



RESEARCH ARTICLE

Spatial variability and GIS-based mapping of soil chemical properties in the Chambal region, Madhya Pradesh

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Abstract

Efficient utilisation of fertilisers is essential for sustainable crop production, as their effectiveness largely depends on soil chemical properties and their spatial variability. The soils in the Morena district (Chambal region) are predominantly alluvial, interspersed with areas of medium black soil. They are susceptible to erosion and salinity, which impact their chemical characteristics and fertility. This study utilised geographic information system (GIS)-based spatial interpolation techniques to assess the spatial variability of key soil chemical properties in the Morena district (Chambal region), Madhya Pradesh. A total of 100 global positioning system (GPS)-referenced surface soil samples (0-15 cm depth) were collected from 4 blocks: Sabalgarh, Jaura, Morena and Ambah. The processed soil samples were analysed using standard methods for soil reaction (pH), electrical conductivity (EC), organic carbon (OC), available nitrogen (N), phosphorus (P), potassium (K), sulphur (S) and diethylenetriaminepentaacetic acid (DTPA)-extractable micronutrients (Fe, Cu, Zn and Mn). Results showed that soil pH ranged from 6.00 to 8.60, EC from 0.18 to 0.86 dS m⁻¹ and OC from 0.23 to 0.86 %. Available nutrient contents varied as follows: N (118.8–255.0 kg ha⁻¹), P (14.60–38.40 kg ha⁻¹), K (168.6–525.0 kg ha⁻¹) and S (6.50–15.80 mg kg⁻¹). The soils in the sampled area generally showed low to medium levels of available macronutrients. DTPA-extractable micronutrients showed wide variability: Fe (0.64–24.25 mg kg⁻¹), Cu (0.20–2.76 mg kg⁻¹), Zn (0.26–1.52 mg kg⁻¹) and Mn (2.10–26.70 mg kg⁻¹), indicating deficient to sufficient levels across the study area. These findings highlight significant spatial heterogeneity in soil chemical properties, providing a basis for site-specific nutrient management in the region. The results suggest that variable-rate fertiliser applications, particularly for S and Zn, could improve nutrient use efficiency and crop yields in this agriculturally important area.

Keywords: GIS; macronutrients; micronutrients; soil fertility mapping; spatial variability

Introduction

Enhancing crop yield and nutrient use efficiency requires a clear understanding of regional heterogeneity and the spatial distribution of soil properties. Soil test-based fertiliser recommendations, supported by soil fertility mapping, are increasingly advocated to sustain agricultural productivity while minimising excessive and inefficient fertiliser use. In this context, geostatistical techniques integrated with geographic information system (GIS) tools are widely used to analyse spatial variability, interpolate soil properties between sampling locations and estimate values with defined levels of uncertainty based on a limited number of observations (1, 2).

The Chambal region of Madhya Pradesh, particularly Morena district, is a major agricultural hub in northern Madhya Pradesh, known for its intensive cropping systems (e.g., wheat, mustard and pulses) on predominantly alluvial and medium black soils. However, these soils often exhibit variability in fertility due to factors like erosion, saline patches and uneven nutrient distribution from long-term farming practices (3, 4). Recent assessments in the Chambal Division have highlighted moderate to high spatial heterogeneity in physico-chemical properties, underscoring the need for localised fertility mapping to guide precision nutrient management (4).

Knowledge of the spatial variability of soil physical, chemical and biological properties is essential for informed crop selection, efficient cropping system design and the adoption of appropriate soil and crop management practices (5). Several studies have reported significant spatial variation in soil pH, organic matter, total and available nitrogen (N), phosphorus (P) and potassium (K) and micronutrients under different soil types and management conditions, highlighting the importance of such information for developing site-specific and precision nutrient management strategies (6, 7).

Soil chemical properties play a critical role in determining nutrient availability and crop productivity across different landscapes. The inherent heterogeneity of soils arises from the combined influence of climate, organisms, relief, parent material and time, resulting in spatial variability in soil properties (8). Characterisation of the spatial variability of soil nutrients using soil fertility maps in relation to site-specific factors such as climate, land use, landscape position and other environmental variables is essential for understanding ecosystem functioning and for predicting the potential impacts of land use change on soil nutrient dynamics (9–11).

Although several studies have assessed soil fertility in Madhya Pradesh, limited research has focused on high resolution spatial variability of soil chemical properties specifically in the Chambal region using GIS-based approaches. Previous studies lack detailed block level nutrient mapping and site-specific nutrient management insights. Therefore, the present study aims to fill this gap by generating spatial distribution maps and evaluating variability to support precision agriculture practices.

Material and Methods

Study area

The present study was conducted in Morena district, northern Madhya Pradesh, India. The district lies between approximately 26°17' N to 26°52' N latitude and 76°30' E to 78°33' E longitude. The average elevation of the district is approximately 177 m above mean sea level. It covers a total geographical area of approximately 4989 km². Administratively, Morena district is divided into 4 development blocks arranged roughly from west to east: Sabalgarh, Joura, Morena and Ambah. A systematic soil sampling survey was undertaken to evaluate the chemical properties of surface soils across this region.

Soil sampling and laboratory analysis

A total of 100 global positioning system (GPS)-based surface soil samples (0–15 cm depth) were collected from different locations across the 4 blocks, representing the major land use systems in the district. The sampling density (100 samples) was selected to ensure adequate spatial coverage across the four blocks and to capture variability in soil properties. Sampling locations were distributed systematically to represent major land use systems and soil types of the district. The study focused on surface soil (0–15 cm), as it is the most biologically active layer influencing crop growth and nutrient availability. The study area is depicted in Fig. 1 and detailed site information is provided in Table 1. The collected samples were thoroughly mixed to form composite samples weighing approximately 1 kg. The samples were air-dried and larger

aggregates were gently crushed using a wooden hammer. The processed samples were then passed through a 2 mm sieve. The sieved soil samples were stored in properly labelled sample bags and transported to the laboratory for further analysis.

Laboratory analysis was carried out at the School of Agricultural Sciences, GD Goenka University, Sohna, Gurugram, Haryana, following standard procedures. Soil reaction (pH) was measured in a 1:2 soil: water suspension using a pH meter (12). Electrical conductivity (EC) was determined in the same suspension using a conductivity meter (12). Organic carbon (OC) content was estimated by the Walkley-Black wet digestion method (13). Available nitrogen (N) of soil was determined using the alkaline potassium permanganate method (14). Available phosphorus (P) was determined by 0.5 M sodium bicarbonate extractant (15), while available potassium (K) was estimated by flame photometer after extracting soil samples with neutral 1 N ammonium acetate (12). Available sulphur (S) was measured by the turbidimetric method (16) using a spectrophotometer after extracting soil samples with 0.15 % CaCl₂ solution. Diethylenetriaminepentaacetic acid (DTPA)-extractable micronutrients [Iron (Fe), copper (Cu), zinc (Zn) and manganese (Mn)] were analysed using an atomic absorption spectrophotometer (17).

Soil fertility rating criteria

The fertility status of soil samples was classified into low, medium and high categories based on standard critical limits commonly used for Indian soils (18). The classification criteria for EC macronutrients, OC and micronutrients are presented in Table 2.

Statistical analysis

Minimum (Min) and maximum (Max) values of required soil parameters were determined for each block of the studied district. Statistical parameters including mean, standard deviation (SD) and coefficient of variation (CV) were computed to assess variability in soil properties (19). The study focuses on spatial variability and GIS-based mapping of soil properties. Further analyses may provide additional insights into the interrelationships among soil properties.

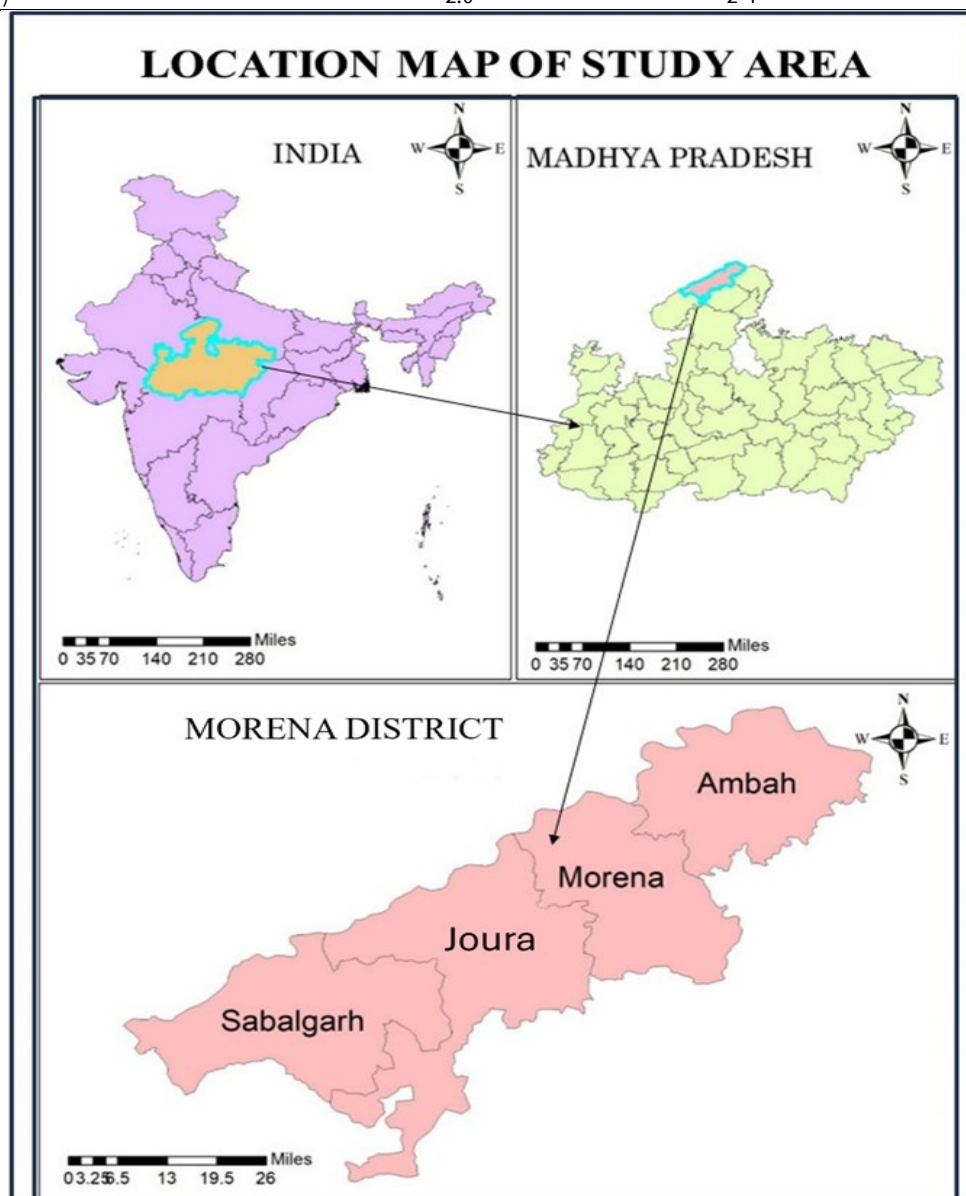
Table 1. Location of soil sample collection sites

