

Land suitability assessment of soils under organic cultivation of CCSHAU, Hisar for improved land use planning

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Abstract

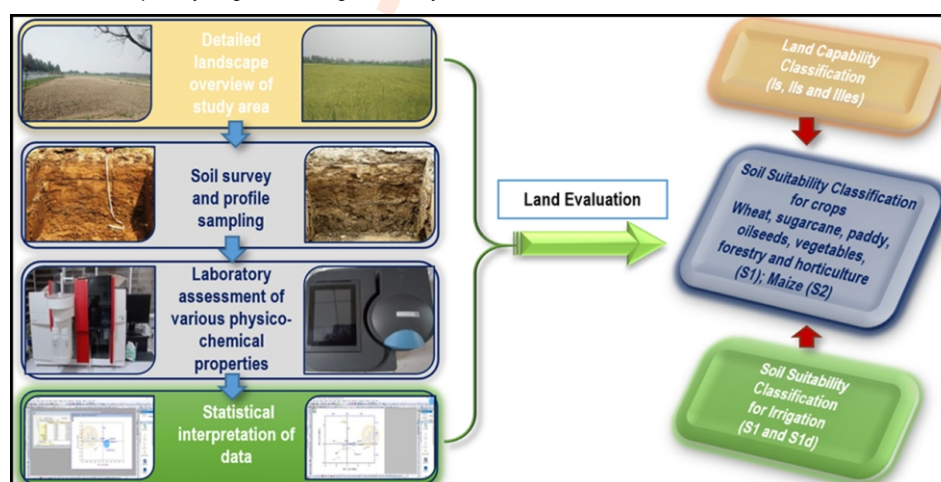
Aim: Evaluation of land capability and soil suitability for organic farming systems in Haryana, India, was conducted to identify critical limitations affecting crop production.

Methodology: This study was conducted in rabi season of 2022-23 at Deen Dayal Upadhyay Centre of Excellence for Organic Farming, Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana, where seven representative soil pedons were selected and subjected to a comprehensive analysis of their morphological and physico-chemical properties.

Results: The soils of study area were neutral to alkaline (7.49 to 10.37), non-saline (0.2 to 1.9 dS m⁻¹), calcareous (0.43 to 11.49%), low to medium in soil organic carbon (0.05 to 0.55%). Available N, P and K were low (28.22 to 148.18 kg ha⁻¹), low to medium (4.98 to 15.93 kg ha⁻¹) and low to high (63.84 to 459.20 kg ha⁻¹), respectively. Soils of all the pedons were sufficient in Mn and Cu, but deficient to sufficient in Zn and Fe.

Interpretation: According to land capability and soil irrigability classification, soils were classified as I, IIs and IIes, and S1 and S1d, respectively. Soil analysis indicated a high suitability (S1) for wheat, paddy, sugarcane, vegetables, oilseeds, horticulture and forestry, while maize exhibited moderate suitability (S2) based on established soil suitability criteria.

Key words: Classification, Land capability, Organic farming, Suitability



Introduction

Growing populations strain resource-limited food production. Reliance on chemical inputs within conventional agricultural systems poses a significant threat to the soil health and long-term sustainability of crop production potential (Sheoran *et al.*, 2018). Current practices deplete soil nutrients and organic matter. Organic agriculture offers a solution by promoting biodiversity and soil health through natural methods, reducing reliance on synthetic inputs and creating a more sustainable food system. This shift is vital for long-term food security and environmental health. Within the agricultural domain, organic farming stands as a meticulously crafted production system. This system prioritizes eschewal or significant minimization of synthetically derived inputs, including fertilizers, pesticides, herbicides, growth regulators and other agrochemicals (Yadav *et al.*, 2023). To achieve optimal crop health and productivity, organic farming strategically leverages diversified crop rotations. Strategic crop rotations serve a dual purpose: biological pest regulation and enhanced plant nutrition via symbiotic nitrogen fixation and biogeochemical cycling (Wortman *et al.*, 2012).

Organic soils, rich in organic matter content, hold immense potential for sustainable agriculture. However, their unique characteristics present distinct challenges for land use planning. To optimize the use of these valuable resources while ensuring long-term productivity, a comprehensive assessment of land suitability is crucial (Kumari *et al.*, 2024). The ever-increasing pressure on land resources necessitates smarter planning strategies. Land suitability assessment emerges as a crucial tool, evaluating the capacity of land for specific uses like agriculture or urban development. This approach fosters sustainable land use, maximizing benefits while minimizing environmental degradation and paving the way for a future where land use aligns with its optimal potential. Limited understanding of soil characteristics contributes significantly to soil degradation through misuse and mismanagement. To effectively address this issue, a comprehensive soil characterization approach is required. This approach should encompass geospatial data on soil location and extent, coupled with detailed analyses of morphological, physico-chemical and fertility properties (Ghode *et al.*, 2023).

