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Integrated Assessment of Soil Health Through Macronutrient Status and Physico-Chemical Properties in Selected Agricultural Blocks of Kangra District, Himachal Pradesh, India

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Abstract

Soil health is a critical determinant of agricultural sustainability, particularly in ecologically sensitive Himalayan regions where intensive cultivation and heterogeneous landscapes influence nutrient dynamics. Balanced macronutrient availability, together with favourable physico-chemical properties, governs crop productivity, soil resilience, and long-term ecosystem functioning. Despite the agronomic importance of Kangra District (Himachal Pradesh), localized assessments integrating nutrient status with physico-chemical indicators across representative agricultural blocks remain limited. This study aimed to evaluate soil health in selected agricultural blocks of Kangra District by quantifying available macronutrients alongside key physico-chemical parameters. A total of 22 surface soil samples (0–15 cm) were collected from cultivated fields across Dharamshala, Bhawarna, and Baijnath blocks using grid-cum-zig-zag composite sampling. Available nitrogen (N), phosphorus (P), potassium (K), and sulphur (S) were estimated in the soil samples. Soil pH, electrical conductivity (EC), and organic carbon (OC) were also measured. Descriptive statistics, one-way ANOVA, and Pearson correlation analysis were applied. The studied soils ranged from slightly acidic to neutral (pH 4.40–7.30) and were non-saline (EC 0.01–0.50 dS m^{-1}). Organic carbon was predominantly high (0.27–2.10%). Available nitrogen showed moderate to high variability (62.7–476.7 kg ha^{-1}). Phosphorus deficiency was widespread, while potassium was generally medium to high. Sulphur was largely adequate to high, with isolated deficiencies. Organic carbon showed significant positive correlations with N, P, K, and S. Although the studied soils were generally non-saline and organically enriched, nutrient imbalances – particularly low available phosphorus and variable nitrogen – may constrain optimal crop productivity. Site-specific, soil test–based nutrient management emphasizing balanced fertilization and organic matter management is recommended for sustaining productivity and long-term soil health in Himalayan agro-ecosystems.

Keywords: Electrical conductivity, Himalayan agriculture, Kangra District, macronutrients, organic carbon, soil fertility, soil health

INTRODUCTION

Soil constitutes the foundation of terrestrial ecosystems and agricultural production, serving not only as a medium for plant growth but also as a dynamic regulator of nutrient cycling, water balance, and carbon sequestration. The concept of soil health extends beyond fertility, encompassing the soil's capacity to function as a living system that sustains biological productivity, environmental quality, and plant–animal well-being over time [1].

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In agricultural landscapes, soil health directly influences crop yield stability, resource-use efficiency, and resilience against land degradation.

Macronutrients play a central role in determining soil fertility and crop performance. Nitrogen (N), phosphorus (P), and potassium (K) are primary macronutrients required in large quantities for plant metabolism and growth, while sulphur (S), commonly considered a secondary macronutrient, is increasingly recognized for its roles in protein synthesis, chlorophyll formation, and enzymatic activity. Deficiencies or imbalances in these nutrients result in suboptimal crop growth, reduced yields, and declining soil productivity. Importantly, nutrient availability is not solely governed by total nutrient content; it is strongly modulated by physico-chemical soil properties such as pH, electrical conductivity, and organic carbon content.

Soil pH regulates nutrient solubility, microbial activity, and root nutrient uptake. Electrical conductivity indicates soluble salt levels and potential salinity stress. Organic carbon, as a proxy for soil organic matter, enhances soil structure, improves water-holding capacity, buffers pH variability, and supports microbial processes vital for nutrient cycling and retention [2]. Therefore, integrated assessment of nutrient status and physico-chemical conditions provides a robust diagnostic approach for understanding soil fertility constraints.