Block	Latitude	Longitude	Block	Latitude	Longitude	Block	Latitude	Longitude	Block	Latitude	Longitude
S1	26.10363	77.25617	J1	25.94830	77.66723	M1	26.42382	78.06761	A1	26.75335	78.51475
S2	26.15391	77.25904	J2	25.94985	77.67097	M2	26.41843	78.06456	A2	26.75040	78.52290
S3	26.12791	77.26576	J3	25.94890	77.66232	M3	26.42112	78.06825	A3	26.74259	78.52057
S4	26.14321	77.25389	J4	25.95545	77.66744	M4	26.41638	78.06301	A4	26.73764	78.51054
S5	26.09197	77.23702	J5	25.94692	77.66924	M5	26.41133	78.06489	A5	26.75947	78.52567
S6	26.19894	77.16854	J6	26.33628	77.54576	M6	26.50374	78.13954	A6	26.64885	78.36420
S7	26.19865	77.18601	J7	26.34039	77.54778	M7	26.50190	78.13098	A7	26.65547	78.36276
S8	26.20790	77.17748	J8	26.32830	77.53426	M8	26.50636	78.13581	A8	26.63867	78.35969
S9	26.18798	77.17787	J9	26.33282	77.54180	M9	26.15033	78.12253	A9	26.64901	78.36836
S10	26.19269	77.16178	J10	26.35105	77.54530	M10	26.51099	78.12994	A10	26.63512	78.35481
S11	26.18487	77.15224	J11	26.18650	77.66010	M11	26.58755	78.09622	A11	26.80906	78.23075
S12	26.17140	77.15862	J12	26.19511	77.66950	M12	26.59316	78.07407	A12	26.81713	78.23552
S13	26.17973	77.17420	J13	26.17615	77.66593	M13	26.61320	78.08867	A13	26.82282	78.22762
S14	26.18652	77.15810	J14	26.17953	77.66589	M14	26.60200	78.09257	A14	26.82164	78.22238
S15	26.16853	77.15364	J15	26.18881	77.67800	M15	26.57511	78.08069	A15	26.81523	78.23269
S16	26.19231	77.47077	J16	26.45089	77.71593	M16	26.43760	78.23678	A16	26.76154	78.40764
S17	26.18051	77.45130	J17	26.44475	77.71561	M17	26.43558	78.23675	A17	26.76158	78.41265
S18	26.17940	77.47709	J18	26.43855	77.71912	M18	26.43601	78.23645	A18	26.75945	78.40391
S19	26.16295	77.46934	J19	26.42939	77.71003	M19	26.43644	78.23492	A19	26.75467	78.41102
S20	26.16811	77.48536	J20	26.44451	77.71814	M20	26.43635	78.23490	A20	26.75919	78.41336
S21	26.13239	77.52167	J21	26.35135	77.72114	M21	26.53940	77.99579	A21	26.70116	78.37919
S22	26.14154	77.54477	J22	26.33833	77.71745	M22	26.55808	77.98771	A22	26.70534	78.38603
S23	26.15807	77.55587	J23	26.33841	77.70188	M23	26.55192	77.98400	A23	26.71360	78.38653
S24	26.16581	77.53410	J24	26.34093	77.69277	M24	26.56373	77.99850	A24	26.72223	78.38567
S25	26.13797	77.54142	J25	26.34267	77.71518	M25	26.55315	78.00017	A25	26.70901	78.39232

Sampling sites: Sabalgarh (S1–S25), Joura (J1–J25), Morena (M1–M25) and Ambah (A1–A25).

Table 2. Soil fertility rating criteria for soil chemical properties

Nutrient	Low	Medium	High
EC (dS m ⁻¹)	< 1	1–3	> 3
Organic carbon (%)	≤ 0.5	0.51–0.75	> 0.75
Alkaline KMnO ₄ -N (kg ha ⁻¹)	≤ 280	281–560	> 560
Olsen's P (kg ha ⁻¹)	≤ 10	11–25	> 25
NH ₄ OAC extractable K (kg ha ⁻¹)	≤ 120	121–280	> 280
Sulphur (mg kg ⁻¹)	< 10	10–15	> 15
Zinc (mg kg ⁻¹)	< 0.6	0.6–1.5	> 1.5
Iron (mg kg ⁻¹)	< 2.5	2.5–4.5	> 4.5
Copper (mg kg ⁻¹)	< 0.2	0.2–5.0	> 5.0
Manganese (mg kg ⁻¹)	< 2.0	2–4	> 4.0

**Fig. 1.** Location map of collected soil samples [Source: ArcGIS Version 10.8, ESRI, Redlands, CA, USA].

Geostatistical analysis

Geostatistical analysis was performed to assess the spatial variability of soil chemical properties and to generate spatial distribution maps. The geographic coordinates of sampling locations were imported into ArcGIS software (ArcGIS Version 10.8, ESRI, Redlands, CA, USA) and all spatial data were projected using the WGS-84 coordinate system. Spatial interpolation tools available in ArcGIS were used to generate continuous surface maps of soil properties based on measured values at sampling locations. These interpolated maps were used to visualise the spatial variability and distribution of soil nutrients across the study area and to identify areas of nutrient deficiency and sufficiency.

Geographic information system mapping

Geographic information system techniques were used to generate spatial distribution maps of soil chemical properties across the study area. The geographic coordinates of soil sampling locations were recorded using a GPS and imported into ArcGIS software (Version 10.8, ESRI, USA). A point shapefile was created for all sampling locations and soil chemical attribute data were linked to their respective geographic coordinates.

Spatial interpolation was performed using the inverse distance weighting (IDW) method to generate continuous raster surfaces for soil properties such as pH, EC, OC, available N, P, K, S and micronutrients (Fe, Cu, Zn and Mn). These interpolated maps

were used to visualise spatial variability and identify nutrient-deficient and nutrient-sufficient zones within the study area. In this study, deterministic interpolation (IDW) was used; therefore, semivariogram modelling was not performed. The IDW method was selected due to its simplicity and effectiveness in representing spatial variability when sample density is moderate. It does not require assumptions about spatial autocorrelation, unlike kriging, making it suitable for preliminary spatial analysis.

Results and Discussion

Soil reaction

Soil pH in Morena district ranged from 6.00 to 8.60 (mean values per block 7.66–8.03), indicating soils that vary from slightly acidic to moderately alkaline. This range reflects considerable spatial heterogeneity across the four blocks (Sabalgarh, Joura, Morena and Ambah), as detailed and illustrated spatially in Fig. 2. In Sabalgarh, pH values were consistently neutral to moderately alkaline (7.20–8.60, mean 8.00), with low variability (CV 4.92 %). The Joura block exhibited comparatively wider variation (6.00–8.60, mean 7.66), indicating the presence of soils ranging from slightly acidic to alkaline in reaction and higher variability (CV 8.43 %). In Morena block, soil pH showed a narrower range (7.50–8.50, mean 8.03) whereas in the Ambah block, values were similar (7.10–8.50, mean 7.86). Both block soils exhibited a predominantly neutral to alkaline soil reaction.

The soil pH in the Morena district varied from slightly acidic to moderately alkaline, indicating considerable spatial heterogeneity across the study area. Most samples exhibited neutral to alkaline reaction, which may be attributed to the calcareous nature of parent material and the presence of basic cations (3). Among the blocks, Joura showed relatively higher variability in pH, suggesting localised differences in land use practices, irrigation water quality and organic matter inputs. In some locations, comparatively lower pH values may be associated with higher organic matter decomposition and localised leaching effects. From a nutrient availability perspective, alkaline conditions prevailing in most parts of the study area can reduce the availability of micronutrients such as Zn and Fe, which is consistent with the deficiencies observed in the present investigation (4). Therefore, appropriate soil amendments and organic matter

additions are required to improve nutrient availability under such conditions.

Electrical conductivity

The EC of soils across the Morena district ranged from 0.18 to 0.86 dS m⁻¹ at 25 °C, with an overall mean value of 0.36 dS m⁻¹. Block-wise data revealed moderate variability in EC, with mean values ranging from 0.27 dS m⁻¹ in the Morena block to 0.43 dS m⁻¹ in the Joura block and CV spanning 18.10 % to 30.66 % across the blocks. The highest individual EC value was recorded in Joura (0.86 dS m⁻¹), while the lowest occurred in Morena (0.18 dS m⁻¹). The spatial distribution of the same in the study area is illustrated in Fig. 3. All soil samples recorded EC values below the critical threshold of 1.0 dS m⁻¹, indicating that the soils of the study area are non-saline in nature and suitable for most crops without salinity related constraints (Table 2).

