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Land capability and suitability assessment of arid and semi-arid soils in southern region of Haryana, India for improved land use planning

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ABSTRACT

Background: The practical application aspect of soil survey lies in land capability and suitability assessment. However, this remains challenging due to high spatial variability in soil properties, complex geomorphic settings, and multiple interacting edaphic constraints. Aim: The present study aimed to determine the constraints on crop production by evaluating the capability and suitability characteristics of semi-arid to arid soils of southern Haryana. Methodology: The study was conducted in the Charkhi Dadri district of Haryana during 2022-23, where five typical pedons, viz. Asawari (P1), Govindpura (P2), Bond Khurd (P3), Ranila (P4) and Loharwara (P5), representing major landforms, were excavated and examined for morphological and physico-chemical properties following standard procedures. Key-results: The studied pedons exhibited neutral to alkaline reactions (pH 7.31-8.87), non-saline to slightly saline top soil (EC 0.07-0.52 dS m^{-1}) and low to medium organic carbon content (0.07-0.57%). Available nitrogen, phosphorus and potassium were low (21.95-195.65 kg ha^{-1}), low to medium (4.00-15.42 kg ha^{-1}) and low to high (80.67-533.78 kg ha^{-1}), respectively. The distribution of exchangeable cations followed the sequence $Ca^{2+}>Mg^{2+}>Na^{+}>K^{+}$. Soils were deficient to marginal in Zn, deficient in Fe, marginal to sufficient Cu and sufficient in Mn. Interpretation: According to LCC and irrigation suitability, soils were classified as IIs, IIIe, IIIes and IVsw, and S2s, S2n, S3s and S3ds, respectively. The soils were marginally suitable (S3) for cotton and wheat, moderately (S2) to marginally suitable (S3) for pearl millet, gram and forestry, and generally suitable (S1) to moderately suitable (S2) for guar and oilseed (raya). Conclusion: Thus, this study contributes a pedon-based, integrated evaluation framework combining soil morphology, fertility, land capability, irrigation suitability, and multivariate analysis, providing site-specific recommendations for sustainable land use planning in arid to semi-arid agroecosystems.

Keywords: *Capability, fertility, landforms, morphological, pedon, semi-arid to arid, suitability.*

1. Introduction

Agriculture is the leading consumer of environmental land resources [3]. A substantial portion of the land has been permanently degraded and is no longer suitable for agriculture [31]. Soil degradation often occurs when there is an imbalance between land use and its inherent potential [44]. About 2.54% of the agricultural GDP of India was lost in 2014-15 because of land degradation and land-use change as per TERI's study on Economics of Desertification, Land Degradation and Drought in India [45]. As per the United Nations' estimation, land degradation hotspots cover about 30% of the total global land, and about 3.2 billion people live in degraded areas [23]. Approximately 12 million hectares of land are degraded annually on a global scale [47]. In arid and semi-arid climatic zones, land degradation accompanied by soil erosion, salinity and declining groundwater levels threatens agricultural productivity and ecosystem stability [1].

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Unsustainable land management practices, such as intensive monocropping, overgrazing and improper irrigation techniques, have further exacerbated land degradation, leading to reduced soil fertility and increased vulnerability to desertification [18]. The growing demand for agricultural expansion, urbanization and industrial development in this region necessitates a scientific approach to land capability classification and suitability assessment to ensure long-term sustainability.

The technique which enables the determination of the most appropriate use of any sort of land is termed land capability classification (LCC) [5]. The land capability is assessed by the soil type, which is vital for productivity, topography, fundamental geology, as well as hydrology [16]. It categorizes land into different classes based on its potential for agricultural, forestry, or conservation purposes over an extended period [2]. Land capability is organized into three levels: capability class, capability subclass and capability unit [48]. The capability class encompasses a group of subclasses and units that share similar hazards and limitations [15]. Similarly, land suitability assessment involves a more detailed evaluation of specific land attributes to ensure that they fulfil the requirements of existing or planned crop production [36].

