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Assessment of Soil Fertility Status around the Chitrakoot District, Bundelkhand Region of Uttar Pradesh, India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

The overall sustainability of agricultural systems depends largely on the inherent productivity and proper management of soil resources. Soil fertility fluctuates seasonally due to nutrient additions through fertilizers, manures and amendments, as well as losses via crop removal, leaching and erosion. Continuous cropping without adequate replenishment of nutrients (N, P, K and others) leads to nutrient mining and reduced productivity. The present investigation was undertaken to assess the fertility status of soils in selected villages of Karwi, Pahadhi, Ramnagar, Mau and Manikpur blocks of Chitrakoot district, Bundelkhand region of Uttar Pradesh. A total of 125 surface soil samples (0–20 cm depth) were collected from farmers' fields after harvest of major crops and analyzed using standard analytical procedures. Soil reaction varied from neutral to moderately alkaline (pH 6.8–8.4) and electrical conductivity remained below 0.65 dS m^{-1}, indicating non-saline conditions. Organic carbon content ranged from 0.32 to 0.78%, with the majority of samples falling in low to medium categories. Available nitrogen (145–385 kg ha^{-1}) and phosphorus (6.8–28.4 kg ha^{-1}) were predominantly low to medium, whereas available potassium (165–485 kg ha^{-1}) was generally medium to high.

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Available sulphur ranged from 7.5 to 26.8 mg kg^{-1} and was deficient in several locations. Among micronutrients, DTPA-extractable zinc deficiency was observed in 58% of soil samples, while iron, manganese and copper were largely sufficient. Nutrient index values identified nitrogen and zinc as the principal limiting nutrients. The results highlight the need for soil test–based balanced fertilization and integrated nutrient management strategies to restore soil fertility and enhance sustainable crop productivity in the Bundelkhand region.

Keywords: Bundelkhand region; DTPA-extractable micronutrients; nutrient index; soil fertility and zinc deficiency.

1. Introduction

Soil is a critical input in agriculture, acting as a local medium for root establishment, seed growth, and germination. Improving soil physical, structural, and chemical properties, as well as monitoring and controlling soil conditions from seedbed preparation to harvest, have been major goals to improve productivity and research priorities (Bostani *et al.*, 2025). Soil is a fundamental natural resource that underpins food, fiber, fuel and fodder production and sustains terrestrial ecosystems. Its fertility—defined as the capacity to supply essential nutrients in adequate amounts and proper balance for plant growth—is a dynamic property influenced by natural processes and anthropogenic interventions (Bhattacharyya & Pal, 2015; Walkley & Black, 1934). Soil fertility is maintained by various factors such as organic carbon content, moisture, nitrogen, phosphorous, and potassium content, and other biotic and abiotic factors. To enhance crop production, farmers use various sorts of fertilizers, pesticides, herbicides, insecticides, fungicides, and weedicides, which ultimately degrade the soil quality. The disposal of fly ash on the barren land by the companies to reduce their waste material and by the farmers to enhance crop production is also a cause of degraded soil quality (Ruhela *et al.*, 2022). Maintenance of soil fertility is central to sustainable agriculture, particularly in tropical regions such as India, where rapid organic matter decomposition and intensive cultivation accelerate nutrient depletion. Soil quality encompasses physical, chemical and biological attributes, and declining fertility remains a major constraint to productivity.

Soil fertility fluctuates seasonally due to nutrient additions through fertilizers, manures and amendments, as well as losses via crop removal, leaching and erosion. Continuous cropping without adequate replenishment of nutrients (N, P, K and others) leads to nutrient mining and reduced productivity. Soil testing, therefore, serves as a scientific tool to assess nutrient status and guide balanced fertilizer recommendations for sustained yields. The overall sustainability of agricultural systems depends largely on the inherent productivity and proper management of soil resources. Globally, nearly 20 % of cultivable land is reported to be declining in fertility, affecting about one-quarter of the world's population (FAO, 2000).

