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Characterization and Classification of Soils of Jalna District of Marathwada Region by Using Remote Sensing and GIS Techniques

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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 present investigation entitled on "Characterization and Classification of Soils of Jalna District of Marathwada Region by Using Remote Sensing and GIS Technique" was carried out characterize and classify the soil based on their morphological, physical, and chemical properties. Satellite data (LISS-III) and DEM were interpreted for terrain features. Ten representative pedons from different landform units were collected and analyzed. The Morphological, physical and chemical properties

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of soils were varied in relation to topographic positions. The soils were very shallow to very deep (19 to 150 cm), Black (10YR 2/1) to Pale brown (10YR6/3) and Dark reddish brown (5YR3/2) to reddish brown (5YR4/4) in colour, medium weak sub angular blocky to medium strong angular blocky in structure, slightly hard to very hard in dry, friable to firm in moist and in wet condition slightly sticky slightly plastic to very sticky very plastic in consistency. The bulk density of study area varied from 1.19 to 1.84 Mg m^{-3}, the saturated hydraulic conductivity of the study area varied from 0.21 to 8.47 cm hr^{-1}, Particle size distribution of sand, silt and clay content of the study area varied from 0.61 to 52.10, 17.33 to 42.80 and 15.16 to 72.96 percent respectively, AWC ranged from 5.65 to 23.52 percent and plant available water capacity (PAWC) varied from 40.68 to 399.82 mm. The soils were slightly alkaline to strongly alkaline (7.44 to 8.74), very low to high (0.11 to 0.86) in organic carbon, slightly calcareous to strongly calcareous in $CaCO_3$ (3.50 to 22.50), CEC varied from 23.62 to 68.71 cmol (P^+) kg^{-1}. The exchangeable cations were in the order of Ca^{2+} > Mg^{2+} > Na^+ > K^+, whereas Base saturation varied from 82.11 to 105.08 %. The ESP varied from 2.81 to 12.44 percent. Taxonomically these soils were classified into Entisols, Inceptisols and Vertisols and at the subgroup level these soils were classified as Typic Ustorthents (P_5, P_7 and P_{10}), Typic Haplustepts (P_9), Calcic Haplustepts (P_1 and P_3), Typic Haplusterts (P_4 and P_6), Calcic Haplusterts (P_2 and P_8). This study highlights significant soil variability, providing essential data for effective soil and land use management.

Keywords: Pedology; physico-chemical properties; remote sensing; GIS; soil morphology; soil taxonomy; soil classification; soil profile; pedons; sustainable agriculture.

1. INTRODUCTION

"Soil is a vital natural resource, fundamental to sustainable development and agricultural productivity. Understanding its distribution across the landscape, along with its characteristics and properties, is crucial for its effective, optimal, and sustainable use. However, indiscriminate use of land resources often leads to degradation and a consequent decline in productivity. To ensure long-term benefits, land resources must be utilized according to their capacity to meet the needs of the population. Achieving this requires thorough investigation and scientific evaluation of these resources, enabling informed decision-making and sustainable land management practices". (Warhade et al. 2022; Ingle et al., 2019; Kuchanwar et al 2021). Understanding soil types and their properties is essential for optimizing crop production in semi-arid regions, where seasonal droughts are frequent. A systematic study of soils, guided by well-defined taxonomic units, forms the foundation for effective land appraisal, crop planning, and agricultural development in these challenging ecosystems. Consequently, soil characterization, classification, and evaluation for specific applications are crucial (Purandhar and Naidu, 2020). Comprehensive knowledge of a soil's morphological, physical, chemical, and biological attributes, along with its spatial distribution, is vital for formulating appropriate land use plans and facilitating the transfer of agrotechnology (Buol et al., 2011).

"Systematic study and characterization of soil resources in the basic need for developing the sustainable agricultural land use plan at farm level. Maintaining high productivity of soil on a sustainable basis is an important for meeting the basic needs of the farmers. The importance of soil survey and mapping for preparing an inventory of a region, the soil properties are used for the evaluation of soil for different crops. The value of soil resource inventory for increasing food production and conservation of natural resources has been receiving significant importance not only for the soil resource database generated but also its quality" (Eswaran and Gathrie, 1982; Ingle et al 2024). The resources particularly soil and land needs not only protection and reclamation but also a scientific basis for the management on a sustainable manner so that the changes proposed to meet the needs of development are brought without diminishing the potential for their future use.

"Remote sensing technology has demonstrated potential of identifying, characterizing, and classifying the problems and potentialities of the natural resources. Satellite remote sensing data has as emerged as a vital tool in soil resource survey and generation of information, which help to evolve the optimum land use plan for sustainable development at scale ranging from regional to micro level" (Sahu et al 2015). "Remote sensing technology together with GIS has spined off the new dimensions in storing and retrieving data and to arrive at optimum solution plan / action plan for sustainable development. In the interpretation of satellite image for soil mapping, proper identification of land type of drainage pattern and drainage condition, vegetation, land use, slope and relief are very essential. Several others have reported that the satellite remote sensing and GIS have proved as promising tool in soil resource mapping". (Shrivastava and Saxena 2004; Reddy et al. 2013; Borse et al 2018 and Vimal et al.,2024).

Due to the variations in physiography, the soils in the Jalna district of the Marathwada region are not universally suitable for the same crops or management practices. Therefore, it is essential to develop large-scale, soil-specific land use plans using GIS-based Decision Support Systems (DSS). Many farmers lack awareness of appropriate land use planning tailored to their available resources, including soil, water, and climate, which is crucial for their socioeconomic development. The GIS and RS-based DSS aids farmers by providing solutions to their challenges and guiding them in implementing suitable land use plans to enhance their socioeconomic progress. By simplifying the process for both farmers and researchers, this DSS bridges the gap between laboratory research and practical application, making the transfer of technology to the field more efficient. With these considerations, the present study, titled "Characterization and Classification of Soils of Jalna District of the Marathwada Region Using Remote Sensing and GIS Techniques," was undertaken.