The evaluation of land suitability is reliant upon land capability, in addition to various other criteria like land quality, accessibility, land ownership, customer interest and economic values [19]. The spatial variability in the inherent characteristics of the soils is often overlooked in scientific studies of land capability and suitability, despite the fact that this knowledge is essential for addressing land management challenges that are specific to particular sites or locations [4].

Almost 60% area of Haryana is under arid and semi-arid conditions [40]. In such tracts of north-western India, a common trend involves expanding cultivated areas to compensate for low yields and exploiting the soil fertility without proper replenishment. Alongside that, limited water availability, erratic rainfall, high evapotranspiration and fragile ecosystems pose a significant challenge to agricultural productivity. Hence, the objectives of our study are (i) to find out whether the area is appropriate for agriculture, forestry, pasture, or other purpose through the land capability classification, (ii) assess the applicability of ongoing irrigation techniques and (iii) suitability for major crops which are already grown and introduction of new crops in the Charkhi Dadri district of Haryana, India.

2. Materials and Methods

Description of the study area

The study was conducted in Charkhi Dadri district, located in the southern region of Haryana in 2022-23, covering 1370.11 sq. km (latitudes 28°23´39.125" N to 28°49´1.308" N and longitudes 75°49´22.944" E to 76°27´19.108" E; at an elevation of 237 m above mean sea level) (Figure 1). Broadly, the area comprises of sand dunes, inter-dunal depressions and undulating fluvio-aeolian plains with orthents, psamments and haplustepts as major soil types. The research area had a unimodal (south-west monsoon) rainfall pattern during late June to the end of August or early September with an average annual precipitation of 483 mm. Figure 2 represents the weekly weather report of the study area of 2022. The area was under tropical dry deciduous forests with main trees species of *Acacia nilotica*, *Dalbergia sissoo*, *Azadirachta indica*, *Ficus religiosa*, *Prosopis cineraria* etc. Bajra and cotton are among the major *kharif* crops of the area, with minor crops such as sugarcane, jowar, chilli, *kharif* pulses (moong) and kharif vegetables. In the *rabi* season, major crops include wheat, gram, and oilseeds, while minor ones consist of barley, *rabi* pulses, and vegetables.

