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Integrated Evaluation of Soil Properties, Land Capability, Productivity, and Crop Suitability in the Deccan Plateau, Central India

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THIS STUDY presents an integrated assessment of soil properties, land capability, productivity, and crop suitability in the Deccan Plateau of central India. The research area, covering 20.10°–21.22° N and 78.61°–78.69° E, features a diverse landscape dominated by *Vertisols*, *Inceptisols*, and *Entisols*, with land uses ranging from rainfed and irrigated agriculture to fallow and degraded forest lands. Comprehensive field surveys and laboratory analyses were conducted on geo-referenced soil profiles, characterizing key physical and chemical properties. Soils were classified according to USDA Soil Taxonomy, revealing significant spatial variability and highlighting major constraints including low organic carbon content, variable drainage, and high clay percentages in *Vertisols*. Land capability was evaluated using the Storie Index method, which identified that only 18% of the area falls under Class II (good capability), while 52% is classified as Class III (moderate limitations) and 30% as Class IV (severe limitations), primarily due to physical constraints and nutrient deficiencies. Actual and potential land productivity, assessed via the FAO frameworks, showed that current productivity indices are suboptimal for major crops, with mean productivity scores of 42–56%, but could be improved by 15–25% through targeted management interventions such as organic amendments and drainage improvements. Crop suitability analysis, based on the parametric approach demonstrated that *Vertisols* are moderately suitable (S2), while *Entisols* and *Inceptisols* are marginally suitable (S3), mainly constrained by low water retention and nutrient status. The integrated evaluation underscores the critical role of soil management in enhancing land productivity and sustainability. Key recommendations include the adoption of organic matter enrichment, balanced fertilization, and improved water management to mitigate identified limitations. The study's multi-criteria approach provides a robust basis for evidence-based land use planning and policy formulation in semi-arid tropical regions. These findings have direct implications for sustainable agricultural intensification in central India, supporting food security and resilience in the face of climatic and socio-economic challenges.

Keywords: *Inceptisols*, Capability, Evaluation, *Entisols*, Land productivity, Soil properties, Suitability, *Vertisols.*

1. Introduction

In the 21st century, the global community faces unprecedented environmental challenges that threaten the very foundation of human well-being and planetary health. Climate change, driven by anthropogenic greenhouse gas emissions, is altering weather patterns, increasing the frequency of extreme events, and disrupting agricultural systems worldwide (Miao & Nduneseokwu 2025). Simultaneously, the world's population continues to grow, projected to reach nearly 10 billion by 2050, thereby intensifying the demand for food, water, and natural resources (Lam, 2025). Food security a condition in which all people have access to sufficient, safe, and nutritious food has become a central concern, particularly in regions where land degradation, resource scarcity, and socio-economic vulnerabilities intersect (Islam, 2025). Therefore, there is an urgent need to a sustainable manage of the different land soil resources in order to secure the environment's resilience as well as the capacity for feeding the grown population (Muchhadiya et al., 2024).

Soil is considered as the most important source for the agricultural production because it is responsible for regulating the water and supporting the growth of the plant to protect it from the environment stresses (Futa et al., 2024). Moreover, the soils are significantly affected by the different types of degradation like erosion, salinization, nutrients' depletion as well as losing the fertility represented by the soil organic matter. All these

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factors are considered as unsustainable factors for the land use and climate change (Selmy et al., 2025). Additionally, precise evaluation of the soil is mandatory for achieving the sustainable land management especially when the soil limitations are addressed in order to solve soil problems and enhance the agricultural productivity (Fadl et al., 2025). The land evaluation provides accurate insights to be provided to the policymakers for achieving better land management at either local, regional, and national scales, and to be involved in fulfilling the sustainable development goals (SDGs) especially those are related to “zero hunger”, “climate action” as well as “life on land” (Sharma et al., 2024).

The assessment of land productivity, capability, and suitability is very crucial research point as the land capability considers the soil properties to classify the lands against their capability to be cultivated and also overview the soil limitations (Dutta et al., 2024). On the other hand, the assessment of the land productivity in actual and potential takes in consideration the different land uses as well as the required improvements which can be done to remove the soil limitations (Mansour, 2025). Moreover, the assessment of the land suitability to be cultivated by different crops through comparing each crop’s requirements with the soil properties in a specific land or local area in order to identify the most suitable crops can be grown (Moursy & Thabit 2022).

India faces many challenges related to the climate change such as land degradation and soil fertility reduction. Although it’s vast and diverse agro-ecological zones, India represents 18% of the world’s population which living on only 2.4% of its land area (Sati, 2024). Moreover, the quick urban sprawl, population growth and climate influences put a huge pressure on India’s soils especially in fragile ecosystems where limited resources (Ghosh et al., 2025). The landscape in Maharashtra and the central Indian plateau is dominated by *Vertisols*, *Inceptisols*, and *Entisols* soil orders whereas reasonable clay content, fertility and strong management limitations (Moharana et al., 2025). This area is mainly rainfed by the erratic monsoons where very sensitive to soil and water limitations. The previous literatures demonstrated these limitations such as low organic carbon, deficiency in nutrients, poor drainage and coarse fragment content which affects the land productivity and the sustainable agriculture (Pramanik et al., 2024; Vadivel et al., 2024; Chore et al., 2021; Malode et al., 2021). Furthermore, the soil variability reflected in soil types, land uses, and climatic conditions makes an area is a reference model for characterizing and evaluating the soil properties, land management, and agricultural productivity. The integration of geographic information systems (GIS) for mapping this variability is necessary for accurate, detailed, geo-referenced assessment of land capability, productivity, and suitability in this area (Selmy et al., 2023).

The novelty of this research lies in an integration of classical and modern techniques for land characterization and evaluation. Incorporating the Storie Index method for land capability, the FAO framework for actual and potential productivity, and the parametric approach for crop-specific suitability can offer an overview about the soil limitations, the potential possible improvements and achieve better management. Compared to previous research efforts which focused in a single aspect, this investigation tried to link the soil properties with different evaluation criteria for providing actionable insights for sustainable land use planning at central India. Utilization of geo-referenced soil profiles, laboratory testing as well as land evaluation systems improve the relevance and applicability of the findings for policymakers, extension agents, or local farmers.

Thus and based on this introduction, the main objectives of this study are: (1) to characterize the physical and chemical properties of soils in Katol tahsil of Nagpur district, Maharashtra; (2) to assess the land capability of the area; (3) to assess the actual and potential land productivity; (4) to determine the crop-specific land suitability using the parametric approach; and (5) to identify the main soil limitations and recommend management interventions for improving land productivity and sustainability.

2. Materials and Methods

2.1. The study area

The employed methodology was displayed in the flowchart (Figure 1). The studied site is located in central India, as indicated by the latitude and longitude coordinates ranging from approximately 20.10° to 21.22° north and 78.61° to 78.69° east (Figure 2). This region falls within the Deccan Plateau, which is characterized by gently undulating to rolling topography. According to previous soil surveys and research in this area, the predominant soil types are *Vertisols*, *Inceptisols*, and *Entisols*. *Vertisols* are deep, clay-rich soils known for their high shrink-swell capacity, while *Inceptisols* and *Entisols* are moderately developed soils with varying degrees of fertility and drainage characteristics (Moharana et al., 2025; NBSS&LUP, 2012). The natural vegetation cover in this region historically consisted of dry deciduous forests, dominated by species such as teak (*Tectona grandis*), sal (*Shorea robusta*), and various Acacia species. However, much of the original forest cover has been altered due to human activities. Presently, the land use is a mosaic of rainfed and irrigated agriculture, mixed cropping systems, fallow lands, and patches of degraded forest or scrubland. Major crops cultivated include cotton, soybean, sorghum, pigeon pea, and wheat, reflecting the semi-arid to sub-humid climate and the adaptability of these crops to local soil and rainfall conditions. Hydrologically, the area is drained by seasonal streams and minor rivers that are tributaries of larger river systems in central India.

The region experiences moderate to low groundwater availability, with water tables fluctuating seasonally. Surface water is primarily available during the monsoon months, contributing to both direct irrigation and groundwater recharge. Climatic conditions are characterized by a tropical monsoon climate, with three distinct seasons: a hot and dry summer (March to June), a rainy season (June to September) with most of the annual rainfall (900–1200 mm) received during this period, and a cool, dry winter (October to February). The temperature ranges from 12°C in winter to over 40°C in summer. The rainfall pattern is highly seasonal, and droughts or dry spells are not uncommon, influencing both crop choices and soil moisture regimes.

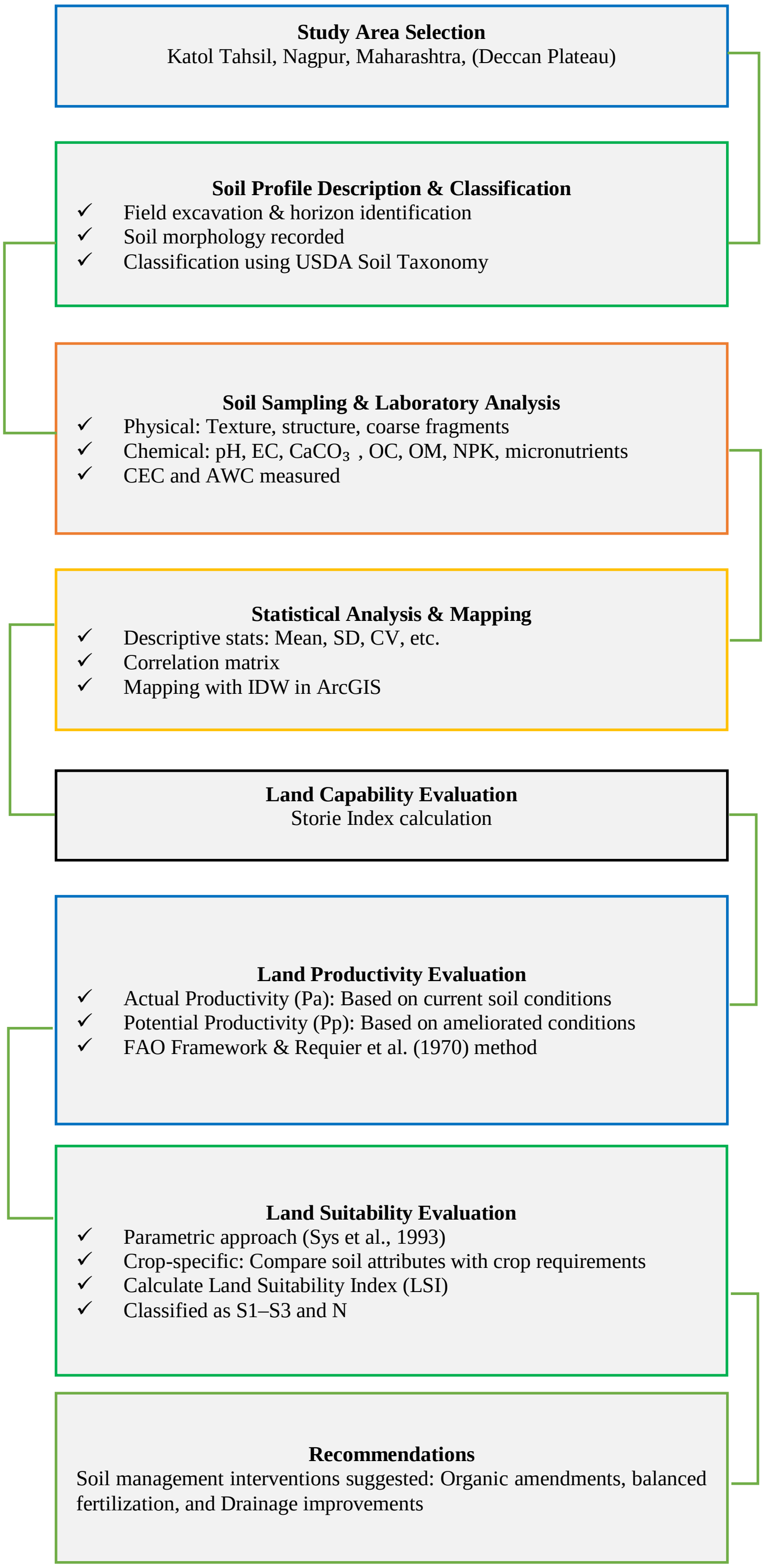


Fig. 1. Flowchart of the employed methodology.