Electrical conductivity values of all soil samples were within the safe limits, indicating that salinity is not a major constraint for crop production in the region. The EC values showed a narrow range with moderate variability, reflecting relatively uniform soil conditions and effective drainage across the blocks (20, 21). However, slightly higher EC values observed in the Joura block may be due to localised salt accumulation influenced by irrigation practices or micro-topographic variations (3, 4). The non-saline nature of soils suggests that management strategies can primarily focus on improving soil fertility rather than addressing salinity-related issues.

Organic carbon

The OC content in the soils of Morena district varied from 0.23 to 0.86 %, with an overall mean of 0.46 %. Block-wise descriptive statistics showed OC mean values varied slightly from 0.43 % (Morena block) to 0.49 % (Ambah block), with moderate variability (CV 20.81–28.49 % across blocks) (Table 3). The maximum OC content (0.86 %) and minimum values observed within Joura indicate considerable variability across different sampling locations within the same area. The spatial distribution of OC of the study area is depicted in Fig. 4. Based on these values, the soils of the study area fall under the low to medium category of OC status (Table 2). This indicates limited to moderate organic matter accumulation typical of the region's semi-arid conditions (20, 21).

Table 3. Status of soil chemical properties in different blocks of Morena district

Block		pH	EC (dS m ⁻¹)	OC (%)	Nutrient content (kg ha ⁻¹)				Nutrient content (mg kg ⁻¹)			
					N	P	K	S	Fe	Cu	Zn	Mn
Sabalgarh	Max	8.60	0.52	0.65	243.8	38.40	524.0	15.70	8.28	0.56	0.94	7.80
	Min	7.20	0.22	0.25	118.8	14.60	270.0	6.50	3.70	0.20	0.26	2.10
	Mean	8.00	0.35	0.46	193.7	26.22	356.5	10.34	5.91	0.36	0.57	4.29
	SD	0.39	0.09	0.12	33.79	6.64	67.64	3.07	1.38	0.10	0.20	2.03
	CV	4.92	25.12	26.43	17.45	25.33	18.97	29.70	23.32	27.56	35.47	47.34
Joura	Max	8.60	0.86	0.86	255.0	30.50	485.0	15.80	10.50	1.45	1.46	25.25
	Min	6.00	0.22	0.23	162.0	15.50	168.6	8.20	0.64	0.30	0.26	2.21
	Mean	7.66	0.43	0.46	198.6	23.13	389.6	11.00	5.88	0.75	0.56	7.84
	SD	0.65	0.13	0.13	24.29	4.06	80.40	2.35	2.15	0.38	0.24	6.74
	CV	8.43	30.66	28.49	12.23	17.54	20.64	21.34	36.61	50.66	43.32	85.95
Morena	Max	8.50	0.42	0.60	235.0	30.00	525.0	15.80	24.25	2.76	1.52	26.70
	Min	7.50	0.18	0.30	143.0	15.50	232.5	7.20	4.30	0.25	0.30	2.25
	Mean	8.03	0.27	0.43	183.9	21.88	384.8	11.04	13.61	1.54	0.86	15.40
	SD	0.32	0.07	0.09	24.77	5.09	76.60	2.38	7.04	1.00	0.35	8.69
	CV	3.95	24.86	20.91	13.47	23.28	19.91	21.55	51.71	65.33	40.84	56.44
Ambah	Max	8.50	0.52	0.68	255.0	30.50	460.0	14.20	15.70	1.45	0.74	25.25
	Min	7.10	0.28	0.35	162.0	18.60	260.0	8.60	2.80	0.45	0.32	8.68
	Mean	7.86	0.41	0.49	198.6	23.52	386.1	10.13	6.26	1.00	0.54	15.25
	SD	0.39	0.07	0.10	26.82	2.80	66.21	1.62	2.91	0.32	0.12	5.22
	CV	5.00	18.10	20.81	13.51	11.89	17.15	15.96	46.40	31.66	22.84	34.20

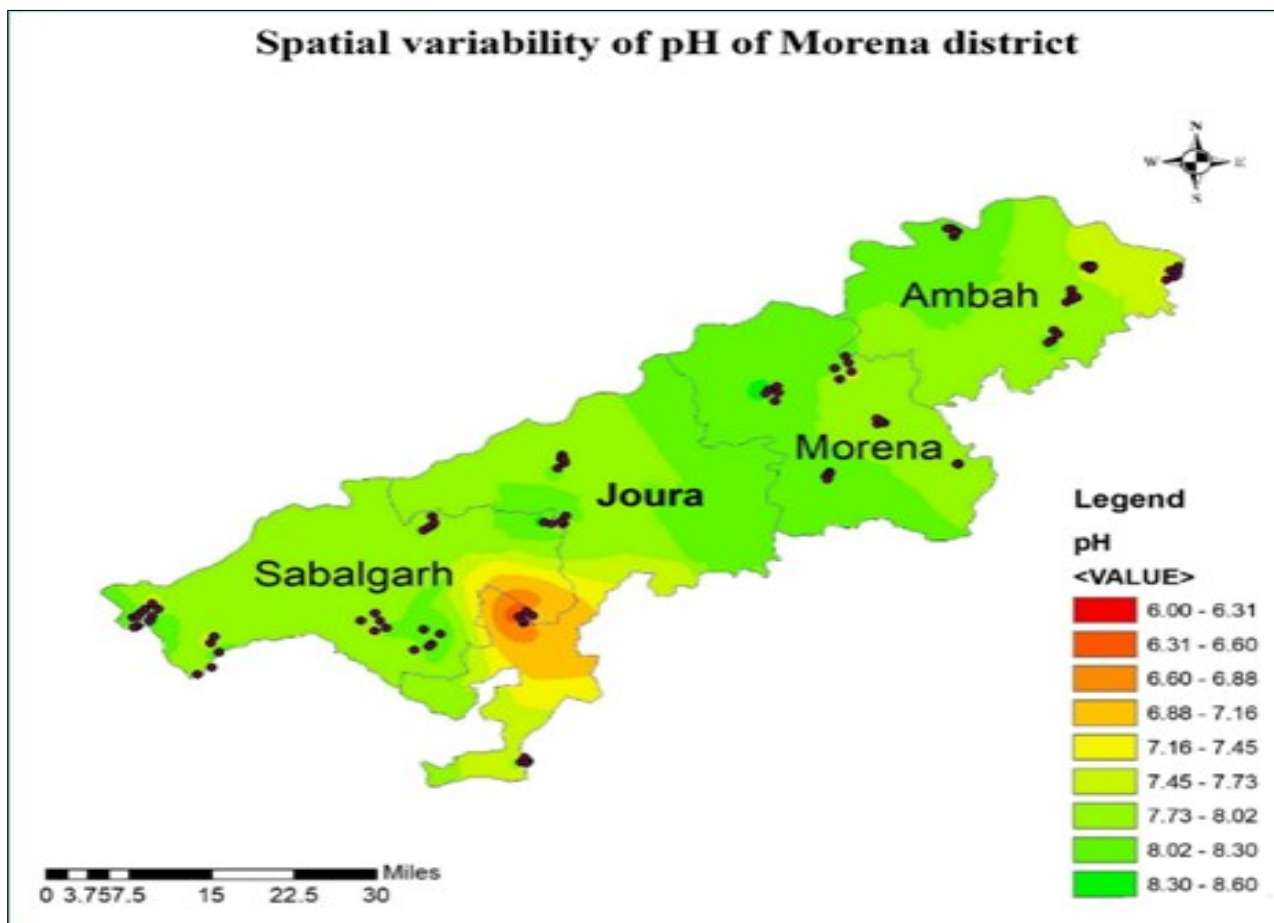


Fig. 2. GIS-based spatial distribution of soil pH [Source: ArcGIS Version 10.8, ESRI, Redlands, CA, USA].

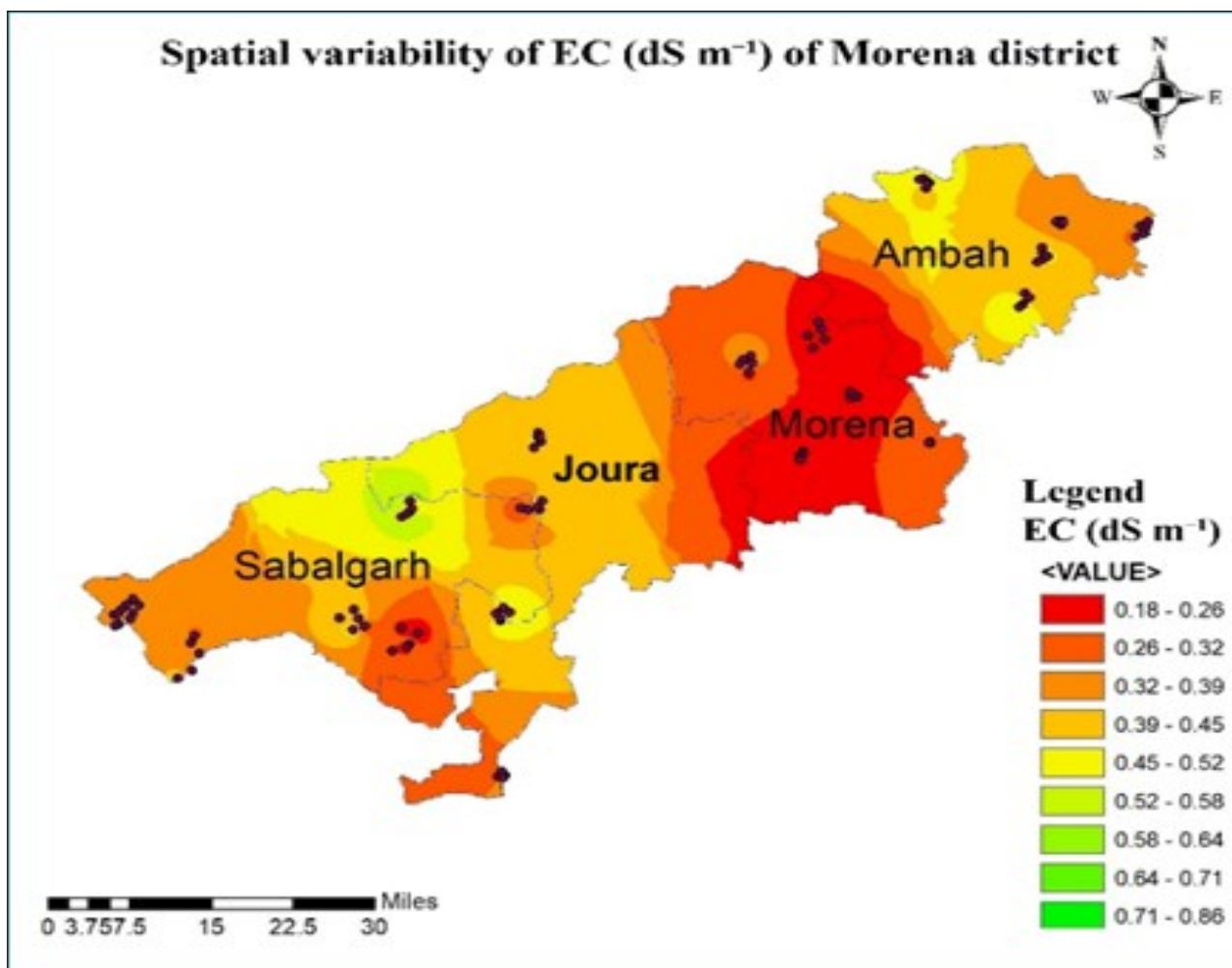


Fig. 3. GIS-based spatial distribution of soil electrical conductivity (dS m^{-1}) [Source: ArcGIS Version 10.8, ESRI, Redlands, CA, USA].