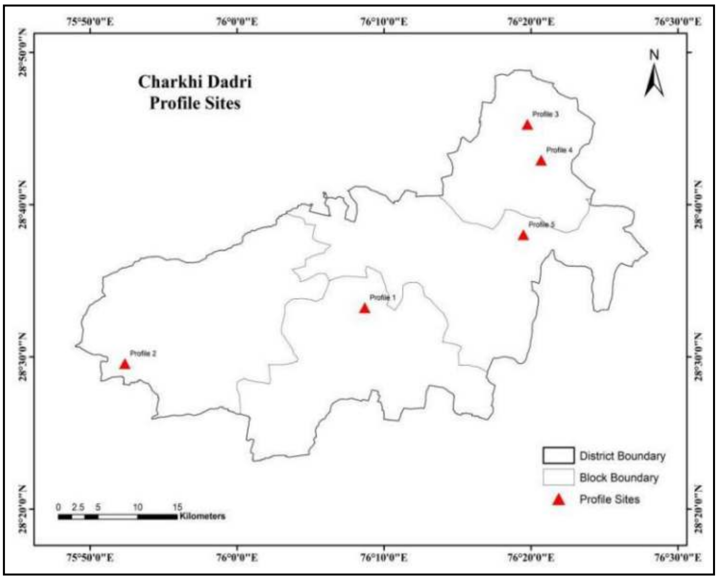

Figure 1: Location of the study area and profile site

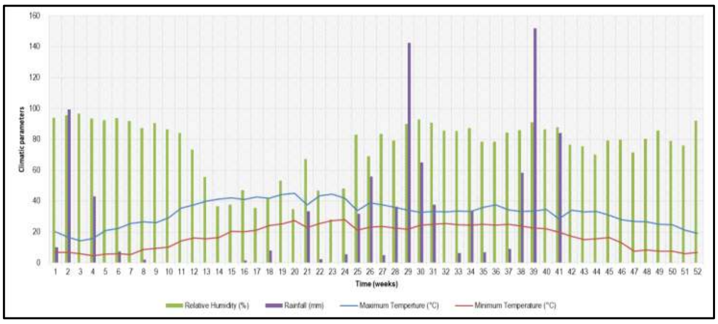

Figure 2: Weather data of the study are

Soil sampling and analysis

A detailed survey map of the area at a scale of 1:50,000, along with aerial photographs, was used as a base map for selecting sampling sites and excavating profiles. After traversing and visually observing the study area on the basis of variations in soil-site characteristics and geomorphic-soil relationship, five profiles were excavated and examined at the representative locations (Table 1). The soil profiles were studied *in situ* to assess morphological parameters as per the FAO Guidelines for Soil Description [13]. A total of 27 soil samples were collected from five pedons, representing different horizons, then shade-dried, ground, sieved and subjected to standard analytical procedures as presented in Table 1. For each geomorphic unit, the weighed means were calculated to compare the observations using the following formula:

$$\text{Weighted mean (Wm)} = \frac{\sum_{i=1}^{n} w_i X_i}{\sum_{i=1}^{n} w_i}$$

Where, n = number of horizons in a pedon

w_i = depth of each horizon

X_i = value or concentration of soil parameters in each horizon

The land capability classification (LCC), irrigation suitability classification, and assessment of suitability for crop cultivation were derived using the concepts and principles provided in the FAO Framework for Land Evaluation [13]. The LCC subclasses were determined by the limitations, including the risk of runoff and erosion (e), wetness (w), climate (c) and physical, chemical and fertility status of soils (s). Land irrigability classification involves the identification of soils for their suitability to irrigation by evaluating quantitative constraints related to soil [9].

The evaluation of land suitability for cultivating specific agricultural crops, vegetable crops and forest plantation was conducted considering the land qualities, i.e., texture, drainage, slope, profile development, salinity, erosion and soil fertility etc.

Table 1: List of soil parameters analyzed in the experiment

Soil parameter	Analytical method
Particle size distribution	International Pipette method [28]
Bulk density (BD)	Core method [10]
pH	Glass electrode method using pH meter in soil:water (1:2) suspension [20]
Electrical conductivity (EC)	Potentiometric method using conductivity meter in soil:water (1:2) suspension [20]
Calcium carbonate ($CaCO_3$) content	Rapid titration method [30]
Cation exchange capacity (CEC)	Ammonium acetate extraction [20]
Organic carbon (OC)	Wet digestion method [51]
Available nitrogen (AN)	Alkaline permanganate method [43],
Available phosphorus (AP)	Sodium bicarbonate extraction, colorimetric detection [27]
Available potassium (AK)	Ammonium acetate extraction, flame photometer detection [20]
Exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+})	Versanate titration method [11]
Available micronutrient cations (Zn, Fe, Cu and Mn)	DTPA extraction, atomic absorption spectrometer (AAS) detection [24]

Statistical analysis

With the help of OriginPro (version 2024, OriginLab Corporation, Northampton, MA, USA), principal component analysis (PCA) was done. PCA was carried out using varimax rotation and Kaiser Normalization, an orthogonal rotation method, to reduce the large dataset while maintaining high loadings on each PC, enabling the interpretation of PCA results. A correlation matrix of the specified soil characteristics was employed for PCA, leading to a normalized PCA analysis.

3. Results and Discussion

Profile-site characteristics

The profile-site characteristics like elevation, slope, erosion and drainage change with the micro-topographic situation of the soils, indicating the crucial role of landforms responsible for various sites, were studied [14]. The overall characteristics of all pedons selected for evaluation are provided in Table 2. Pedons P1 and P2 were very gently sloping, developed from well-drained sand dunes having severe to moderate erosion. Pedons P3, P4 and P5 were nearly levelled fluvio-aeolian plains with slight to moderate erosion. Wind erosion was predominant due to the prevailing dry climate, sand-dominated soil and sparse natural vegetation [41]. Although pedons P3 and P4 were moderately well drained, pedon P5 was imperfectly drained because of lower elevation and high ground water table.