Kangra District of Himachal Pradesh represents a geographically and ecologically diverse agricultural region within the north-western Himalayan belt. Variations in altitude, climate, rainfall, and land-use practices contribute to pronounced spatial heterogeneity in soil properties. Agriculture remains a major livelihood, making soil health assessment essential for sustainable crop production and economic stability. However, systematic, block-level evaluations integrating macronutrient availability with physico-chemical attributes are limited.

National initiatives, such as the Soil Health Card Scheme, emphasize soil testing for balanced nutrient management; nonetheless, localized scientific evaluations are required to interpret soil fertility constraints under specific agro-ecological conditions and to guide site-specific interventions.

Accordingly, this study was undertaken to quantify available macronutrients (N, P, K, and S) in agricultural soils of selected blocks of Kangra District; evaluate soil pH, electrical conductivity, and organic carbon status; and classify soils into fertility categories and interpret overall soil health using integrated indicators.

MATERIALS AND METHODS

Study Area

The study was conducted in Kangra District, Himachal Pradesh, India, located in the north-western Himalayan foothills. Three agriculturally important blocks – Dharamshala, Bhawarna, and Baijnath – were selected to represent spatial heterogeneity in altitude, climate, rainfall, and land-use practices. The regional climate ranges from humid subtropical to temperate with pronounced monsoonal rainfall, influencing nutrient dynamics and organic matter turnover.

Sampling Strategy and Sample Size

A total of 22 surface soil samples were collected from cultivated fields across the three blocks. Surface soils (0–15 cm) were targeted because this layer is biologically active and most influenced by cultivation and fertilization. Sampling followed a grid-cum-zig-zag composite approach to ensure representativeness. Multiple subsamples were collected while avoiding atypical areas (field boundaries, irrigation channels, tree bases, and localized fertilizer spots) and composited to obtain one representative sample per site.

Sample Collection and Preparation

Soils were collected using a soil auger/spade after removing surface litter. Composite samples were placed in labelled polyethylene bags. In the laboratory, samples were air-dried under shade, gently crushed, sieved through a 2 mm mesh, homogenized, and stored in airtight containers prior to analysis.

Physico-Chemical Analysis

- *Soil pH:* Determined in a 1:2.5 soil–water suspension using a calibrated digital pH meter (buffered at pH 4.0, 7.0, and 9.2).
- *Electrical Conductivity (EC):* Measured in the same 1:2.5 extract using a conductivity meter and expressed as dS m^{-1} at 25°C.
- *Organic Carbon (OC):* Determined by Walkley and Black wet oxidation method [3].

Macronutrient Analysis

- *Available Nitrogen (N):* Estimated using alkaline $KMnO_4$ method [4].
- *Available Phosphorus (P):* Determined by Olsen's method ($NaHCO_3$ extraction, molybdenum blue colour development) [5].
- *Available Potassium (K):* Extracted using neutral ammonium acetate (1 N, pH 7.0) and quantified by flame photometry.
- *Available Sulphur (S):* Estimated by turbidimetric method using $CaCl_2$ extraction and measurement of $BaSO_4$ turbidity.

Soil Fertility Classification

Samples were categorized into low, medium, and high fertility classes for each nutrient using established critical limits commonly applied in Indian soil fertility assessment. Physico-chemical parameters were interpreted using standard agronomic thresholds.

Statistical Analysis

Data were analyzed using SPSS (Version 26.0). Descriptive statistics (mean, SD, range, and percentage distribution) were computed. One-way ANOVA was applied to test block-wise differences; Tukey's HSD was used for post-hoc comparisons where applicable. Pearson correlation analysis was performed to examine associations between OC and macronutrient availability. Significance was evaluated at $p < 0.05$.

RESULTS

Twenty-two surface soil samples (0–15 cm) from Dharamshala (8 samples), Bhawarna (7 samples), and Baijnath (7 samples) were analyzed. Results are presented for physico-chemical properties, macronutrients, fertility class distribution, and OC–nutrient relationships.