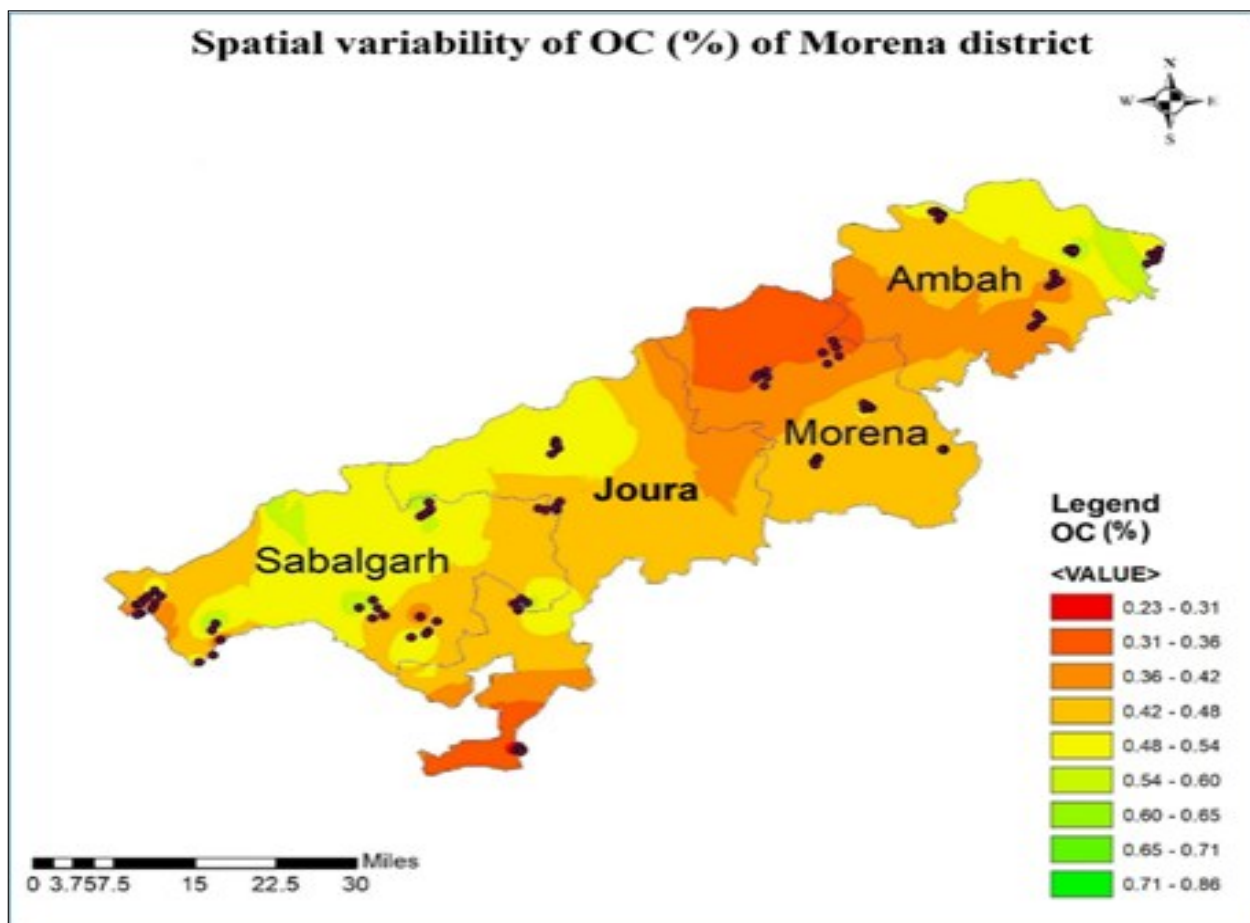


Fig. 4. GIS-based spatial distribution of soil organic carbon (%) [Source: ArcGIS Version 10.8, ESRI, Redlands, CA, USA].

Organic carbon content in the study area ranged from low to medium, which is typical of semi-arid regions where high temperature and rapid decomposition limit organic matter accumulation. The variation in OC across different blocks reflects differences in cropping systems, residue management and organic input application (22–24). Relatively higher OC levels in certain locations indicates better management practices such as incorporation of crop residues or use of organic manures, whereas lower values in other areas suggest poor organic matter recycling (3, 4). Since organic carbon plays a crucial role in improving soil structure, water holding capacity and nutrient availability, its enhancement through sustainable practices like farmyard manure (FYM) application, green manuring and conservation agriculture is essential (25).

Available nitrogen

The available N content in the soils of the Morena district ranged from 118.8 to 255.0 kg ha⁻¹, with an overall mean value of 193.7 kg ha⁻¹. The block-wise descriptive statistics of available N are presented in Table 3, while the spatial distribution of available N in the study area is illustrated in Fig. 5. The highest maximum values were observed in the Joura and Ambah blocks at 255.0 kg ha⁻¹ each, whereas the lowest minimum was in the Sabalgarh block at 118.8 kg ha⁻¹. Mean N values varied across blocks, with Joura and Ambah both at 198.6 kg ha⁻¹, slightly higher than Morena at 183.9 kg ha⁻¹ and Sabalgarh at 193.7 kg ha⁻¹, reflecting moderate variability as indicated by CV ranging from 12.23 % in Joura to 17.45 % in Sabalgarh. Based on standard soil fertility ratings, the soils of the study area fall under the low to medium category of available N status (Table 2).

Available N content was predominantly in the low to medium range across all blocks, indicating insufficient N supply for optimum crop growth. The spatial variation in N closely followed the trend of OC, highlighting the strong dependence of N availability on soil organic matter (26). Lower N levels in several locations may be attributed to continuous cropping, low organic inputs and rapid mineralisation under semi-arid climatic conditions (27). In contrast, relatively higher N content observed in some areas may be due to better residue incorporation and nutrient management practices. These findings emphasise the need for integrated nutrient management strategies combining organic and inorganic sources to enhance N availability and improve N use efficiency (28).

Available phosphorus

The available P content in the soils of the Morena district ranged from 14.60 to 38.40 kg ha⁻¹, with an overall mean value of 23.69 kg ha⁻¹. The block-wise distribution and descriptive statistics of available P are presented in Table 3, while its spatial variability across the study area is illustrated in Fig. 6. The Sabalgarh block showed the widest range of P content (14.60–38.40 kg ha⁻¹) with a mean of 26.22 kg ha⁻¹, while Ambah had the narrowest variability with a CV of 11.89 %. Mean values of available P were highest in Sabalgarh at 26.22 kg ha⁻¹, followed by Ambah at 23.52 kg ha⁻¹, Joura at 23.13 kg ha⁻¹ and Morena at 21.88 kg ha⁻¹. Based on standard soil fertility ratings, the surface soils of the study area are classified under the medium category of available P (Table 2).

The variation in available P across the study area may be attributed to differences in soil pH, organic matter content, fertiliser practices and P fixation behaviour. The overall medium P status indicates a moderate nutrient supply for crop growth. In