2.2. Soil profile description and classification

Nineteen soil profile description was conducted in the field by carefully excavating soil pits to a depth that allowed observation of all significant soil horizons, typically until unweathered parent material was reached. Each horizon was identified and described based on color, texture, structure, consistency, root abundance, presence of coarse fragments, and effervescence using standard soil survey techniques. The soil profiles were geo-referenced using GPS coordinates, and environmental parameters including slope, landform, vegetation, erosion status, and land use were recorded. Soil classification followed the criteria outlined in the USDA Soil Taxonomy system (Soil Survey Staff, 2022). Profiles were classified sequentially from the order to subgroup level, based on diagnostic horizons and features. The classification process utilized both field morphology and laboratory data to assign soils into orders such as *Entisols*, *Inceptisols*, or *Vertisols*.

2.3. Soil sampling

Approximately 500 grams of soil were collected from each horizon from the nineteen representing different soil profiles, and placed in labelled, clean polythene bags indicating the profile number, horizon, depth, latitude, and longitude. After collection, the soil samples were transported to the laboratory where air-dried at room temperature in a dust-free environment. The soil samples were crushed and passed through 2 mm sieve to eliminate the non-soil materials and then stored in airtight containers (Jones, 2018; Moursy et al., 2022).

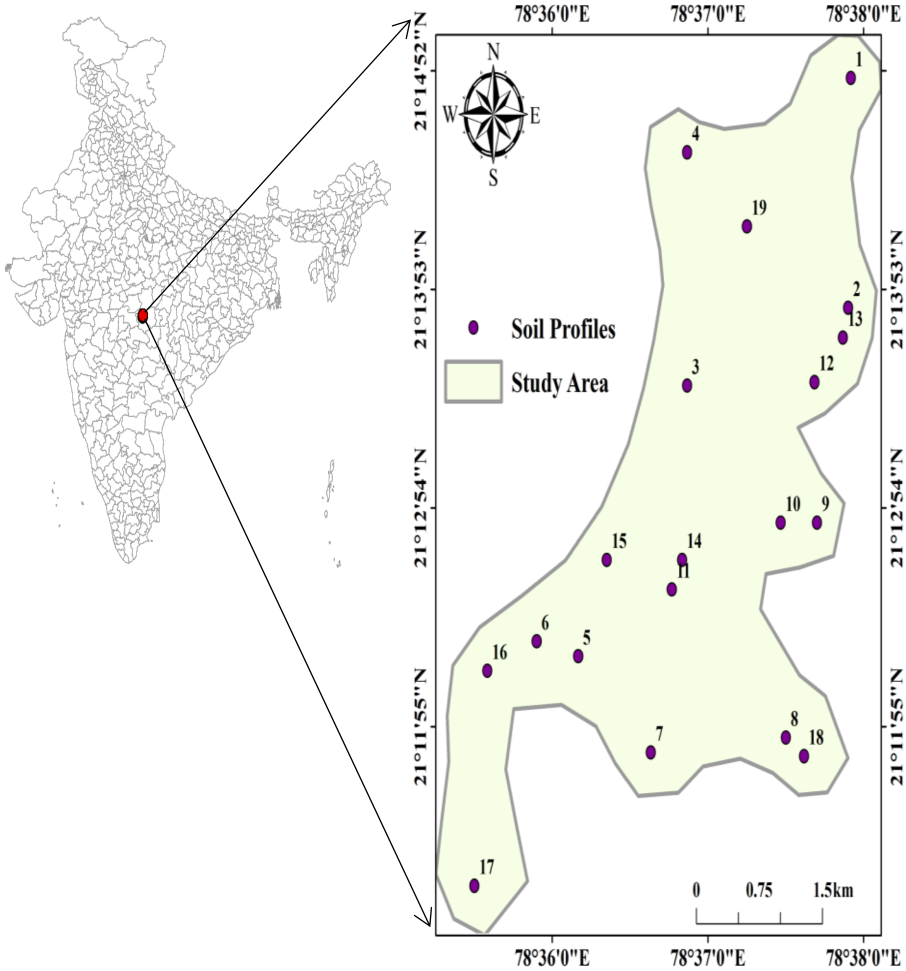


Fig. 2. Study area and soil sampling locations.

2.4. Soil testing

Soil physical and chemical determinations were conducted following the standards methods described in Jones (2018). The soil pH was determined using 10 grams of each sample, mixed with 25 mL of distilled water and, and the pH values were measured utilizing a calibrated pH meter after thoroughly stirring. The electrical conductivity (EC) is determined in 1:5 soil-to-water extract after one hour shaking by a calibrated conductivity meter. The calcium carbonate content is determined by a calcimeter. For soil texture, including sand, silt, and clay percentages, the hydrometer method is used, where soil is dispersed in water with a dispersing agent, allowed to settle, and the fractions are measured at specific intervals. Coarse fragments are quantified by drying a representative soil sample, sieving through a 2 mm seive, and weighing the residue to calculate the percentage relative to the total sample mass. Available nitrogen is typically extracted using alkaline potassium permanganate, followed by colorimetric analysis. Available phosphorus and potassium are extracted with Mehlich 2 solution, shaken, and analyzed using appropriate chemical methods as colorimetry for phosphorus and flame photometry for potassium. Micronutrients (Fe, Mn, Cu, and Zn) were extracted using DTPA solution, shaken, filtered, and analyzed using atomic absorption spectrophotometry. Available sulfur was extracted with Barium chloride and measured colorimetrically. Organic carbon is determined using the Walkley-Black method, where soil organic carbon is oxidized with potassium dichromate and sulfuric acid, and the excess dichromate is titrated with ferrous sulfate. Cation exchange capacity (CEC) is measured by saturating the soil with ammonium acetate, displacing the ammonium with sodium, and quantifying the ammonium released using Kjeldahle distillatory.

2.5. Land capability evaluation

The Storie Index (equation 1) is calculated using four main factors, each representing a key aspect of land capability (A is soil depth and texture; B is soil permeability; C is soil chemical characteristics such as soil pH, salinity (EC), calcium carbonates, and nutrient status; and D is the drainage). Each factor is assigned a rating between 0 and 100 (%) based on the measured soil properties and established criteria (Storie, 1978; Sys et al., 1991). The overall Storie Index (SI) is calculated as:

$$\text{Storie Index (\%)} = [(A/100) \times (B/100) \times (C/100) \times (X/100)] \times 100 \qquad \text{Equation (1)}$$

The final SI value is used to classify land capability as follows (Storie, 1978) as shown in table (1).

Table 1. The Storie index rating and classes of lad capability.

Storie Index (%)	Land Capability Class
80–100	Excellent (Class I)
60–79	Good (Class II)
40–59	Fair (Class III)
20–39	Poor (Class IV)
<20	Very Poor (Class V)

2.6. Actual and potential land productivity evaluation

For assessing the land productivity in actual and potential conditions, the FAO framework for land evaluation (FAO, 1976; FAO, 2024; Requier et al., 1970) were utilized which provide detailed guidelines for matching land characteristics with cultivation in order to classify the study area based on its future possible productivity. For calculating the actual and potential land productivity indices, the equations (2 and 3) given by Requier et al. (1970) are described below.

$$Pa = A_a \times B_a \times C_a \times D_a \times \ldots \times N_a \qquad \text{Equation (2)}$$

$$Pp = A_p \times B_p \times C_p \times D_p \times \ldots \times N_p \qquad \text{Equation (3)}$$

Where: Pa = Actual productivity index; Pp = Potential productivity index which these indices are expressed as a percentage or decimal fraction; A, B, C, D, ⋯, N in actual (a) or potential (p) = Ratings (in %) for each soil property like pH, EC, $CaCO_3$, texture, nutrients, etc., whereas 100% rating is an optimal (no limitation), and near to zero is the lowest (strong limitation) based on table (2).

Table 2. Classes of actual and potential land productivity.

Class Name	Productivity (P) / Potentiality (Pf) Range (%)
Excellent (I)	65 – 100
Good (II)	35 – 64
Average (III)	20 – 34
Poor (IV)	8 – 19
Extremely Poor (V)	0– 7

2.7. Land suitability evaluation for different crops

The methodology given by Sys et al. (1991, 1992, and 1993) for land suitability evaluation is a systematic, parametric approach designed to assess the suitability of land for different crops based on a range of soil and site characteristics. This method proposes that for each crop, the requirements for optimal growth must be established for each parameter. Each measured soil property is then compared to the crop requirement, and a rating or suitability coefficient is assigned. The rating scale typically uses values such as 100 (no limitation), 75 (slight limitation), 50 (moderate limitation), 25 (severe limitation), and 0 (unsuitable). The overall land suitability index (LSI) for a given crop is calculated using the parametric (multiplicative) equation (4) and the classes were demonstrated in table (3). For each profile and crop, the ratings for all relevant parameters are recorded, and the LSI is computed.

$$\mathrm{LSI} = (\mathrm{A} \times \mathrm{B} \times \mathrm{C} \times \mathrm{D} \times \ldots \times \mathrm{N})^{1/n} \qquad \text{Equation (4)}$$

Where: LSI = Land Suitability Index; $\mathrm{A}, \mathrm{B}, \mathrm{C}, \mathrm{D}, \ldots, \mathrm{N}$ = Suitability ratings (expressed as percentages or decimals) for each soil or site characteristic; n = Number of characteristics considered.

Table 3. Land Suitability classes.

Suitability Class	LSI (%)	Interpretation
S1	75–100	Highly suitable
S2	50–74	Moderately suitable
S3	25–49	Marginally suitable
N	<25	Not suitable

2.8. Statistical analysis, mathematical calculations, and mapping

For the statistical analysis and mathematical calculations of the soil properties and land evaluation indices, commonly used Microsoft Excel (2023), while mapping was done using Inverse Distance Weighing (IDW) interpolation method in ArcGIS 10.8.1 (ESRI, 2023). Descriptive statistics (mean, median, standard deviation, minimum, maximum, coefficient of variation), and basic correlation analysis were computed. For calculations related to land capability, productivity, and suitability evaluation, Excel is used to apply the multiplicative and geometric mean formulas across multiple profiles, as it allows for easy formula application and result tabulation.

3. Results

3.1. Morphological description and classification of the soil profiles

The dataset presented in table (4) summarizes morphological characteristics and taxonomic classifications for the investigated soil profiles, reflecting a diversity of soil types in the study area. The texture ranged between clayey or clay loam with accumulation in the coarse fragments varying between 3–5% up to 20–30% in majority of soil profiles. Regarding the soil structure, the sub-angular blocky structure is dominant with high level of aggregation, stickiness, plasticity, and shrinkage-swelling features (e.g., Pedons 6 and 13). Effervescence and the presence of calcium carbonate were weak in these soils. These soils were classified up to texa as *Ustorthents*, *Haplustepts*, and *Haplusterts*.

Table 4. Morphological characteristics and taxonomic classifications for the soil profiles over the study area.