Physico-Chemical Properties

Soil Reaction (pH)

Soil pH ranged from 4.40 to 7.30 (overall mean 5.92 ± 0.86), indicating slightly acidic to neutral soils (Table 1). Slightly acidic soils (pH < 6.5) comprised 68.2% of samples and near-neutral soils (pH 6.5–7.5) comprised 31.8%. Block-wise mean pH differed significantly among blocks ($p < 0.05$).

Electrical Conductivity (EC)

EC ranged from 0.01 to 0.50 dS m^{-1} (mean 0.18 ± 0.15 dS m^{-1}), indicating non-saline soils across the study area. All samples were below 1.0 dS m^{-1}. EC differed significantly among blocks ($p < 0.01$) (Table 1).

Organic Carbon (OC)

OC ranged from 0.27% to 2.10% (mean 1.13 ± 0.47%) and was predominantly high across sites) (Table 1). High OC (>0.75%) occurred in 77.3% of samples, medium in 18.2%, and low in 4.5% (Table 3). Block-wise OC did not differ significantly ($p > 0.05$).

Macronutrient Status

Available Nitrogen (N)

Available N ranged from 62.7 to 476.7 kg ha^{-1} (mean 308.4 ± 117.2 kg ha^{-1}) (Table 2). Low N occurred in 22.7% of samples, medium in 50.0%, and high in 27.3% (Table 3). Nitrogen differed significantly among blocks ($p < 0.01$).

Available Phosphorus (P)

Available P ranged from 13.4 to 286.7 kg ha^{-1} (mean 78.6 ± 72.4 kg ha^{-1}) (Table 2). Most samples (68.2%) were low in P, indicating widespread deficiency (Table 3). Differences among blocks were significant ($p < 0.05$).

Table 1. Physico-chemical properties of soils across blocks.

Parameter	Dharamshala (N = 8) Mean ± SD	Bhawarna (N = 7) Mean ± SD	Baijnath (N = 7) Mean ± SD	Overall (N = 22) Mean ± SD	Overall range (Min–Max)	ANOVA p-value
pH	5.99 ± 1.07	6.37 ± 0.53	5.46 ± 0.64	5.92 ± 0.86	4.40–7.30	<0.05
EC (dS m^{-1})	0.026 ± 0.014	0.29 ± 0.14	0.16 ± 0.08	0.18 ± 0.15	0.01–0.50	<0.01
OC (%)	1.22 ± 0.53	1.05 ± 0.31	1.10 ± 0.54	1.13 ± 0.47	0.27–2.10	>0.05

Available Potassium (K)

Available K ranged from 134.4 to 1276.8 kg ha^{-1} (mean 653.1 ± 371.6 kg ha^{-1}) (Table 2). Low K occurred in 31.8% of samples, medium in 31.8%, and high in 36.4% (Table 3). Block-wise differences were significant ($p < 0.05$) (Table 2).

Available Sulphur (S)

Available S ranged from 20.0 to 169.3 ppm (mean 88.6 ± 46.2 ppm) (Table 2). Most samples (72.7%) were high in S; low S occurred in 9.1% (Table 3). Differences among blocks were significant ($p < 0.05$).

Table 2. Available macronutrient status across blocks.

Nutrient	Dharamshala Mean ± SD	Bhawarna Mean ± SD	Baijnath Mean ± SD	Overall Mean ± SD	Overall range	ANOVA p-value
Available N (kg ha^{-1})	276.7 ± 116.9	256.3 ± 116.4	403.2 ± 69.8	308.4 ± 117.2	62.7–476.7	<0.01
Available P (kg ha^{-1})	83.7 ± 86.4	111.4 ± 82.9	46.5 ± 66.9	78.6 ± 72.4	13.4–286.7	<0.05
Available K (kg ha^{-1})	647.8 ± 439.6	745.7 ± 353.8	400.7 ± 282.5	653.1 ± 371.6	134.4–1276.8	<0.05
Available S (ppm)	72.7 ± 45.8	121.4 ± 30.6	89.6 ± 53.4	88.6 ± 46.2	20.0–169.3	<0.05

Table 3. Fertility class distribution (overall, N = 22).