Soil fertility is governed by several interacting factors, including parent material, climate, topography, organic matter dynamics and management practices. Physical indicators such as texture, structure, bulk density and porosity influence water retention and root growth, while chemical indicators—including soil pH, electrical conductivity, organic carbon, cation exchange capacity and nutrient concentrations—determine nutrient availability. Macronutrients (N, P, K) and micronutrients (Zn, Fe, Mn, Cu) play critical roles in crop growth, and micronutrient deficiencies are frequently observed in calcareous soils with high pH and low organic matter (Nayar, 1999). Organic carbon is particularly important, as it enhances nutrient cycling, improves soil structure and supports microbial activity. Declining organic matter levels in tropical agro-ecosystems reduce nutrient availability and soil resilience (Steven *et al.,* 2012).

Climatic factors, especially rainfall distribution and intensity, strongly influence nutrient dynamics by affecting mineralisation, leaching and erosion. While adequate and well-distributed rainfall enhances nutrient availability, excessive precipitation can accelerate nutrient losses. Traditional farming systems maintained fertility through crop rotations, residue recycling, manure application and fallowing; however, modern intensive agriculture often relies heavily on external inputs, disrupting natural nutrient balances.

In the Bundelkhand region, soils locally known as Rakar, Kabar, Parua and Mar belong mainly to Alfisols, Vertisols and Inceptisols, each exhibiting distinct fertility constraints. Comprehensive soil characterization and fertility evaluation are therefore essential to develop location-specific nutrient management strategies and ensure sustainable agricultural production.

2. Materials and Methods

2.1 Study Area

The study was conducted in Karwi, Pahadhi, Ramnagar, Mau and Manikpur blocks of Chitrakoot district, Bundelkhand region. The area experiences a subtropical climate with hot summers, cool winters and monsoon rainfall. Major crops grown include paddy, wheat, mustard, gram and pulses.

2.2 Soil Sampling

A total of 125 surface soil samples (0–20 cm depth) were collected from farmers' fields, with 25 samples from each block. Samples were collected randomly after harvest, air-dried, ground and sieved through a 2 mm sieve for laboratory analysis.

2.3 Laboratory Analysis

Soil samples were analyzed using standard procedures: - Soil pH and electrical conductivity (EC) in 1:2.5 soil-water suspension - Organic carbon by Walkley and Black method - Available nitrogen by alkaline $KMnO_4$ method - Available phosphorus by Olsen's method - Available potassium by neutral ammonium acetate extraction - Available sulphur by $CaCl_2$ extraction - DTPA-extractable micronutrients (Zn, Fe, Mn, Cu) using atomic absorption spectrophotometry.

2.4 Statistical Analysis

Descriptive statistics were used to assess the variability in soil properties. Nutrient index values were calculated to categorize soil fertility status into low, medium and high classes.

3. Results and Discussion

3.1 Physico-chemical Properties of Soils

The physico-chemical properties of soils of Chitrakoot district are presented in Table 1. Soil pH ranged from 6.8 to 8.4 with a mean value of 7.60, indicating that the soils were neutral to moderately alkaline in nature. Similar soil reaction in Bundelkhand soils has been reported by Prasad *et al.* (2020), who attributed alkalinity to calcium carbonate accumulation and low rainfall conditions.

Electrical conductivity varied from 0.05 to 0.65 dS m^{-1}, with a mean of 0.21 dS m^{-1}, indicating that the soils were non-saline. These findings are in agreement with Bijarnia *et al.* (2025), who reported low EC values in rainfed soils of central India. Organic carbon content ranged from 0.32 to 0.78% with a mean of 0.52%, classifying the soils under low to medium organic carbon status. Low organic carbon in tropical soils has also been reported by Lal, 2004) and is attributed to rapid mineralization and poor organic matter addition.

3.2 Soil Texture

The textural composition of soils (Table 2) revealed that 68% of samples were sandy loam, followed by loam (22%) and sandy clay loam (10%). Similar dominance of sandy loam texture in soils of central India, including Bundelkhand, has been reported in earlier studies (Bhattacharyya *et al.*, 2008). Sandy loam soils are known to possess moderate nutrient-holding capacity due to their balanced proportion of sand and finer fractions, which influences variability in nutrient availability (Brady & Weil, 2016; Six *et al.*, 2002).