By elucidating the relationships between these factors and geomorphic processes, we can gain a deeper understanding of soil formation and develop targeted strategies for soil conservation and sustainable management (Kumar *et al.*, 2022). Land evaluation utilizes a ranking system based on soil unit capabilities. This ranking takes into account particular management techniques and socio-economic elements in order to anticipate optimal profits per unit area while also conserving natural resources for generations to come. Essentially, land appraisal is a technique of estimating the potential of land for various usage scenarios (Sahoo *et al.*, 2021). Soil resource inventories provide a comprehensive characterization of soil types and their spatial distribution within a defined area. This data undergoes subsequent interpretation and evaluation procedures.

These procedures group soils based on shared characteristics and assess their land capability, irrigability and crop suitability. This information is crucial for land-use planning and agricultural management in a spatially explicit manner, enabling informed decision-making by administrators and stakeholders for long-term sustainable development (Ma *et al.*, 2023).

This research delves into the land suitability assessment of farm soils under organic cultivation for various agricultural applications. By identifying both strengths and limitations of these soils, this study aims to provide a framework for informed land management decisions. By employing established land suitability assessment frameworks and integrating recent advancements in soil science and geospatial analysis, this study aims to develop a robust and data-driven approach in assessing the agricultural potential of these soils. The resulting insights will inform land-use planning decisions, guide optimal crop selection practices and ultimately promote the long-term sustainability and productivity of these valuable ecosystems.

Materials and Methods

Study area: A study was conducted during rabi season of 2022-2023 at Deen Dayal Upadhyay Centre of Excellence for Organic Farming, a 139 acres research facility located within the geospatial coordinates of 29°08'00"N-29°08'30"N and 75°41'15"E - 75°42'30"E, situated at Chaudhary Charan Singh Haryana Agricultural University (CCSHAU), Hisar, Haryana, India. The base map of study area is shown in Fig. 1.

As per soil taxonomy, soils were classified as Typic Haplustepts. The study area is characterized by a semi-arid subtropical climate with an Ustic and Hyperthermic soil moisture and temperature regime, respectively. Average annual precipitation is 450 mm approximately and the elevation is 215 meters above sea level. The centre exhibits high yields within various organic cropping systems. The centre employs a diversified approach with cereals such as wheat, mustard, barley, gram, pearl millet and greengram cultivated in grain-based systems. For vegetable production potato, carrot, pea, onion, garlic, radish, spinach and tomato are the primary crops, while the orchard system includes banana, guava, mango, plum, pear, pomegranate, sweet orange, kinnow, ber, bael, jamun and lemon.

Soil sampling: To investigate soil morphological and physico-chemical properties, 31 samples were collected across seven soil profiles encompassing various horizons, following a geomorphic soil association approach. Morphological features were documented in the field for each horizon, adhering to the FAO guidelines (1993). Collected samples were air-dried under shade conditions to minimize alterations. Subsequently, the samples were pulverized using a mortar and pestle crafted from wood. The pulverized material was then fractionated using a series of sieves.

Soil analysis: This section presents a compilation of determined physico-chemical properties, including the analytical methods

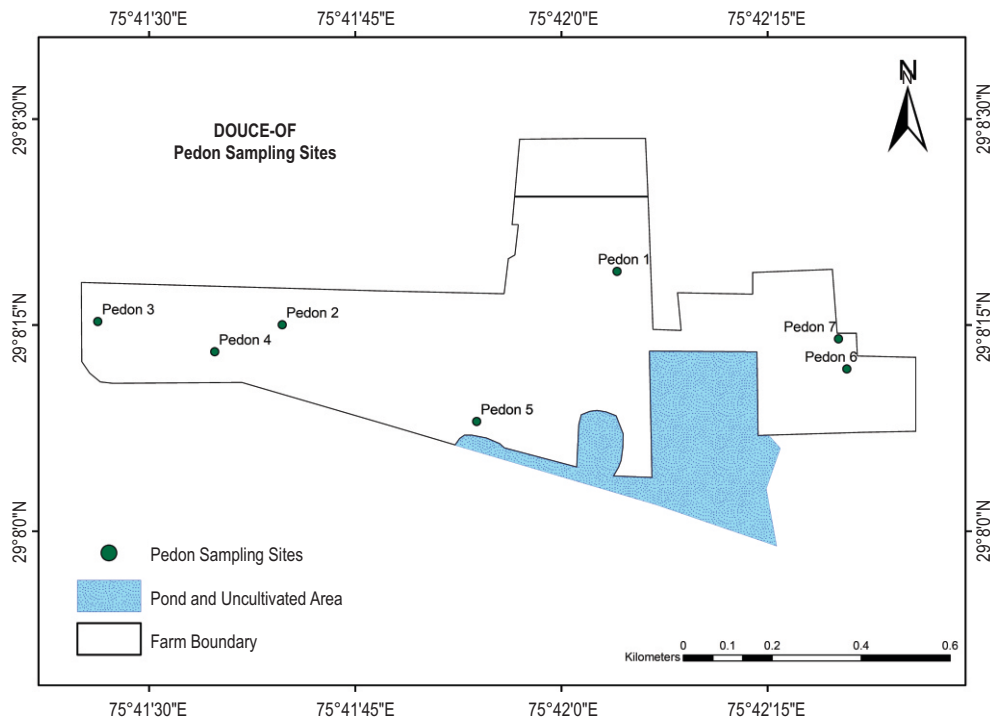


Fig.1: Map of study area.