Table 2: General profile-site characteristics

Profile-site characteristics	P1	P2	P3	P4	P5
Physiography	Sand dune stabilized	Sand dune stabilized	Nearly level plain	Nearly level plain	Nearly level plain
Drainage	Well	Well	Moderately well	Moderately well	Imperfect
Erosion	Severe (e3)	Moderate (e2)	Slight (e1)	Moderate (e2)	Slight (e1)
Parent material	Aeolian	Aeolian	Fluvio Aeolian	Fluvio Aeolian	Fluvio Aeolian
Slope (%)	1-3	1-3	0-1	0-1	0-1
Slope direction	W-E	W-E	N-S	N-S	W-E

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

Physical properties

The physical properties of the soils of all pedons are depicted in Table 3. While considering all pedons, sand content ranged from 52.60-97.05% with the highest Wm (93.36%) in P1 and lowest (55.46%) in P5. Silt content varied from 1.15-26.85% with the highest Wm (25.73%) in P3 and lowest (2.31%) in P1. The clay content ranged from 1.80-23.70% with highest Wm (20.41%) in P5 and the lowest (4.15%) in P1. Dominance of sand in mechanical fractions due to physical weathering of siliceous parent material was also identified by Sahoo *et al*. [35] and Singh *et al*. [37] in the arid to semi-arid tracts of Haryana. Subsurface horizons had higher clay content due to clay migration and *in-situ* weathering phenomenon [37]. The bulk density (BD) of pedons under study varied from 1.18-1.55 Mg $m^{-3,}$ with the highest Wm (1.49 Mg m^{-3}) in P2 and the lowest (1.24 Mg m^{-3}) in P5. There was an increasing trend in BD with depth. These findings may be attributed to subsequent compaction from the filling of alluvial material, decreasing organic matter (OM), and reduced aggregate formation [26, 46]. Msanya *et al*. [25] suggested that a bulk density below 1.5 Mg m^{-3} is crucial for achieving optimal crop yields through proper influx of air and water, along with optimum availability of nutrients for plant uptake.

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

Pedon	Statistical parameter	Sand (%)	Silt (%)	Clay (%)	Bulk Density (Mg m^{-3})
P1	Range	91.25-97.05	1.15-3.70	1.80-6.60	1.42-1.51
	Wm	93.36	2.31	4.15	1.46
P2	Range	80.40-88.20	7.10-10.00	4.40-10.35	1.43-1.55
	Wm	84.18	9.01	6.80	1.49
P3	Range	59.65-65.45	23.05-26.85	9.10-13.50	1.34-1.44
	Wm	62.42	25.73	11.70	1.40
P4	Range	54.05-64.20	23.15-26.30	11.20-21.30	1.28-1.47
	Wm	60.47	25.23	14.30	1.41
P5	Range	52.60-60.20	23.70-25.10	14.70-23.70	1.18-1.28
	Wm	55.46	24.39	20.41	1.24

Chemical properties

The chemical properties of the soils are displayed in Table 4. The soils exhibited a neutral to alkaline reaction (pH 7.31-8.87). The highest Wm of pH (8.25) was found in P2 and the lowest (7.79) in P3. The higher base saturation of these areas due to lower rainfall and lack of leaching of cations leads to the overall higher soil pH [12, 38]. Electrical conductivity (EC) values indicated that the soils were generally non-saline (except pedon P5). Migration of salts down the depth with irrigation water was observed due to the sandy texture of the soils [29]. Pedon P1 was devoid of $CaCO_3$ concretions. Pedon P5 had such concretions throughout the profile, whereas P2, P3 and P4 had such concretions in subsurface horizons. Such *in situ* build-up of $CaCO_3$ may be attributed to the calcification process occurring in these semiarid to arid climatic regions [34, 39]. Calcium (Ca^{2+}) was the dominant cation in the exchange complex in all pedons and varied from 2.05-6.85 cmol(p^+) kg^{-1}, followed by Mg^{2+} [0.40-4.50 cmol(p^+) kg^{-1}], Na^+ [0.22-2.02 cmol(p^+) kg^{-1}] and K^+ [0.11-0.89 cmol(p^+) kg^{-1}]. The CEC was low and ranged from 3.17-4.02 cmol(p^+) kg^{-1} in Pedon P1 and P2, pertaining to the light texture and low OC content, whereas pedons P3, P4 and P5 showed an increased CEC [9.95-13.35 cmol(p^+) kg^{-1}] due to comparatively higher clay and OC content. Similar relations were also reported by Karmakar [21]. Base saturation percentage (BSP) ranged from 91.48-98.43% indicating that basic cations dominated the exchange complex. Exchangeable sodium percentage (ESP) varied from 6.21-17.49, suggesting the non-sodic nature of soils (ESP<15) (except Pedon P4).