Pedon No.	Morphological Characteristics	Classification (Taxonomy)	Soil Order
1	Ap to Bw3k horizons: A depth of 118 cm; clay to clay loam, 10–25% coarse fragments, m2sbk to f1sbk structure, weak to normal effervescence by calcium carbonates	*Typic Haplustepts (*Fine clayey, smectitic, *hyperthermic)*	*Inceptisols*
2	Ap to Bw2k: A depth of 70 cm; clay texture, 20–30% coarse fragments, m1sbk to m2sbk structure, stones up to 7 inches, weak effervescence by calcium carbonates	*Typic Haplustepts (*Fine clayey, smectitic, *hyperthermic)*	*Inceptisols*
3	Single Ap horizon: A depth of 17 cm; clay loam, 3–5% gravel, weak m1sbk, friable, non-sticky/plastic	*Typic Ustorthents (*Fine loamy mixed, *hyperthermic)*	*Entisols*
4	Ap horizon: A depth of 17 cm; clay, 3–5% coarse fragments, moderate m2sbk, very friable, non-sticky/plastic	*Typic Ustorthents (*Very fine clayey, smectitic, *hyperthermic)*	*Entisols*
5	Ap horizon: A depth of 15 cm; clay loam, 5–10% gravel, weak m1sbk, friable, non-sticky/plastic	*Typic Ustorthents (Fine loamy mixed, hyperthermic)*	*Entisols*
6	Ap to Bw2: A depth of 140 cm; clay, shrink-swell features (Bss), 3–5% gravel, m2sbk to m3sbk structure, weak to normal effervescence by calcium carbonates	*Typic Haplusterts (*Very fine clayey, smectitic, *hyperthermic)*	*Vertisols*
7	Ap to Bw1: A depth of 27 cm; clay, 5–10% gravel, weak m1sbk, slightly sticky/plastic, 20–40% coarse fragments, weak effervescence by calcium carbonates	*Typic Ustorthents (*Fine clayey, smectitic, *hyperthermic)*	*Entisols*
8	Ap horizon: A depth of 13 cm; clay loam, 10–20% gravel, weak sbk, friable, non-sticky/plastic, slight effervescence	*Typic Ustorthents (*Fine clayey, smectitic, *hyperthermic)*	*Entisols*
9	Ap horizon: A depth of 12 cm; clay loam, 5–10% gravel, moderate sbk, friable, non-sticky/plastic	*Typic Ustorthents (*Fine loamy mixed, *hyperthermic)*	*Entisols*
10	Ap to Bw3: A depth of 33 cm; clay, 3–5% gravel, moderate sbk, sticky/plastic, slight effervescence, pressure faces in lower horizons	*Vertic Haplustepts (*Fine clayey, smectitic, *hyperthermic)*	*Inceptisols*
11	A horizon: A depth of 8 cm; loam, slight effervescence, non-sticky/plastic, moderate sbk	*Typic Ustorthents (*Fine clayey, smectitic, *hyperthermic)*	*Entisols*
12	Ap to Bw1: A depth of 36 cm; clay, 1–3% coarse fragments, very hard, very sticky/plastic, moderate sbk, slightly alkaline	*Typic Haplustepts (*Fine clayey, smectitic, *hyperthermic)*	*Inceptisols*
13	Ap to Bw2: A depth of 150 cm; clay, 3–5% coarse fragments, shrink-swell features (Bss), very sticky/plastic, slickensides, weak effervescence	*Typic Haplusterts (*Very fine clayey, smectitic, *hyperthermic)*	*Vertisols*
14	Ap horizon: A depth of 15 cm; clay, 5–10% gravel, weak sbk, friable, non-sticky/plastic, moderately alkaline	*Typic Ustorthents (*Fine clayey, smectitic, *hyperthermic)*	*Entisols*
15	Ap horizon: A depth of 14 cm; clay loam, 15–20% gravel, weak sbk, friable, non-sticky/plastic	*Typic Ustorthents (*Fine loamy mixed, *hyperthermic)*	*Entisols*
16	Ap horizon: A depth of 17 cm; clay, 15–20% gravel, moderate sbk, friable, slightly sticky/plastic	*Typic Ustorthents (*Fine clayey, smectitic, *hyperthermic)*	*Entisols*
17	A horizon: A depth of 20 cm; clay loam, 5–10% gravel, moderate sbk, friable, non-sticky/plastic, 15–20% stoniness	*Typic Ustorthents (*Fine loamy mixed, *hyperthermic)*	*Entisols*
18	Ap horizon: A depth of 15 cm; clay, moderate sbk, friable, sticky/plastic	*Typic Ustorthents (*Fine clayey, smectitic, *hyperthermic)*	*Entisols*
19	Ap horizon: A depth of 23 cm; clay, moderate sbk, very friable, sticky/plastic	*Typic Ustorthents (*Fine clayey, smectitic, *hyperthermic)*	*Entisols*

The Ap horizon is the plowed or disturbed surface horizon (A = topsoil, p = plowed); and the Bw horizon is the subsurface mineral horizon with evidence of alteration (B = subsoil, w = development of color or structure without significant clay accumulation). The numbers (Bw1, Bw2, and Bw3) indicate subdivisions within the Bw horizon based on changes in properties with depth. The k suffix in Bw3k denotes the accumulation of carbonates within that particular sub-horizon.

3.2. Characterization of the soil profiles

Table (5) showed the weighted mean data for the soil profiles collected from the study area. The pH values are tightly clustered, with a mean of 7.60 (range: 7.10–7.90) and a narrow standard deviation of 0.18, indicating that most soils are neutral to slightly alkaline. Electrical conductivity (EC) values are uniformly low (mean 0.22 dS/m), with range between 0.19 and 0.27 dS/m whereas these soils are non-saline confirming the absence of salinity issues. Calcium carbonate ($CaCO_3$) content averages 2.1% with a moderate range (1.50-3.0%) which non-slight-calcareous. The soil texture is dominated by clay, with a mean clay content 47.7% (range: 35.0–69.2%), sand at 27.2% (range: 12.0–38.6%), and silt at 25.1% (range: 14.7–38.0%); and these soils are clayey and loamy clay. The mean coarse fragment content is 9.3%, but with considerable variability (range 0–26%). The macronutrient status revealed that available nitrogen (mean 184.8 kg/ha), phosphorus (13.5 kg/ha), and potassium (306.8 kg/ha). Micronutrient levels included iron (mean 4.09 mg/kg), manganese (9.10 mg/kg), copper (1.08 mg/kg), and zinc (0.52 mg/kg). Sulfur levels (mean 11.97 mg/kg) are adequate, while soil organic carbon (mean 0.53%) and organic matter (mean 0.91%) are relatively low; and cation exchange capacity (CEC) averages 32.24 cmolc/kg.

Table 5. The weighted mean data for the soil profiles over the study area.

Statistics	pH	EC	$CaCO_3$	Sand	Silt	Clay	Coarse Fragments	N	P	K	Fe	Mn	Cu	Zn	S	OC	OM	CEC
Unit	---	*dS/m*			*(%)*				*Available (kg/ha)*				*Available (mg/kg)*				*(%)*	*cmol/kg*
Mean	7.6	0.2	2.1	27.2	25.1	47.7	9.3	184.8	13.5	306.8	4.1	9.1	1.1	0.5	12.0	0.5	0.9	32.2
SE	0.0	0.0	0.1	1.6	1.8	2.2	1.5	2.6	0.2	4.4	0.0	0.2	0.0	0.0	0.2	0.0	0.0	0.3
Median	7.6	0.2	2.0	28.9	21.6	46.4	7.5	185.0	13.5	310.0	4.1	9.1	1.1	0.5	12.3	0.5	0.9	32.4
Mode	7.6	0.2	2.0	29.5	20.0	50.5	7.5	170.0	14.0	330.0	4.2	9.5	1.1	0.5	12.5	0.6	1.0	32.9
SD	0.2	0.0	0.4	7.1	7.9	9.7	6.4	11.5	1.0	19.3	0.2	0.8	0.1	0.0	1.0	0.0	0.1	1.2
SV	0.0	0.0	0.2	50.6	62.8	94.0	41.0	131.9	1.0	370.9	0.0	0.7	0.0	0.0	1.1	0.0	0.0	1.4
Kurtosis	2.5	-0.4	-0.2	0.6	-0.7	-0.2	1.0	-1.5	-1.2	-1.4	-1.2	-1.1	-1.0	-1.2	-1.1	-1.1	-1.2	-1.1
Skewness	-0.9	0.2	0.3	-0.8	0.7	0.6	1.2	0.0	0.2	-0.2	-0.1	0.1	-0.3	0.0	-0.1	-0.1	-0.1	-0.3
Range	0.8	0.1	1.5	26.6	25.4	34.7	24.0	34.0	3.2	60.0	0.6	2.6	0.2	0.2	3.3	0.1	0.2	3.9
Minimum	7.1	0.2	1.5	12.0	14.7	34.5	2.0	168.0	12.0	275.0	3.8	7.8	1.0	0.4	10.2	0.5	0.8	30.2
Maximum	7.9	0.3	3.0	38.6	40.1	69.2	26.0	202.0	15.2	335.0	4.4	10.4	1.2	0.6	13.5	0.6	1.0	34.1

EC = Electrical Conductivity; OC = Organic Carbon; OM = Organic Matter; CEC = Cation Exchange Capacity; SE = Standard Error; SD = Standard Deviation; SV = Sample Variance.

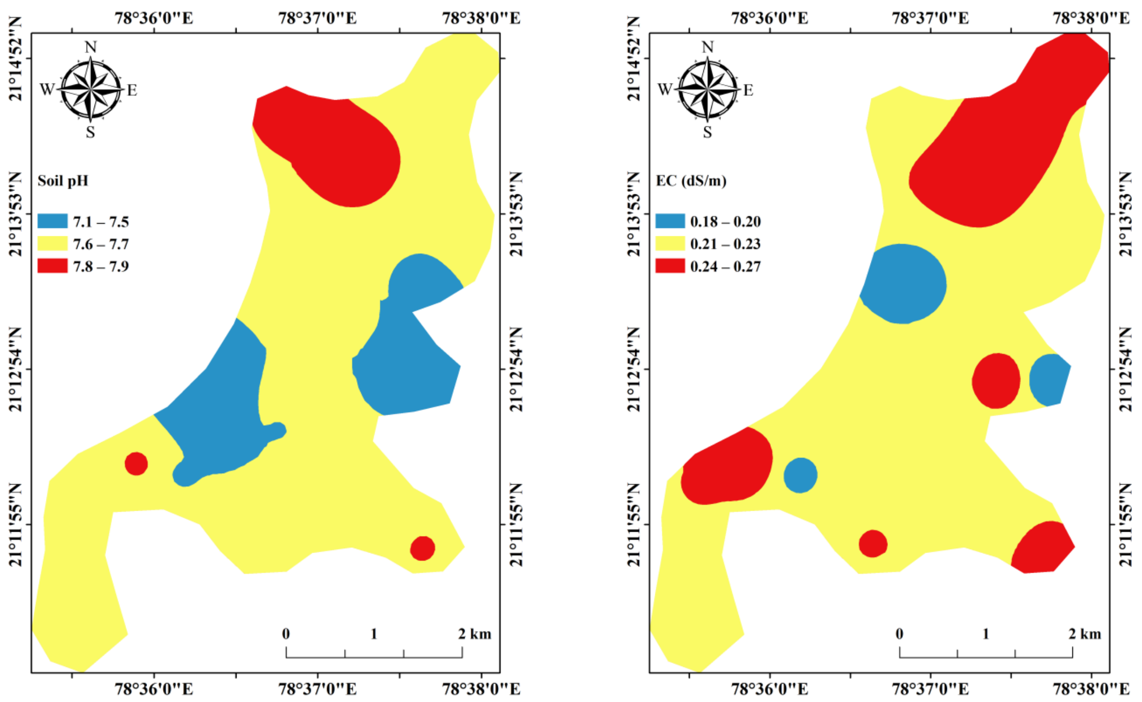
3.3. The correlation between soil properties in the soil profiles

The correlation matrix (table 6) of the soil properties demonstrates several strong and meaningful relationships that have direct implications for soil health and agricultural productivity. Soil pH is positively correlated with EC (r = 0.50), $CaCO_3$ (r = 0.41), and clay content (r = 0.49), while being negatively correlated with silt (r = -0.46) and sand (r = -0.16). The relationship between EC and $CaCO_3$ is particularly strong (r = 0.81), and also strongly correlated with clay (r = 0.57). There are positive correlations between $CaCO_3$ and clay (r = 0.59), clay content with available nitrogen (r = 0.72), phosphorus (r = 0.66), potassium (r = 0.66), and micronutrients such as iron (r = 0.66), manganese (r = 0.67), copper (r = 0.67), and zinc (r = 0.67). Organic carbon and organic matter are almost perfectly correlated (r = 0.99), and both show strong positive correlations with CEC (r = 0.99). There are strong positive correlations between organic matter and available nutrients (all above r = 0.95). The available macronutrients and micronutrients are all extremely strongly correlated with each other, with correlation coefficients typically above 0.97. Coarse fragments are negatively correlated with clay (r = -0.41) and show weak or negative correlations with most chemical properties.

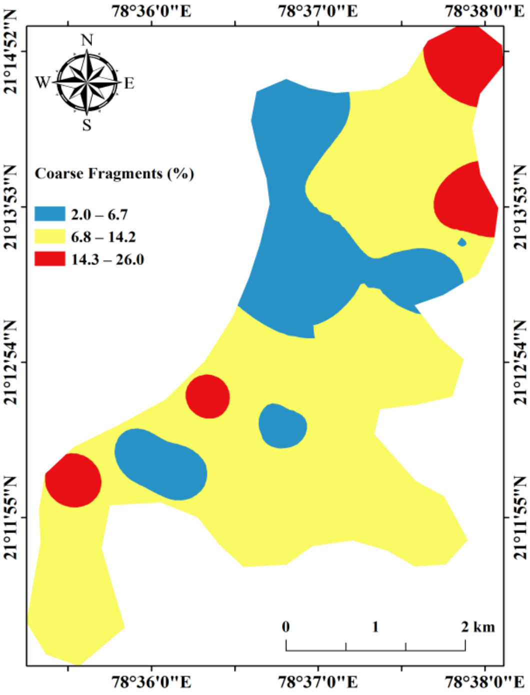
Table 6. The correlation matrix of the soil properties.