2. MATERIALS AND METHODS

Jalna district is approximately at the centre of Maharashtra state and in the northern direction of Marathwada region. The Jalna district lies between 19^o 01' to 21o $^{03'}$ N Latitudes and 75^o 04' to 76^o 04' E Longitude. It covers an area of about 7,612 sq. Kms, which is 2.47% of the total state area. Geologically the district essentially belongs to Deccan traps (middle traps) as the district is a part of Deccan plateau sloping south-eastwards from the Sahyadris. The middle traps are supposed to fit in between these two broad divisions i.e. Alluvium recent of sub-recent and Deccan trap-Cretaceo Eocene. The district has a Sub-Tropical climate, in which the bulk of rainfall is received from the southwest monsoon, between June to September. The average annual rainfall of the district ranges between 650 to 750 mm. The district often experiences drought with rainfall recording as low as 400 to 450 mm. The district has moderately to gently sloping undulated topography ((Jalna district, NIC, GOI. May 01, 2024).

The broad landforms were extracted by using SOI topographical sheet and the SRTM DEM (30m resolution) was used to prepare a counter, slope, aspect, drainage and Hillshade map in the Arc-GIS environment. Survey of India (SOI) toposheet No. 43D/9, 43D/10, 43D/11, 43D/12, 43D/13, 43D/14, 43D/15, 43E/2, 43E/3, 43V/12, 43V/14, 43V/16, 43W/3, 43W/4 (1:50,000 scale) was used to collect topographic and location information. The toposheets were georeferenced and merged to prepare base map for different landforms, generation of slope and drainage for planning the traverse route for ground truth collection. The ten soil profiles were positioned in each of the identified landforms. Soil morphological characteristics were noted in the fields and horizon-wise samples were collected from each pedon as per the guideline given by Soil Survey Staff (1975). Samples were analyzed in the laboratory for their physical, chemical, and biological characteristics.

After collection, the soil samples were allowed to dry in shaded ground and sieved by using a 2 mm sieve and analyzed by standard procedures. The bulk density of the soil was determined by the clod coating method (Black 1965). Particle size distribution analysis of the sample was carried out by the international pipette method (Jackson 1973). Hydraulic conductivity was determined by the constant head method (Richards 1954). Water retention at 33 kPa and 1500 kPa pressure were determined by pressure plate apparatus and plant available water capacity (PAWC) was determined as outlined by Gardner et al. 1984. The pH and electrical conductivity (EC) were determined by standard procedure (Jackson 1979), while organic carbon (OC) was determined by Walkley and Black (1934) and cation exchange capacity (CEC) was determined by the procedure as outlined by Jackson (1973). The $CaCO_3$ was determined by the method outlined by Jackson (1973) and exchangeable cations were determined by the method of Richards (1954). The soil classificaton was carried out by Soil Survey Staff (2014).

3. RESULTS AND DISCUSSION

3.1 Landforms

A detailed landform analysis was carried out based on elevation contour, slope, and drainage channel network. Contour lines created at different heights were superimposed on the picture to create a landform map, which included eleven key landform units: (i) hilltop; (ii) higher plateau; (iii) lower plateau; and (iv) undulating upland and interpreted the slopes of the escarpment (v), the foot slopes (vi), the upper pediment (viii), the middle pediment (ix), the lower pediment (x), the pediplain (xi), and the valley and water body (xi) were delineated using SOI toposheet, SRTM (30m) data of digital elevation model and IRS-6 LISS III FCC. The DEM was further used to delineate four slope classes namely level (0-1%) nearly level plane (1-3% slope), undulating (3-8% slope) rolling (8-16%), hilly (16-30%), steep (30-60%) and very steep (>60 %). The soil profile samples were analyzed and classified on cultivated areas only.

