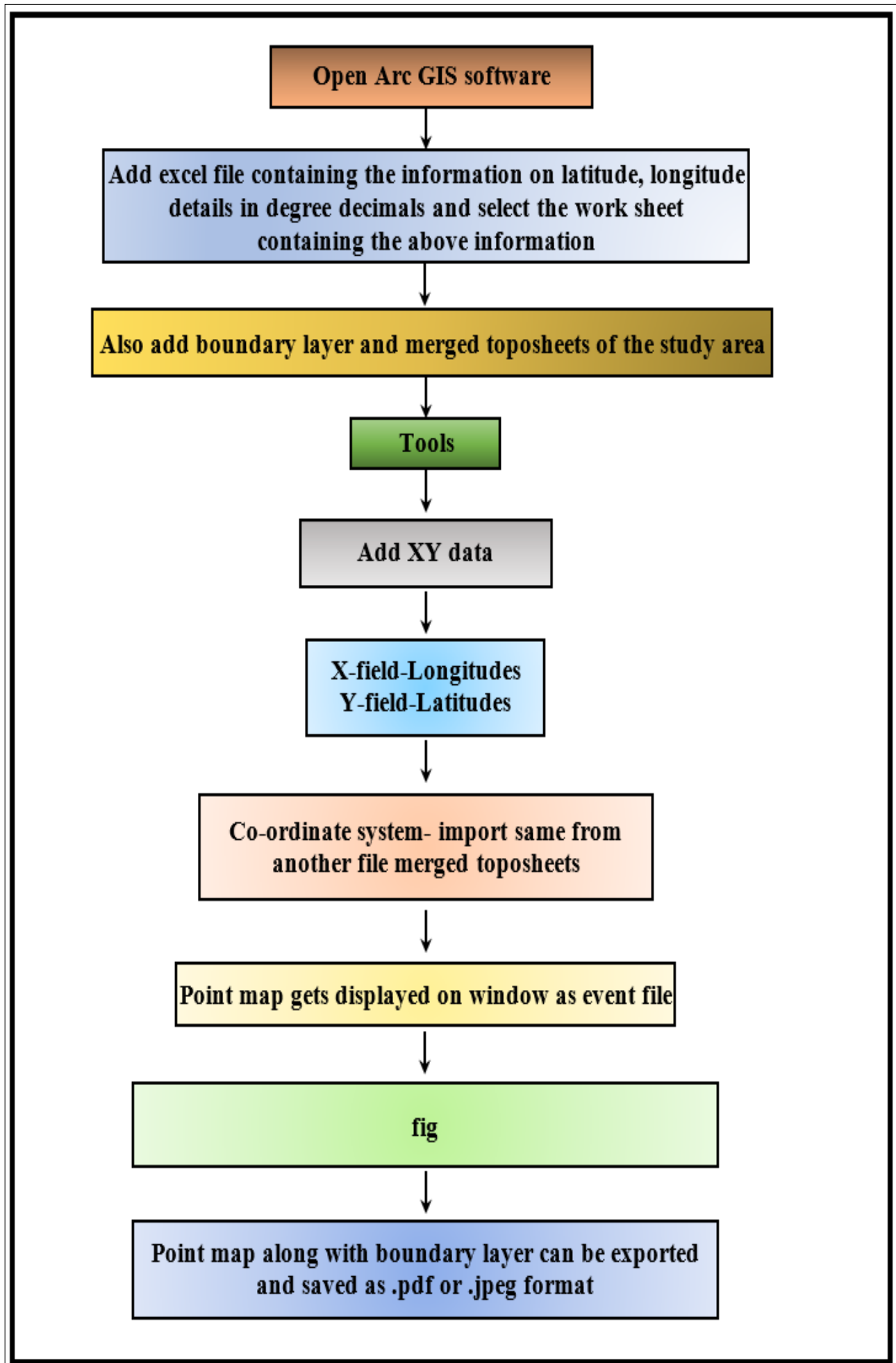


Fig. 3. Preparation of point map showing sampling sites using Arc GIS.

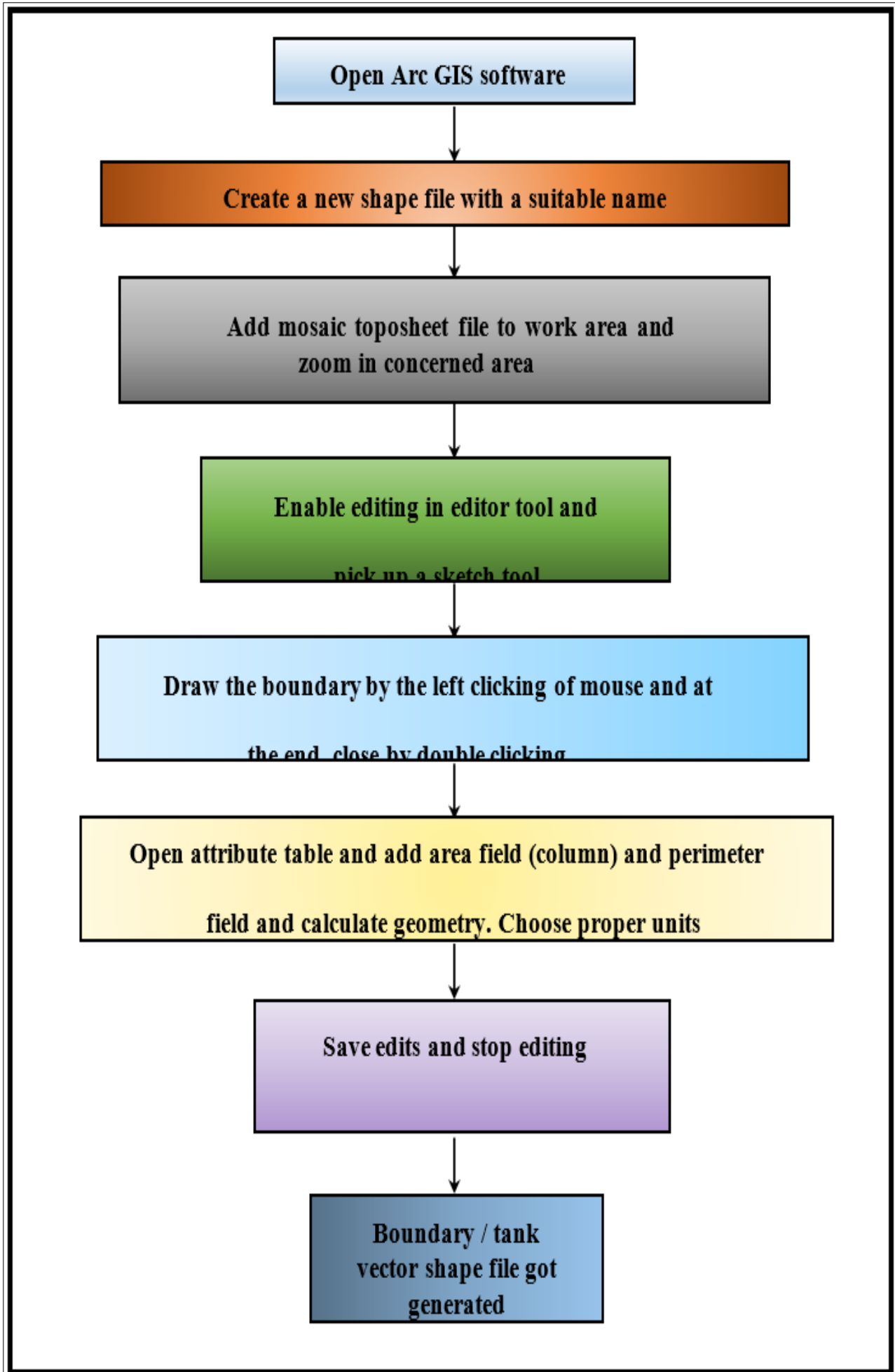


Fig. 4. Preparation of vector layer (shape file) of study area boundary using Arc GIS.