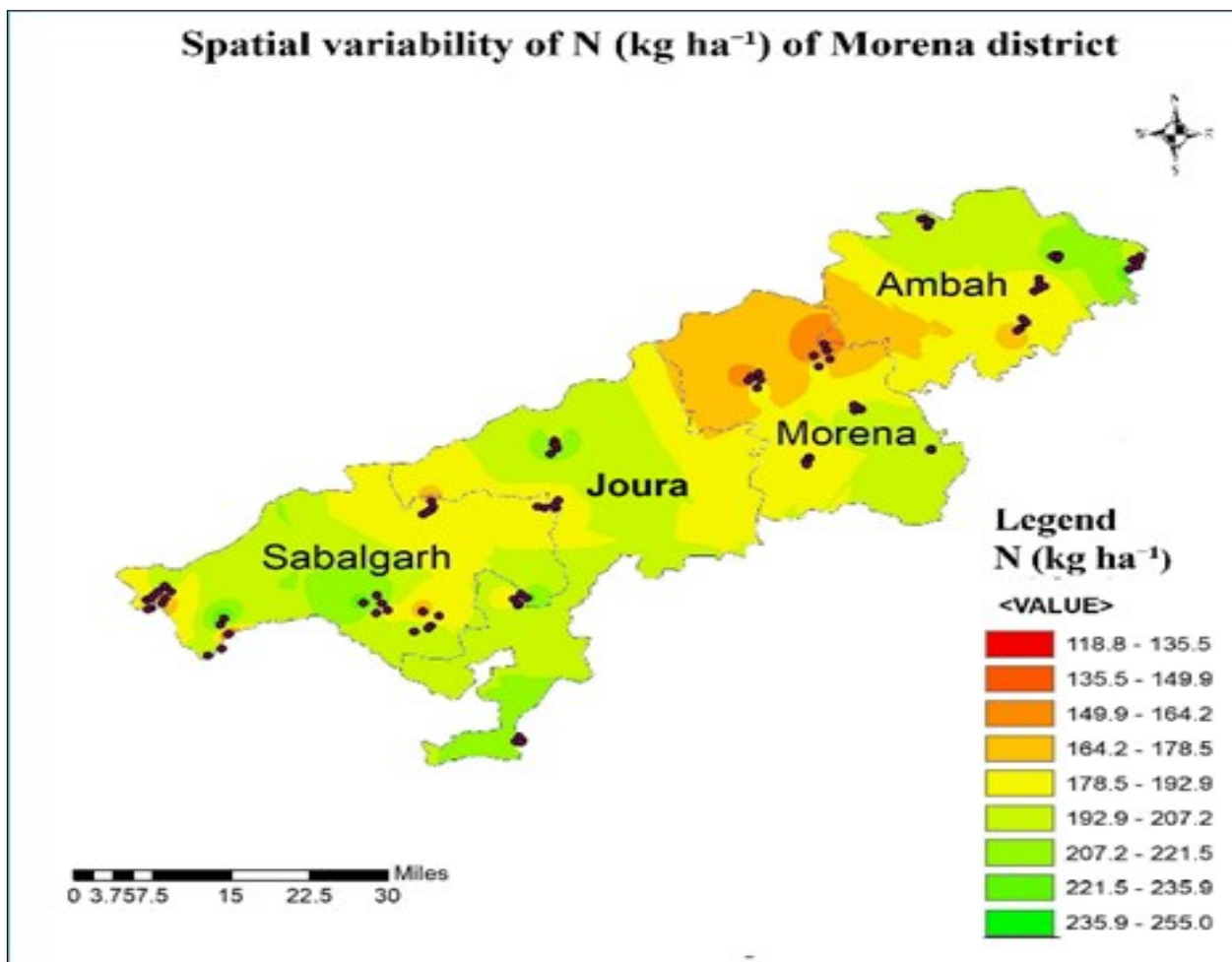


Fig. 5. GIS-based spatial distribution of available nitrogen (kg ha^{-1}) [Source: ArcGIS Version 10.8, ESRI, Redlands, CA, USA].

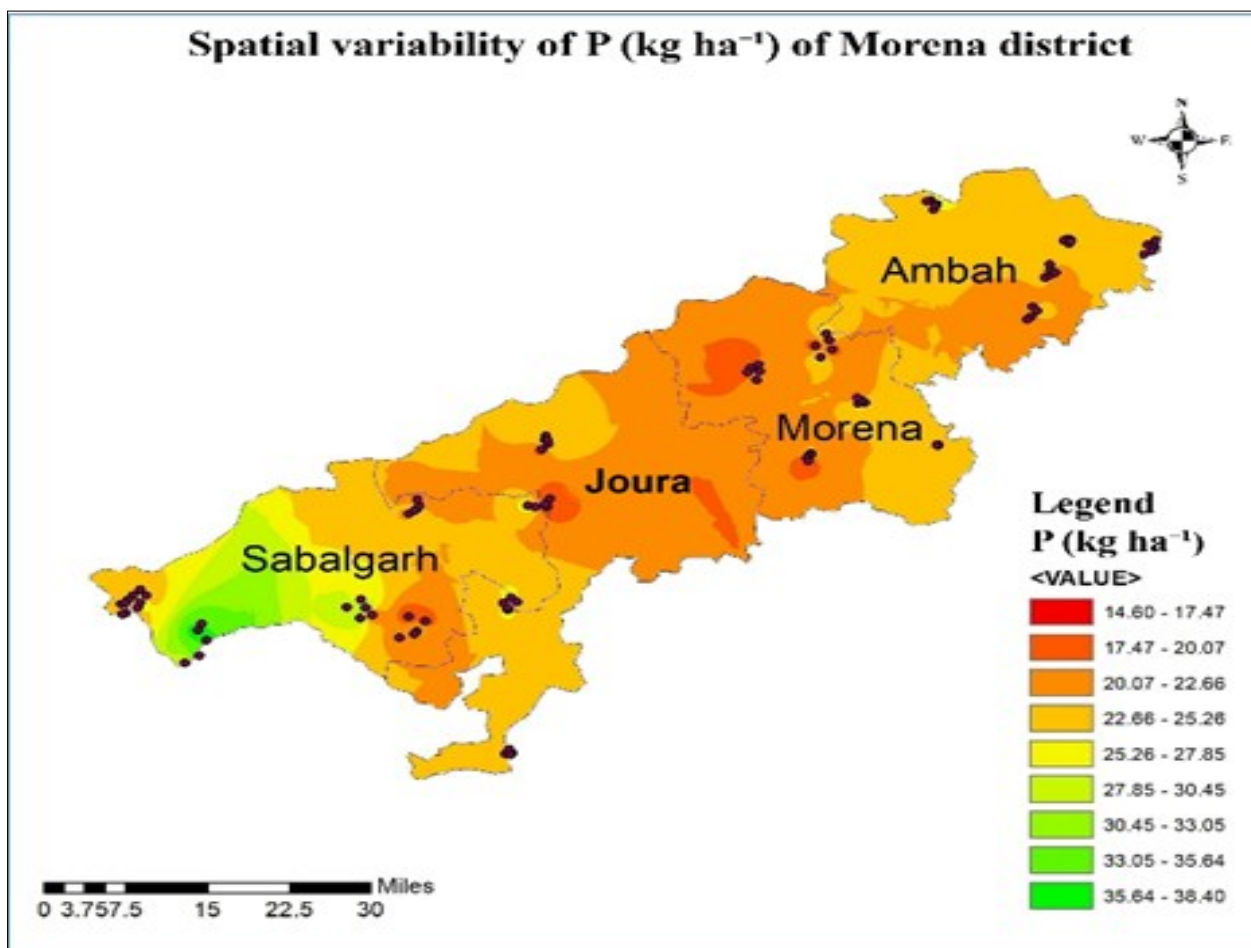


Fig. 6. GIS map showing spatial distribution of soil phosphorous (kg ha^{-1}) [Source: ArcGIS Version 10.8, ESRI, Redlands, CA, USA].

alkaline soils, P availability is often reduced due to fixation in calcium-bound forms, while lower organic matter further limits its availability. These findings are consistent with earlier reports from similar agroecological regions, where available P ranged from low to medium (29). Studies in the Chambal region have also shown spatial variability in P, influenced by parent material, erosion and management practices (3, 4). Similar trends have been reported in Indore district, where soil pH and organic carbon significantly affected P availability (28). These results highlight the need for soil test-based P management and the use of organic amendments to improve its availability.

Available potassium

The available K content in the soils of the study area ranged from 168.6 to 525.0 kg ha⁻¹, indicating considerable variability across the district. The block-wise distribution and descriptive statistics of available K are presented in Table 3, while the spatial variability of K across the study area is illustrated in Fig. 7. The maximum K values were observed at 525.0 kg ha⁻¹ in Morena and 524.0 kg ha⁻¹ in Sabalgarh blocks. The lowest amount of available K (168.6 kg ha⁻¹) was observed in Joura block. Mean concentrations of K were relatively consistent, ranging from 356.5 kg ha⁻¹ in Sabalgarh to 389.6 kg ha⁻¹ in Joura, with CV between 17.15 % in Ambah and 20.64 % in Joura. The overall mean of available K content was 379.3 kg ha⁻¹. This classifies the studied soils predominantly under the medium to high category of K availability (Table 2).

The medium to high levels of available K in the study area can be attributed to the presence of K-bearing minerals in the parent material, along with its replenishment through fertilisers, organic manures and crop residues. Due to its low mobility and resistance to leaching, K tends to accumulate in soils, resulting in a

relatively stable nutrient reserve. These findings are consistent with earlier studies reporting medium to high K status in similar agricultural soils (30). In western Madhya Pradesh, including Indore district, such levels have been linked to K-rich minerals like illite and supported by geospatial analysis for balanced nutrient management (29). Similar variability in available K has also been observed in nearby regions, reflecting contributions from both exchangeable and non-exchangeable forms (31).

Available sulphur

The available S content in the soils of Morena district ranged from 6.50 to 15.80 mg kg⁻¹, with a mean value of 10.63 mg kg⁻¹, indicating low to medium S status (Table 3; Fig. 8). Lower S content was observed mainly in the Sabalgarh and Joura blocks, while comparatively higher values were recorded in the Morena and Ambah blocks. Specifically, maximum available S values reached 15.80 mg kg⁻¹ in both Joura and Morena, with minima at 6.50 mg kg⁻¹ in Sabalgarh and 8.20 mg kg⁻¹ in Joura. Mean levels varied from 10.13 mg kg⁻¹ in Ambah to 11.04 mg kg⁻¹ in Morena, with CV showing higher variability in Sabalgarh at 29.70 % compared to lower in Ambah at 15.96 %.