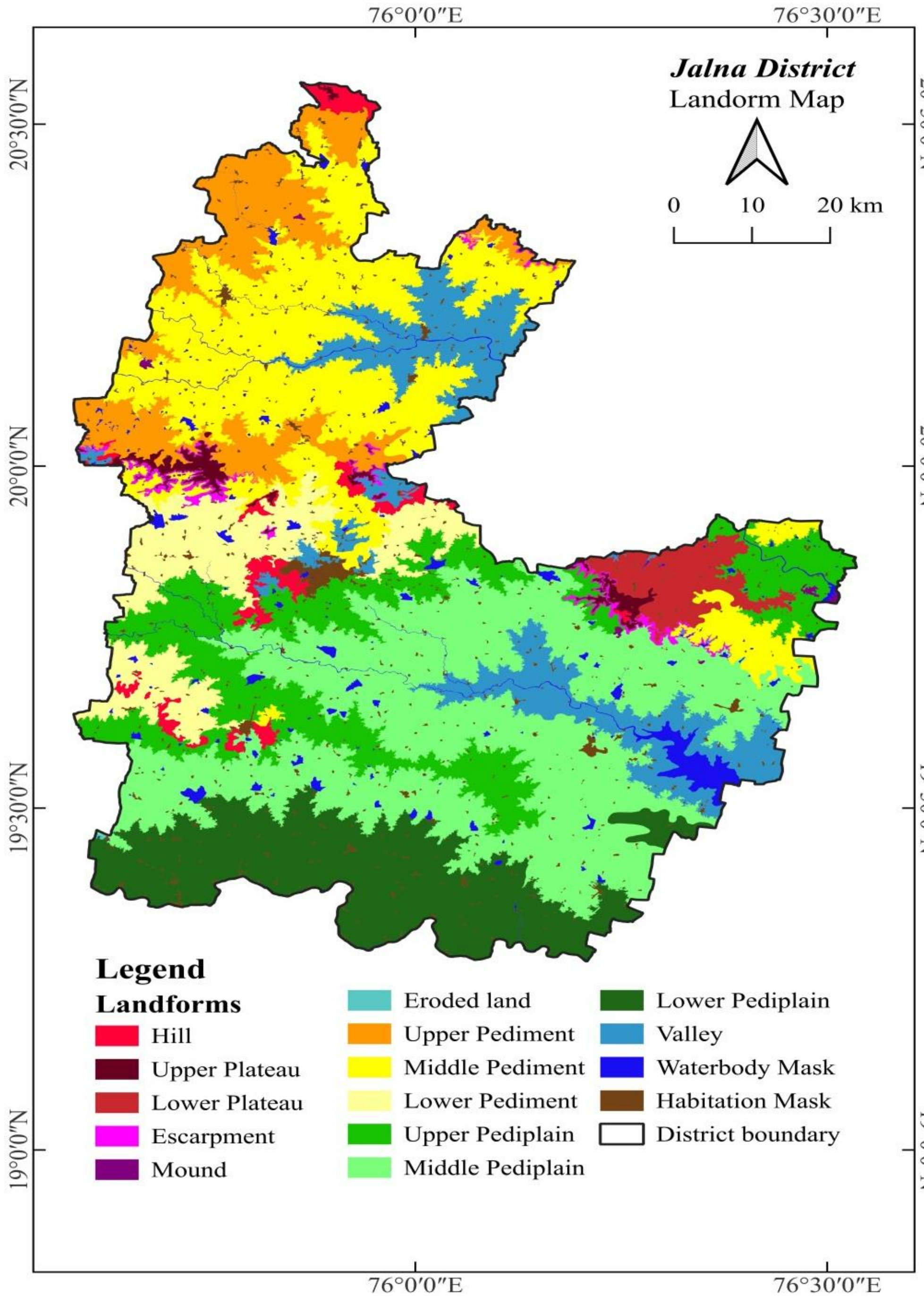

Fig. 1. Lanform map of Jalna district

Table 1. Soil site characteristics of Jalna district of Maharashtra

Location	Landform	Parent material	Slope	Runoff	Drainage	Erosion	Stoniness %
Pedon 1 Tithapuri Tq. Ghansavangi, Dist. Jalna 19^0 25' 57" N, 75^0 56' 53" E	Nearly level Plain	Weathered Basalt	0-1	Slow	Permeable	Very Slow	<3
Pedon 2 Bhutegaon Tq. Ghansavangi Dist. Jalna**.** 19^0 39' 47" N, 76^0 02' 16"" E	Nearly level Plain	Basaltic alluvium	1-3	Slow	Impermeable	Moderate	<3
Pedon 3 Shelgaon Tq. Partur, Dist. Jalna 19^0 28' 52.87" N, 76^0 19' 03.02"E	Moderately Sloping	Weathered Basalt	1-3	Medium	Well drained	Sever	<3
Pedon 4 Wadhona Tq. Partur, Dist. Jalna 19^0 37' 50.23" N, 76^0 16' 51.74" E	Level Plain	Basaltic alluvium	0-1	Very Slow	Impermeable	Very Slow	<3
Pedon 5 Wadi Seradone Tq. Ambad, Dist. Jalna. 19^0 39' 34" N, 75^0 44' 17" E	Moderately Sloping	Weathered Basalt	3-5	Medium	Well drained	Moderate	15-40
Pedon 6 Sawargaon tq. Jalna, Dist. Jalna 19^0 47' 55" N, 76^0 02' 56" E	Moderately Sloping	Basaltic alluvium	1-3	Slow	Impermeable	Moderate	<3
Pedon 7 Asola Tq. Badnapur, Dist. Jalna 19^0 56' 46" N, 75^0 50' 31" E	Undulating	Weathered Basalt	3-5	Medium	Well drained	Moderate	3-15
Pedon 8 Khamkheda Tq.Jafrabad,Dist. Jalna 20^0 10' 50" N, 76^0 01' 17" E	Moderately Sloping	Basaltic alluvium	1-3	Medium	Moderate	Slight	<3
Pedon 9 Malkapur, Tq.Bhokardan, Dist. Jalna 20^0 18' 30" N, 75^0 46' 49" E	Gently Sloping	Weathered Basalt	1-3	Slow	Moderate Well drained	Moderate	<3
Pedon 10 Asai, Tq.Jafrabad Dist. Jalna 20^0 15' 17" N, 75^0 53' 15" E	Undulating	Weathered Basalt	3-5	Rapid	Well drained	Severe	3-15

Table 2. Morphological characteristics of soils of Jalna district of Maharashtra

Horizon	Depth (cm)	Boundary		Matrix Colour	Texture	Structure			Consistency			Pores		Root		Efferve sces
		D	T			Size	Grade	Type	Dry	Moist	Wet	Size	Quantity	Size	Quantity	
Pedon 2 (Very fine, smectitic, isohyperthermic,Calcic Haplusterts)																
Ap	0-18	c	s	10YR4/2	c	m	2	sbk	h	fr	vsvp	vf,f	m,m	vf	m	e
Bw_1	18-32	c	s	10YR4/2	c	m	2	abk	h	fr	vsvp	vf,f	m,m	f	f	e
Bw_2	32-58	c	s	10YR3/1	c	m	3	abk	h	fi	vsvp	vf,f	m,m	f	m	e
Bss_1	58-85	c	s	10YR3/2	c	m	3	abk	vh	fi	vsvp	vf,f	m,m	f	f	e
Bss_2	85-120	c	s	10YR3/2	c	m	3	abk	vh	fi	vsvp	vf,f	m,m	f	f	e
Bss_3	120-150	c	s	10YR3/2	c	m	3	abk	vh	fi	vsvp	vf,f	m,m	f	f	e
Pedon 3 (Fine, smectitic, isohyperthermic Calcic Haplustepts)																
Ap	0-20	c	S	10YR3/2	c	m	2	sbk	sh	fr	vsvp	vf,f	m,m	f	m	e
Bw_1	20-40	d	w	10YR3/1	c	m	2	sbk	sh	fr	vsvp	vf,f	m,m	f	f	es
Bw_2	40-60	d	w	10YR3/1	c	m	2	abk	sh	fr	vsvp	vf,f	m,m	f	f	es
Cr	60+		-	10YR5/2	l	m	2	gr	l	fr	nsnp	c	f	-	-	ev
Pedon 4 (Fine, smectitic, isohyperthermic, Typic Haplusterts)																
Ap	0-20	c	s	10YR3/2	c	m	3	sbk	h	h	vsvp	vf,f	m,m	vf,c	m,f	e
Bw_1	20-39	c	s	10YR3/1	c	m	3	abk	h	fr	vsvp	vf,f	m,m	f	m	e
Bw_2	39-51	c	s	10YR2/2	c	m	3	abk	vh	fi	vsvp	vf,f	m,m	f	m	e
Bss_1	51-78	c	s	10YR2/1	c	m	3	abk	vh	fi	vsvp	vf,f	m,m	f	f	e
Bss_2	78-98	c	s	10YR2/2	c	m	3	abk	vh	fi	vsvp	vf,f	m,m	f	f	e
Bss_3	98-150	c	s	10YR4/2	c	m	3	abk	vh	fi	vsvp	f	m	f	f	e
Pedon 5 (Fine, smectitic, isohyperthermic Typic Ustorthents)																
Ap	0-22	c	s	5YR3/3	l	m	2	sbk	s	fr	sssp	vf,f	m,m	vf,	m	nil
Cr	22+	c	s	5YR3/4	Sl	c	2	gr	h	fr	nsnp	c	f	c	f	nil
Pedon 9 (Very fine, smectitic, isohyperthermic, Typic Haplustepts)																
Ap	0-21	c	s	10YR3/2	sic	m	2	sbk	sh	fr	sssp	vf,f	m,m	vf,c	mm	e
Bw_1	21-42	c	s	10YR3/2	sic	m	2	sbk	sh	fr	sssp	vf,f	m	vf,c	mf	es
Cr	42+	d	s	10YR6/3	l	c	2	gr	l	l	nsnp	c	m	f	f	es