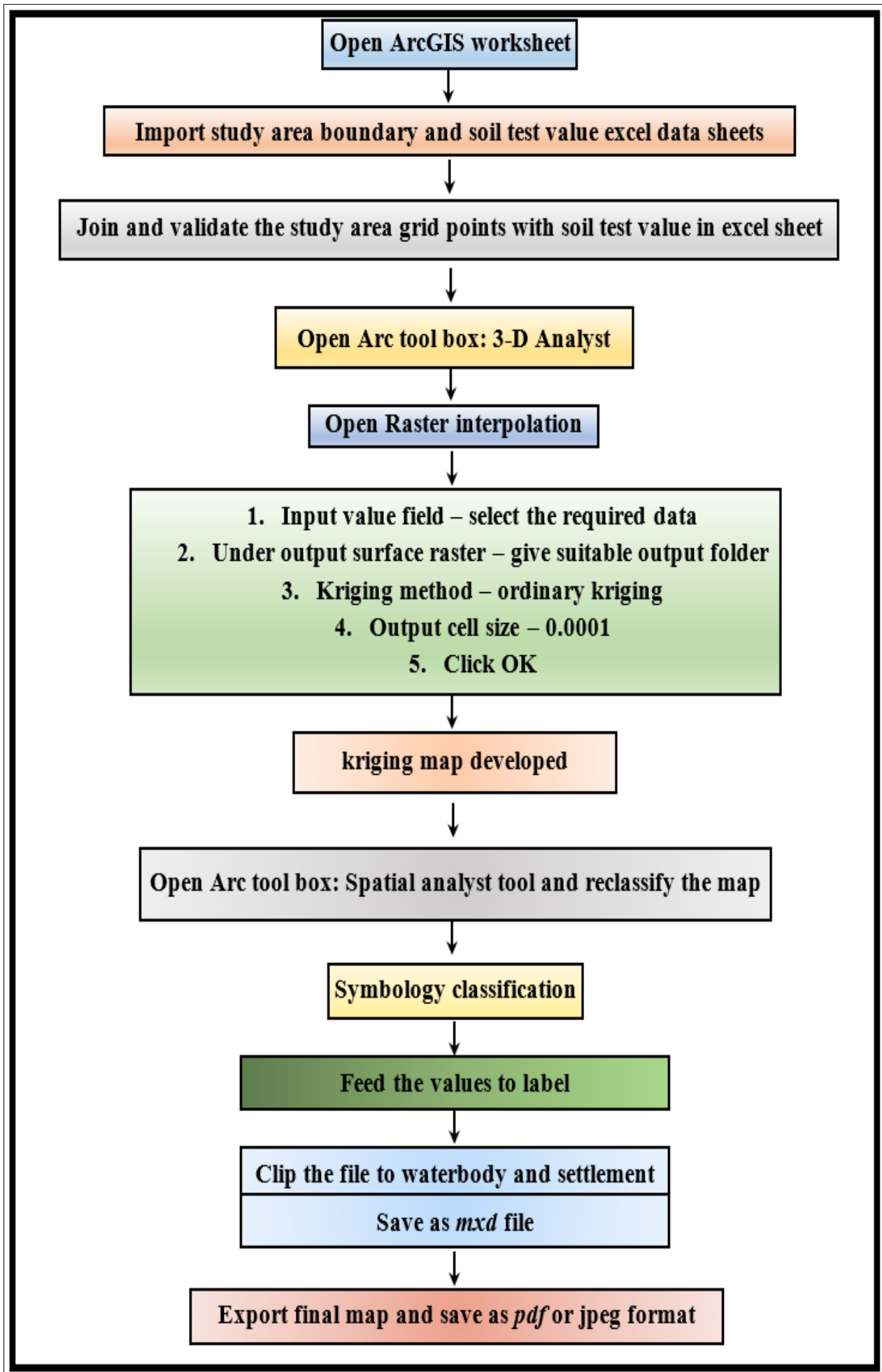


Fig. 5. Soil fertility map using kriging function in Arc GIS.

Where,

FN = Fertilizer N SN = Soil test value N OM = Organic matter

F P₂O₅ = Fertilizer P₂O₅ S P₂O₅ = Soil P₂O₅ T = Targeted yield

F K₂O = Fertilizer K₂O S K₂O = Soil K₂O

GIS-based spatial variability mapping

The GIS-created fertility maps of a specific area aid in assessing the geographical and temporal variability of soil fertility as well as in computing complex spatial correlations between soil fertility parameters. Maps of the spatial variability of all soil parameters were created using GIS techniques by spatial interpolation of point-based measurements of the soil properties.

The kriging interpolation was performed using the Inverse Distance Weighting (IDW) method. Where applicable, semivariogram parameters such as nugget, sill and range were evaluated; however, due to the limited number of sample points, a standard IDW approach without fitted semivariogram parameters was adopted for mapping nutrient distributions.

The IDW is used for interpolation of the map. The assigned values to unknown points are calculated with a weighted average of the values available at the known points. This method can also be used to create spatial weights matrices in spatial autocorrelation analyses. IDW is easy to implement and available in almost any GIS software, so it is applied frequently in various disciplines. The well-known advantage of IDW is that keeping the measured value at sample location.

Validation of fertilizer recommendation maps in farmer's field on growth and yield of paddy

In the farmer fields of the study area, a field experiment was conducted based on the levels of organic carbon to validate the fertilizer recommendation maps. Split plot design was used for the experiment, with the main plot housing 3 levels of organic carbon (C₁: high, C₂: medium and C₃: low) and subplot containing 3 fertilizer recommendations based on STCR approach for targeted yield with 1 check (T₁: 40 q ha⁻¹, T₂: 50 q ha⁻¹, T₃: 60 q ha⁻¹ and T₄: Farmer's practice) with plot size of 200 m². Total 12 treatment combinations and 3 replications were followed.

The STCR targeted yield fertilizer recommendations were implemented using urea, single super phosphate and muriate of potash. During transplanting, the full amount of potassium, phosphorus and 50 % of nitrogen were applied. Remaining 50 % of nitrogen was split in two doses viz., 25 % applied at 30 DAT and another 25 % applied at panicle initiation stage, respectively. On the other hand, fertilisers such as urea, diammonium phosphate,

muriate of potash and complex fertiliser were applied by farmers (20:20:0:13 N: P₂O₅: K₂O:S kg ha⁻¹). Field layout provided in Table 2.