Soil parameter/Unit		pH	EC	$CaCO_3$	Sand	Silt	Clay	Coarse Fragments	N	P	K	Fe	Mn	Cu	Zn	S	OC	OM	CEC
		---	*dS/m*			*(%)*				*Available (kg/ha)*				*Available (mg/kg)*				*(%)*	*cmol/kg*
pH	---	1																	
EC	*dS/m*	0.49	1																
$CaCO_3$		0.41	0.81	1															
Sand		-0.16	0.01	-0.04	1														
Silt	*(%)*	-0.45	-0.69	-0.68	-0.17	1													
Clay		0.49	0.56	0.58	-0.59	-0.69	1												
Coarse Fragments		-0.24	0.05	-0.12	0.47	0.07	-0.40	1											
N		0.52	0.85	0.78	-0.15	-0.73	0.71	-0.06	1										
P	*Available (kg/ha)*	0.56	0.83	0.79	-0.24	-0.64	0.70	-0.15	0.97	1									
K		0.57	0.82	0.82	-0.12	-0.68	0.65	-0.05	0.96	0.98	1								
Fe		0.61	0.76	0.81	-0.18	-0.67	0.68	-0.16	0.94	0.97	0.98	1							
Mn		0.57	0.79	0.79	-0.24	-0.63	0.69	-0.11	0.96	0.99	0.98	0.98	1						
Cu	*Available (mg/kg)*	0.59	0.79	0.80	-0.20	-0.66	0.69	-0.12	0.94	0.97	0.98	0.98	0.98	1					
Zn		0.57	0.78	0.78	-0.18	-0.65	0.66	-0.05	0.95	0.98	0.98	0.98	0.98	0.98	1				
S		0.57	0.79	0.80	-0.18	-0.66	0.67	-0.08	0.95	0.98	0.99	0.98	0.99	0.99	0.99	1			
OC	*(%)*	0.57	0.82	0.81	-0.17	-0.68	0.69	-0.04	0.95	0.97	0.98	0.97	0.98	0.98	0.99	0.99	1		
OM		0.59	0.81	0.81	-0.17	-0.69	0.69	-0.05	0.96	0.97	0.98	0.98	0.98	0.98	0.99	0.99	0.99	1	
CEC	*cmol/kg*	0.59	0.81	0.81	-0.14	-0.68	0.66	-0.07	0.95	0.97	0.98	0.98	0.98	0.98	0.98	0.99	0.99	0.99	1

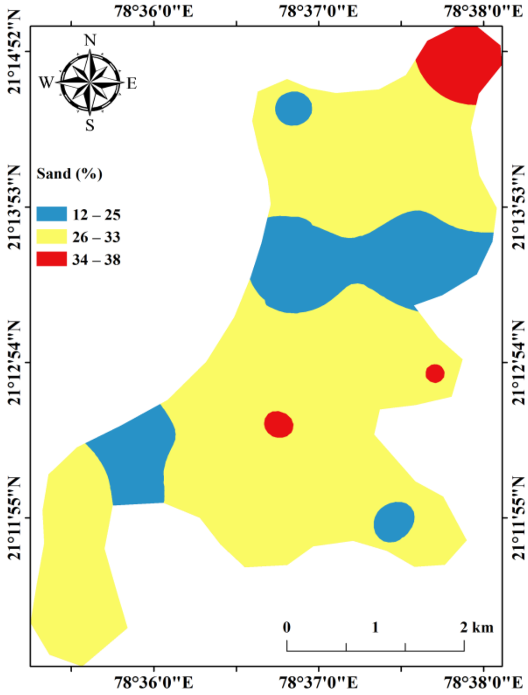
Figure (3) displayed the spatial variability maps of the soil properties over the study area using the weighted mean values which done by the inverse distance weighing (IDW) method. Each soil property is classified into three levels based on its values. These levels are in different colors (blue (the lowest), yellow (the moderate), and red (the highest).



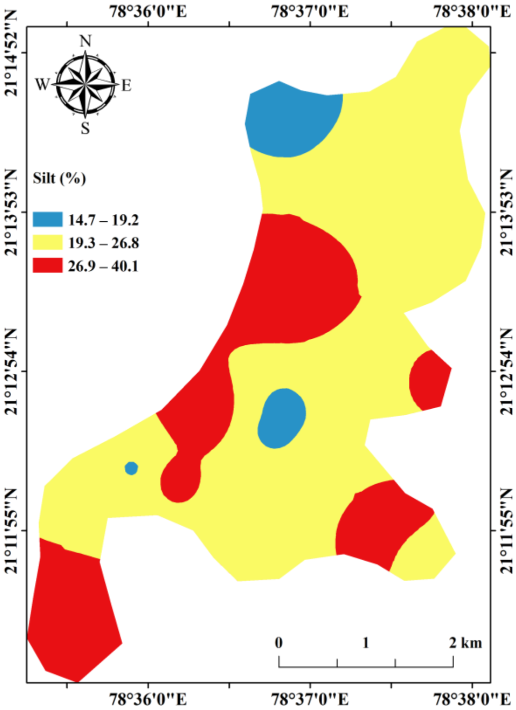
A B


Coarse Fragments (%)
2.0 – 6.7
6.8 – 14.2
14.3 – 26.0
N
S
W
E
78°36'0"E
78°37'0"E
78°38'0"E
21°14'52"N
21°13'53"N
21°12'54"N
21°11'55"N
0
1
2 km

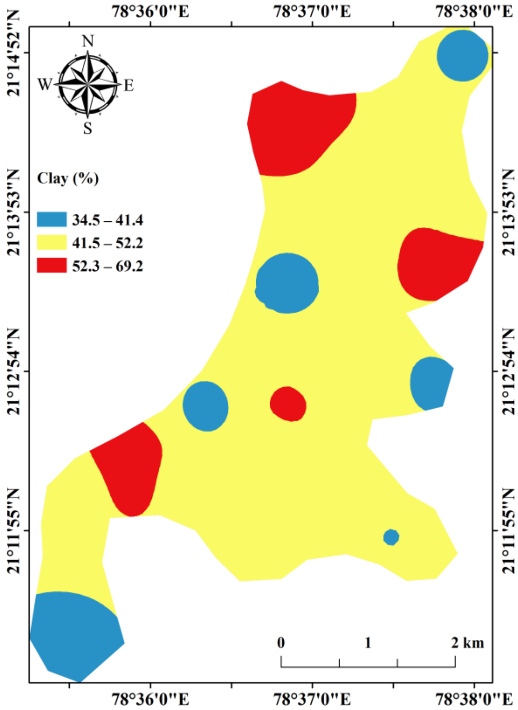
C


Sand (%)
12 – 25
26 – 33
34 – 38
N
S
W
E
78°36'0"E
78°37'0"E
78°38'0"E
21°14'52"N
21°13'53"N
21°12'54"N
21°11'55"N
0
1
2 km

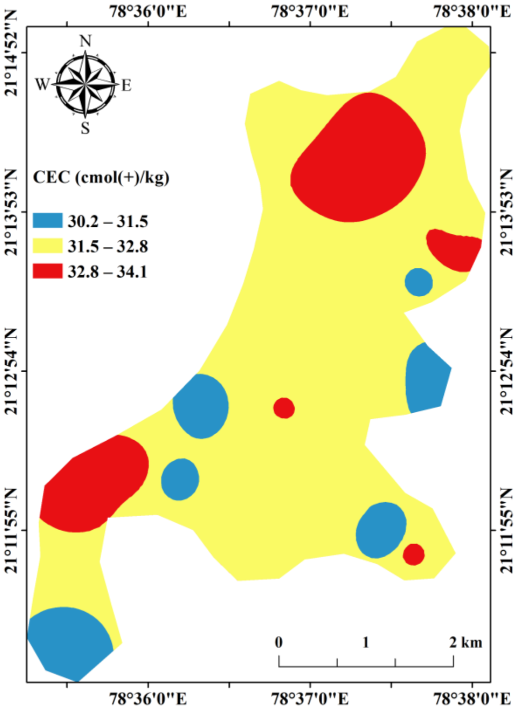
D


Silt (%)
14.7 – 19.2
19.3 – 26.8
26.9 – 40.1
N
S
W
E
78°36'0"E
78°37'0"E
78°38'0"E
21°14'52"N
21°13'53"N
21°12'54"N
21°11'55"N
0
1
2 km

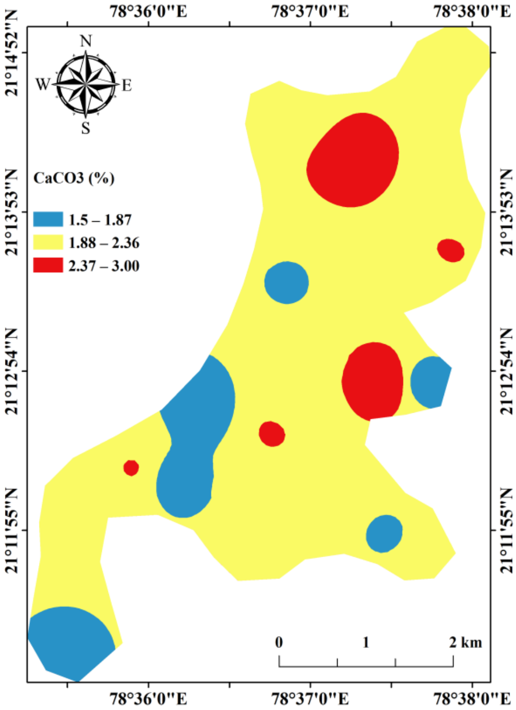
E


Clay (%)
34.5 – 41.4
41.5 – 52.2
52.3 – 69.2
N
S
W
E
78°36'0"E
78°37'0"E
78°38'0"E
21°14'52"N
21°13'53"N
21°12'54"N
21°11'55"N
0
1
2 km

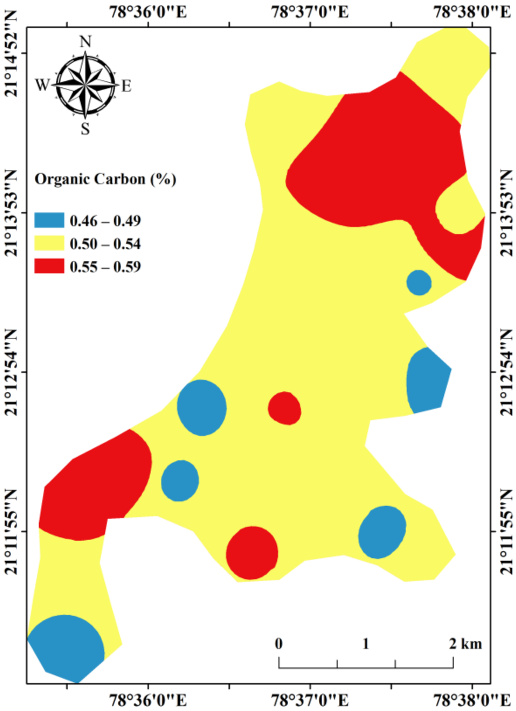
F


78°36'0"E
78°37'0"E
78°38'0"E
21°14'52"N
21°13'53"N
21°12'54"N
21°11'55"N
N
W
E
S
CEC (cmol(+)/kg)
30.2 – 31.5
31.5 – 32.8
32.8 – 34.1
0
1
2 km

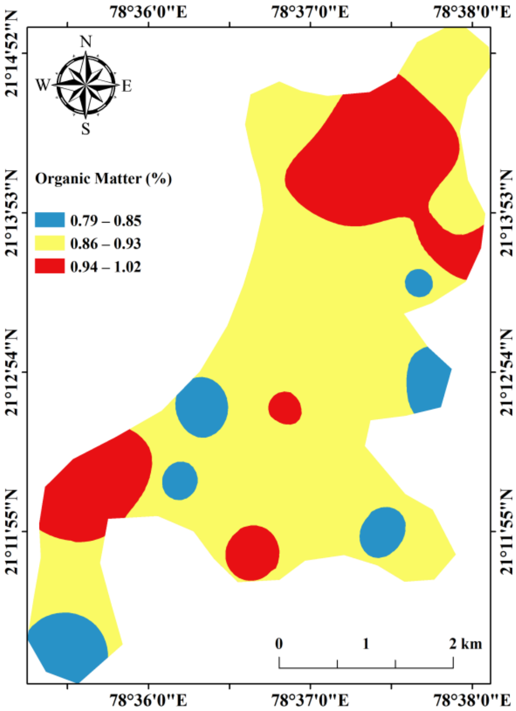
G


78°36'0"E
78°37'0"E
78°38'0"E
21°14'52"N
21°13'53"N
21°12'54"N
21°11'55"N
N
W
E
S
CaCO3 (%)
1.5 – 1.87
1.88 – 2.36
2.37 – 3.00
0
1
2 km