3.2 Soil Morphological Characteristics

The soils on the higher topographic position were shallow and gradually became deeper down the slope, shallow to moderately shallow on the undulating lands. Further down the slope near the upland valley region, soil depth was found moderately deep. The depth was deep to very deep in the alluvial pediplain near the valley. The soil depth ranged from 19 to 64 cm on the hilly and undulating landscape of pedons P_5, P_7, and P_{10} (Typic Ustorthents), and from 42 to 60 cm on the upper pediment with nearly level plains in pedons P_9 (Typic Haplustepts) and P_1 and P_3 (Calcic Haplustepts). The soil depth ranged from 120 to 150 cm on leveled plains close to the valley pedons P_2 and P_8 (Calcic Haplusterts) and P_4 and P_6 (Typic Haplusterts). The soil colour of study area varies from Black (10YR 2/1) to Pale brown (10YR6/3) and Dark reddish brown (5YR3/2) to Reddsih brown (5YR4/4). Soils developed on topographically higher elevations were dark brown and those formed on lower elevations were very dark greyish brown in colour (Maji et al*.* 2005). The presence of titaniferous magnetite mineral and clay-humus complexes contribute to the black colour (Chandran and Singh 2012). The dark colour of soil may be due to the dominance of highly dispersible forms of humus and smectite minerals (Zoon 1986). Variation in soil colour appears to reflect chemical and mineralogical composition and also the textural makeup and it is majorly influenced by topographical positions and moisture regime of the area (Sekhar et al*.* 2014; Nasre et al*.* 2013; Patil et al*.* 2013 and Ingle et al., 2024).

The soil consistency in pedons of Typic Ustorthents (Entisols) (P_5 and P_7 and P_{10}) varied from, soft to slightly hard in dry, friable to very friable in moist and slightly sticky slightly plastic to non sticky non plastic in wet condition. Whereas, in Typic and Calcic Haplustepts (P_1, P_3 and P_9) soil consistency varied from slightly hard to very hard in dry, friable to firm in moist and slightly sticky slightly plastic to very sticky very plastic in wet condition. In Typic and Calcic Haplusterts (Vertisols) (P_4, P_6, P_2 and P_8) soil consistency varied from slightly hard to very hard in dry, friable to firm in moist and very sticky very plastic to slightly sticky very plastic in wet condition. Furthermore, result shows that the soil consistency in Vertisols and Inceptisols was found to be hard to very hard in dry conditions, firm to very firm in moist conditions, slightly sticky to very sticky and plastic to very plastic in wet conditions which might be due to high clay content of the soil (Vaidya and Pal, 2002; Geetha et al., 2017 and Patil, 2023).

The soil structure in Typic Ustorthents (Entisols) (P_5 and P_7 and P_{10}) varied from medium weak subangular blocky to fine or medium moderate subangular blocky whereas in lower layers of P7 coarse weak granular structure was observed. The medium moderate subangular blocky to medium strong angular blocky structure was observed in Typic (P_9) and Calcic (P_1 and P_3) Haplustepts. Whereas, in Typic (P_4 and P_6) and Calic Haplusterts (P_2 and P_8) had medium moderate subangular blocky to medium strong angular blocky structure. The surface and sub-surface horizons of pedons are associated with sub-angular blocky structure of varying grade and size but angular blocky structure associated with slickenside is a common feature of sub-soils in Vertisols (Dhale and Prasad 2009). The blocky structure *i.e.,* angular and subangular blocky structure was attributed to the presence of higher quantity of clay fraction (Sekhar et al*.,* 2014 and Sharma et al*.,* 2004). The single grained structure was due to inert nature of parent material. Shrinking and swelling of clay due to wetting and drying cycles resulted in formation of pedogenic slickensides, angular to sub angular peds and wedge-shaped structural aggregates (Vaidya, 2001; Patil et al*.,* 2013 and Ghode et al*.,* 2023).

3.3 Soil Physical characteristics

The bulk density of study area varied from 1.19 to 1.84 Mg m^{-3}. The variation in bulk density of these soils was due to high amount of expanding type of clay minerals (Sekhar et al*.*, 2014 and Zade et al., 2020). In comparison to the murum layer (C horizon), the bulk density of the surface (A horizon) and subsurface (B horizon) layers is lower. The increasing bulk density with depth was observed which might be due to compaction caused by the overburden of surface layers (Ingle et al. 2019; Kuchanwar et al 2021). The subsurface layer's bulk density was often found to be greater than that of the surface layer. The findings suggest that bulk density increased gradually with depth. This phenomenon may be attributed to various factors such as compaction from overburdening the surface layer (Thangasamy et al*.,* 2005).