The variation in available S may be attributed to differences in soil OC, land use, cropping intensity and organic matter management. Lower S levels are likely due to continuous cropping, limited use of S-containing fertilisers and leaching losses, while higher values may be associated with better residue incorporation and balanced nutrient practices. These findings are consistent with reports from the Indo-Gangetic Plains, where S availability ranged from low to medium and was closely linked with OC and land use systems (32). Significant S deficiencies have also been observed under intensive cropping systems such as rice

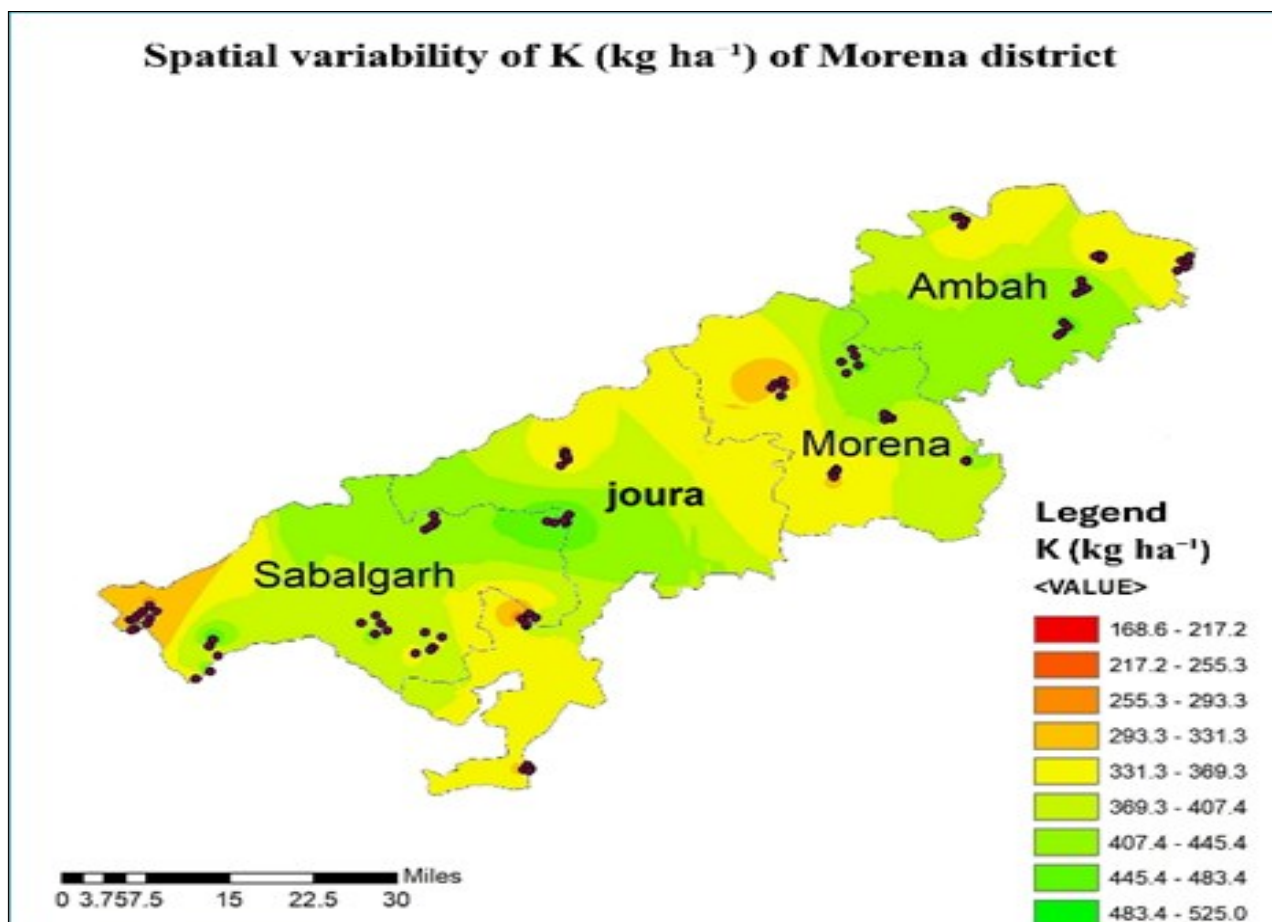


Fig. 7. GIS-based spatial distribution of available potassium (kg ha⁻¹) [Source: ArcGIS Version 10.8, ESRI, Redlands, CA, USA].

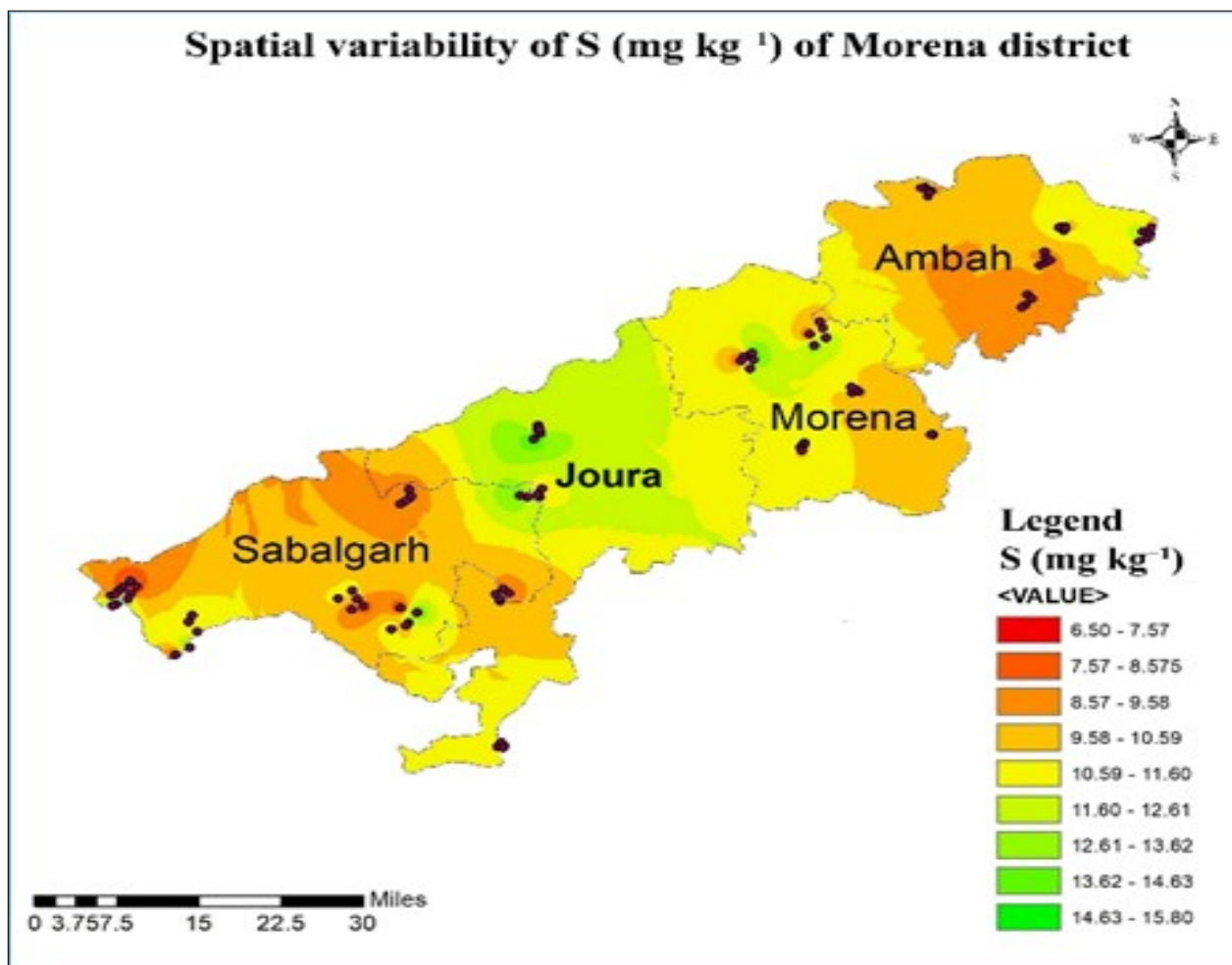


Fig. 8. GIS-based spatial distribution of available sulphur (mg kg⁻¹) [Source: ArcGIS Version 10.8, ESRI, Redlands, CA, USA].

–wheat, leading to increased crop response to S fertilisation (33). At a broader scale, widespread S deficiency in Madhya Pradesh soils further emphasises the need for its balanced application to sustain soil fertility and crop productivity (34).

Available iron

The available Fe content in the soils of the Morena district exhibited considerable spatial variability. The DTPA-extractable Fe ranged from 0.64 to 24.25 mg kg⁻¹, indicating soil conditions varying from deficient to sufficient in Fe status (Table 2). The block-wise descriptive statistics of available Fe are presented in Table 3, while the spatial distribution of Fe across the study area is illustrated in Fig. 9. Lower Fe availability was predominantly observed in the Sabalgarh and Joura blocks, whereas comparatively higher Fe concentrations were recorded in the Morena block, followed by the Ambah block.

The variation in available Fe may be attributed to high soil pH and sodicity, which promote the precipitation of Fe²⁺ into less available forms, thereby reducing its availability to plants (35). Similar patterns of Fe availability have been reported in various regions, including northern Madhya Pradesh, the Malaprabha command area, Patan district and Nagpur district (36–39). In alkaline soils, such as those prevalent in the Indo-Gangetic Plains and central India, DTPA-extractable Fe is generally sufficient due to parent material influence; however, deficiencies may occur under conditions of high pH and low organic matter. This is consistent with national-level observations indicating that Fe deficiency affects a notable proportion of soils across India (40, 41).

Available copper

The available Cu content in the soils of the Morena district exhibited wide variability across the four blocks. The DTPA-extractable Cu ranged from 0.20 to 2.76 mg kg⁻¹, indicating soil conditions varying from deficient to sufficient in Cu status (Table 2). The block-wise descriptive statistics of available Cu are presented in Table 3, while the spatial distribution of Cu across the study area is illustrated in Fig. 10. The lowest Cu concentrations were recorded in the Sabalgarh block, whereas comparatively higher Cu levels were observed in the Morena block, followed by the Ambah and Joura blocks. Overall, the availability of Cu across the blocks followed the order: Morena > Ambah > Joura > Sabalgarh.

The variation in available Cu may be attributed to differences in soil pH, OC content and organic matter decomposition, which influence the solubility and availability of cationic micronutrients. Similar patterns of Cu variability have been reported in earlier studies (42). In alkaline soils, Cu availability is generally adequate and deficiencies are relatively rare, affecting only a small proportion of soils. However, low OC and high pH can reduce Cu availability by limiting chelation processes. The generally sufficient Cu status observed in the Chambal region may be attributed to moderate organic matter and clay content, which enhance Cu retention in soils (40, 41).