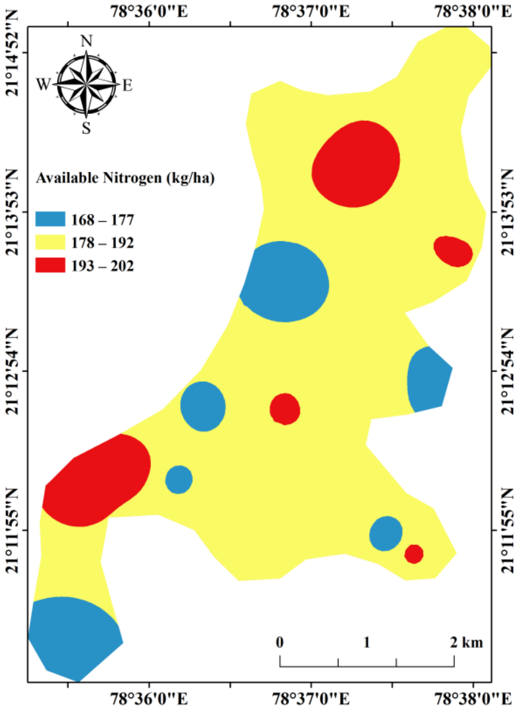
H


78°36'0"E
78°37'0"E
78°38'0"E
21°14'52"N
21°13'53"N
21°12'54"N
21°11'55"N
N
W
E
S
Organic Carbon (%)
0.46 – 0.49
0.50 – 0.54
0.55 – 0.59
0
1
2 km

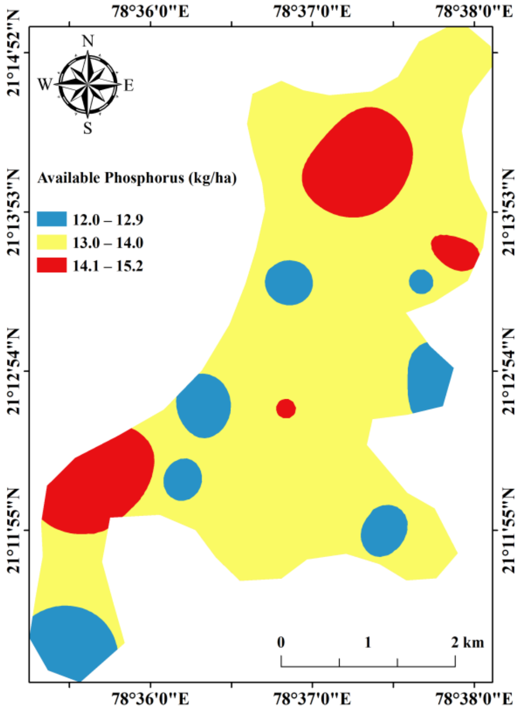
I


78°36'0"E
78°37'0"E
78°38'0"E
21°14'52"N
21°13'53"N
21°12'54"N
21°11'55"N
N
W
E
S
Organic Matter (%)
0.79 – 0.85
0.86 – 0.93
0.94 – 1.02
0
1
2 km

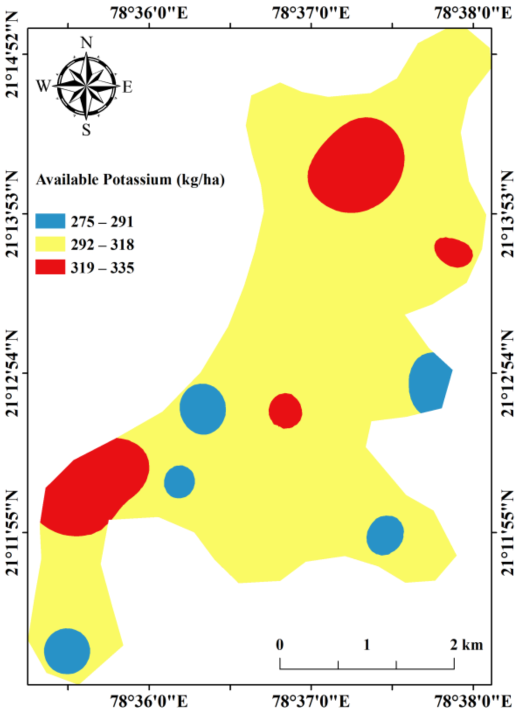
J


78°36'0"E
78°37'0"E
78°38'0"E
21°14'52"N
21°13'53"N
21°12'54"N
21°11'55"N
N
W
E
S
Available Nitrogen (kg/ha)
168 – 177
178 – 192
193 – 202
0
1
2 km

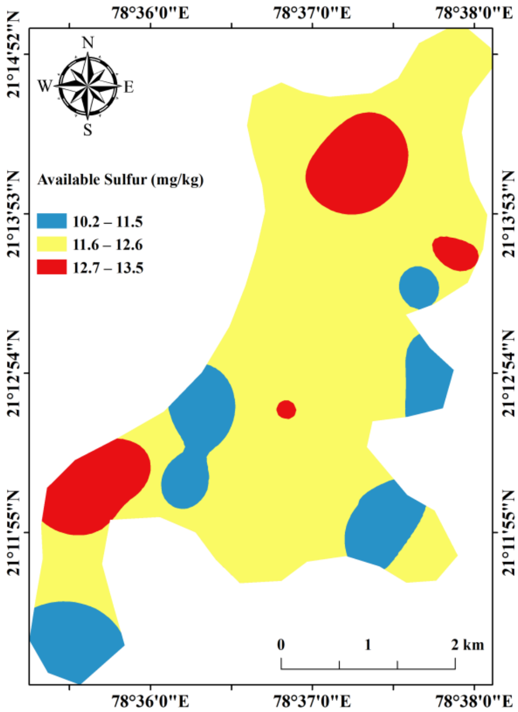
K


78°36'0"E
78°37'0"E
78°38'0"E
21°14'52"N
21°13'53"N
21°12'54"N
21°11'55"N
N
W
E
S
Available Phosphorus (kg/ha)
12.0 – 12.9
13.0 – 14.0
14.1 – 15.2
0
1
2 km

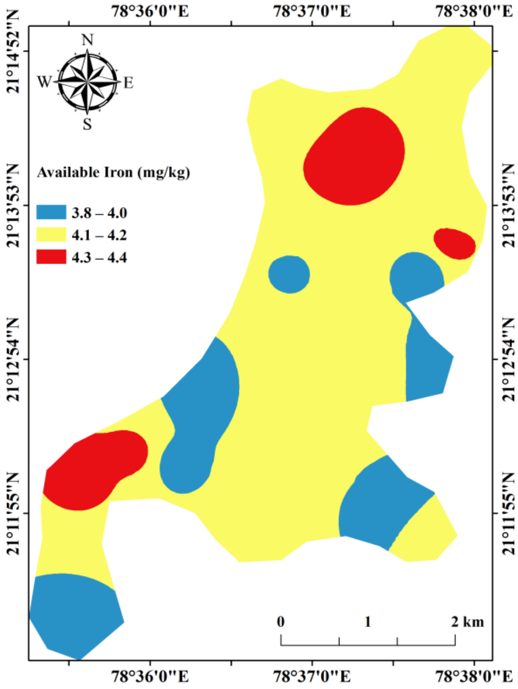
L


78°36'0"E
78°37'0"E
78°38'0"E
21°14'52"N
21°13'53"N
21°12'54"N
21°11'55"N
N
W
E
S
Available Potassium (kg/ha)
275 – 291
292 – 318
319 – 335
0
1
2 km

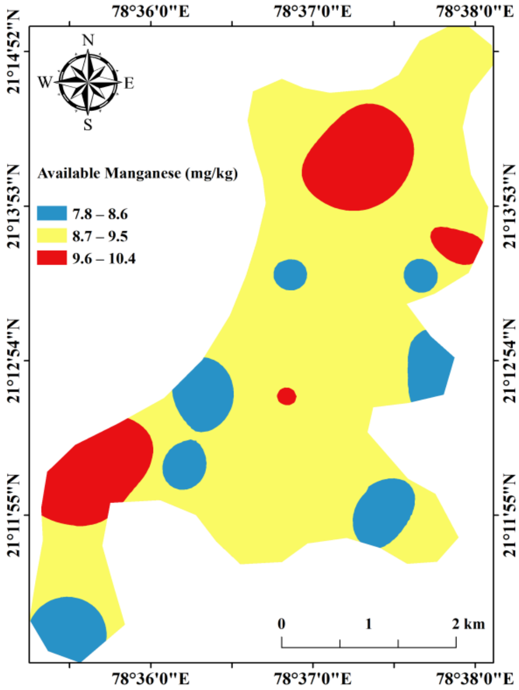
M


78°36'0"E
78°37'0"E
78°38'0"E
21°14'52"N
21°13'53"N
21°12'54"N
21°11'55"N
N
W
E
S
Available Sulfur (mg/kg)
10.2 – 11.5
11.6 – 12.6
12.7 – 13.5
0
1
2 km

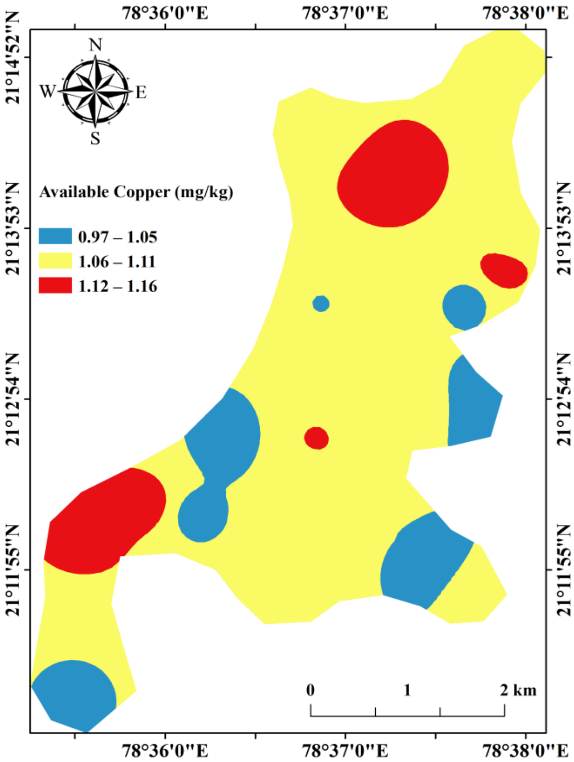
N



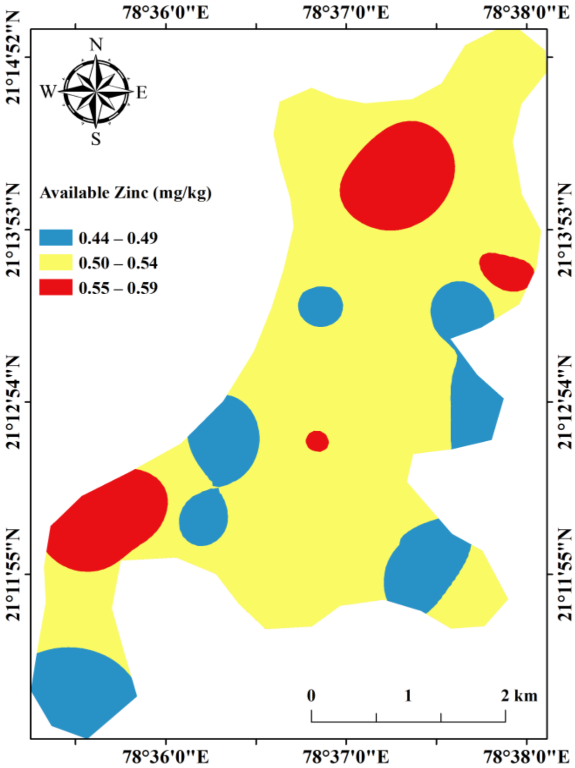
O



P



Q



R

Fig. 3. Spatial Variability maps of the soil properties over the studied area: A) Soil pH; B) EC (dS/m); C) Coarse Fragments (%); D) Sand (%); E) Silt (%); F) Clay (%); G) CEC (Cmol(+)/kg); H) CaCO3 (%); I) Soil Organic Carbon (%); J) Organic Matter (%); K) Available Nitrogen (kg/ha); L) Available Phosphorus (kg/ha); M) Available Potassium (kg/ha); N) Available sulfur (mg/kg); O) Available Iron (mg/kg); P) Available Manganese (mg/kg); Q) Available Copper (mg/kg); R) Available Zinc (mg/kg) Land Capability assessment.