At 30, 60, 90 and harvest, observations were made on the different growth parameters. Following the collection of representative plant samples (grain and straw), the samples were dried in an oven set at 65 °C for 48 hrs and then ground using a grinder. Using Jackson's description of the micro Kjeldahl digestion and distillation procedure, the total nitrogen content of the plant sample was estimated (12). The Vanado molybdate phosphoric acid yellow colour method was used to determine the total phosphorus in the plant sample and a spectrophotometer was used to estimate the phosphorous content in the digest (12). The total potassium content in the digested plant samples was estimated using flame photometer (12). Total N, P and K uptake was calculated for each treatment separately using the following formula and uptake of N, P and K were expressed in kg ha⁻¹.

Nutrient uptake=

$$\frac{\text{Per cent of nutrient concentration}}{100} \times \text{Biomass (kg ha}^{-1}\text{)}$$

Statistical analysis

The data recorded on soil properties, yield attributes and grain yield from the farmers' field experiments were subjected to statistical analysis following Fisher's method of Analysis of Variance (ANOVA)(13).

The experiment was laid out in a split-plot design, with three levels of organic carbon as main plots and 4 fertilizer treatments (three STCR targeted yields and one farmer's practice) as sub-plots, replicated 3 times. Data from the replicated treatments were first tested for homogeneity of variance.

The treatment means were compared using the F-test at the 5 % probability level. Wherever the F-test indicated significant differences among treatments, the means were separated using the Critical Difference (CD) at the 5 % level of significance to identify pairwise differences.

All statistical computations were carried out using standard procedures, ensuring that results are reproducible. This analytical approach allowed for testing the effects of organic carbon levels, fertilizer treatments and their interactions on soil fertility, crop growth, nutrient uptake and yield.

Table 2. Field layout of treatments

Organic carbon level (OC)	Fertilizer treatments (Target yield)	Description
High (C1)	T1: 40 q ha ⁻¹	STCR recommendation for 40 q ha ⁻¹
	T2: 50 q ha ⁻¹	STCR recommendation for 50 q ha ⁻¹
	T3: 60 q ha ⁻¹	STCR recommendation for 60 q ha ⁻¹
	T4: Farmer's practice	Conventional farmer fertilizer practice
Medium (C2)	T1: 40 q ha ⁻¹	STCR recommendation for 40 q ha ⁻¹
	T2: 50 q ha ⁻¹	STCR recommendation for 50 q ha ⁻¹
	T3: 60 q ha ⁻¹	STCR recommendation for 60 q ha ⁻¹
	T4: Farmer's practice	Conventional farmer fertilizer practice
Low (C3)	T1: 40 q ha ⁻¹	STCR recommendation for 40 q ha ⁻¹
	T2: 50 q ha ⁻¹	STCR recommendation for 50 q ha ⁻¹
	T3: 60 q ha ⁻¹	STCR recommendation for 60 q ha ⁻¹
	T4: Farmer's practice	Conventional farmer fertilizer practice

Note: The experiment followed a split-plot design with three organic carbon levels as main plots and four fertilizer treatments as sub-plots, replicated 3 times.

Results and Discussion

Soil fertility status

Soil pH: The study area's soil pH ranges from 4.20 to 5.80, with a mean of 4.84, a standard deviation of 0.43 and a percentage CV of 8.94. The soil pH falls under an acidic condition. The complete study area (23.94 ha) comes under acidic (< 6.5) condition. The spatial distribution of soil reaction is depicted in Fig. 6. In contrast to other soil parameters, soil acidity (pH between 3.90 and 6.45) showed a low level of variability (10 %) (14). A total of 41 % of the command area is severely acidic (4.67), 42 % is moderately acidic (4.67-5.23) and 17 % is slightly acidic (> 5.23). The excessive precipitation enhances soil acidity by causing soluble bases to leak away (15, 16).

Electrical conductivity: The study area had soils with electrical conductivity ranging from 0.036 to 0.474 dS m⁻¹, with a mean value of 0.155, a standard deviation of 0.094 and a CV of 60.48 %. Fig. 7 shows the spatial distribution of EC. The command area's efficient natural drainage system kept salts from penetrating lower strata, keeping the soil there free of salinity issues. Due to a significant association between them ($R^2 = 0.70$), the EC may increase as water volume increases (17).

Organic carbon: In the study area, the organic carbon (OC) (%) ranged from 0.33 to 1.02 %, with a mean of 0.56 %, a standard deviation of 0.18 % and a CV of 33.03 %. Fig. 8 shows the spatial distribution of soil organic carbon. In the study area 12.19 ha (50.84 %) was under low organic carbon range, which was brought on by farmers' continued paddy farming and failure to fertilise their fields with organic matter or the FYM that was advised. 7.72 ha (32.20 %) of the field's medium organic carbon area resulted primarily from the application of recommended FYM, while 4.06 ha (16.94 %) had a high organic carbon area due to litter fall from nearby plantation crops, straw incorporation and FYM application, all of which increased the amount of organic matter. Farmers use animal dung to make fuel briquettes rather than adding it to the soil to increase soil organic carbon (18).

Available nitrogen: The study area's available N content varies from 175.62 to 765.18 kg ha⁻¹, with a mean value of 369.73 kg ha⁻¹, a standard deviation of 98.40 and a coefficient of variation of 26.61 %. Fig. 9 shows the spatial distribution of available N in the soil. The major area of command area *i.e.* 19.91 ha (83.05 %) was under medium available nitrogen range, this resulted from the study area's regular application of nitrogenous fertilisers (19). The 3.25 hectares (13.55 %) of soil in the command area had a low available nitrogen range because of decreased levels of organic carbon and less nitrogenous fertilisers. Due to atmospheric nitrogen fixation, the rice-pulse cropping strategy in that region increased the nitrogen content; only 0.81 ha (3.38 %)

were under high available nitrogen range.

Available phosphorus: The amount of phosphorus available in the soil ranged from 1.15 to 43.09 kg ha⁻¹, with a mean value of 9.25 kg ha⁻¹, a standard deviation of 7.85 and a confidence level of 84.85 %. Fig. 10 shows the spatial distribution of soil available P. The soils had low levels of phosphorus that was readily available. P might be fixed in acidic soils, which would account for this. Furthermore, because of soil erosion, poor land management and abundant agricultural yield, the availability of P in most soils steadily declines (20, 21). Low levels of readily available phosphorus were present in the majority of the soils in the command area of the Hosahalli village tank. The use of acid-forming fertilisers such as urea, continuous paddy farming and the lack of lime application were the causes of the acidic pH (22). Only 1.21 ha (or 05.09 %) of the area had a medium level of accessible phosphorus because the farmers used complex fertilisers and soil amendments extensively to balance the pH of the soil.