Table 4: Range and weighted mean (Wm) of chemical properties

Pedon	Statistical parameter	$pH_{(1:2)}$	$EC_{(1:2)}$ (dS m^{-1})	$CaCO_3$ (%)	CEC	Ca^{2+}	Mg^{2+}	Na^+	K^+	BSP	ESP
					[cmol(p^+) kg^{-1}]						
P1	Range	7.58-8.10	0.07-0.27	0.00-0.00	3.39-3.83	2.45-2.70	0.40-0.70	0.22-0.27	0.11-0.20	93.42-98.43	6.21-7.39
	Wm	7.90	0.13	0.00	3.60	2.59	0.49	0.25	0.14	96.44	7.03
P2	Range	7.82-8.87	0.16-0.26	0.00-9.63	3.17-4.02	2.05-2.45	0.45-1.00	0.25-0.36	0.11-0.25	95.02-97.85	7.89-8.96
	Wm	8.25	0.18	1.00	3.62	2.31	0.72	0.31	0.15	96.44	8.41
P3	Range	7.52-8.08	0.43-2.53	0.49-9.93	10.05-13.02	4.65-6.80	3.00-3.80	1.01-1.77	0.18-0.89	91.54-95.33	10.05-12.63
	Wm	7.79	1.60	7.37	12.21	6.19	3.43	1.43	0.38	93.57	11.67
P4	Range	7.44-8.47	0.23-2.12	0.00-10.21	9.95-13.35	5.60-6.85	2.05-3.90	1.00-2.02	0.29-0.57	92.67-94.46	10.05-17.49
	Wm	8.17	0.90	2.23	12.10	6.18	2.99	1.74	0.45	93.84	14.44
P5	Range	7.31-8.08	0.52-3.84	12.06-21.95	11.76-12.48	4.75-6.05	4.00-4.50	1.15-1.36	0.41-0.60	91.48-93.03	9.21-11.56
	Wm	7.82	1.33	18.57	12.20	5.09	4.36	1.27	0.52	92.17	10.45

Fertility status

The organic carbon (OC), macro- and micro-nutrient status of soils of the studied pedons are shown in Table 5. Soils had low to medium organic carbon (OC) content (0.07-0.57%) and OC had a decreasing trend with depth. The higher root biomass alongside application of organic sources during cultivation contributes to OC in the surface soils as compared to sub-surface soils [50]. Available nitrogen (AN) was low ranging from 21.95-195.65 kg ha^{-1}, with the highest Wm in P5 (88.56 kg ha^{-1}) and lowest in P1 (58.53 kg ha^{-1}). The low levels of AN in the studied pedons are due to insufficient fertilizer applications, which fail to replenish the nitrogen utilized by crop and the depletion of humified carbon as a result of leaching and cultivation [22]. Available phosphorus (AP) ranged between 4.00-15.42 kg ha^{-1}, indicating the low to medium status throughout the pedons. The decreasing trend of AP down the profile may be attributed to increasing clay content resulting in P fixation, decreasing OM content and low input P sources [6]. Available potassium (AK) ranged from low to high, between 80.67 and 533.78 kg ha^{-1}. The occurrence of minerals containing potassium like illite, mica and feldspars in silt and clay fractions may have contributed to such a result [32]. The DTPA extractable content of iron (Fe), zinc (Zn), manganese (Mn) and copper (Cu) of the soils ranged from 1.03-3.40, 0.19-0.66, 3.58-10.28 and 0.14-2.70 mg kg^{-1}, respectively. Based on the critical limits for DTPA-extractable micronutrients for plant growth [24], it can be concluded that the soils under study area were generally deficient to marginal in Zn, deficient in Fe, marginal to sufficient in Cu, and sufficient in Mn. The distribution of DTPA-extractable micronutrients showed no consistent pattern and varied throughout the soil profile. These findings are in agreement the results of Sahoo *et al.* [33].