The saturated hydraulic conductivity (sHC) of the study area varied from 0.21 to 8.47 cm hr^{-1}, The sHC in all the Pedons decreased with depth except in P_5, P_7 and P_{10} were observed increases with depth which may be due to textural differences of soils. The decreasing trend of sHC with depth in swell shrinks soils might be due to increasing clay content with depth as this fact is evident from the significant and negative correlation of sHC with soil depth (-0.664*) (Table 5). Similar results were also reported by Vaidya and Pal, 2002 and Kadu et al*.,* 2003. The higher value of sHC of surface horizons was found in some pedons which may be due to porous nature because of continuous tillage operations and organic carbon content (Kuchanwar, et al*.* 2017). The higher exchangeable Mg^{++} in soil profile causes dispersion of clay colloid and reduction in hydraulic conductivity this fact is evident from significant and negative correlation between hydraulic conductivity and exchangeable magnesium (r= - 0.687*) (Vaidya and Pal, 2002; Kadu and Kharche, 2017; Zade et al*.,* 2020; Warhade et al*.,* 2022; Kuchanwar et al.,2022).

The sand, silt and clay content of the study area varied from 0.61 to 52.10, 17.33 to 42.80 and 15.16 to 72.96 per cent respectively. Soils of P_1, P_2, P_3, P_4, P_6, P_8 and P_9 were clayey to silty clayey in texture. Whereas, P_5, P_7 and P_{10} were clay loam to sandy clay loam in texture. The texture of the soils on the lower slopes varied from silty clay to clay, the upper slopes (P5, P7, and P10) had sandy clay loams to loams (Sarkar et al., 2001). The amount of clay in all pedons (P_1, P_2, P_3, P_4, P_6, P_8, and P_9) were increased with depth, whereas in pedons (P_5, P_7, and P_{10}) pedons dropped with depth.

The increase in clay content with depth might be due to downward translocation of finer clay particles from surface layer to subsurface layer (Murthy, 1988). Enrichment of the clay in Bw horizonof pedons (P_1, P_2, P_3, P_8,) and Bss horizons of pedons (P_2, P_4, P_6, P_8) of study area was primarily due to in situ weathering of parent material (Sarkar et al*.,* 2002). The enrichment of the clay in the Bss horizon was likely due to the illuviation of clay from upper horizons (Pal et al*.* 2009). For a long time the apparent uniform distribution of clay throughout Vertisols was considered to be effect of haploidisation within the pedon caused by pedoturbation and in some cases the observed gradual increase in clay content with depth was thought to be d0ue to inheritance from parent material (Pal., D.K. 2018). Silt content shows irregular trend with depth might be due variation in weathering of parent material or in situ formation (Kumar and Naidu, 2012).

The soils with fine texture were found at the lowland topographic unit than the upland and midland units mainly due to lateral migration of finer fractions from upland and midlands difference in parent material, in situ weathering and the translocation of clay this fact is evident from significant and positive correlation (r=0.787**) (Table 5) between soil depth and clay content (Basvaraj et al*.* (2005). Topography and slope were found responsible for variation in the particle size distribution of the soils (Vaidya and Pal, 2002; Ghode, et al*.* 2023). Topographically variation in soil texture is likely to be the variation in the intensity of erosion of upland and deposition of carried material on the lowland plains. The finer particles were readily translocated from higher elevated areas towards lower elevated areas due to rapid movement runoff of rainwater while coarse particles remained which could be the main cause of texture variation with slope (Vaidya, 2001; Patil et al*.* 2013; Meena et al. 2014 and Ghode et al*.* 2023).

PAWC of the study area were highest in P_2, P_4, P_6, and P_8 followed by P_1, P_3, P_7 and P_9 and lowest in P_5 and P_{10}. The order of PAWC of soils of study area was P_2 and P_4 (373.54 to 399.82 mm) > P_6 (302.98 mm) > P_8 (269.33 mm) > P3 (104.26 mm) > P_7 (69.11 mm) > P1 and P_9 (64.76 to 66.69 mm) > P_7 and P_{10} (34.2 to 40.68). Moreover, the data revealed a highly significant and positive relation between PAWC with soil depth (0.981**) and clay content (0.789**) (Table 5) this indicated that the PAWC increased with an increase in depth and clay content.

3.4 Chemical Characteristics of Soils

Soil reaction (pH) varied from slightly to strongly alkaline (7.44 to 8.74) (Table 4). Increasing trend with depth was observed be due to of movement of soluble salts and increase in calcium carbonate content (Vaidya and Pal, 2002; Meena et al*.,* 2014; Patel et al., 2024). Higher pH in sub-surface soils is due to higher pedogenic $CaCO_3$ content, which forms $NaHCO_3$ and increases the pH (Vasu et al. 2022; Kuchanwar et al., 2022). Electrical conductivity varied from 0.11 to 0.47 dSm^{-1}. Low EC in the soils of study area might be due to proper management of soils and in that way leaching of salts takes place from upper surface horizon to sub surface horizon (Patil et al*.,* 2018). Organic carbon of study area varied from 0.11 (very low) to 0.86 (High) per cent (Table 4) and found decreased with soil depth in all the pedons.