Available potassium: The study area had soils with available potassium status ranging from 41.53 to 897.36 kg ha⁻¹. The mean value was 265.59 kg ha⁻¹, with a standard deviation of 127.23 and a percentage of 47.90. The spatial distribution of soil available K is depicted in Fig. 11. The bulk of the soils in the command area had a medium potash concentration. Most of the region, 17.07 hectares (71.18 %), had medium potassium availability. 98 % of the potassium will be in non-exchangeable form, which weathers over time and releases available potassium into the soil solution for crops to use. The command area only exhibited high levels of accessible potassium in 2.03 hectares (8.47 %) due to the area receiving little to no potassium fertiliser application. The amount of clay, the soil's capacity for cation exchange and the amount of organic matter all affect the soil's ability to fix potassium (23). The climate, elevation and slope of the watershed directly affect the water flow and infiltration, which in turn affects the availability and leaching of potassium (24).

Fertilizer recommendations for paddy

Based on the spatial variability of NPK status in study area, fertilizer recommendations for paddy to obtain a targeted yield of 40 q ha⁻¹ (Fig. 12-14), 50 q ha⁻¹ (Fig. 15-17) and 60 q ha⁻¹ (Fig. 18-20) are given in Table 3. Eight ranges were created for thematic mapping of the study area based on the available nitrogen status determined by a soil test in the study area. Seven ranges were identified for thematic mapping of the study area based on the available phosphorus status in the study area, as determined by soil test results. Eight ranges were created for thematic mapping of the study area based on the available potassium status determined by a soil test in the study area.

Table 3. Soil test-based fertilizer recommendation for paddy to get a target yield of 40, 50 and 60 q ha⁻¹ in command area of Hosahalli village tank.

Available nutrients range (kg ha ⁻¹)			Fertilizer recommendations (kg ha ⁻¹)								
			40 q ha ⁻¹			50 q ha ⁻¹			60 q ha ⁻¹		
N	P	K	N	P	K	N	P	K	N	P	K
< 200	<5	<100	92.42	73.92	107.94	145.86	92.91	148.50	199.30	111.89	189.05
200-250	05 to 10	100-150	66.43	71.44	25.12	119.86	90.42	65.68	173.30	109.40	106.23
250-300	10 to 15	150-200	27.43	68.45	-15.73	80.87	87.43	24.83	134.30	106.42	65.39
300-350	15-20	200-250	-12.44	64.52	-69.00	41.00	83.51	-28.44	94.44	102.49	12.11
350-400	20-30	250-300	-39.85	61.41	-122.23	13.59	80.40	-81.67	67.03	99.38	-41.11
400-450	30-40	300-400	-73.02	53.58	-193.49	-19.58	72.56	-152.93	33.85	91.55	-112.37
450-500	>40	400-500	-111.23	47.48	-283.38	-57.79	66.47	-242.83	-4.36	85.45	-202.27
>500	-	>500	-213.06	-	-562.88	-159.62	-	-522.32	-106.18	-	-481.76

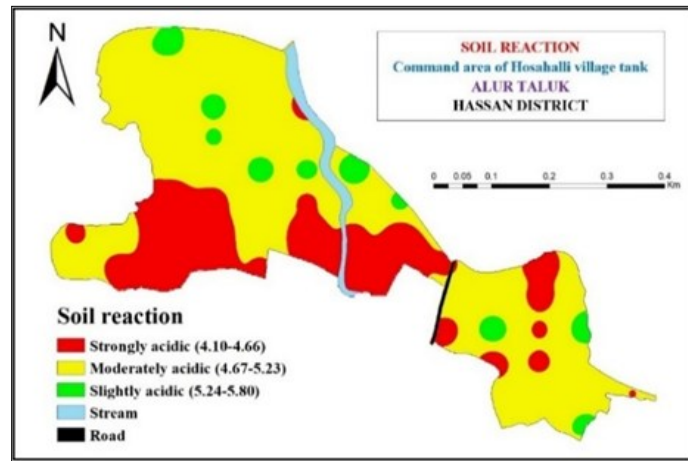


Fig. 6. Spatial distribution of soil reaction (pH) in command area of Hosahalli village tank.

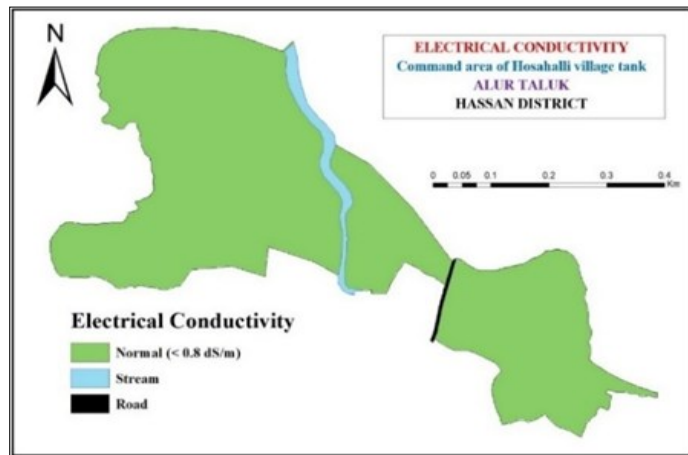


Fig. 7. Spatial distribution of soil EC in command area of Hosahalli village tank.

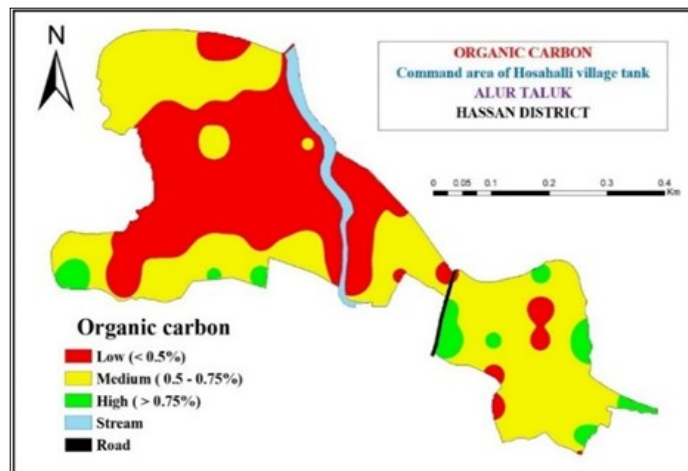


Fig. 8. Spatial distribution of organic carbon in command area of Hosahalli village tank.

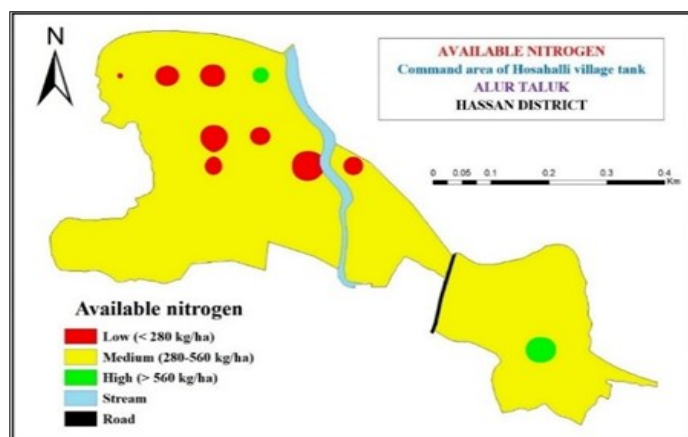


Fig. 9. Spatial distribution of available nitrogen in command area of Hosahalli village tank.