The results of the land capability evaluation using the Storie Index for the 19 soil profiles (table 7) indicate a marked variability in land quality across the study area. The calculated Storie Index values range from 24% to 64%, with the majority of profiles falling into the lower end of the capability spectrum. Specifically, profiles 1, 2, 4, 6, 8, 12, 16, and 18 have Storie Index values between 24% and 38%, classifying them as Class IV (Poor). Profiles 3, 5, 11, 13, and 15, with Storie Index values of 60% or above, are rated as Class II (Good), while profiles 7, 9, 10, 14, 17, and 19, with values between 48% and 48%, fall into Class III (Fair). Clustering the results by percentage, it is evident that only five profiles (3, 5, 11, 13, 15) achieve a Storie Index of 60% or higher, indicating good land capability, while six profiles (7, 9, 10, 14, 17, 19) are in the fair range (48%), and the remaining eight profiles are classified as poor. The main soil limitations were texture (B) and coarse fragments (D). This was a major limiting factor in profiles 2, 8, and 18, which had the lowest Storie Index values (24–36%), placing them in Class IV (Poor). Chemical properties (C) were generally favorable in this dataset, but in profiles where C dropped to 80, such as profiles 4, 6, 12, and 16, the overall capability was further reduced.

Table 7. Land capability evaluation using the Storie Index for the soil profiles over the study area.

Profile	A (Depth)	B (Texture)	C (Chemical)	D (Coarse Fragments)	Storie Index (%)	Capability Class
1	100	60	100	60	36	IV (Poor)
2	100	60	100	40	24	IV (Poor)
3	100	100	80	80	64	II (Good)
4	100	60	80	80	38	IV (Poor)
5	100	60	100	100	60	II (Good)
6	100	60	80	80	38	IV (Poor)
7	100	60	100	80	48	III (Fair)
8	100	60	100	60	36	IV (Poor)
9	100	100	80	60	48	III (Fair)
10	100	60	100	80	48	III (Fair)
11	100	60	100	100	60	II (Good)
12	100	60	80	80	38	IV (Poor)
13	100	100	80	80	64	II (Good)
14	100	60	100	80	48	III (Fair)
15	100	60	100	100	60	II (Good)
16	100	60	80	80	38	IV (Poor)
17	100	60	100	80	48	III (Fair)
18	100	60	100	60	36	IV (Poor)
19	100	100	80	60	48	III (Fair)

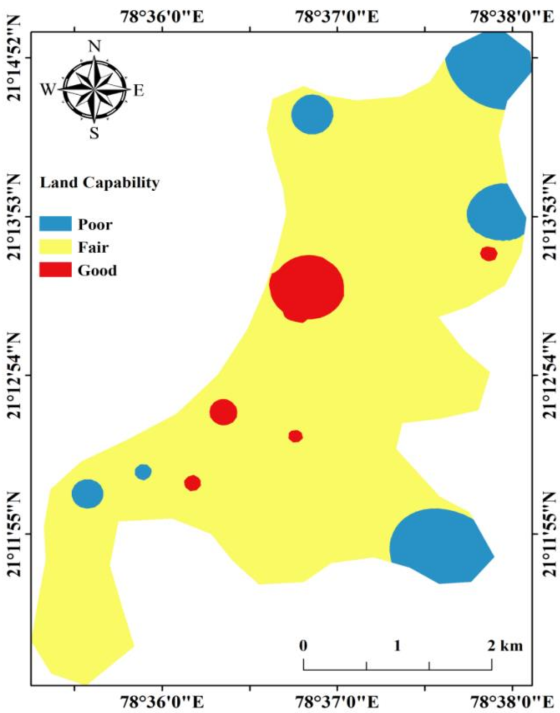


Fig. 4. The spatial variability map of the land capability over the study area.

3.4. Land productivity evaluation for current and potential conditions

Table (8) and figure (5) demonstrated the actual and potential land productivity of the all studied soil profiles in the study area. The land productivity evaluation table shows that, under current conditions, all soil profiles are classified as moderately suitable (S2) with Land Suitability Index (LSI) values ranging from 60% to 67%, except for profile 4 which is at the lower end of this range. The main improvable limitations across almost all profiles are low organic carbon and low available phosphorus, with occasional additional constraints such as low nitrogen (profile 3), high clay content (profile 4), and coarse fragments (profile 2). The improvements include enhancing soil organic carbon above 0.8% as well as optimizing available macronutrients by fertilization. After improvements, these soils will increase to 83% (From S2 to S1) except profiles 2, 3, and 4 remain in the S2. The results revealed that the SOC varied from 0.46% to 0.59% which is lower 0.75% (the barrier between the two SOC levels ‘low’ and ‘moderate’). Therefore, we assumed that improvement must enhance the SOC level beyond 0.75% as (0.8%). For SOC and nutrient status’ improvement, some practices like applying organic amendments (manure, compost), cover crops, and conservation tillage are suggested. Moreover, the agro-forestry as well as diversity in crop rotation may enhance SOC. Regarding enhancement of the macronutrient, integrated nutrients’ management including organic and inorganic fertilizers as well as site-specific fertilizer application, slow-release fertilizers, and bio-fertilizers may be also effective materials. Thus, such strategies are suggested for future implementation to improve soil productivity and nutrient balance in the studied area. Figure (5) displayed the current and potential condition of the land productivity over the studied site. These maps are considered as guide for the decision makers specifically the local farmers for understanding the major limitation in their lands and taking suitable decisions regarding their crops and general agricultural activities including the required improvements. These maps are also important for the readers to imagine the size of enhancements after improving the soil characteristics (removing limitations).

Table 8. Actual and potential land productivity of the all studied soil profiles in the study area.

Profile	Pa		Limitations	Pp		Improvements
	%	*Class*		*(%)*	*Class*	
1	67	S2	Low Org. C, Low P	83	S1	
2	62	S2	Low Org. C, Low P, Coarse Fragments	77	S2	
3	62	S2	Low N, Low P, Low Org. C	77	S2	
4	60	S2	High clay, Low P, Low Org. C	75	S2	
5	67	S2		83	S1	
6	67	S2		83	S1	
7	67	S2		83	S1	
8	67	S2		83	S1	
9	67	S2		83	S1	
10	67	S2		83	S1	Organic and chemical fertilization
11	67	S2		83	S1	
12	67	S2	Low Org. C, Low P	83	S1	
13	67	S2		83	S1	
14	67	S2		83	S1	
15	67	S2		83	S1	
16	67	S2		83	S1	
17	67	S2		83	S1	
18	67	S2		83	S1	
19	67	S2		83	S1	

Pa = Actual Productivity; Pp = Potential Productivity

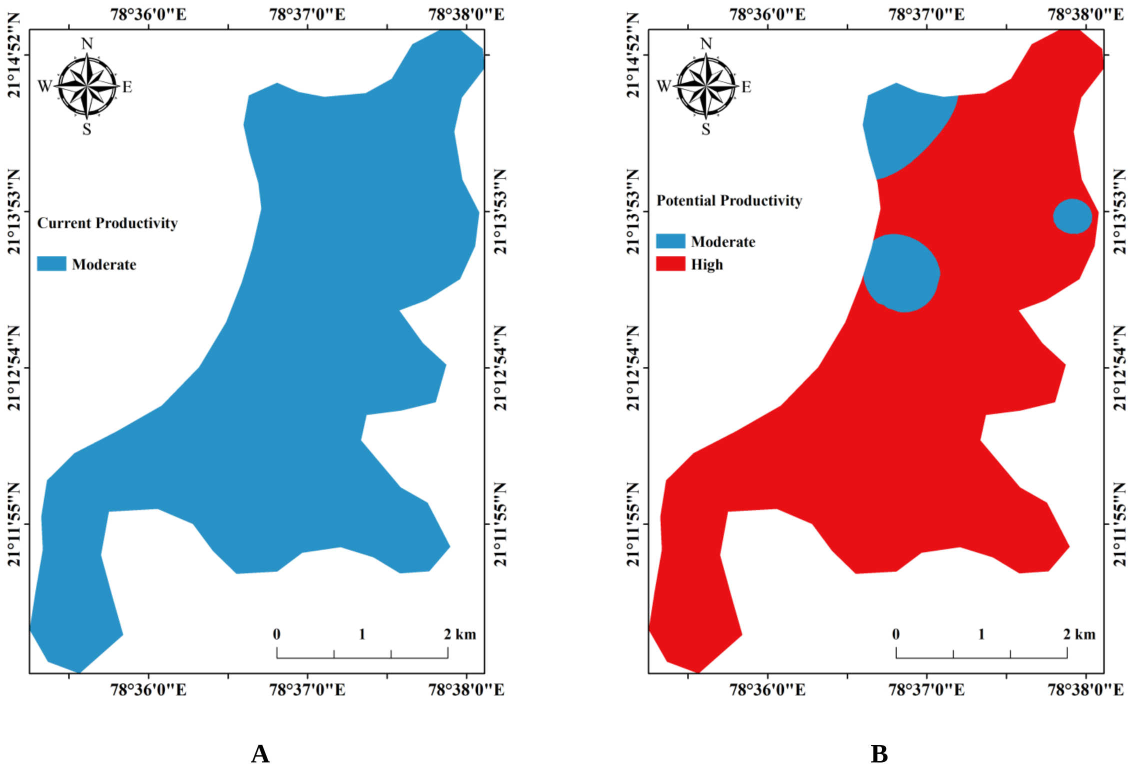


Fig. 5. Spatial variability maps of the land productivity over the study area: A) Current land productivity; and B) Potential land productivity.

3.5. Land Suitability Evaluation for different crops

The land suitability assessment (tables 9 and 10) reveals clear patterns when crops are grouped into vegetables, fruits, legumes, and others. The overall suitability vegetables is low to marginal, while root and tuber crops such as sweet potato, cassava, yam, carrot, radish, and turnip fall into the "not suitable" with very low suitability indices (LSI = 13–21%), and main limitations are high soil pH, high clay content, low organic carbon, low available phosphorus, and coarse fragments or calcium carbonate. Leafy and fruiting vegetables like spinach, amaranthus, lettuce, capsicum, cucumber, okra, pumpkin, bitter gourd, and bottle gourd generally show marginal suitability (SI around 35%), with the dominant constraints being low organic carbon and phosphorus, and occasionally moderate to high pH. Only a few vegetables, such as onion and potato, are moderately suitable (SI 67%), limited mainly by low organic carbon and phosphorus.

Fruits exhibit a wide range of suitability. Mango, guava, banana, apple, pineapple, watermelon, and strawberry are mostly marginally suitable (SI 25–35%), with low phosphorus and organic carbon as common constraints, and some, like citrus and pear, also affected by high pH and clay. Grapes and pear fall into the not suitable class due to high pH, low nutrients, and coarse fragments. However, crops like muskmelon, date palm, figs, and plums show moderate suitability (SI 62–67%), limited mainly by low organic carbon and phosphorus. Therefore, fruit crops are more frequently marginal than moderately suitable, and none are highly suitable under the current soil conditions.

Legumes, including chickpea, pigeonpea, blackgram, greengram, horsegram, cowpea, field pea, beans, lentils, and soybean, generally show moderate suitability (SI 62–67%). Their main limitations are low organic carbon and phosphorus, but the absence of severe physical or chemical constraints allows them to perform relatively well. This group stands out for its higher overall suitability compared to vegetables and fruits, suggesting that the soil conditions are more favorable for leguminous crops.

Other crops, such as cereals (wheat, maize, barley, millet, rice), oilseeds (groundnut, sesame, sunflower, castor, linseed, mustard), fiber crops (jute, kenaf, ramie, cotton), sugar crops (sugar beet, sugarcane), and plantation crops (tea, coffee, coconut, rubber), show varied suitability. Cereals like wheat, maize, barley, and millet are moderately suitable (SI 62–67%), mainly limited by low organic carbon and phosphorus. Rice is marginally suitable (SI 50–52%) due to high pH and low nutrients. Oilseeds and fiber crops are mostly marginally suitable (SI 25–35%), with high pH, high clay, low organic carbon, and low phosphorus as recurring limitations. Sugar beet and sugarcane are moderately suitable (SI 62–67%) with similar nutrient limitations. Plantation crops are generally not suitable, especially coconut, rubber, and tea, due to high pH and poor nutrient status, while coffee is moderately suitable (SI 65–70%).

Table 9. Land suitability evaluation for different crops over the study area using parametric method.