Available zinc

The available Zn content in the soils of the Morena district ranged from 0.26 to 1.52 mg kg⁻¹, with an overall mean value of 0.63 mg kg⁻¹. The block-wise distribution and descriptive statistics of available Zn are presented in Table 3, while the spatial variability of Zn across the study area is illustrated in Fig. 11. Based on critical limits,

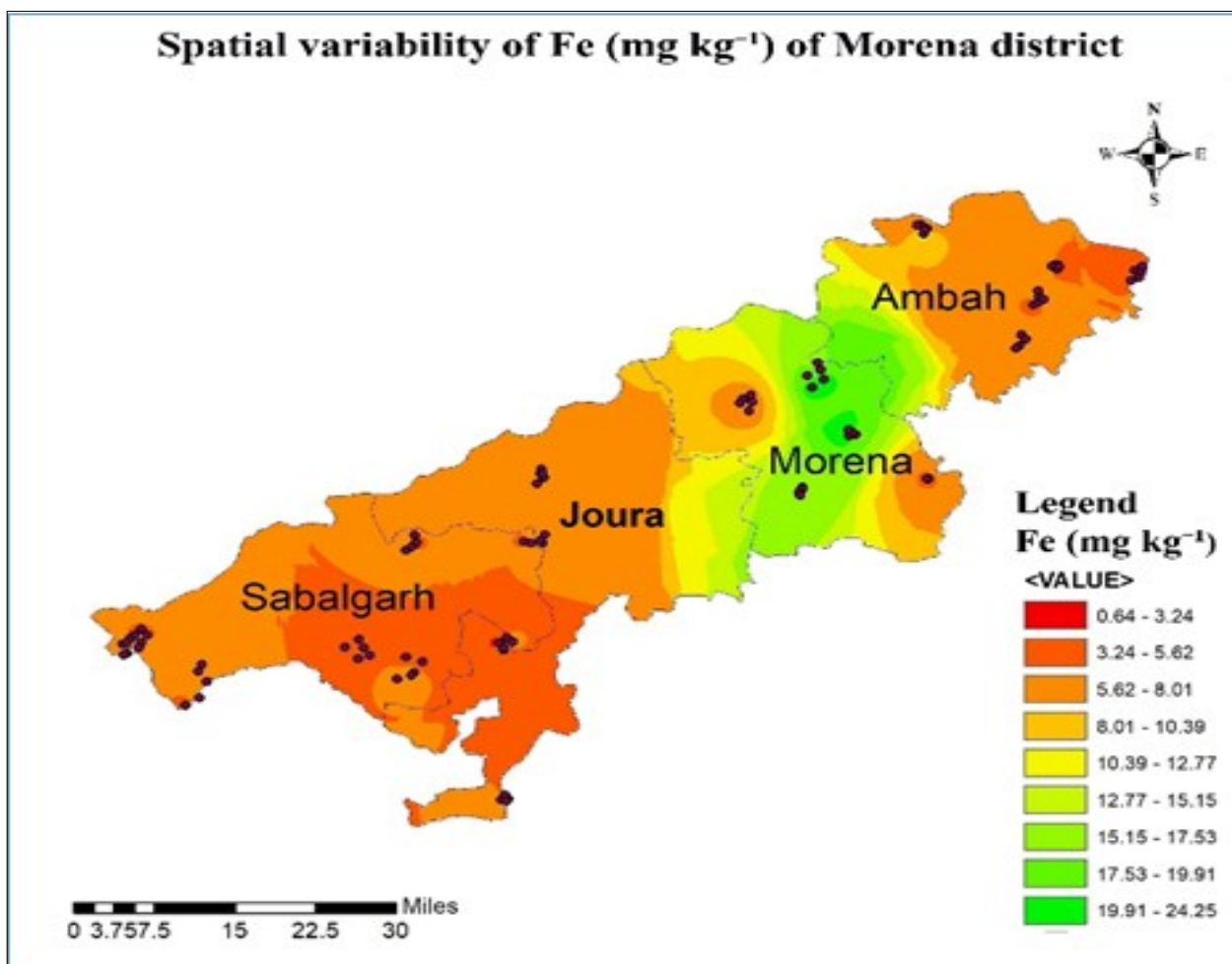


Fig. 9. GIS-based spatial distribution of available iron (mg kg^{-1}) [Source: ArcGIS Version 10.8, ESRI, Redlands, CA, USA].

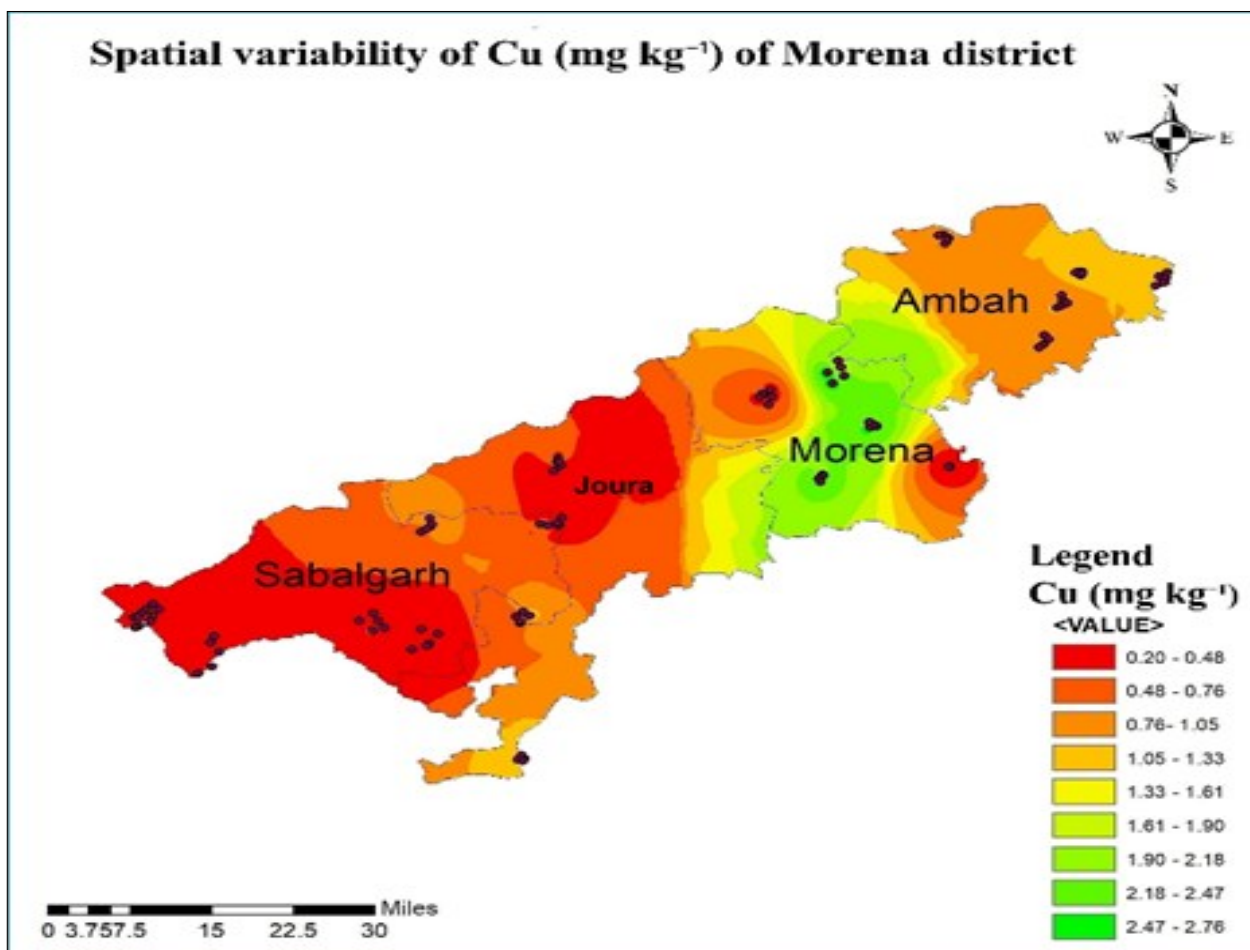


Fig. 10. GIS-based spatial distribution of available copper (mg kg^{-1}) [Source: ArcGIS Version 10.8, ESRI, Redlands, CA, USA].

the soils of the study area varied from low to medium in Zn status (Table 2). However, a considerable proportion of soil samples exhibited Zn deficiency, particularly in areas characterised by high soil pH, low OC content and coarse-textured soils.

The widespread occurrence of Zn deficiency in the study area may be attributed to alkaline soil reaction, low organic matter content and continuous cropping without adequate micronutrient supplementation. High soil pH, along with declining OC, reduces Zn availability by enhancing its fixation in soil complexes. Similar observations of Zn deficiency under alkaline conditions have been reported in earlier studies (43–45). Previous studies have also indicated that soils low in organic matter and inadequately supplied with micronutrients are more susceptible to Zn deficiency (44). The Zn deficiency is one of the most prevalent micronutrient constraints in Indian soils, particularly in alkaline regions of central and northern India, affecting a large proportion of soils in Madhya Pradesh and limiting crop productivity (40, 41).

Available manganese

The available Mn content in the soils of the study area ranged from 2.10 to 26.70 mg kg⁻¹, with an overall mean value of 10.70 mg kg⁻¹. The block-wise descriptive statistics of available Mn are presented in Table 3, while its spatial distribution across the study area is illustrated in Fig. 12. Based on critical limits, deficient, moderate and sufficient Mn status were observed in a smaller proportion of soil samples (Table 2); however, most samples fell under the sufficient category, indicating adequate Mn availability in most parts of the study area. Among the revenue villages, the lowest DTPA-extractable Mn content (2.10 mg kg⁻¹) was recorded in Rampur Kalan village of the Sabalgarh block, followed by Dipera

and Tilawali villages of the Joura block. In contrast, the highest DTPA-Mn content (26.70 mg kg⁻¹) was observed in Basaiya village of the Morena block, followed by Madhogarh and Jarara villages, indicating relatively higher Mn availability in these areas.