Table 5: Range and weighted mean (Wm) of fertility parameters

Pedon	Statistical parameters	OC (%)	AN	AP	AK	Fe	Mn	Cu	Zn
			(kg ha^{-1})			(mg kg^{-1})			
P1	Range	0.09-0.26	23.52-106.24	6.00-20.00	89.74-125.53	1.44-2.04	3.58-4.52	0.14-0.22	0.19-0.34
	Wm	0.14	58.53	11.20	103.41	1.83	3.97	0.19	0.26
P2	Range	0.07-0.22	47.04-101.92	4.00-10.40	80.67-198.64	2.08-2.72	5.68-9.08	0.30-0.60	0.24-0.39
	Wm	0.11	66.21	6.33	110.98	2.42	6.69	0.47	0.33
P3	Range	0.25-0.53	28.22-181.54	4.08-15.42	131.08-533.78	1.56-1.98	4.90-8.40	0.28-0.44	0.18-0.31
	Wm	0.32	61.78	7.72	238.24	1.78	6.45	0.34	0.26
P4	Range	0.29-0.50	21.95-170.92	6.03-14.48	175.40-383.17	1.03-1.94	5.50-6.64	0.94-1.08	0.15-0.29
	Wm	0.37	73.30	8.71	310.81	1.20	6.34	1.02	0.20
P5	Range	0.36-0.57	48.61-195.65	9.34-13.55	147.22-323.68	2.49-3.40	9.48-10.28	1.80-2.70	0.49-0.66
	Wm	0.44	88.56	10.85	252.21	2.77	9.92	2.08	0.58

Land evaluation

Land evaluation is a fundamental concept in land management and spatial planning, providing a systematic framework to assess the potential uses and limitations of land for agriculture, forestry, urban development and conservation. It is a multi-disciplinary approach to conserve land resources that includes LCC and soil suitability classification for irrigation and selected crops.

Land capability classification

Pedons P1 and P2 were classified as LCC class IIIes due to sandy texture resulting in low fertility status, under developed profile and erosion (Table 6). The soils of pedon P3 were put under LCC class IIs due to presence of a calcic horizon in the profile, while LCC class IIIe was assigned to the soils of pedon P4 because of erosion hazards. The soils of pedon P5 were classified as LCC class IVsw due to combined limitation of poor drainage and less profile development [7].

Soil suitability classification for irrigation

This section aims to assess the suitability of an area for sustainable use under irrigation. Results depicted in Table 6 indicate that pedons P1 and P2 were marginally suitable (S3s) for surface irrigations due to sandy surface texture, whereas P3 was moderately suitable (S2s) with the limitation of calcic layer. Pedon P4 was also moderately suitable (S2n), having sodic layer and P5 was marginally suitable (S3ds) for surface irrigations bearing limitations of $CaCO_3$ content and impeded drainage condition. Srinivasan *et al*. [42] categorized the soils of Ganjam block, Odisha, into 2ds, 2d, 2s and 4ds land irrigability subclasses.

Table 6: Land capability classification and soil suitability classification for irrigation

Pedon	Landform/ Topography (t)			Wetness (w)	Physical characteristics (s)		Chemical characteristics and fertility status (f)				LCC	Irrigability classification
	Slope	Erosion	Depth	Drainage	Texture	PD	EC	OC	CEC	BS		
P1	II	III	I	I	V	III	I	IV	IV	II	IIIes	S3s
P2	II	III	I	I	V	III	I	IV	IV	II	IIIes	S3s
P3	I	II	I	II	III	IV	II	IV	III	II	IIs	S2s
P4	I	III	I	II	III	IV	I	IV	III	II	IIIe	S2n
P5	I	II	IV	IV	III	VII	II	IV	III	II	IVsw	S3ds