Crop Name	SI (%)	Suitability Class	Soil Limitations	Crop Name	SI (%)	Suitability Class	Soil Limitations
Wheat	67	S2 (Moderate)	Low Org. C, Low P	**Bottle Gourd**	35	S3 (Marginal)	Moderate pH, Low P, Low Org. C
Rice	52	S3 (Marginal)	High pH, Low Org. C, Low P	**Spinach**	35	S3 (Marginal)	Low P, Low Org. C
Maize (Corn)	67	S2 (Moderate)	Low Org. C, Low P	**Amaranthus**	35	S3 (Marginal)	Moderate pH, Low P, Low Org. C
Barley	67	S2 (Moderate)		**Lettuce**	35	S3 (Marginal)	High pH, Low Org. C, Low P
Millet	67	S2 (Moderate)		**Capsicum**	35	S3 (Marginal)	
Chickpea	67	S2 (Moderate)		**Cucumber**	35	S3 (Marginal)	
Pigeonpea	67	S2 (Moderate)		**Eggplant**	21	N (Not Suitable)	High pH, Low P, Low Zn, Low Org. C
Blackgram	67	S2 (Moderate)		**Garlic**	35	S3 (Marginal)	High pH, Low Org. C, Low P
Greengram	67	S2 (Moderate)		**Onion**	67	S2 (Moderate)	Low Org. C, Low P
Horsegram	67	S2 (Moderate)		**Tomato**	35	S3 (Marginal)	High pH, High clay, Low Org. C, Low P
Cowpea	67	S2 (Moderate)		**Potato**	67	S2 (Moderate)	Low Org. C, Low P
Fieldpea	67	S2 (Moderate)		**Mango**	35	S3 (Marginal)	
Beans	67	S2 (Moderate)		**Guava**	35	S3 (Marginal)	Moderate pH, Low P, Low Org. C
Lentils	67	S2 (Moderate)		**Papaya**	67	S2 (Moderate)	Low Org. C, Low P
Soybean	67	S2 (Moderate)		**Banana**	35	S3 (Marginal)	
Groundnut	67	S2 (Moderate)		**Citrus**	25	S3 (Marginal)	High pH, High clay, Low Org. C, Low P
Sesame	35	S3 (Marginal)	High pH, High clay, Low Org. C, Low P, Coarse Fragments	**Apple**	35	S3 (Marginal)	Low P, Low Org. C
Sunflower	35	S3 (Marginal)	High clay, Low Org. C, Low P, Coarse Fragments	**Pear**	13	N (Not Suitable)	High pH, moderate coarse fragments, low P, low organic C
Castor	35	S3 (Marginal)	High pH, High clay, Low Org. C, Low P, Coarse Fragments	**Plums**	67	S2 (Moderate)	Low Org. C, Low P
Linseed	35	S3 (Marginal)		**Grapes**	~7	N (Not Suitable)	High pH, low P, moderate organic C, coarse fragments
Mustard	35	S3 (Marginal)		**Pineapple**	35	S3 (Marginal)	Slightly high pH, moderate P, organic C
Jute	67	S2 (Moderate)	Low available P, Low organic C	**Watermelon**	35	S3 (Marginal)	
Kenaf	35	S3 (Marginal)	High pH, High clay, Low Org. C, Low P, Coarse Fragments	**Muskmelon**	67	S2 (Moderate)	Low Org. C, Low P
Ramie	35	S3 (Marginal)		**Datepalms**	67	S2 (Moderate)	
Cotton	35	S3 (Marginal)		**Figs**	67	S2 (Moderate)	
Sugar Beet	67	S2 (Moderate)	Low Org. C, Low P	**Olives**	35	S3 (Marginal)	High pH, Low Org. C, Low P
Sugarcane	67	S2 (Moderate)		**Pomegranate**	21	N (Not Suitable)	High pH, High clay, Low Org. C, Low P

Sweet Potato	21	N (Not Suitable)	High pH, Low P, Low Org. C, High Clay, Coarse Fragments	**Strawberry**	35	S3 (Marginal)	Low P, low Org. C
Cassava	21	N (Not Suitable)		**Coriander**	35	S3 (Marginal)	
Yam	21	N (Not Suitable)		**Cumin**	35	S3 (Marginal)	
Carrot	13	N (Not Suitable)	High pH, $CaCO_3$, High clay, Low P, Low Org. C, Coarse Fragments	**Fenugreek**	35	S3 (Marginal)	Moderate pH, low P, low Org. C
Radish	13	N (Not Suitable)		**Turmeric**	35	S3 (Marginal)	
Turnip	13	N (Not Suitable)		**Ginger**	35	S3 (Marginal)	
Cabbage	13	N (Not Suitable)		**Chilli**	67	S2 (Moderate)	Low Org. C, Low P
Cauliflower	35	N (Not Suitable)	High pH, Low P, Low Org. C	**Alfalfa**	0	N (Not Suitable)	pH too high (alkaline), low P, low Org. C
Okra	35	S3 (Marginal)	Low P, Low Org. C	**Tea**	~14	N (Not Suitable)	High pH, low P, moderate Org. C, moderate clay
Pumpkin	35	S3 (Marginal)		**Coffee**	70	S2 (Moderate)	Slightly high pH, moderate P, organic C
Bitter Gourd	35	S3 (Marginal)		**Coconut**	0	N (Not Suitable)	pH too high (alkaline), low P, low Org. C
				Rubber	0	N (Not Suitable)	

SI (%) = Suitability Index Percentage; S2 = Moderately Suitable, S3 = Marginally Suitable, N = Not Suitable; "Low Org. C" = Low Organic Carbon, "Low P" = Low Phosphorus, "CF" = Coarse Fragments, "AP" = Available Phosphorus.

Table 10. Land suitability for different crops based on their suitability classes and soil limitations.

Suitability Class	SI (%) Range	Crops	Main Soil Limitations
S2 (Moderate)	67–70	Wheat, Maize (Corn), Barley, Millet, Chickpea, Pigeonpea, Blackgram, Greengram, Horsegram, Cowpea, Fieldpea, Beans, Lentils, Soybean, Jute, Sugar Beet, Sugarcane, Onion, Potato, Papaya, Plums, Muskmelon, Datepalms, Figs, Chilli, Coffee	Low available P, Low organic C (some: OC, AP for Wheat)
S3 (Marginal)	25–52, 35	Rice, Sesame, Sunflower, Castor, Linseed, Mustard, Kenaf, Ramie, Cotton, Okra, Pumpkin, Bitter Gourd, Bottle Gourd, Spinach, Amaranthus, Lettuce, Capsicum, Cucumber, Garlic, Tomato, Mango, Guava, Banana, Citrus, Apple, Pineapple, Watermelon, Olives, Strawberry, Coriander, Cumin, Fenugreek, Turmeric, Ginger	High pH, High clay, Low Org. C, Low P, Coarse Fragments (varies per crop; some have moderate pH)
N (Not Suitable)	0–21, ~7–14	Sweet Potato, Cassava, Yam, Carrot, Radish, Turnip, Cabbage, Cauliflower, Eggplant, Pear, Grapes, Pomegranate, Alfalfa, Tea, Coconut, Rubber	High pH, High clay, Low P, Low Org. C, Coarse Fragments, High $CaCO_3$, Low Zn (varies per crop)

4. Discussion

4.1. Morphological description and classification of the soil profiles

In the studied area, most soil profiles presented fine texture grades like (clayey and clay loam), reflecting advanced level of soil profiles' development by weathering as well as fine-particles-accumulation where these soils are developed over basaltic parent material. Regarding the formation and distribution of the gravels / coarse fragments, it was obvious in several soil profiles which indicated presence of different depositional environments, erosion influences (especially in the terrains with slopes). In the study area, good clay-aggregation was observed due to the moderate development in the blocky structure (sbk) in the soil horizons. As the soil profiles had stickiness and plasticity which present in the phenomenon of shrink-swell (common in the *Vertisol),* the smectite is dominant and offer good characteristics support the soil physical nature which is preferable in management implications for crops, particularly under rainfed conditions. Moreover, it is recorded that the dominant texa are *Ustorthents*, *Haplustepts*, and *Haplusterts* which revealed that the area had limited leaching and semiarid moisture regimes with variability in the development among the horizons as well as the base saturation, and clay activity (shrink-swell potential) which is very sensitive feature for land management and conservation.

4.2. Characterization of the soil profiles

The most soils in the study area are neutral to slightly alkaline which generally optimal for most crops, supporting nutrient availability and microbial activity, though the higher end may slightly reduce the bioavailability of micronutrients such as iron and zinc (Shakeri & Azadi 2024). These findings are very agreed with those obtained in *Vertisols* and *Inceptisols* in central India (Premalatha et al., 2024; Ingle at al., 2024). Moreover, these soils are not-saline which could provide seed germination and crop growth. The soil salinity in general is not considered as a limitation for the land productivity in the study area as reported by Rathore et al. (2025). These soils are slightly calcareousness but not to a degree likely to cause widespread nutrient imbalances. However, the presence of $CaCO_3$ can still reduce micronutrient availability, particularly for sensitive crops. These observations are matched with central Indian *Vertisols* (Kuchanwar et al., 2022; Srivastava & Pal 2024). Moreover and as known that the moderate soil carbonates enhance soil pH buffer while high carbonate content increase the micronutrient deficiency such as (iron and zinc) as explained by Sharma et al. (2021) in Maharashtra's black soil evaluation. Regarding the soil texture, the soils are clay-rich have high nutrient and water retention capacity, which is beneficial for crop growth, especially in dry periods. However, excessive clay can lead to poor drainage, slow permeability, and increased risk of compaction, which may restrict root development and delay field operations. These findings align closely with other studies in the region, confirming the heavy-textured nature of these soils (i.e. Deshmukh & Aher 2017). Furthermore, coarse fragment in the studied profiles can locally reduce the effective soil volume for roots and water storage. Our observations are slightly higher than many reports for cultivated *Vertisols*, where values are often below 5% (Shilpa Babar et al., 2015). High coarse fragment content can reduce crop yields, especially in dry conditions. Based on the macronutrients' status in the study area, the available potassium is generally sufficient while available nitrogen and phosphorus are at moderate levels and may limit yields without supplementation. Therefore, there is a necessity for regular fertilization, while potassium is generally adequate due to the mineralogy of the parent material. These levels are within the typical ranges reported for cultivated soils in Maharashtra (Sharma et al. 2021; Shilpa Babar et al., 2015). The relatively low phosphorus values are particularly significant, as phosphorus is often a limiting nutrient in clay soils due to fixation. Regular monitoring and judicious fertilization are recommended to prevent nutrient depletion and sustain productivity. However, the micronutrient levels of iron, manganese, copper, and zinc are generally within or near sufficiency ranges for most crops. These micronutrients' levels are comparable to values reported by Sharma et al. (2021) and Dorlikar & Thengare (2025) for similar soils. However, the lower values for zinc and iron, combined with the neutral to alkaline pH and presence of $CaCO_3$, suggest that deficiencies could occur, especially in sensitive crops or under intensive cultivation. Available sulfur levels are adequate, supporting protein synthesis and crop quality. Regarding the soil organic carbon, it is relatively low which is common in intensively cultivated tropical soils. Low organic carbon can reduce soil structure stability, water holding capacity, and biological activity, potentially impacting long-term soil health. The limitation in the organic matter is due to high decomposition rates and limited organic inputs (Kuchanwar et al., 2022; Hadole et al., 2024). Finally, the CEC revealed a high clay and moderate organic matter content, and indicating good nutrient retention potential as described in Patil & Parkhe (2023).

4.3. The correlation between soil properties in the soil profiles

The correlation of the soil properties showed strong relationships which are directly implicating the soil health as well as agricultural productivity. Soil pH is positively correlated with EC, and clay content; and negatively correlated with silt and sand. Therefore, if these soils become more alkaline and accumulate more calcium carbonate, they tend to have higher clay content and lower silt and sand fractions. This is typical of calcareous clay soils, where higher pH and $CaCO_3$ can limit the availability of micronutrients such as iron and zinc, potentially leading to deficiencies in sensitive crops (Zhou, 2024). The relationship between EC and $CaCO_3$ is particularly strong indicating that soils with higher calcium carbonate content also tend to have higher soluble salt concentrations. EC is also strongly correlated with clay which is expected since clay-rich soils have a greater capacity to retain soluble ions. However, the overall EC values remain low, so salinity does not appear to be a limiting factor for crop growth in these soils (Moursy et al., 2025). The strong positive correlation between $CaCO_3$ and clay further supports the association between fine texture and calcareousness (Asgari Hafshejani & Jafari 2023). Clay content itself is highly positively correlated with available nitrogen, phosphorus, potassium, and micronutrients. This indicates that soils with higher clay content generally have a greater nutrient-holding capacity, which can be beneficial for crop production. However, high clay can also lead to drainage and aeration issues, potentially restricting root growth and increasing the risk of waterlogging, especially under heavy rainfall or irrigation (Kumari & Mohan 2021). Organic carbon is almost perfectly correlated with CEC. This highlights the importance of organic matter in enhancing the soil's nutrient retention capacity and overall fertility (Wu et al., 2022). The strong positive correlations between organic matter and available nutrients underscore the role of organic inputs in sustaining soil fertility and supporting productive agriculture. Soils with higher organic matter content are better able to supply nutrients to crops, improve soil structure, and enhance biological activity, all of which are vital for long-term soil health (Liu et al., 2025). The available macronutrients and micronutrients are all extremely strongly correlated with each other. This suggests that nutrient availability is closely linked, likely due to similar sources such as organic matter decomposition and similar retention mechanisms involving clay and organic colloids. Such strong interrelationships mean that management practices affecting one nutrient, such as fertilization or organic amendments, are likely to influence the availability of others (Guo et al., 2025). This reinforces the importance of balanced fertilization and integrated soil fertility management. Coarse fragments are negatively correlated with clay and show weak or negative correlations with most chemical properties, indicating that soils with more coarse fragments tend to be sandier and less fertile. High coarse fragment content can reduce the effective rooting volume and water-holding capacity, which may limit crop yields, particularly in dry conditions (Robertson et al., 2021).