Parameter	Class	Threshold	N	%
OC (%)	Low	<0.40	1	4.5
	Medium	0.40–0.75	4	18.2
	High	>0.75	17	77.3
N (kg ha^{-1})	Low	<250	5	22.7
	Medium	250–400	11	50.0
	High	>400	6	27.3
P (kg ha^{-1})	Low	<100	15	68.2
	Medium	100–199	4	18.2
	High	≥200	3	13.6
K (kg ha^{-1})	Low	<400	7	31.8
	Medium	400–800	7	31.8
	High	>800	8	36.4
S (ppm)	Low	<20	2	9.1
	Medium	20–40	4	18.2
	High	>40	16	72.7

Correlation Between OC and Macronutrients

Organic carbon showed significant positive correlations with N (r = 0.61, p < 0.01), P (r = 0.48, $p < 0.05$), K (r = 0.52, $p < 0.05$), and S (r = 0.57, p < 0.01) (Table 4; Figures 1 and 2).

Table 4. Pearson correlation between OC and macronutrients.

Relationship	r	p-value
OC vs N	0.61	<0.01
OC vs P	0.48	<0.05
OC vs K	0.52	<0.05
OC vs S	0.57	<0.01

Note: N = 22.

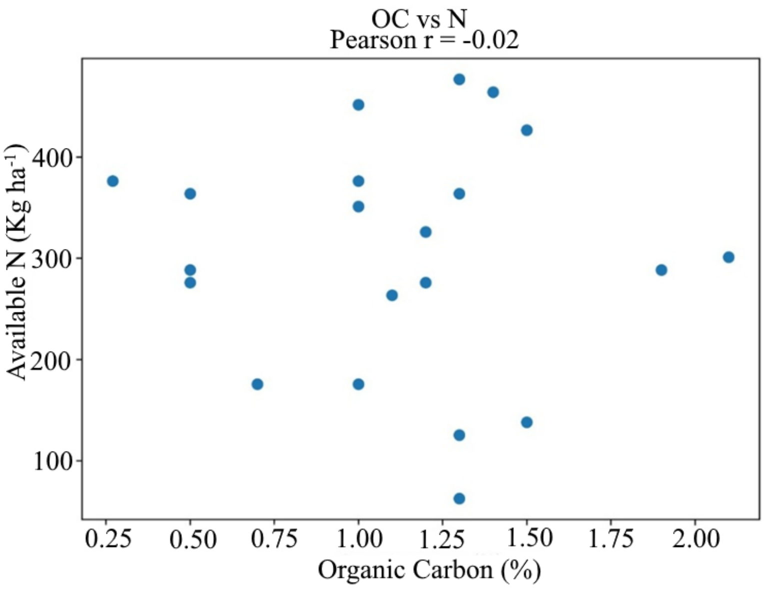

Figure 1. Relationship between organic carbon (%) and available nitrogen showing correlation trends.