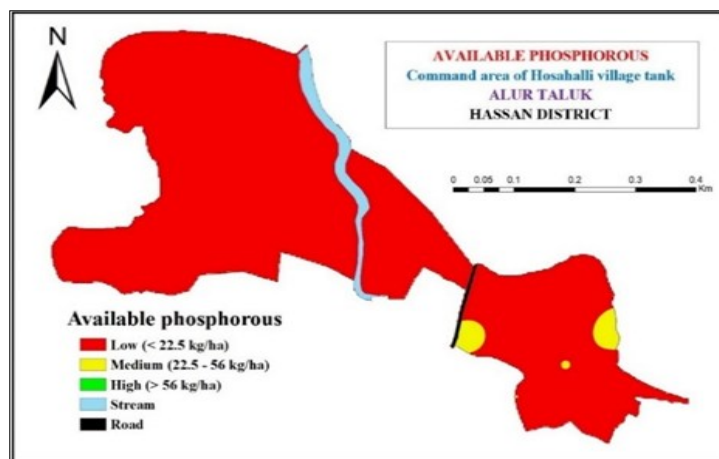


Fig. 10. Spatial distribution of available phosphorus in command area of Hosahalli village tank.

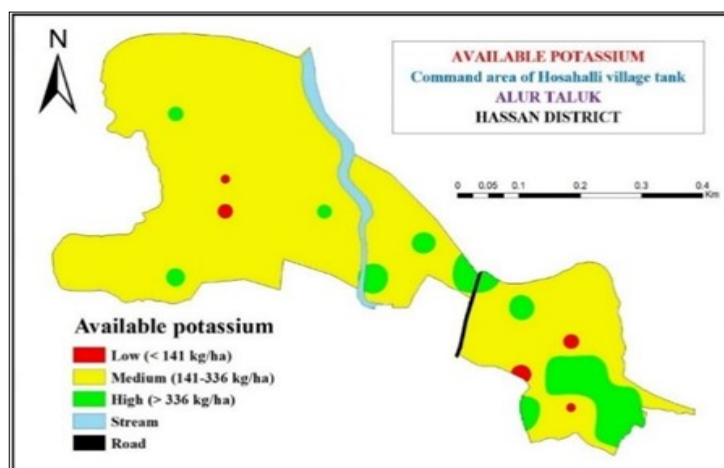


Fig. 11. Spatial distribution of available potassium in command area of Hosahalli village tank.

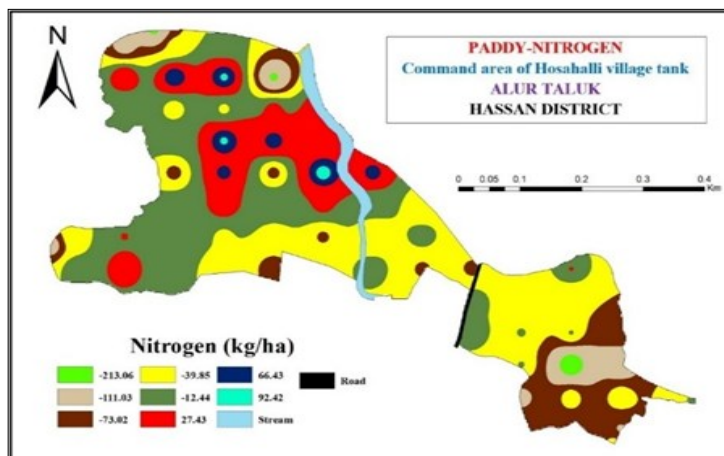


Fig. 12. Nitrogen fertilizer recommendation map for paddy (40 q ha^{-1}) based on STCR approach in command area of Hosahalli village tank.

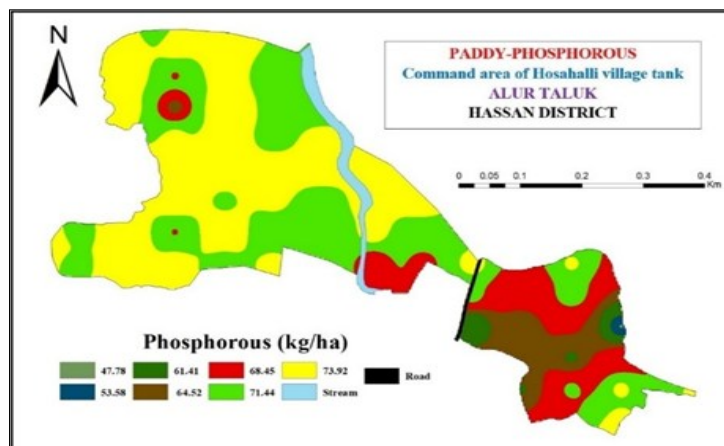


Fig. 13. Phosphorus fertilizer recommendation map for paddy (40 q ha^{-1}) based on STCR approach in command area of Hosahalli village tank.

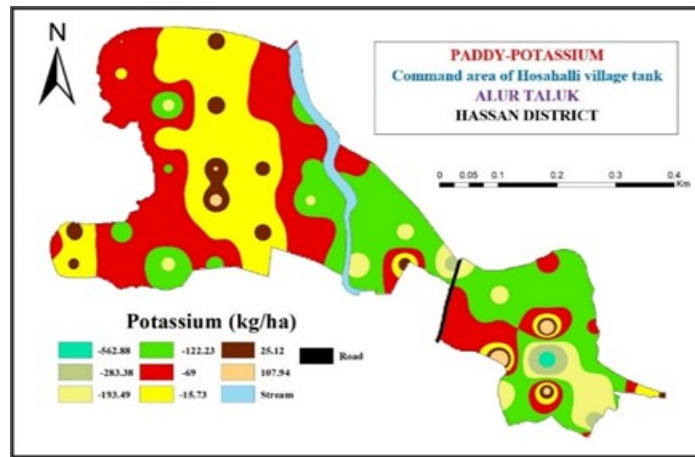


Fig. 14. Potassium fertilizer recommendation map for paddy (40 q ha⁻¹) based on SPCR approach in command area of Hosahalli village tank.