The mapping of the spatial variability of the soil properties over the studied site is crucial for understanding the relation between these properties, and to achieve better evaluation of the current status of the soil, discover the limitations, and propose potential improvements. The spatial variability distribution of the soil properties reflects the strong correlation between the soil organic carbon with macro and micronutrients. It also revealed the strong relation among the soil fractions (clay, silt, and sand) with the coarse fragments and CEC.

4.4. Land Capability assessment

The Storie index is employed to evaluate the current land capability conditions of the soil profiles which indicated a marked spectrum capability between Class IV (Poor) and Class II (Good). This distribution highlights that a significant portion of the study area is constrained by one or more limiting factors, most commonly texture (B) and coarse fragments (D), reducing the overall index despite optimal ratings for depth (A) and chemical properties (C) in most profiles. The multiplicative nature of the Storie Index calculation means that even a single low rating can substantially lower the overall capability score, as observed in profiles where the D factor (coarse fragments) was low-rated, leading to poor capability classes even when other factors were optimal. This pattern aligns with the known limitations of the Storie Index, where the product of ratings can sharply reduce the final score if any one factor is suboptimal (O'Geen et al., 2008; Abd-Elazem et al., 2024; Fadl et al., 2025). Another example is for texture ratings; in most profiles was moderate and indicated suboptimal soil texture, such as heavy clay or sandy soils, which can restrict root growth, water movement, and nutrient availability (Azadi et al., 2024). This limitation is well-documented in *Vertisols* and other shrink-swell soils common in central India, where high clay content impairs hydraulic conductivity and makes soil management challenging, especially under rainfed conditions (Pawar-Patil et al., 2024). Our observations from the land evaluation are very matched to those studies conducted in the *Vertisols* of Vidarbha region, Maharashtra where had fair to poor capability because of soil limitations of texture, drainage, and coarse fragment content (Shilpa Babar et al., 2015; Ingle at al., 2019; Kuchanwar et al., 2021). Another study was carried out in Nagpur district to evaluate the land capability using the Storie Index showed that 20 to 30% of these lands were in good capability (Class II) while the rest part was in fair or poor capability because of typical constraints (Azadi et al., 2024). In Akola and Amravati districts, the major limitations in the land capability were gravels, texture and fertility which caused classifying the lands to classes III and IV (Kathe et al., 2024). Shrivastav et al. (2023) evaluated the land capability in a part of Purna valley and found that less than 25% of this area was highly capable for agriculture and the rest lands had soil limitations such as drainage and physical properties. Similarly in Satpura and Melghat regions where the limitations of the land capability were low depth, coarse fragments as well as low fertility which led to classify the lands in fair to poor categories (NBSS&LUP, 2012). These physical limitations prevented higher capability ratings, illustrating the multiplicative effect of the Storie Index where a single low factor can sharply reduce the overall score (Fadl et al., 2025). The results are consistent with findings from similar studies in Maharashtra and central India, where texture, coarse fragments, and sometimes chemical fertility are the principal limitations to land capability (Athare et al., 2024; Kathe et al., 2024; Shrivastav et al., 2023). These findings align with broader regional research, which shows that in the *Vertisol*-dominated landscapes of Maharashtra and Vidarbha, land capability is most often constrained by clayey texture, high gravel content, and, to a lesser extent, chemical imbalances or low organic matter. It has emphasized that such soils require careful management, including organic matter addition, deep tillage, and erosion control, to mitigate these inherent limitations and improve agricultural productivity (Shrivastav et al., 2023).

4.5. Land productivity evaluation for current and potential conditions

The actual land productivity evaluation indicated that all soil profiles are under the moderately suitable (S2) category whereas the main improvable limitations across almost all profiles are low organic carbon and low available phosphorus, with occasional additional constraints such as low nitrogen, high clay content, and coarse fragments. The recommended management practices to overcome these limitations are the application of compost, manure, green manuring, and balanced NPK fertilization, which are well-established approaches for improving soil fertility and structure in Indian agricultural systems. When potential improvements are assumed raising organic carbon and optimizing available nitrogen, phosphorus, and potassium through fertilization, the LSI values for most profiles can be increased and shifting the soil profiles' suitability class from S2 (moderately suitable) to S1 (highly suitable). Few soil profiles will remain in the S2 class under potential conditions, primarily due to inherent limitations such as coarse fragments and high clay content, which are not easily ameliorated through standard agronomic practices. Moreover, these limitations offer insights about the necessity of the soil organic matter management as well as nutrient replenishment which had positive influences on the land productivity in such soils. Additionally, the strong impact of the physical soil properties cannot be easily improved. Compared to our results, many studies in Maharashtra were conducted in *Vertisol* and *Inceptisol* where low organic carbon and phosphorus as considered as main limitations to land productivity (Swami & Parthasarathy 2021; Gorain et al., 2024; Ingle et al., 2021; Chorey et al., 2022). However, the persistence of S2 ratings in profiles with high clay or coarse fragments also aligns with the broader literature, which notes that physical soil limitations such as heavy texture and stoniness are difficult to overcome and often set an upper limit on land capability, regardless of fertility management (NBSS&LUP, 2012).

4.6. Land Suitability Evaluation for different crops

Land suitability assessment of vegetables ranged from low to marginal, while root and tuber crops were not suitable with limitations of high soil pH, high clay content, low organic carbon, low available phosphorus, and, in several cases, a high proportion of coarse fragments or calcium carbonate. Moreover, the leafy and fruiting vegetables were marginal suitability with limitations as low organic carbon and phosphorus, and occasionally moderate to high pH. Only a few vegetables (onion and potato) were moderately suitable limited by low organic carbon and phosphorus. Additionally, fruits exhibit a wide range of suitability from marginally suitable (limitations: low phosphorus, organic carbon and high pH) to not suitable class (limitation: high pH, low nutrients, and coarse fragments). However, some fruits showed moderate suitability and limited mainly by low organic carbon and phosphorus. Therefore, fruit crops are more frequently marginal than moderately suitable, and none are highly suitable under the current soil conditions. Regarding the legumes, they generally show moderate suitability with main limitations of low organic carbon and phosphorus, but the absence of severe physical or chemical constraints allows them to perform relatively well. This group stands out for its higher overall suitability compared to vegetables and fruits, suggesting that the soil conditions are more favorable for leguminous crops. The cereals, oilseeds, fiber crops, sugar crops, and plantation crops show varied suitability whereas cereals are moderately suitable limited by low organic carbon and phosphorus; and oilseeds and fiber crops are mostly marginally suitable with high pH, high clay, low organic carbon, and low phosphorus as recurring limitations. The sugar crops are moderately suitable with similar nutrient limitations, while the plantation crops are generally not suitable due to high pH and poor nutrient status. However, the legumes and cereals are the most promising crop groups for the assessed land, with moderate suitability and manageable nutrient limitations, while vegetables and fruits are more often marginally or not suitable, primarily due to chemical and physical soil constraints. Regarding the oilseeds, fiber, and plantation crops face greater challenges, with most falling into the marginal or not suitable categories. Therefore, the overall suitability pattern indicates that improving soil organic carbon and phosphorus levels would have the most significant positive impact on land suitability for a wider range of crops. Several studies have been conducted in Maharashtra and other Indian states for evaluating the land suitability for cultivation by different crops. Sathiyamurthi et al. (2024) assessed the land suitability against the requirements of cotton crop in south India using analytical hierarchy process (AHP) and GIS. They found that 20% of the study area was highly suitable for cultivating cotton, while 30% (moderate) and rest (marginally suitable). Dey et al. (2024) used classical and new techniques for land suitability evaluation in West India for cultivating the grassland and understanding the best management system and they found that 35% of the land can be highly suitable for grass, while 27% were moderately suitable and the rest were not-suitable. For turmeric cultivation, Banu et al. (2024) evaluated the land suitability under current and future climate scenarios using advanced geospatial techniques in Kerala. They found that 28% of the area is highly suitable, 41% moderately suitable and 11% not suitable for turmeric cultivation. They also mentioned that by 2050, about 19% declines will be in highly suitable areas. Sawant et al. (2025) used fusion of remote sensing data, geospatial analysis and multi-criteria decision making for crop suitability in coastal region of India. Their findings reflected that 13.68% of the study area was highly suitable for rice, 19.26% and 18.35% being moderately and marginally suitable; while for coconut, 11% (highly suitable), 27.40% and 18.34% are moderately and marginally suitable, respectively.

4.7. Limitations of the study's findings

There are few limitations in this study such as the study area's spatial coverage whereas number of the soil profiles may be moderate as capturing full heterogeneity in soil conditions requires more details. However, this study is considered as guide for further studies in the region and similar areas. Moreover, the study's findings are obtained on the basis of the both field and laboratory observations in a specific time which may not account for temporal variations in soil properties because of the seasonal agricultural changes, management and climate changes. Furthermore, the evaluation in this study is based on using the frameworks like the Storie Index and

FAO whereas robust and based on true assumptions but these criteria may not fully reflect the site-specific management's practices and socio-economic factors impacted the different land-uses. From another point of view, the offered suggestions and recommendations for enhancing the SOC and nutrients are based on standard management and practices which can be impacted by local resources' availability, farmer's preferences as well as policies' supports. On the other hand, although these limitations, this research study provides informative and valuable insights about different land-uses' planning as well as land resource's management in the region of central India. Therefore, the future research studies can address those minor limitations by incorporating the both spatial and temporal scopes and including the socio-economic factors in the land evaluation. Integrating these criteria with RS and GIS as well as machine learning models is very essential for more dynamic and scalable evaluations.

5. Conclusion

This integrated assessment of soil properties, land capability, productivity, and crop suitability in the Deccan Plateau of central India provides a comprehensive understanding of the region's land resources and their potential for sustainable agricultural development. The study revealed significant spatial variability in soil characteristics, with *Vertisols*, *Inceptisols*, and *Entisols* each presenting distinct physical and chemical constraints most notably, low organic carbon, variable drainage, and high clay content in *Vertisols*, and limited water retention and nutrient status in *Entisols* and *Inceptisols*. Land capability evaluation using the Storie Index method indicated that only a small proportion (18%) of the area is classified as Class II (good capability), while the majority falls under Classes III and IV, reflecting moderate to severe limitations primarily due to soil physical constraints and nutrient deficiencies. Productivity assessments, based on FAO frameworks, demonstrated that current land productivity for major crops such as cotton, soybean, and sorghum remains suboptimal, with mean productivity indices ranging from 42% to 56%. However, scenario-based analysis suggests that targeted management interventions such as organic matter enrichment, balanced fertilization, and improved drainage could enhance productivity by 15–25%. Crop suitability analysis, employing the parametric approach further highlighted that *Vertisols* are moderately suitable for cotton and soybean, while *Entisols* and *Inceptisols* are only marginally suitable for wheat and pigeon pea, largely due to water and nutrient limitations. These findings underscore the need for site-specific soil management strategies to address inherent constraints and optimize land use. The study demonstrates the value of integrating classical and modern evaluation frameworks for a holistic understanding of land resources. By linking detailed soil characterization with capability, productivity, and suitability assessments, this research provides actionable insights for land use planning, policy formulation, and sustainable intensification in semi-arid tropical regions. Ultimately, the adoption of recommended soil and crop management practices will be essential to improve land productivity, ensure food security, and enhance the resilience of agricultural systems in central India. Future research should focus on long-term monitoring of management interventions and the integration of socio-economic factors to further refine land evaluation and support sustainable rural development.

List of abbreviations:
Electrical Conductivity (EC)
Organic Carbon (OC)
Organic Matter (OM)
Cation Exchange Capacity (CEC)
Available Nitrogen (AN)
Available Phosphorus (AP)
Available Potassium (AK)
Available Sulfur (AS)
Actual Productivity (Pa)
Potential Productivity (Pp)
Land Suitability Index (LSI)
Capability Index (CI)

Declarations

Ethics approval and consent to participate

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