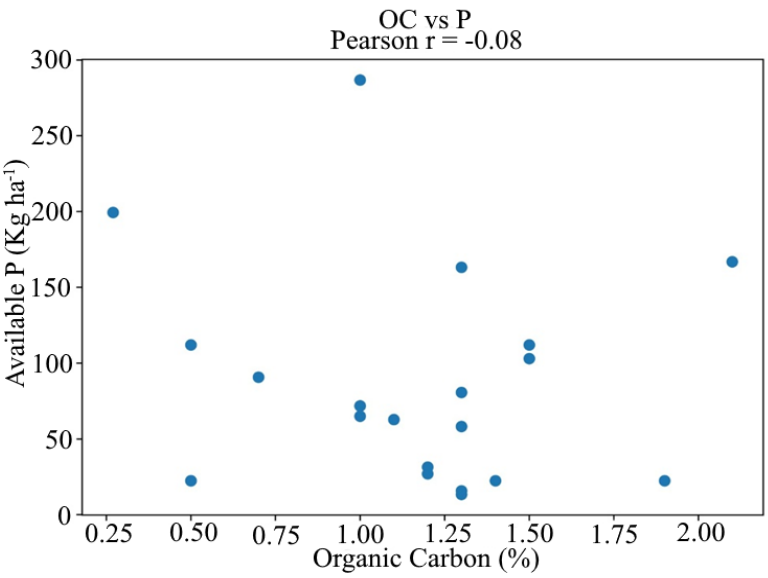

Figure 2. Relationship between organic carbon (%) and available phosphorus showing correlation trends.

DISCUSSION

This integrated evaluation of soil health across selected blocks of Kangra District demonstrates that while soils are generally non-saline and organically enriched, nutrient imbalances persist, especially phosphorus deficiency. Such integrated assessments are particularly relevant in Himalayan agro-ecosystems where nutrient dynamics are shaped by interacting influences of topography, rainfall, parent material, and management.

The slightly acidic to neutral pH observed aligns with earlier reports from Himalayan foothill soils [6, 7]. High rainfall and leaching of base cations can promote acidity, which may limit phosphorus bioavailability through fixation processes. The widespread phosphorus deficiency in the present study is consistent with known constraints on plant-available phosphorus in acidic to near-neutral soils [8, 9]. EC remained well below salinity thresholds, consistent with high rainfall regions where soluble salts are typically leached rather than accumulated [10]. Thus, major constraints to productivity are likely nutritional rather than salinity related.

OC was predominantly medium to high, indicating favourable organic matter status. Organic matter is critical for nutrient retention and mineralization and is strongly linked with sustainable fertility [2]. The significant positive correlations between OC and all assessed macronutrients underscore the role of organic carbon in regulating nutrient availability through improved cation exchange capacity, microbial activity, and nutrient cycling.

Nitrogen showed substantial variability, consistent with its dynamic behaviour in soils and sensitivity to management and environmental losses [11, 12]. This highlights the need for site-specific nitrogen recommendations rather than uniform fertilizer application.

Phosphorus emerged as the most widespread fertility constraint. Because phosphorus is relatively immobile in soils and can become strongly fixed under certain pH conditions, deficiencies may persist unless addressed through targeted soil-test-based interventions [8, 9]. Potassium was generally medium to high, potentially reflecting the mineralogical contribution of potassium-bearing parent material, although localized depletion under continuous cultivation can occur [13]. Sulphur was largely adequate to high; however, emerging sulphur deficiency has been reported in various Indian soils, especially under changing fertilizer practices, and therefore, continued monitoring remains important [14].

Overall, the findings support integrated nutrient management approaches and soil test–based advisory systems, consistent with national soil health initiatives [15].

CONCLUSION

Agricultural soils of the studied blocks in Kangra District are largely non-saline, structurally stable, and organically enriched. However, substantial nutrient imbalances exist, with phosphorus deficiency as the most widespread constraint and nitrogen showing marked spatial variability. Potassium and sulphur are generally adequate, though localized deficiencies indicate potential nutrient depletion risks. Strong positive relationships between organic carbon and nutrient availability emphasize the central role of organic matter in sustaining fertility. The study highlights the importance of site-specific, soil test-based nutrient management to support long-term agricultural sustainability in Himalayan agro-ecosystems.

Limitations of the Study

The sample size, while adequate for block-level exploratory assessment, limits fine-scale extrapolation. Sampling was conducted during a single period; seasonal variation was not captured. Biological indicators of soil health were not included.

Future Scope and Recommendations

Future research should include larger sampling, multi-season monitoring, and biological indicators to develop a more holistic soil health index. Site-specific phosphorus supplementation, balanced fertilization, periodic liming where needed, and integrated nutrient management are recommended to improve long-term soil fertility and productivity.

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Conflict of Interest

The authors declare no conflict of interest.

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