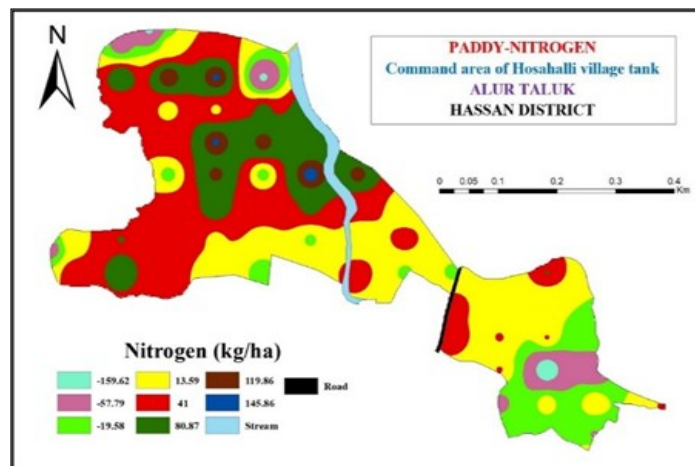


Fig. 15. Nitrogen fertilizer recommendation map for paddy (50 q ha⁻¹) based on SPCR approach in command area of Hosahalli village tank.

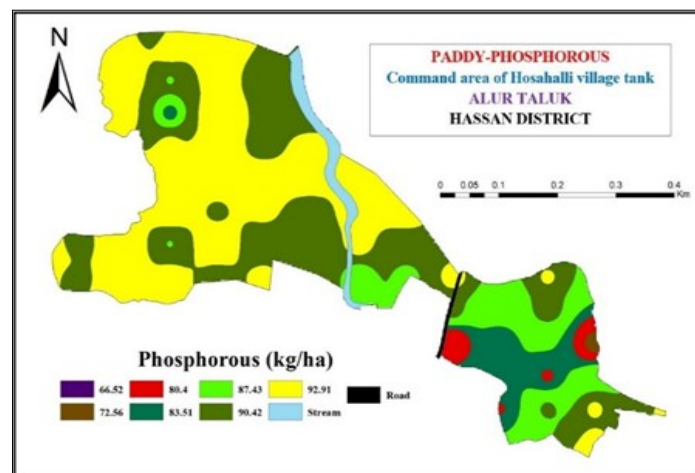


Fig. 16. Phosphorus fertilizer recommendation map for paddy (50 q ha⁻¹) based on SPCR approach in command area of Hosahalli village tank.

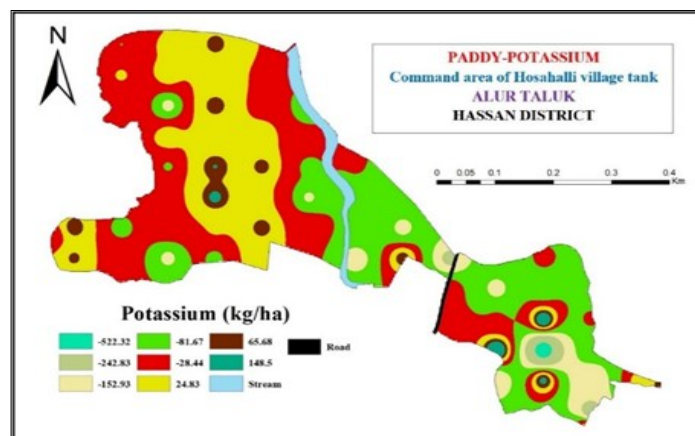


Fig. 17. Potassium fertilizer recommendation map for paddy (50 q ha⁻¹) based on SPCR approach in command area of Hosahalli village tank.

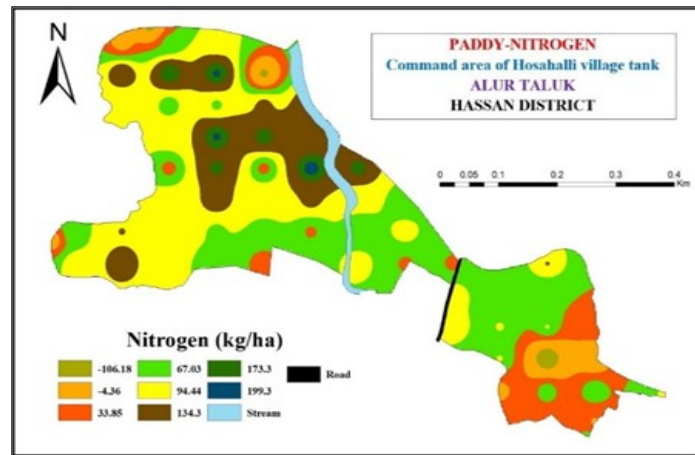


Fig. 18. Nitrogen fertilizer recommendation map for paddy (60 q ha^{-1}) based on STCR approach in command area of Hosahalli village tank.

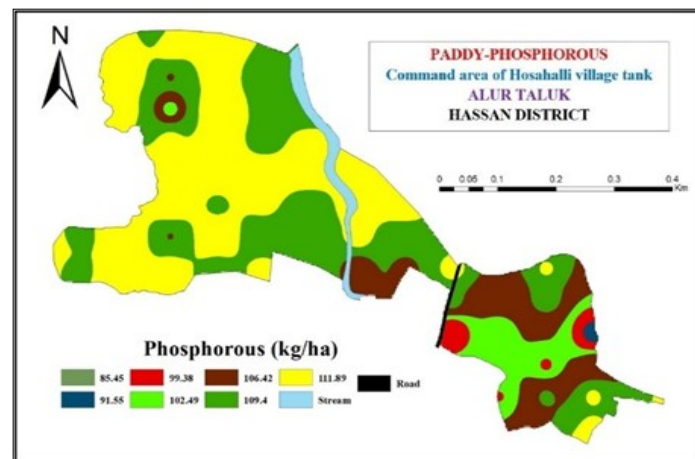


Fig. 19. Phosphorus fertilizer recommendation map for paddy (60 q ha^{-1}) based on STCR approach in command area of Hosahalli village tank.

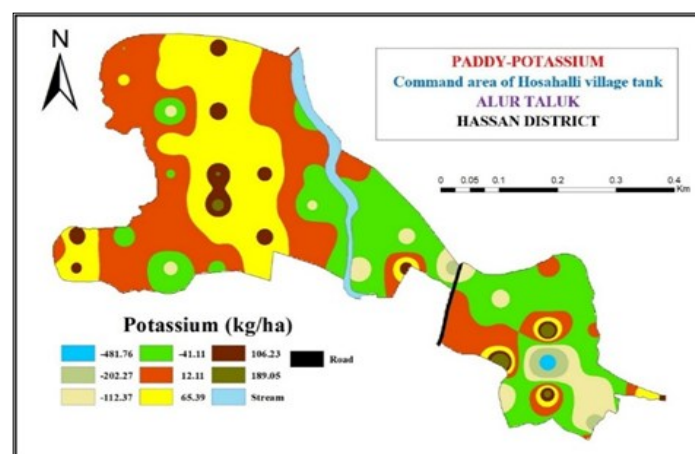


Fig. 20. Potassium fertilizer recommendation map for paddy (60 q ha^{-1}) based on STCR approach in command area of Hosahalli village tank.

Validation of STCR fertilizer recommendation maps in farmer's field on growth and yield of Paddy

There was a statistically significant difference observed with the STCR fertiliser recommendations for targeted yield in all growth stages, while the effect of organic carbon levels and their interaction with the recommendations for targeted yields were recorded statistically on par dry matter production at different growth stages. The data are displayed in Table 4.