utilized for their characterization. The mechanical analysis of soil was conducted using the international pipette method (Piper, 1950). Bulk density (Mg m^{-3}) was determined by the core method (Blake, 1965). The pH (1:2) and electrical conductivity (dS m^{-1}) were measured using a 1:2 soil-water suspension (Jackson, 1973). Soil organic carbon (%) was estimated through the wet digestion method (Walkley and Black, 1934). Available nitrogen (kg ha^{-1}) was determined using the alkaline permanganate method (Subbiah and Asija, 1956), while available phosphorus (kg ha^{-1}) was analyzed using the 0.5M NaHCO_3 method (Olsen et al., 1954). Available potassium (kg ha^{-1}) and cation exchange capacity ($\text{cmol (p}^+) \text{ kg}^{-1}$) were both assessed using the neutral normal NH_4OAc method (Jackson, 1973). Calcium carbonate (%) was estimated by the rapid titration method (Puri, 1949). DTPA extractable Fe, Mn, Cu and Zn (mg kg^{-1}) were determined using the DTPA extraction method (Lindsay and Norvell, 1978). Exchangeable Ca^{2+} and Mg^{2+} ($\text{cmol (p}^+) \text{ kg}^{-1}$) were measured by Versenate titration method (Cheng and Bray, 1951), while exchangeable Na^+ and K^+ ($\text{cmol (p}^+) \text{ kg}^{-1}$) were analyzed using flame photometer method (Jackson, 1967). Weighted means were employed to account for potential heterogeneity within geomorphic units, resulting in a more statistically robust average that accurately reflects the underlying data distribution for each unit using below formula:

$$\text{Weighted mean (Wm)} = \frac{\text{Concentration of each horizon} \times \text{Depth of each horizon}}{\text{Total profile depth}}$$

This investigation employed FAO Framework for Land Evaluation (FAO, 1993) to evaluate land capability, irrigability and soil suitability classification for different agricultural, vegetable, horticulture crops and forest plantation. Land capability classification designates eight soil classes, with Class I indicating the fewest limitations for crop production and greatest adaptability to management practices. Conversely, Class VIII soils have most severe limitations and least management potential. Subclasses further categorize limitations including erosion risk (e), wetness or floods (w), root zone limitation owing to acidity, density or shallowness (s) and climatic limitation (c). Soil suitability evaluation employs a hierarchical classification system to assess land potential for specific uses. Land suitability orders (suitable/not suitable) denote broad categories of utilization, while classes (highly, moderately and marginally suitable) and subclasses (e.g., drainage limitations, fertility limitations) provide progressively more refined information regarding constraints and management considerations. Land suitability is categorized into four classes: S1 (highly suitable) referred to land that had no significant limitations for agricultural productivity, S2 (moderately suitable) included land that had some limitations, which were severe enough to impact sustained productivity. S3 (marginally suitable) represented land that had major limitations affecting long-term agricultural productivity. Finally, N (unsuitable) classified land that had extreme limitations, making it unsuitable for sustained agricultural use (Olaniyi et al., 2015). Irrigability classification employs a systematic grouping of soils based on inherent limitations impacting their long-term response to

irrigation practices. Soil drainage (d), topography (t) and soil limitations (s) were employed as subclass criteria.

Statistical analysis: Principal component analysis (PCA) was performed on a correlation matrix of soil properties data using Origin Pro version 2024. Varimax rotation, an orthogonal rotation method, was employed to maximize variance explained by each principal component (PC). This facilitated the interpretation of PCA results by ensuring high factor loadings on each component. The use of a correlation matrix ensured that the PCA analysis was conducted on normalized data.

Results and Discussion

The characterization of a study area encompassing its location, topography, physiography, climate, geology, drainage patterns and current land use, is of paramount importance in any pedological investigation. This comprehensive data serves a dual purpose: firstly, for the proper classification of soil types within the study area and secondly for the interpretation of the pedogenic data collected. This integrated approach allows researchers to elucidate the relationships between soil formation and various environmental factors that influence it. Table 1 represents the general characteristics of all the studied pedons. All the pedons were nearly levelled alluvial plains and well drained with no

erosion in P1, P2, P6 and P7 whereas P3, P4 and P5 were moderately to imperfectly drained with slight to moderate erosion.