Note: PD = Profile development

Soil suitability classification for crops

Pedons P1 and P2 were found to be suitable for guar (cluster bean) and oilseed (raya), and marginally to moderately suitable for wheat, pearl millet, gram, cotton and forestry due to light texture and low soil fertility, which can be improved by the addition of organic matter (Table 7). The soils of pedon P3 were suitable for oilseed (raya) but marginally to moderately suitable for cotton, wheat, pearl millet, gram, guar and forestry. Due to higher sodicity, the soils of pedon P4 were put under a moderately to marginally suitable category for cotton, wheat, gram and forestry, although they were suitable for guar, pearl millet and oilseed (raya). The soils of pedon P5 were categorized under the marginally to moderately suitable group for wheat, pearl millet, oilseed (raya) and forestry but considered unsuitable for cotton, gram and forestry due to high $CaCO_3$ content, water stagnation and poor profile development. All soils were unsuitable for vegetable cultivation due to limitations in climate, physical soil characteristics and fertility status. The soils can be further upgraded to moderately suitable (S2) through appropriate interventions, i.e., application of organic matter and timely irrigation, but cannot be upgraded to the S1 category as the limitations lie in climatic requirements [17].

Table 7: Soil suitability classification for crops

Soil units	Soil Suitability Classes							
	Cotton	Wheat	Guar	Pearl Millet	Gram	Oilseed (Raya)	Vegetable	Forestry
P1	S3	S2	S1/S2	S2	S2/S3	S1/S2	N	S2/S3
P2	S3	S2	S1/S2	S2	S2/S3	S1/S2	N	S2/S3
P3	S2/S3	S1/S2	S2	S2	S2/S3	S1/S2	N	S2/S3
P4	S3	S2	S1/S2	S1/S2	S2/S3	S1/S2	N	S2/S3
P5	N	S3	S2	S2/S3	S3/N	S3	N	S3/N

Principal component analysis

Four principal components (PC1, PC2, PC3 and PC4) having eigenvalues greater than 1 were identified (Table 8). PCA reduced the initial dataset to these four components, accounting for 90.67% of the total variation. PC1 explained 53.26% of the total variability, characterized by positive loadings of silt, clay, OC and CEC, and a negative loading of BD, indicating it as the organic matter component due to the influence of OC on these properties. PC2 accounted for an additional 17.46% of the total variance and showed positive loadings of OC, AN, AP and AK. PC3, contributing 14.60% of the variance, was dominated by positive loadings of Fe, Mn, Cu, and Zn, and is considered the "soil micronutrient-supplying capacity" component. PC4 explained 5.35% of the variability, primarily dominated by the loading of pH. These findings align with those of Behera *et al*. [8] and Sahoo *et al*. [33], who reported three and six principal components, respectively, summarizing the variation in the soil properties in southern India and north-west India, respectively.

Table 8: Principal component analysis of soil parameters

Parameters	PC1	PC2	PC3	PC4
Sand	-0.284	0.084	0.053	-0.047
Silt	0.275	-0.039	-0.136	0.047
Clay	0.261	-0.141	0.094	0.052
BD	-0.216	-0.226	-0.183	0.199
pH	-0.052	-0.357	0.015	0.572
EC	0.220	-0.193	0.033	-0.368
$CaCO_3$	0.216	-0.150	0.275	-0.196
OC	0.243	0.271	-0.043	-0.001
AN	0.045	0.468	0.053	0.177
AP	-0.020	0.445	0.030	-0.197
AK	0.180	0.307	-0.177	0.310
CEC	0.276	-0.063	-0.141	-0.116
Ca^{2+}	0.249	-0.071	-0.231	-0.16
Mg^{2+}	0.282	-0.071	-0.01	-0.135
Na^{+}	0.255	-0.119	-0.219	-0.016
K^{+}	0.217	0.265	-0.075	0.208
BSP	-0.249	0.037	-0.006	-0.076
ESP	0.211	-0.161	-0.264	0.213
Fe	0.033	-0.058	0.507	0.072
Mn	0.198	0.058	0.264	0.346
Cu	0.211	0.087	0.281	0.099
Zn	0.128	-0.089	0.468	0.014
Eigenvalues	11.716	3.842	3.212	1.177
Variance (%)	53.26	17.46	14.60	5.35
Cumulative Variance (%)	53.26	70.72	85.32	90.67

A bi-plot chart (Figure 3) graphically visualizes the variability contributions of PC1 and PC2 along with the loadings for different soil properties. This bi-plot illustrates the grouping of soil properties that function similarly, which can be effectively utilized for prioritization and decision-making in precision nutrient management and efficient soil fertility restoration [49].