Among the fertiliser recommendations, the STCR targeted yield of 60 q ha^{-1} showed higher dry matter production at 30, 60, 90 and harvest (25.59, 129.26, 334.61 and $464.73 \text{ g hill}^{-1}$, respectively) which was significantly higher as compared to 50 q ha^{-1} (22.69, 114.31, 299.92 and $412.50 \text{ g hill}^{-1}$, respectively), 40 q ha^{-1}

(20.71, 103.88, 271.23 and $374.22 \text{ g hill}^{-1}$, respectively) and farmer's practice (18.17, 87.45, 247.21 and $342.51 \text{ g hill}^{-1}$, respectively). When the intended yields were increased from 40 to 60 q ha^{-1} , there was an increase in the dry matter output. As crops grew older, more dry matter accumulated. The targeted yield of 60 q ha^{-1} produced significantly more dry matter on average than other treatments at all development phases. The ear's weight increased significantly after heading and flowering and until harvest, dry matter production progressively increased. The maximum concentration of dry materials is caused by the longer, heavier panicle and filled grains. The amount of dry matter that accumulates depends on the rate of photosynthesis and respiration. This, in turn, affects how quickly plants grow in terms of their tillers, height and other features (25).

Table 4. Total dry matter production and yield of paddy as influenced by organic carbon levels and STCR based fertilizer recommendations for different targeted yields

Treatments	Dry matter production (g hill ⁻¹)				Yield	
	30 DAT	60 DAT	90 DAT	At harvest	Grain yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)
Organic carbon levels (C)						
C ₁ : High	22.09	112.37	293.32	402.11	44.07	69.27
C ₂ : Medium	21.71	107.70	287.10	397.64	42.39	68.31
C ₃ : Low	21.57	106.11	284.31	395.71	41.59	64.18
S. Em ±	0.14	1.61	2.95	1.53	0.81	1.75
CD (p=0.05)	NS	NS	NS	NS	NS	NS
Fertilizer recommendations for targeted yield (T)						
T ₁ : 40 q ha ⁻¹	20.71	103.88	271.23	374.22	38.50	62.41
T ₂ : 50 q ha ⁻¹	22.69	114.31	299.92	412.50	46.74	72.14
T ₃ : 60 q ha ⁻¹	25.59	129.26	334.61	464.73	53.59	80.36
T ₄ : Farmer's practice	18.17	87.45	247.21	342.51	31.89	54.12
S. Em ±	0.34	1.97	3.83	5.19	0.80	1.91
CD (p=0.05)	1.00	5.84	11.38	15.43	2.36	5.66
Interaction (C × T)						
S. Em ±	0.52	3.36	6.46	7.94	1.44	3.35
CD (p=0.05)	NS	NS	NS	NS	NS	NS

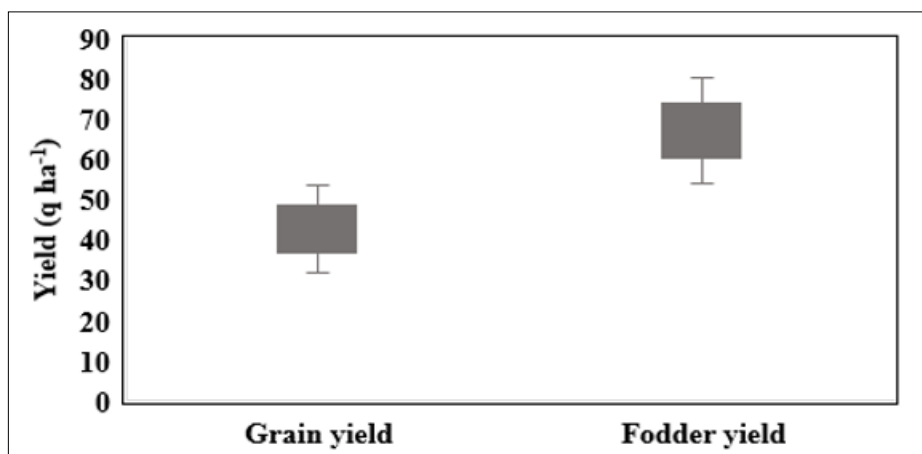
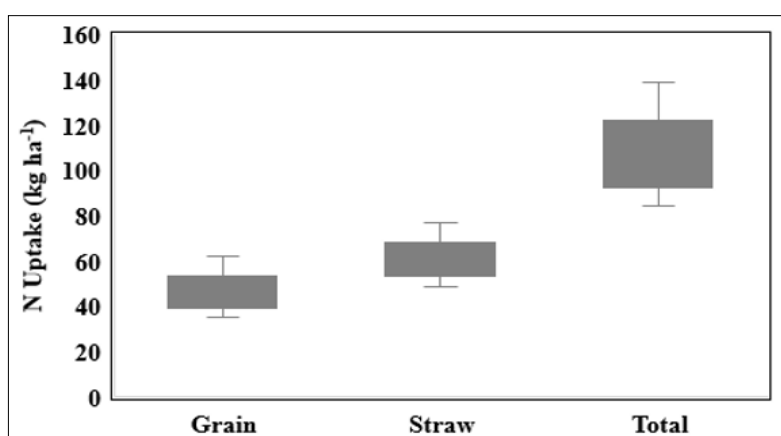
NS: Non-significant, DAT: Days after transplanting

Data presented in Fig. 21 on grain yield varied significantly due to fertilizer recommendations for STCR targeted yields. Among STCR targeted yields, 60 q ha⁻¹ recorded higher grain yield (53.59 q ha⁻¹) and straw yield (80.36 q ha⁻¹), which was significantly superior over 50 q ha⁻¹ (46.74 and 72.14 q ha⁻¹, respectively), 40 q ha⁻¹ (38.50 and 62.41 q ha⁻¹, respectively) and farmer's practice (31.89 and 54.12 q ha⁻¹, respectively).

With regard to STCR fertiliser recommendations, there were notable variations in nutrient uptake by rice grain, straw and total uptake. The treatment that received the highest fertiliser dose for the STCR targeted yield of 60 q ha⁻¹ showed noticeably higher nitrogen uptake by grains, straw and total N uptake among

fertiliser recommendations, such as grain and straw yields (62.02, 77.09 and 139.10 kg ha⁻¹, respectively) followed by 50 q ha⁻¹ (50.71, 65.58 and 116.30 kg ha⁻¹, respectively), 40 q ha⁻¹ (40.71, 54.85 and 95.56 kg ha⁻¹, respectively) and farmer's practice (35.45, 48.81 and 84.26 kg ha⁻¹, respectively) (Fig. 22).

Similarly, significantly higher P uptake by grains, straw and total uptake were recorded by the STCR fertiliser recommendation that supplied the highest fertiliser dose, i.e., for 60 q ha⁻¹ targeted yield (14.10, 10.86 and 24.96 kg ha⁻¹, respectively) followed by 50 q ha⁻¹ (12.01, 9.25 and 21.26 kg ha⁻¹, respectively), 40 q ha⁻¹ (8.95, 6.89 and 15.83 kg ha⁻¹, respectively) and lowest uptake was recorded in farmer's practice (8.59, 6.61 and 15.20 kg ha⁻¹, respectively) (Fig. 23).