The data regarding physical characteristics of pedons P1-P7 are presented in Table 2. Detailed analysis of all the pedons revealed that sand content varied from 47.15 to 79.70% having lowest wm (49.30%) in P7 and highest (75.78%) in P1. The silt content varied from 9.10 to 36.13% having lowest wm (12.26%) in P1 and highest (34.46%) in P6. The clay content varied from 9.18 to 18.13% having lowest wm (11.91%) in P4 and highest (17.78%) in P7. The dominant soil fraction, typically composed of sand-sized mineral particles, reflected both the parent material's siliceous nature and the prominence of physical weathering processes during soil formation (Sahoo et al., 2019).

Notably, the observed increase in clay content with increasing soil depth can be attributed primarily to illuviation which involved translocation of clay particles downward through soil profile, followed by their accumulation in lower horizons (Kumar et al., 2022; Pradeep et al., 2021; Wakwoya et al., 2023). Bulk density varied from 1.36 to 1.44 Mg m⁻³ having lowest Wm (1.37 Mg m⁻³) in P7 and highest (1.41 Mg m⁻³) in P2 and P4. The observed increase in bulk density with depth can be attributed to progressive compaction due to infilling of soil pores with eluviated materials from upper horizons, reduced soil aggregation and

Table 1: General soil-site characteristics

Characters	P1	P2	P3	P4	P5	P6	P7
Physiography	Alluvial plain	Alluvial plain	Alluvial plain	Alluvial plain	Alluvial plain	Alluvial plain	Alluvial plain
Drainage	Well	Well	Moderately	Imperfectly	Imperfectly	Well	Well
Erosion	Nil	Nil	Slight	Moderate	Moderate	Nil	Nil
Parent material	Alluvium	Alluvium	Alluvium	Alluvium	Alluvium	Alluvium	Alluvium
Slope (%)	0-1	0-1	2-3	2-3	2-3	0-1	0-1
Slope direction	E-W	E-W	E-W	E-W	E-W	E-W	E-W

Erosion (No erosion-e0, Slight-e1, Moderate-e2, Severe-e3, V. severe-e4); Slope Direction (E-east, W-west, N-north, S-south)

Table 2: Range and weighted mean (Wm) of physical properties

Pedons	Statistical parameter	Sand (%)	Silt (%)	Clay (%)	Bulk density (Mg m ⁻³)
P1	Range	63.09-79.70	9.10-19.75	9.18-17.16	1.36-1.44
	Wm	75.78	12.26	11.97	1.39
P2	Range	64.45-71.21	11.98-19.03	16.52-16.81	1.38-1.43
	Wm	68.42	14.93	16.65	1.41
P3	Range	67.68-68.41	15.95-16.98	15.34-15.91	1.36-1.41
	Wm	68.12	16.27	15.61	1.38
P4	Range	61.27-73.68	15.45-22.72	10.87-16.01	1.39-1.42
	Wm	70.65	17.44	11.91	1.41
P5	Range	50.92-66.77	17.28-30.95	15.38-18.13	1.38-1.42
	Wm	60.17	23.48	16.35	1.40
P6	Range	49.70-53.64	30.05-36.13	13.03-16.31	1.37-1.39
	Wm	51.26	34.46	14.28	1.38
P7	Range	47.15-53.32	29.16-34.87	17.52-17.98	1.36-1.38
	Wm	49.30	32.92	17.78	1.37

Table 3: Range and weighted mean (Wm) of chemical properties

Pedons	Statistical parameter	pH	EC (dS m ⁻¹)	CaCO ₃ (%)	[cmol (p ⁺) kg ⁻¹]						
					Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	CEC	ESP (%)	BSP (%)
P1	Range	8.18-8.54	0.20-0.50	3.34-6.65	4.07-4.98	1.61-2.26	1.21-1.36	0.08-0.19	7.71-9.04	13.38-17.50	92.83-94.54
	Wm	8.41	0.30	4.47	4.40	1.94	1.31	0.14	8.32	15.80	93.51
P2	Range	8.12-9.08	0.20-0.40	0.73-6.70	4.70-6.67	1.52-2.63	1.53-1.83	0.07-0.40	8.44-11.69	15.66-18.12	93.28-98.66
	Wm	8.63	0.31	2.65	5.64	1.81	1.68	0.21	9.73	17.32	95.73
P3	Range	7.90-8.08	0.50-1.30	0.71-3.19	4.27-5.86	1.42-2.74	1.36-1.48	0.10-0.14	7.81-10.47	12.99-18.95	93.10-96.47
	Wm	7.98	0.80	1.85	4.94	2.02	1.41	0.12	8.97	16.04	94.46
P4	Range	9.30-10.23	0.50-1.90	1.81-3.17	3.91-4.35	1.03-1.83	1.07-1.21	0.17-0.36	6.93-8.15	13.13-17.46	91.20-93.40
	Wm	9.88	1.01	2.65	4.09	1.40	1.16	0.21	7.46	15.59	91.90
P5	Range	8.70-9.26	0.70-1.40	0.52-11.49	3.70-5.67	1.06-2.05	1.19-1.43	0.12-0.37	7.64-9.71	12.25-18.45	92.89-95.54
	Wm	8.98	0.98	5.11	4.76	1.58	1.33	0.21	8.39	16.07	93.83
P6	Range	8.24-10.37	0.20-1.10	2.99-8.43	4.10-5.78	1.27-2.75	1.11-1.44	0.10-0.24	7.40-9.78	11.35-19.46	93.19-96.50
	Wm	8.85	0.65	5.78	4.84	1.88	1.29	0.16	8.64	15.27	94.47
P7	Range	7.49-8.34	0.30-0.50	0.43-3.32	5.71-7.78	1.36-4.48	2.04-2.21	0.27-0.48	11.67-15.85	12.87-18.94	93.24-96.83
	Wm	7.96	0.39	1.59	6.90	2.88	2.14	0.38	12.86	16.92	95.74