Table 3. Physical characteristics of soils of Jalna district of Maharashtra

Horizon	Depth (cm)	Layer (cm)	Coarse fragments %	BD (Mg m^{-3})	HC (cm hr^{-1})	Particle size analysis (%)			Moisture retention (%)		AWC (%)	PAWC mm
						Sand	Silt	Clay	33 kPa	1500kPa		
Pedon 2(Very fine, smectitic, isohyperthermic,Calcic Haplusterts)												
Ap	0-18	18	6.58	1.32	7.26	1.70	34.08	64.20	39.43	27.68	11.76	
Bw_1	18-32	14	7.38	1.52	4.24	0.88	38.12	60.99	42.02	26.82	15.19	
Bw_2	32-58	26	9.45	1.57	1.40	0.72	31.25	68.04	40.99	24.01	16.98	373.54
Bss_1	58-85	27	11.66	1.57	1.04	0.84	30.05	69.11	41.38	26.09	15.29	
Bss_2	85-120	35	12.98	1.61	0.21	0.61	26.43	72.96	47.55	30.27	17.28	
Bss_3	120-150	30	14.88	1.69	0.33	1.80	37.16	61.01	26.19	9.57	16.61	
Pedon 3(Fine, smectitic, isohyperthermic Calcic Haplustepts)												
Ap	0-20	20	9.14	1.19	4.71	2.7	37.9	59.4	37.45	25.35	12.09	
Bw_1	20-40	20	15.69	1.37	2.28	3.6	42.8	53.6	27.71	13.18	14.53	104.26
Bw_2	40-60	20	22.54	1.37	1.88	4.0	37.6	58.5	38.59	25.55	13.04	
Cr	60+		40.22	1.75	9.64	31.6	44.7	23.7	32.53	21.04	11.48	
Pedon 4 (Fine, smectitic, isohyperthermic, Typic Haplusterts)												
Ap	0-20	20	8.54	1.28	1.32	1.3	37.7	61.0	39.41	26.40	13.01	
Bw_1	20-39	19	10.64	1.36	1.24	5.75	35.35	58.90	36.46	24.91	11.56	
Bw_2	39-51	12	15.44	1.44	1.04	1.49	36.30	62.16	37.31	25.88	11.43	399.82
Bss_1	51-78	27	17.88	1.60	0.98	1.06	34.06	64.88	37.66	24.85	12.81	
Bss_2	78-98	20	17.92	1.69	0.89	1.82	37.57	60.62	30.22	16.03	14.20	
Bss_3	98-150	52	18.02	1.74	0.66	1.65	38.42	59.93	52.40	28.88	23.52	
Pedon 5 (Fine, smectitic, isohyperthermic Typic Ustorthents)												
Ap	0-22	22	14.33	1.40	2.74	49.3	35.5	15.16	26.48	15.42	11.07	34.2
Cr	22+		42.33	1.65	8.49	57.32	28.64	14.02	29.29	18.90	10.39	
Pedon 9 (Very fine, smectitic, isohyperthermic, Typic Haplustepts)												
Ap	0-21	21	10.22	1.39	1.75	11.5	41.13	47.35	36.03	25.44	10.59	
Bw_1	21-42	21	16.64	1.67	1.27	12.78	40.97	46.26	33.21	22.96	10.25	66.69
Cr	42+		28.54	1.76	4.38	24.96	49.09	25.96	38.83	27.32	11.51	

Table 4. Chemical characteristics of soils of Jalna District of Maharashtra

Horizon	Depth (cm)	pH	EC dSm^{-1}	OC g/kg	$CaCO_3$ %	CEC $Cmol(P^+)\ kg^{-1}$	Exchangeable Cations [$Cmol(P^+)\ kg^{-1}$]				Sum of Cation $Cmol(P^+)\ kg^{-1}$	B.S. %
							Ca^{++}	Mg^{++}	K^+	Na^+		
Pedon 2 (Very fine, smectitic, isohyperthermic,Calcic Haplusterts)												
Ap	0-18	7.56	0.33	5.66	10.5	59.47	45.61	6.66	1.21	2.70	56.17	94.46
Bw_1	18-32	7.68	0.43	6.12	13.3	57.44	43.03	11.55	1.01	3.01	58.59	102.0
Bw_2	32-58	7.77	0.44	4.74	13.25	61.48	41.18	11.80	1.01	3.99	57.98	94.31
Bss_1	58-85	8.14	0.41	4.44	15.5	63.97	40.78	11.23	0.72	4.80	57.53	89.93
Bss_2	85-120	8.47	0.44	4.29	16.25	68.71	36.96	12.86	0.77	4.80	55.40	80.62
Bss_3	120-150	8.58	0.47	2.30	17.5	59.86	34.38	17.31	0.74	5.02	57.45	95.97
Pedon 3 (Fine, smectitic, isohyperthermic Calcic Haplustepts)												
Ap	0-20	8.08	0.43	6.73	14.5	60.37	46.26	4.94	0.68	3.17	55.05	91.18
Bw_1	20-40	8.11	0.37	4.59	20.5	51.22	42.36	8.98	0.66	3.55	55.55	100.28
Bw_2	40-60	8.08	0.28	4.29	22.5	59.72	36.36	11.01	0.37	4.22	51.96	87.01
Cr	60+	8.32	0.25	0.31	23.25	51.24	33.92	4.54	0.26	4.26	42.98	83.89
Pedon 4 (Fine, smectitic, isohyperthermic, Typic Haplusterts)												
Ap	0-20	7.97	0.18	6.12	8.5	66.70	52.46	6.15	0.98	2.25	61.84	92.72
Bw_1	20-39	8.13	0.13	4.59	10.5	66.83	50.26	7.94	0.74	3.11	62.05	92.84
Bw_2	39-51	8.29	0.17	4.13	10.5	61.49	49.94	8.27	0.49	4.44	63.14	102.68
Bss_1	51-78	8.43	0.22	3.67	11.75	67.23	48.66	8.62	0.64	4.44	62.36	92.76
Bss_2	78-98	8.72	0.23	3.37	12.25	58.33	37.87	12.21	0.32	4.86	55.26	94.74
Bss_3	98-150	8.74	0.32	2.45	12.25	56.55	29.04	15.65	0.68	4.90	50.27	88.89
Pedon 5 (Fine, smectitic, isohyperthermic Typic Ustorthents)												
Ap	0-22	7.84	0.14	6.12	4.25	38.95	29.10	5.57	0.94	2.88	38.49	98.81
Cr	22+	7.96	0.14	3.83	10.5	48.22	22.29	3.58	0.38	2.86	29.12	60.38
Pedon 9 (Very fine, smectitic, isohyperthermic, Typic Haplustepts)												
Ap	0-21	7.44	0.32	6.58	3.5	48.66	36.19	36.19	1.25	3.59	45.56	93.63
Bw_1	21-42	7.92	0.34	3.83	10.25	49.22	34.11	34.11	2.19	4.54	46.97	95.43
Cr	42+	8.08	0.25	0.92	13.75	32.22	26.21	22.21	0.12	5.10	31.03	96.32

Relatively high organic carbon content in surface horizon may be due to the addition of cropped plant residues and farm yard manure to the surface horizon (Kumar and Prasad 2010). Similar results were observed by Sekhar et al*.,* 2017; Ghode et al*.,* 2018; Ingle et al., 2021. The surface and sub-surface horizons of pedons P1 to P10 had $CaCO_3$ ranging from slightly to strongly calcareous (3.50 to 22.50 %). The distribution of calcium carbonate in soil profiles invariably shows an increasing pattern with increase in soil depth, which indicates the process of leaching down of calcium and subsequent precipitation at lower depth due to high pH level (Pal et al., 1999 and Challa et al., 2000) in the soils of semi-arid tropics of India.