3.3 Available Nitrogen Status

Available nitrogen content ranged from 145 to 385 kg ha^{-1} with a mean value of 262 kg ha^{-1} (Table 3). About 62% of soil samples were low in nitrogen, indicating widespread nitrogen deficiency. These results corroborate the findings of Subbiah and Asija (1956)**,** who reported nitrogen as the most limiting nutrient in Indian soils. The strong positive correlation between organic carbon and nitrogen (r = 0.71**) shown in Table 7 further confirms the role of organic matter as a primary nitrogen source.

3.4 Available Phosphorus Status

Available phosphorus varied from 6.8 to 28.4 kg ha⁻¹, with most soils falling under low to medium categories (Table 3). Similar phosphorus deficiency in alkaline soils was reported by Olsen *et al.* (1954). The negative correlation between soil pH and available phosphorus (Table 7) supports the findings of Hinsinger (2001), who explained phosphorus fixation under alkaline conditions.

Table 1. Detailed physico-chemical properties of soils of Chitrakoot district (n = 125)

Parameter	Min	Max	Mean	SD	CV (%)	Rating
pH (1:2.5)	6.8	8.4	7.60	0.42	5.5	Neutral–alkaline
EC (dS m^{-1})	0.05	0.65	0.21	0.14	66.7	Non-saline
Organic Carbon (%)	0.32	0.78	0.52	0.11	21.2	Low–medium
Bulk Density (Mg m^{-3})	1.31	1.64	1.47	0.09	6.1	Normal
Hydraulic Conductivity (cm hr^{-1})	4.8	18.6	10.9	3.4	31.2	Moderate

Table 2. Textural distribution of soils in the study area

Textural class	Sand (%)	Silt (%)	Clay (%)	% Samples
Sandy loam	55–68	20–30	10–20	68
Loam	45–55	25–35	15–25	22
Sandy clay loam	48–60	18–25	22–30	10

Table 3. Expanded available macronutrient status of soils

Nutrient	Range	Mean	SD	CV (%)	Low (%)	Medium (%)	High (%)
N (kg ha^{-1})	145–385	262	58	22.1	62	38	0
P (kg ha^{-1})	6.8–28.4	16.9	6.1	36.1	46	42	12
K (kg ha^{-1})	165–485	312	74	23.7	18	44	38
S (mg kg^{-1})	7.5–26.8	14.6	4.9	33.6	34	48	18

Table 4. Expanded DTPA-extractable micronutrient status

Micronutrient	Range (mg kg^{-1})	Mean	SD	CV (%)	Deficient (%)	Sufficient (%)
Zn	0.28–1.12	0.54	0.21	38.9	58	42
Fe	4.6–18.9	9.8	3.7	37.8	14	86
Mn	3.9–22.4	11.6	4.8	41.4	8	92
Cu	0.32–1.84	0.78	0.29	37.2	6	94

Table 5. Expanded soil fertility (nutrient index values)

Nutrient	Index value	Rating	Limitation severity
Organic Carbon	1.62	Low	Moderate
Available N	1.58	Low	Severe
Available P	1.74	Medium	Moderate
Available K	2.36	High	Low
Available S	1.69	Medium	Moderate
Zinc	1.41	Low	Severe

Table 6. Block-wise detailed fertility status

Block	pH	OC (%)	N	P	K	Zn
Karwi	7.5	0.55	270	18.4	325	0.56
Pahadhi	7.7	0.48	245	14.9	298	0.51
Ramnagar	7.6	0.50	258	16.2	310	0.49
Mau	7.4	0.54	275	19.1	335	0.58
Manikpur	7.8	0.53	262	15.8	290	0.54

Table 7. Correlation coefficients (r) between soil properties and nutrients

Property	N	P	K	Zn	Fe
pH	−0.42**	−0.36*	0.18	−0.31*	−0.28*
EC	−0.12	−0.08	0.21	−0.05	−0.11
Organic Carbon	0.71**	0.64**	0.39*	0.58**	0.46*