EC – Electrical conductivity; CaCO₃ – Calcium carbonate; CEC – Cation exchange capacity; ESP – Exchangeable sodium percentage; BSP – Base saturation percentage

decrease in organic matter content with depth (Dinesh *et al.*, 2017; Mustafa *et al.*, 2016; Sahoo *et al.*, 2021). Various chemical properties of all the pedons are shown in Table 3. Soils were neutral to alkaline (7.49 to 10.37). The lowest Wm (7.96) was observed in P7 and the highest (9.88) in P4. The elevated soil pH can be due to higher degree of base saturation and ESP values (Sahoo *et al.*, 2021). Subsurface horizons displayed a higher pH compared to surface horizons. This trend likely results from the greater incorporation of organic matter in surface layers, which can have a buffering effect and contribute to a lower pH. The investigated pedons exhibited low EC values ranging from 0.2 to 1.9 dS m⁻¹, indicative of a non-saline soil profile. However, a trend of increasing EC with depth was observed. This phenomenon could be attributed to mobilization of dissolved salts from the surface horizons via downward movement of drainage water, with subsequent accumulation in the lower depths of soil profile (Sashikala *et al.*, 2019). CaCO₃ ranged from 0.43 to 11.49% with lowest Wm (1.59%) in P7 and highest (5.78%) in P6 and showed increasing trend with increasing depth. Under semiarid climatic conditions, pedogenic processes can facilitate the *in-situ* formation of calcium carbonate via calcification (Sahoo *et al.*, 2019). Reddy and Naidu (2016) also observed an increase in CaCO₃ content with depth, potentially attributable to combined effects of clay-bound CaCO₃ illuviation and subsequent precipitation triggered by elevated soil pH. CEC varied from 6.93 to 15.85 cmol (p⁺) kg⁻¹.

The observed low CEC of these soils is likely attributable to the combined effects of a sand-dominated particle size distribution, paucity of soil organic carbon and limited clay content (Chandrakala *et al.*, 2021; Nungula *et al.*, 2024). Calcium (Ca²⁺) [3.70 to 7.78 cmol (p⁺) kg⁻¹] dominated the exchange complex followed by magnesium [1.03 to 4.48 cmol (p⁺) kg⁻¹], sodium [1.07 to 2.21 cmol (p⁺) kg⁻¹] and potassium [0.07 to 0.48 cmol (p⁺) kg⁻¹] ions. Exchangeable sodium percentage (ESP) ranged from 11.35 to 19.46%. Cation exchange sites were predominantly occupied by basic cations, as evidenced by base saturation percentages (BSP) ranging from 91.20 to 98.66%. This high BSP likely stems from the prevalence of exchangeable cations, with Ca²⁺ playing a significant role. The elevated base saturation observed in surface layers can potentially be attributed to intensified biogeochemical cycling of essential cations facilitated by plant growth (Ghode *et al.*, 2023).

Table 4 presents data related to soil fertility characteristics of the investigated pedons. The SOC content was low to medium and ranged from 0.05 to 0.55% with lowest wm (0.12%) in P3 and highest (0.27%) in P2. The observed depletion of SOC with increasing depth within these pedons is likely attributable to the enhanced decomposition rates of organic matter under hyperthermic soil temperature regimes which fosters highly oxidizing conditions that promote the microbial breakdown of organic substrates (Kumari *et al.*, 2024; Satish *et al.*, 2018). The status of available N was low and ranged from