The higher Mn content in the soils may be attributed to the presence of Mn-bearing minerals in the parent material and relatively favourable soil conditions. However, its availability varies across the study area due to the influence of soil pH, OC and redox conditions. Higher soil pH promotes the formation of insoluble higher-valent Mn oxides, thereby reducing its availability, as reported in earlier studies (45). In alkaline soils, Mn deficiency is generally less common, as sufficient reserves are maintained through mineral sources; however, pH-induced oxidation can limit its availability in calcareous conditions. Similar trends of adequate Mn status have been observed in central Indian soils, including regions comparable to the Chambal area (40, 41).

Conclusion

The soils of Morena district in the Chambal region showed neutral to moderately alkaline reaction with non-saline conditions, indicating suitability for crop production. However, low to medium OC and nutrient status highlight constraints in soil fertility. Available N and P were predominantly low to medium, while K was largely sufficient. Among the micronutrients, Zn deficiency emerged as a major limitation, whereas Fe, Cu and Mn showed variable but generally adequate status. Sulphur availability was also low to medium and closely associated with organic matter levels. The study clearly demonstrated significant spatial variability

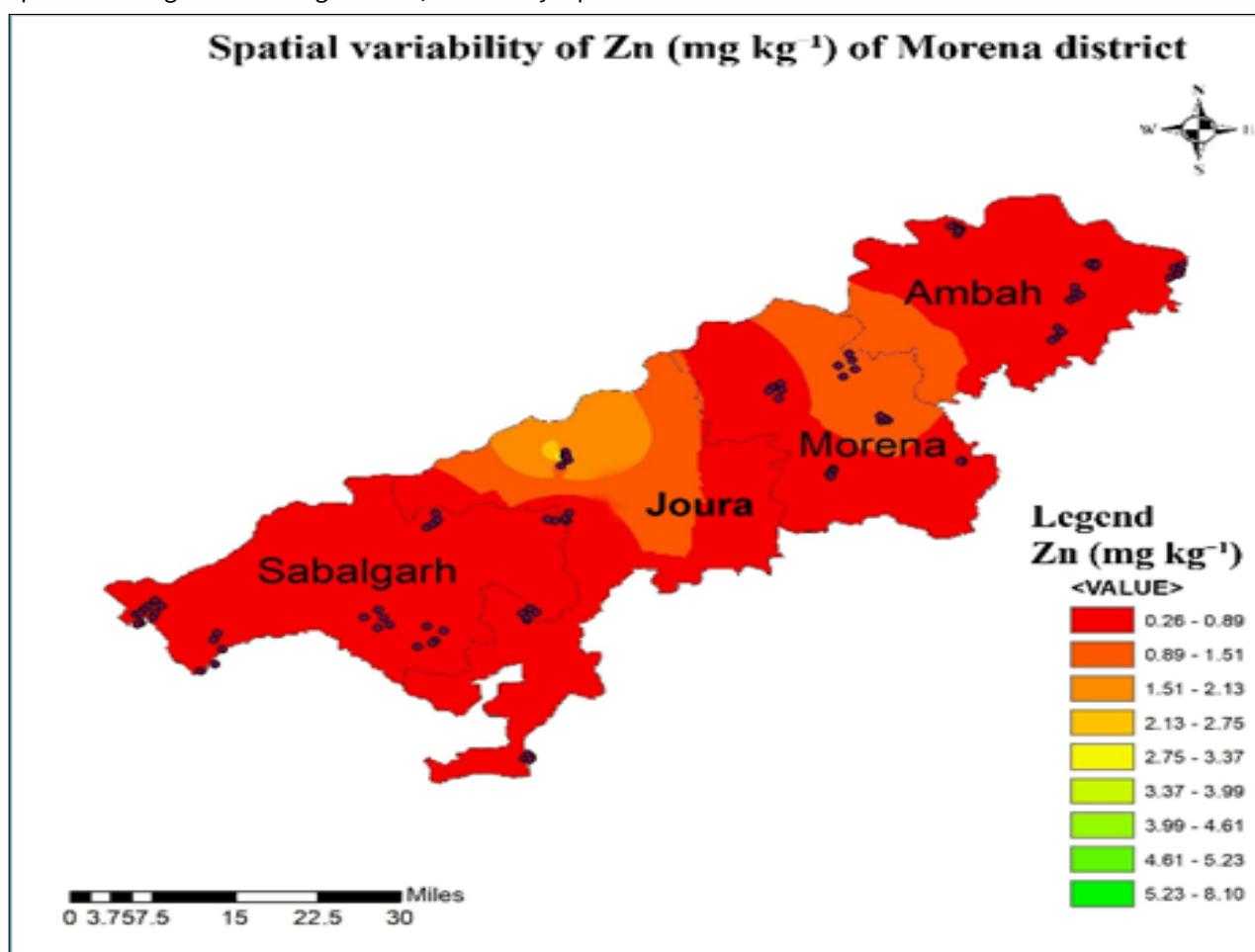


Fig. 11. GIS-based spatial distribution of available zinc (mg kg⁻¹) [Source: ArcGIS Version 10.8, ESRI, Redlands, CA, USA].

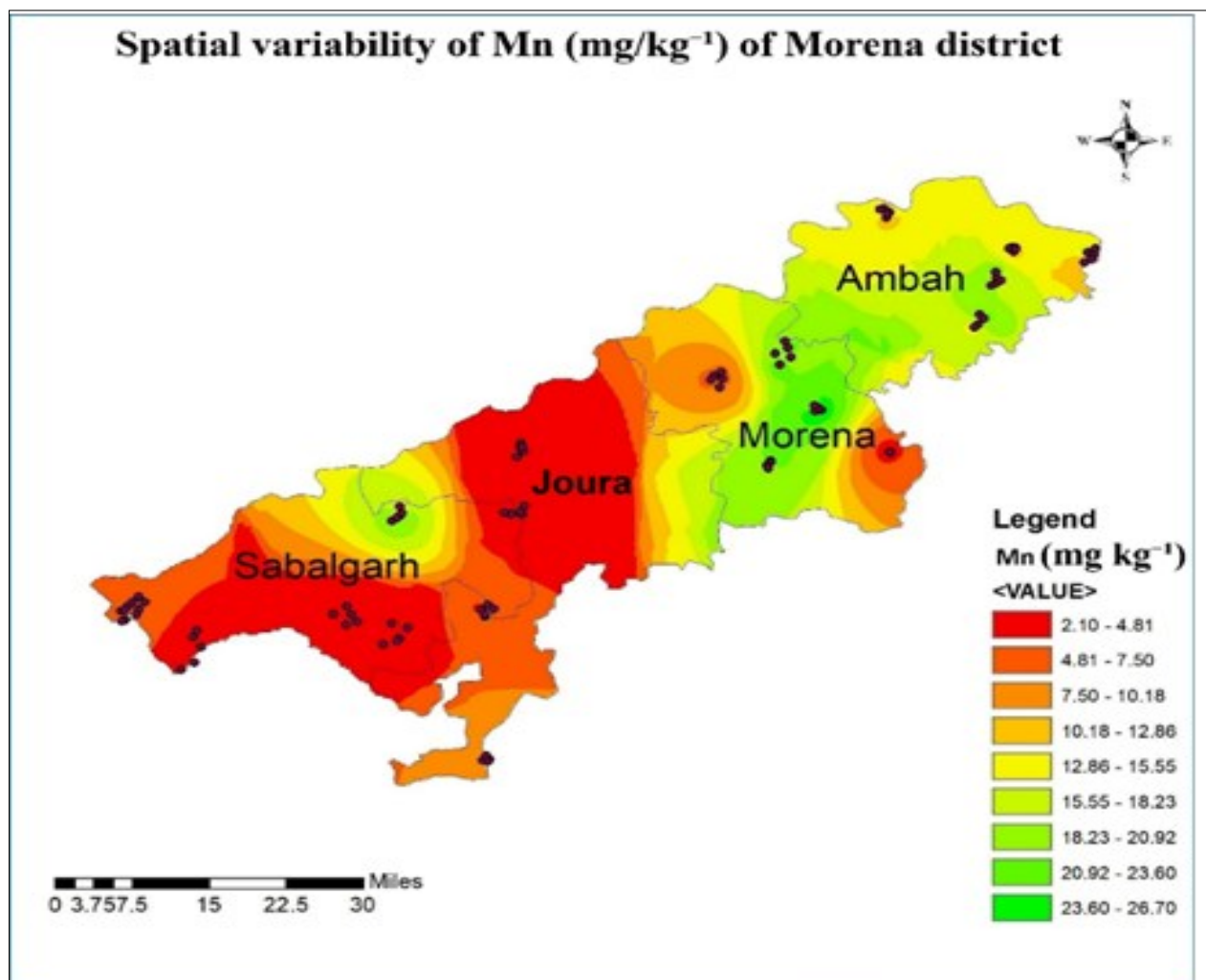


Fig. 12. GIS-based spatial distribution of soil manganese content (mg kg⁻¹) [Source: ArcGIS Version 10.8, ESRI, Redlands, CA, USA].

in soil chemical properties across different blocks.

Based on these findings, site-specific nutrient management is essential. Farmers should adopt soil test-based fertiliser application, with particular emphasis on N, P, S and Zn supplementation in deficient areas. The use of organic manures, crop residues and integrated nutrient management practices should be promoted to improve OC and overall soil health.

At the policy level, there is a need to strengthen GIS-based soil fertility mapping and advisory services to support precision agriculture. Extension programmes should focus on awareness and training of farmers regarding balanced fertilisation and micronutrient management. Such targeted interventions will help enhance nutrient use efficiency, sustain soil fertility and improve crop productivity in the region.

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Authors' contributions

BT conducted field sampling, performed laboratory analysis and prepared the manuscript. PRP designed and supervised the research work. VP and AR assisted with data analysis and interpretation. SKA and SST provided technical and laboratory support. ANS reviewed the manuscript and offered valuable suggestions. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used QuillBot (AI-assisted tools) for language improvement. The authors reviewed and edited the content and take full responsibility for the final manuscript.

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