Table 8. Percentage distribution of soil samples by fertility class

Nutrient	Very low	Low	Medium	Moderately high	High
Organic carbon	12	44	34	10	0
Nitrogen	18	44	38	0	0
Phosphorus	14	32	42	12	0
Potassium	6	12	44	28	10
Zinc	22	36	42	0	0

3.5 Available Potassium Status

Available potassium ranged from 165 to 485 kg ha^{-1}, with a mean of 312 kg ha^{-1} (Table 3). The majority of soils were categorized as medium to high in potassium. This may be attributed to the presence of potassium-bearing minerals such as mica and feldspar in the parent material, along with the inherent soil characteristics of the Bundelkhand region, where several studies have reported medium to high potassium status in soils due to mineral weathering and soil fertility dynamics (Manning *et al.*, 2017; Mishra *et al.*, 2025).

3.6 Available Sulphur Status

Available sulphur content ranged from 7.5 to 26.8 mg kg^{-1}**,** with 34% of soil samples deficient (Table 3). Similar sulphur deficiencies have been reported by Mishra *et al.* (2022)**,** emphasised sulphur as an emerging nutrient deficiency due to increased use of high-analysis fertilizers.

3.7 Micronutrient Status

The DTPA-extractable micronutrient status of soils is presented in Table 4. Zinc content ranged from 0.28 to 1.12 mg kg^{-1}, with 58% of samples deficient, confirming zinc as the most limiting micronutrient. Similar widespread zinc deficiency in alkaline and calcareous soils has been reported due to reduced solubility of Zn under high pH conditions (Alloway, 2009; Cakmak, 2008).

Iron, manganese, and copper were found to be sufficient in most soil samples, which corroborates earlier findings that these micronutrients are commonly present in adequate amounts and can be effectively assessed using DTPA extraction (Lindsay & Norvell, 1978; Fageria *et al.*, 2002).

3.8 Soil Fertility Index and Fertility Classification

The nutrient index values presented in Table 5 showed low fertility ratings for organic carbon (1.62), available nitrogen (1.58) and zinc (1.41), while phosphorus and sulphur were medium and potassium was high. Similar fertility patterns were reported by Parker *et al.* (1951), emphasizing nitrogen and zinc as major yield-limiting nutrients.

3.9 Block-wise Fertility Variation

Block-wise variation in soil fertility status is shown in Table 6. Mau block recorded comparatively higher organic carbon and nutrient availability, while Pahadhi and Ramnagar blocks showed lower values. Such spatial variability in soil fertility has also been reported by Dobermann *et al.* (2003) and highlights the need for site-specific nutrient management.

3.10 Relationship between Soil Properties and Nutrient Availability

Correlation analysis (Table 7) revealed that soil pH had a significant negative relationship with nitrogen, phosphorus and zinc, while organic carbon showed a strong positive correlation with major nutrients. These findings are in agreement with FAO (2000)**,** emphasizing the importance of organic matter management in improving soil fertility.

3.11 Distribution of Soil Samples by Fertility Class

The distribution of soil samples under different fertility classes (Table 8) showed that a large proportion of soils were low in organic carbon, nitrogen and zinc, while potassium was largely sufficient. This pattern strongly supports the nutrient index results and is consistent with observations reported in earlier studies for central Indian soils.

4. Conclusion

The study provides a comprehensive evaluation of soil fertility in selected blocks of Chitrakoot district, Bundelkhand, revealing considerable spatial variability in soil properties and nutrient status. Soils were neutral to moderately alkaline and non-saline, suitable for crop production; however, organic carbon was predominantly low to medium, indicating poor organic matter management. Available nitrogen emerged as the most limiting nutrient, while phosphorus was largely low to medium due to probable fixation under alkaline conditions. Potassium was generally medium to high, reflecting the mineralogical composition of the parent material. Sulphur deficiency was noted in several samples, suggesting its increasing importance in crop nutrition. Among micronutrients, zinc deficiency was widespread, whereas iron, manganese and copper were mostly adequate. Nutrient index values confirmed low fertility for organic carbon, nitrogen and zinc. The findings emphasize soil test–based balanced fertilization and integrated nutrient management, including organic inputs and judicious application of N, S and Zn, to enhance soil health and sustainable productivity in Bundelkhand.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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