Table 4: Range and weighted mean (Wm) of fertility parameters

Pedons	Statistical parameter	Soil organic carbon (%)	N	P	K	Zn	Mn	Fe	Cu
				(kg ha ⁻¹)			(mg kg ⁻¹)		
P1	Range	0.07-0.55	70.56-148.18	4.98-10.95	92.96-182.56	0.11-1.28	4.21-8.60	6.52-20.72	0.72-1.40
	Wm	0.22	102.95	7.97	129.23	0.43	6.99	9.95	0.89
P2	Range	0.17-0.51	68.21-141.12	5.97-11.45	63.84-380.80	0.04-1.64	4.56-12.73	3.59-23.14	0.61-1.59
	Wm	0.27	97.45	7.93	201.44	0.47	8.20	10.26	0.96
P3	Range	0.05-0.31	68.21-105.84	5.97-8.96	103.04-124.32	0.03-0.39	4.96-8.51	5.09-8.21	0.48-0.87
	Wm	0.12	89.58	6.88	117.12	0.13	7.31	6.08	0.60
P4	Range	0.11-0.39	56.45-127.01	8.46-11.08	164.64-339.36	0.05-2.34	4.06-9.77	6.99-21.30	0.68-1.27
	Wm	0.18	83.29	9.58	218.00	0.52	7.33	10.61	0.86
P5	Range	0.14-0.43	54.10-148.18	10.45-15.93	98.56-332.64	0.04-1.62	4.44-10.37	6.02-22.60	0.57-1.24
	Wm	0.21	90.73	13.43	201.07	0.41	7.05	9.81	0.75
P6	Range	0.14-0.42	32.93-136.42	5.48-15.43	92.96-208.32	0.02-1.19	8.34-11.93	4.09-11.39	0.48-0.86
	Wm	0.22	75.69	8.57	138.46	0.38	9.73	6.56	0.66
P7	Range	0.18-0.44	28.22-133.84	8.46-13.98	220.64-459.20	0.13-5.08	8.59-11.47	8.94-21.88	0.68-1.16
	Wm	0.26	59.10	11.36	342.90	1.27	10.43	12.83	0.87

Table 5: Land capability classification

Pedons	Land form/ Topography		Wetness	Physical characteristics			Chemical characteristics				LCC
	Slope	Erosion	Drainage	Depth	PD	Texture	EC	SOC	CEC	BSP	
P1	I	I	I	II	V	III	I	III	IV	II	I
P2	I	I	I	II	V	III	I	III	IV	II	I
P3	II	II	II	II	V	III	I	IV	IV	II	IIIs
P4	II	III	III	II	V	III	I	IV	IV	II	IIIes
P5	II	III	III	II	V	III	I	IV	IV	II	IIIes
P6	I	I	I	II	V	III	I	IV	IV	II	I
P7	I	I	I	II	V	III	I	IV	III	II	I

PD – Profile development; LCC – Land capability classification

28.22 to 148.18 kg ha⁻¹ with lowest Wm (59.10 kg ha⁻¹) in P7 and highest (102.95 kg ha⁻¹) in P1. Surface layers exhibited the highest concentration of nitrogen followed by a downward decrease throughout the soil profile. This trend likely corresponds to the diminishing content of soil organic carbon with depth, coupled with potentially high soil temperature (Dash *et al.*, 2019; Dinesh *et al.*, 2020). Status of available P was low to medium and ranged from 4.98 to 15.93 kg ha⁻¹ with lowest wm (6.88 kg ha⁻¹) in P3 and highest (13.43 kg ha⁻¹) in P5. A progressive decrease in phosphorus was observed down the soil profile which could be due to increasing clay content with depth. Clay minerals possess a high capacity for phosphorus fixation, thus limiting its bioavailability in deeper horizons (Leelavathy *et al.*, 2021).

Organic anions effectively displace phosphate ions from soil adsorption sites, thereby enhancing the release of organically bound P and its subsequent mineralization to plant-available inorganic P (Dinssa and Elias, 2021; Havlin *et al.*, 2016). Whereas, available K status was low to high and ranged from

63.84 to 459.20 kg ha⁻¹ with lowest wm (117.12 kg ha⁻¹) in P3 and highest (342.90 kg ha⁻¹) in P7 and decreased with increasing depth of soil profile which may be due to release of readily bioavailable K from organic residues concentrated in surface horizons and upward movement of K from deeper layers via capillary rise of groundwater (Sahoo *et al.*, 2020). Corroborating this, Reza *et al.* (2014) reported that the existence of K-bearing minerals (illite, mica, and feldspar) within silt and clay fractions enhances soil K availability.