This increasing trend of lime with depth was also observed by many researchers (Kadu et al., 2009; Adkine et al*.,* 2018 and Ghode et al*.,* 2023). The higher CaCO3 content may be due to the formation of pedogenic carbonate facilitated by the semi-arid climate and calcium-rich parent material (Kuchanwar et al., 2021; Vasu et al. 2022). Cation exchange capacity (CEC) of study area varied from 23.62 to 68.71 Cmol(P^+) kg^{-1}. The CEC in P_2 and P_8 (Calcic Haplusterts) was found higher followed by P4 and P6 (Typic Haplusterts), P1 and P3 (Calcic Haplustepts), P9 (Typic Haplustepts), and lowest in P5, P7, P10 (Typic Ustorthents). This variation in CEC of soils of study area might be due to of high amount of clay with smectitic mineralogy (Pal and Deshpande, 1987 and Kumar and Naidu, 2012). The CEC of soil increases with the increase in soil depth indicating the influence of clay on CEC (Gangopadhyay et al. 2022). The low CEC values were observed in Typic Ustorthents (P_5, P_7 and P_{10}) might be due to the low clay content in soil. Because of the quick weathering of the parent materials, low activity clays dominate the mineral composition of soils, as evidenced by the decrease in CEC with a rise in negative pH increasing altitude (Bandyopadhyay et al. 2018). The low to moderate CEC of pedons may be due to the coarse texture, sandy nature of the parent material and low activity clay (Vasu et al., 2022). The significant positive relationship between CEC and clay content (r=0.887**) confirms the above fact. The exchangeable cations were in the order of Ca^{2+} > Mg^{2+} > Na^+ > K^+. Similar observations were made by Mohekar et al. (2020) and Gangopadhyay et al. (2022). Exchangeable Ca^{2+}, Mg2$^+$, Na^+, K^+ of study area varied from 17.06 to 52.46, 2.08 to 18.37, 1.50 to 7.59 and 0.11 to 2.19 cmol p^+ kg^{-1}, respectively.

In all the pedons, the exchangeable Ca^{2+} generally declined irregularly with depth. In all pedons, the exchangeable Mg^{2+} rises with soil depth; this phenomenon may be explained by Mg^{2+} preferentially leaching to the lower horizon over Ca^{2+}. The decline in the Ca/Mg ratio in these soils with depth was also indicative of it shows a substantial positive correlation (r= 0.734*) between exchangeable magnesium and pH.

Base saturation (BS) of study area varied from 82.11 to 105.08 per cent. BS in P_5, P_7 and P_{10} was varied from 87.47 to 99.56 %, BS of P_9 was varied from 93.63 to 95.43 and in pedon P_1 and P_3 from 87.16 to 101.30 per cent. In P_4 and P_6 base saturation ranging from 90.80 to 105.08 per cent whereas in P_2 and P_8 ranging from 82.11 to 102.00 per cent. The high base saturation of these soils is due to their occurrence in non-leaching environment of semi-arid tropics and less weathering. The base saturation in all pedons ranged from 82.11 to 105.08 per cent, which is more than 100% due to the presence of Ca-zeolites (Pal et al*.,* 2006). The low to moderate BS of the pedons (P5, P7, P10) could be attributed to the pre-dominantly coarse soil texture as sandy loam and sandy clay loam were the common texture of the pedons (Vasu et al., 2022). The exchangeable sodium percentage (ESP) of study area (P_1 to P_{10}) varied from 2.81 to 12.44 per cent and ESP of the all pedons of study area increased with depth whereas maximum ESP was found in subsurface horizons of pedon P_1 (Calcic Haplustepts) which might be ascribed to the formation of pedogenic carbonates leading to the development of sub-soil sodicity (Kalaiselvi et al. 2022). The semiarid climate is responsible for the pedogenetic processes, resulting in the depletion of Ca^{2+} ions from the soil solution and the formation of $CaCO_3$ with the concomitant increase of ESP with pedon depth (Balpande et al*.* 1996; Vaidya and Pal 2002). The prevailing semi-arid environment leads to the depletion of Ca^{2+} ions in the soil solution in the form of calcretes and the concurrent increase in ESP with depth may be the cause of high $CaCO_3$ in the soils (Balpande et al. 2007; Warhade et al. 2022 and Vasundhara et al*.* 2022).

3.5 Soil Classification

Based on morphological, physical, and physicochemical properties, the ten pedons of the Jalna district were classified according to Soil Taxonomy (Soil Survey Staff 2003). The dominant soils of the study area are typified under three orders *viz.* Entisols, Inceptisols and Vertisols. The soils (P_5, P_7, and P_{10}) developed on gently to moderately sloping elevated area on hilly terrain were lack of diagnostic horizons in sub surface, presence of Ustic moisture regime, and because these soils do not key out for another sub group the soils are classified as Typic Ustorthents. The order Inceptisols has been assigned to the pedons (P1, P3, and P9) that exhibit an ochric epipedon, followed by cambic subsurface diagnostic layers within 100 cm of the mineral soil surface and its lower limit at a depth of at least 25 cm below the mineral soil surface. Furthermore, these were classed as Ustepts at the sub-orders since the research region was approaching a ustic moisture regime. Due to the lack of other surface and subsurface diagnostic features, pedon (P9) was categorized as a Haplustept at the large group level. Additionally, at the subgroup level, the soils in this series reflect the fundamental idea of the Inceptisols soil order, which led them to Typic Haplustepts.