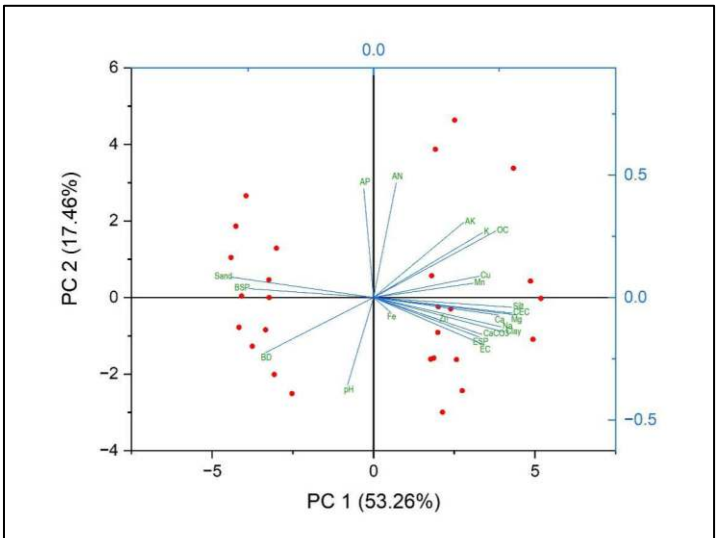

Figure 3: PCA bi-plot (PC1 vs. PC2) of soil properties in all profile

4. Conclusion

The studied pedons were deep (except pedon P5) with well to imperfect natural drainage and slightly alkaline and non-saline at the surface. The soils were dominated by the sand fraction with low organic matter and nitrogen content. Due to lack of rainfall, soils were highly base-saturated indicating their low weathering. The land capability assessment indicated that soils were arable but with major limitations of erosion, light texture, poor profile development and low organic matter content. The land suitability assessment for irrigation revealed that soils were moderately to marginally suitable for surface irrigation, primarily due to sandy surface texture facilitating fast drainage. Therefore, drip or sprinkler irrigation methods were recommended for farmers to save water. The suitability of the soil for different crops was determined by grouping the soil: mostly (S1) to moderately (S2) for oilseed (raya) and cluster bean (guar); moderately (S2) to marginally (S3) for gram, pearl-millet and forestry; and marginally (S3) for wheat and cotton. However, due to multiple edaphic constraints, the soil was found to be unsuitable (N) for vegetable cultivation. Poor profile development, erosion hazards, light texture, low OC, CEC and overall poor soil nutrient status are the primary limiting factors identified through soil and land suitability assessment. The combination of mineral fertilizer and organic manure will be beneficial for any productive farming venture in the area. In addition to conventional cropping, cultivation of groundnut, beans and soybean should be introduced to tackle nutrient leaching and erosion menace. Water conservation practices like watershed development along with improved agricultural practices are recommended in these arid to semi-arid tracts of India.

5. Future Scope

The present study provides a comprehensive pedon-level assessment of land capability, irrigability, and crop suitability in the arid to semi-arid region of southern Haryana. A key future scope lies in up-scaling the point-based soil information to landscape and regional scales using GIS, remote sensing, and digital soil mapping approaches. Integration of pedon data with terrain attributes and satellite-derived indices can improve spatial prediction of soil constraints and support block- or district-level land use planning. The study was based on single season sampling which may not capture the temporal variability of soils across the district. Therefore, multi-season observations can be adopted to improve the generalizability of the findings.

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Conflict of interest

The authors declare that there is no conflict of interest.

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Data availability statement

Data will be made available upon request from corresponding author.

Author contributions:

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Dinesh Tomar- Writing – original draft, Writing – review & editing, Conceptualization, Investigation, Resources

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Mohammad Amin Bhat- Writing – review & editing, Methodology, Software

Ankit Singh- Writing – original draft, Conceptualization, Data curation, Formal analysis

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