The DTPA-extractable Fe, Mn, Zn and Cu content varied from 3.59 to 23.14 mg kg⁻¹, 4.06 to 12.73 mg kg⁻¹, 0.02 to 5.08 mg kg⁻¹ and 0.48 to 1.59 mg kg⁻¹, respectively. The soils were deficient to sufficient in Zn and Fe whereas all were sufficient in Mn and Cu. All pedons exhibited a significant decrease in micronutrient concentration with increasing depth. Organic matter amendments enhance microbial activity resulting in the production of complexing ligands. These ligands strongly bind Cu, Fe and Mn reducing their mobility and promoting their long-

Table 6: Soil suitability classification for irrigation

Pedon	Land form characteristics			Physical characteristics	Chemical characteristics			Suitability sub-class
	Slope	Drainage	Depth	Texture	EC	ESP	Free CaCO ₃	
P1	S1	S1	S1	S3	S1	S2	S1	S1
P2	S1	S1	S1	S3	S1	S3	S1	S1
P3	S1	S1	S1	S3	S1	S2	S1	S1
P4	S1	S2	S1	S3	S1	S2	S1	S1d
P5	S1	S2	S1	S3	S1	S2	S1	S1d
P6	S1	S1	S1	S3	S1	S2	S1	S1
P7	S1	S1	S1	S3	S1	S2	S1	S1

Table 7: Soil suitability classification for crops

Pedon	Soil suitability class							
	Wheat	Maize	Sugarcane	Paddy	Oilseed	Vegetable	Forestry	Horticulture
P1	S1	S2	S1	S1	S1	S1	S1	S1
P2	S1/S2	S1	S1	S1	S1/S2	S1	S1	S1
P3	S1	S2	S1/S2	S1	S1	S2	S1/S2	S2
P4	S1	S2/S3	S1/S2	S1	S3	S3	S1	S1
P5	S1	S2/S3	S2	S1	S2/S3	S3	S1/S2	S1
P6	S1	S1	S1	S1	S3	S1	S1	S1
P7	S1	S1	S1	S1	S1	S1	S1	S1

term plant availability due to high affinity of these metals for organic matter (Jiao *et al.*, 2021; Saroha *et al.*, 2024). While Zn forms labile organo-mineral complexes, its availability also increases with SOC content. The elevated concentrations of Fe and Mn in soils can likely be attributed to the presence of ferromagnesian minerals within the parent material (Behera *et al.*, 2011; Jain *et al.*, 2023; Neha *et al.*, 2020; Saharan *et al.*, 2023).

Land evaluation constitutes a multifaceted scientific endeavour aimed at assessing and classifying land suitability for designated use types. Qualitative land assessments within this framework focus on sustainable land use and preservation. These procedures encompass land capability and soil suitability classification systems specifically designed for irrigation and crop production. Land capability classification as depicted in Table 5 revealed that soils in pedons P1, P2, P6 and P7 were categorized as LCC class I. In contrast, pedon P3 was assigned to LCC class II due to limitations of low fertility. Pedons P4 and P5 were classified under LCC class III due to a combination of soil texture constraints, low fertility status and erosion. The results presented in Table 6 depicted that all investigated pedons exhibited a high suitability for surface irrigation (S1). However, pedons 4 and 5 were categorized as S1d, suggesting a slight limitation in drainage characteristics.

Table 7 presents soil suitability classification for various crops. For wheat crop, the soils were found highly suitable (S1)

except for pedon P2 which was found to be highly to moderately suitable (S1/S2) due to higher ESP. For maize crop, the soils of pedon P2, P6 and P7 were found suitable to be highly suitable (S1) while pedons P1 and P3 were found to be moderately suitable (S2), pedons P4 and P5 were moderately to marginally suitable (S2/S3). For sugarcane, the soils of pedon P1, P2, P6 and P7 were found to be highly suitable (S1), pedons P3 and P4 were highly to moderately suitable (S1/S2) and pedon P5 was found to be moderately suitable (S2) due to higher pH, EC and imperfect drainage. For paddy crop, all the pedons were highly suitable (S1). Regarding oilseeds, soils of pedon P1, P3 and P7 were found to be highly suitable (S1) while pedon P2 was found to be highly to moderately suitable (S1/S2) and pedon P5 moderately to marginally suitable (S2/S3).

Pedons P4 and P6 were marginally suitable (S3) due to drainage problems. For vegetable crops, pedons P1, P2, P6 and P7 were found to be highly suitable (S1) whereas pedon P3 was moderately suitable (S2) and pedons P4 and P5 were found to be marginally suitable (S3). For forestry, pedons P1, P2, P4, P6 and P7 were highly suitable (S1) whereas pedons P3 and P5 were highly to moderately suitable (S1/S2). For horticultural crops, all pedons were found to be highly suitable (S1), except pedon P3 which was found to be moderately suitable (S2). The performance of pedons P4 and P5 can be significantly improved by implementing improved drainage strategies and enriching soil organic matter content. Principal component analysis (PCA) is a