**Fig. 21.** Yield of paddy as influenced by STCR fertilizer recommendations in command area of Hosahalli village tank.**Fig. 22.** Nitrogen uptake of paddy as influenced by STCR fertilizer recommendations in command area of Hosahalli village tank.

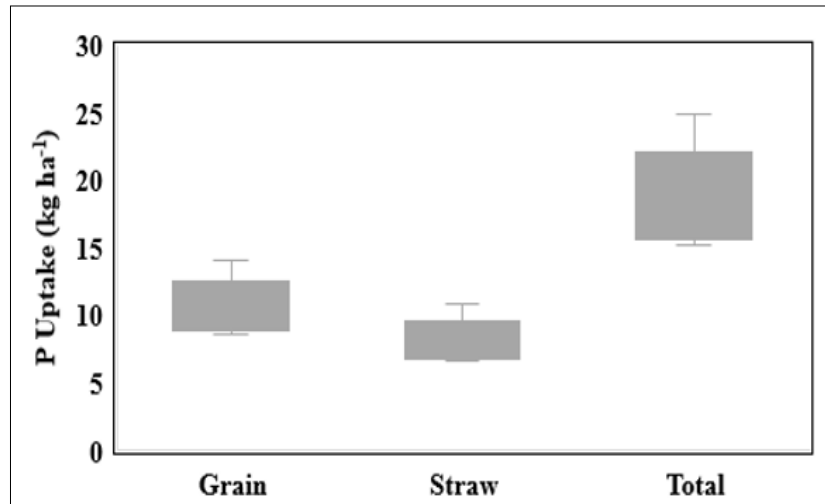


Fig. 23. Phosphorous uptake of paddy as influenced by STCR fertilizer recommendations in command area of Hosahalli village tank.

In line with N and P uptake, the highest fertiliser dose recommended for a targeted yield of 60 q ha⁻¹ resulted in noticeably higher K uptake by grains, straw and total K uptake (15.95, 90.94 and 106.89 kg ha⁻¹, respectively) followed by 50 q ha⁻¹ (13.28, 75.72 and 89.01 kg ha⁻¹, respectively), 40 q ha⁻¹ (10.23, 58.30 and 68.53 kg ha⁻¹, respectively) and lowest uptake was recorded in farmer's practice (9.53, 54.38 and 63.91 kg ha⁻¹, respectively) (Fig. 24).

Similar studies integrating STCR equations with GIS-based nutrient mapping have been conducted in other regions. For example, a 24 % increase in paddy grain yield was reported using site-specific nutrient management (SSNM) in contrast to recommended doses (26), while another works observed improved productivity and profitability in rice-wheat systems (27). These studies, along with the current findings, underscore the potential of integrating soil testing and spatial mapping technologies to enhance nutrient management and crop productivity across diverse agro-ecological zones.

Total N intake followed the patterns observed in grain and straw yields because it is a multiple of yield and content. When N input is increased, total uptake increases because more nitrogen is available in the soil or because the roots are denser and stronger (28). The increasing N levels resulted in an improvement in N uptake was reported (29). The administration of the appropriate fertiliser dose plus FYM at 10 t ha⁻¹ resulted in significantly greater potassium uptake (94.0 kg ha⁻¹) (30). In contrast to general recommended dose and soil test-based treatments, previous results found that for targeted yields of 25 and 35 q ha⁻¹ with and

without FYM, the total K uptake under the STCR method treatment was statistically greater (31).

The targeted yield approach not only improved productivity but also resulted in notable economic benefits. The STCR fertilizer recommendation for 60 q ha⁻¹ achieved up to 30-40 % fertilizer savings compared to conventional farmer practices while increasing grain yield by 68 %. Where available, calculation of the benefit-cost (B:C) ratio further confirmed the economic viability of site-specific nutrient management through GIS integration.

Conclusion

To effectively utilise soil, it is important to be aware of both its potential and its limitations. Digital maps can be produced on the ArcGIS platform using GIS and GPS. Digital maps are precise, powerful tools that can be used to visually tie a feature to any geographic location. To boost crop development and output, the notion of grid-based fertiliser application, through fertiliser advice, will be useful in supplying nutrients as per crop demand. Site-specific management of fertilisers will aid in the prudent application of fertilisers when the field is divided into smaller management plots. The Soil test crop response equation saves fertilizer levels applied by farmers to attain a target yield set up by the farmer. Farmers will be able to update the nutrient level of their fields with the use of the computerised maps, allowing for exact control. The farmers will benefit from the validation results

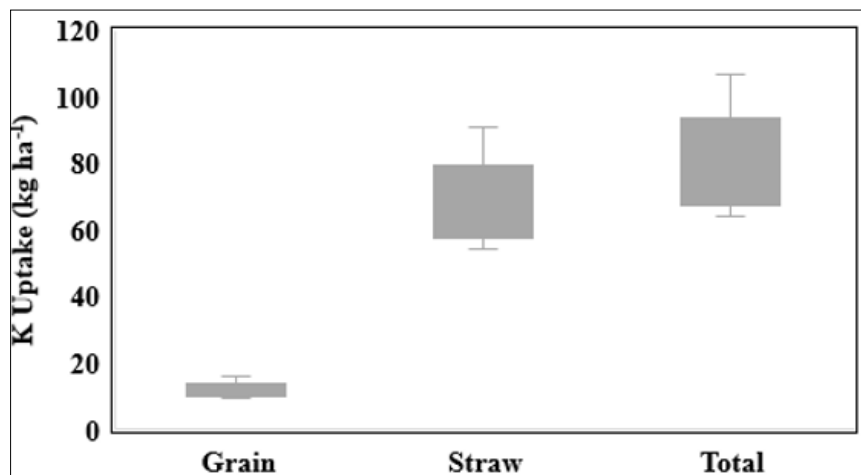


Fig. 24. Potassium uptake of paddy as influenced by STCR fertilizer recommendations in command area of Hosahalli village tank.

by being able to precisely administer nutrients to paddy crops. The methodology developed in this study holds significant potential for scaling across other crops and regions. By integrating soil testing with GIS-based mapping, location-specific nutrient management can be extended to enhance productivity and resource efficiency in diverse agro-climatic zones.

Practical recommendations and policy implications:

- Promote the adoption of GIS-based nutrient recommendation tools by agricultural extension services to support farmers in precision fertilizer management.
- Encourage policymakers to integrate soil health databases with spatial mapping platforms for targeted fertilizer subsidies and resource planning.
- Expand the use of STCR-guided fertilization models to other major crops, ensuring efficient nutrient use, cost savings and improved environmental sustainability.

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Authors' contributions

Data curation, formal analysis, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing the original draft, review and editing were done by PU. STB performed the funding acquisition, methodology and project administration. Conceptualization, methodology, resources, supervision was done by HMJ. HMJ, TT and GR wrote the review and editing. GGK performed the project administration and formal analysis. Software and formal analysis were performed by GR. Validation was done by KR. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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