Table 8: Principal component analysis of different soil properties

Parameters	PC1	PC2	PC3	PC4
pH	-0.192	-0.126	0.411	0.146
EC	-0.191	0.043	0.349	0.130
SOC	0.255	-0.159	0.144	-0.081
N	0.181	-0.382	-0.067	-0.097
P	0.192	-0.151	0.254	0.102
K	0.258	-0.029	0.173	0.313
Zn	0.228	-0.126	0.162	0.020
Mn	0.259	0.033	0.066	-0.152
Fe	0.251	-0.200	0.187	0.107
Cu	0.234	-0.243	0.096	0.115
CaCO ₃	-0.198	0.150	0.245	-0.196
CEC	0.266	0.180	-0.138	0.077
Ca ²⁺	0.265	0.151	-0.147	0.130
Mg ²⁺	0.221	0.102	-0.140	-0.194
Na ⁺	0.141	0.380	-0.151	0.341
K ⁺	0.264	0.017	0.177	0.293
ESP	-0.171	0.301	-0.007	0.389
BSP	0.205	0.172	-0.225	-0.063
Sand	-0.126	-0.365	-0.359	0.227
Silt	0.095	0.344	0.393	-0.296
Clay	0.167	0.249	0.055	0.130
Bulk density	-0.214	-0.068	0.060	0.421
Eigen values	10.601	3.519	1.994	1.630
Variance (%)	48.19	16.00	9.06	7.41
Cumulative variance (%)	48.19	64.19	73.25	80.66

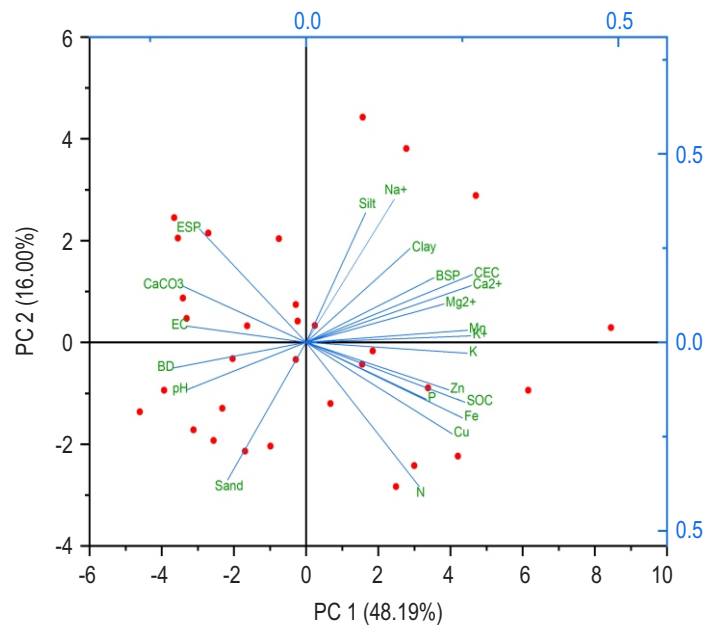


Fig. 2: PCABi-plot (PC1 Vs PC2) of different soil properties.

dimensionality reduction technique for datasets with multiple factors. It identifies latent variables (principal components) capturing the most significant sources of variance. Correlations among soil properties were statistically significant, prompting the

application of PCA to identify the most influential properties for immediate management strategies targeting soil quality improvement (Verma *et al.*, 2021). PCs with eigenvalues ≥ 1.0 were retained for further analysis. The first four PCs fulfilled this

criterion, accounting for a cumulative explained variance of 80.66% (Table 8). PC1 explained 48.19% of total variance in data and exhibited positive loading of SOC, Zn, Mn, Fe, Cu, CEC, Ca²⁺ and Mg²⁺. PC2 accounted for 16% of total explained variability and exhibited positive loading of Na⁺ and clay and negative loading of available N and sand. PC3 explained for 9.06% of total explained variability and exhibited positive loading of pH, EC, P, CaCO₃ and silt. PC4 accounted for 7.41% of total explained variability and exhibited positive loading of K, K⁺, Na⁺, ESP and BD.

Biplot visualization effectively portrays the contribution of principal components (PC1 and PC2) to total variance alongside the loadings of various soil properties (Fig. 2). This graphical representation allows for the identification of correlated soil properties, which can be subsequently grouped for optimized nutrient management strategies and expedited soil fertility restoration (Behera et al., 2018). The results of studied pedons indicated that soils were deep, nil to slight erosion, well to imperfectly drained, neutral to alkaline, non-saline and low to medium in SOC. Soils of pedons P1, P2, P6 and P7 were classified as LCC class I, pedon P3 as IIs and pedons P4 and P5 as IIIes. As per soil suitability criteria, soils were found to be highly suitable (S1) for wheat, oilseeds, paddy, vegetables, sugarcane, forestry and horticulture while for maize crop, soils were moderately suitable (S2). A comprehensive evaluation of land capability and suitability identified several key edaphic factors limiting soil productivity that were limited pedogenesis, poor drainage, low CEC, SOC and overall fertility. Agricultural management strategies promoting soil organic matter accrual, including cover cropping, compost applications and minimization of tillage, can be effectively utilized to augment SOC stocks, CEC, overall fertility and drainage conditions.

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