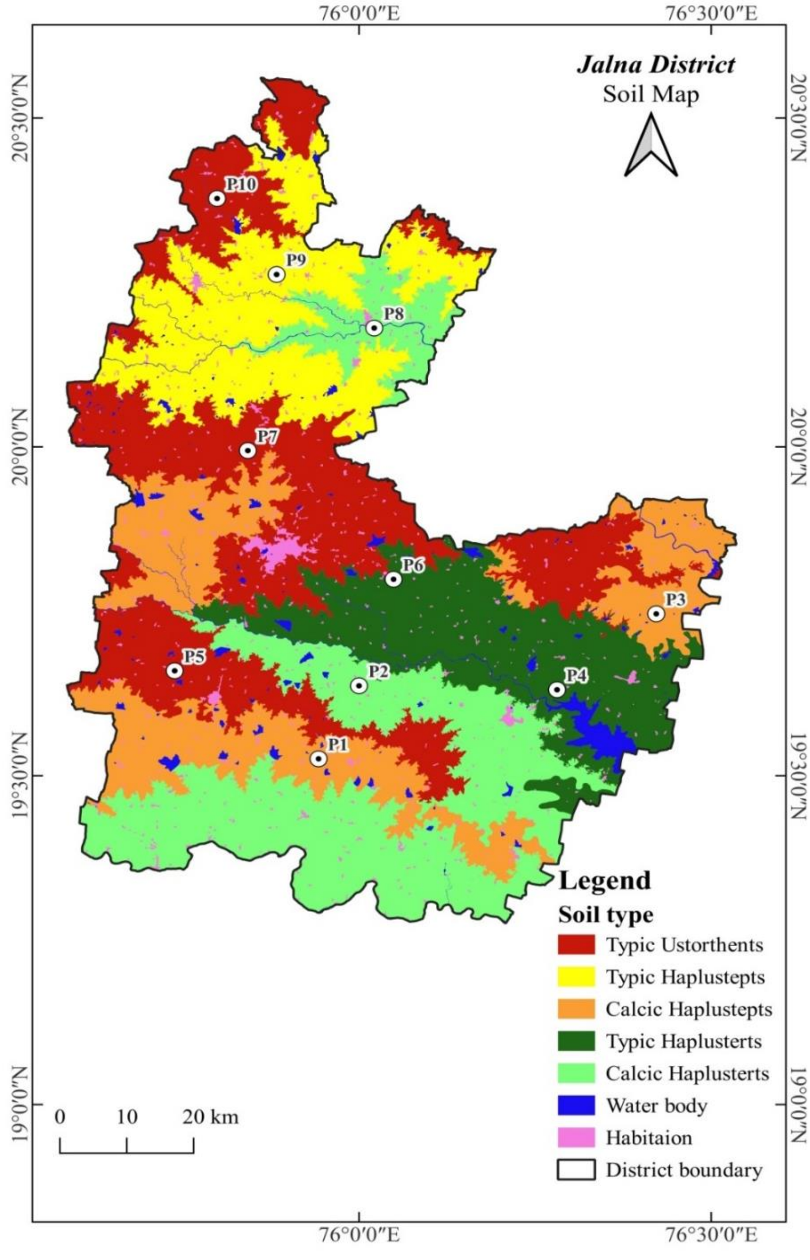

Fig. 2. Soil map of Jalna district of Maharashtra

Table 5. Correlation coefficient between physical and chemical properties

	Depth	HC	Clay	PAWC	CEC	Exch. Mg	Ca: Mg	pH
Depth	1.000							
HC	-0.664*	1.000						
Clay	0.787**	-0.369	1.000					
PAWC	0.981**	-0.627	0.789**	1.000				
CEC	0.711**	-0.805**	0.887**	0.770**	1.000			
Exch. Mg	0.818**	-0.687*	0.688*	0.832**	0.447	1.00		
Ca: Mg	-0.566	0.334	-0.322	-0.600	0.158	-0.823**	1.000	
pH	0.776**	-0.486	0.458	0.744*	0.359	0.734*	-0.697*	1.00

Significant at 5%- (r=0.632) Significant at 1%-** (r=0.762)*

Table 6. Soil classification of Jalna district of Maharashtra

Pedon No.	Order	Suborder	Great Group	Subgroup	Family
P_1	Inceptisols	Ustepts	Haplustepts	Calcic Haplustepts	fine, smectitic, isohyperthermic
P_2	Vertisols	Usterts	Haplusterts	Calcic Haplusterts	very fine, smectitic, isohyperthermic
P_3	Inceptisols	Ustepts	Haplustepts	Calcic Haplustepts	fine, smectitic, isohyperthermic
P_4	Vertisols	Usterts	Haplusterts	Typic Haplusterts	fine, smectitic, isohyperthermic
P_5	Entisols	Orthents	Ustorthents	Typic Ustorthents	fine, smectitic, isohyperthermic
P_6	Vertisols	Usterts	Haplusterts	Typic Haplusterts	fine, smectitic, isohyperthermic
P_7	Entisols	Orthents	Ustorthents	Typic Ustorthents	fine, smectitic, isohyperthermic
P_8	Vertisols	Usterts	Haplusterts	Calcic Haplusterts	very fine, smectitic, isohyperthermic
P_9	Inceptisols	Ustepts	Haplustepts	Typic Haplustepts	fine, smectitic, isohyperthermic
P_{10}	Entisols	Orthents	Ustorthents	Typic Ustorthents	fine, smectitic, isohyperthermic

Conversely, the pedon soils (P1 and P3) were classified as Calcic Haplustepts because they had a calcic horizon within 100 cm of the mineral soil surface. The pedon (P_2, P_4, P_6 and P_8) having more than 25 cm thick layer, within 100 cm of the mineral soil surface along with slickensides, wedge shaped peds that having long axes tilted 10 to 60 degrees from the horizontal and deep cracks that open and close periodically and contain more than 30 percent clay in the fine-earth fraction. Since, these soils were classified in order Vertisols. Pedon (P_4 and P_6) classified at sub-group level pedon as Typic Haplusterts because these soils do not key out for another sub-group. Moreover Pedon (P_2 and P_8) classified at sub-group level pedon as Calcic Haplusterts because these soils having calcic horizon within 150 cm of the mineral soil surface.

4. CONCLUSION

The present study highlighted significant variations in the morphological and physicochemical properties of soils in the Jalna district of the Marathwada region, Maharashtra. These properties varied with topographic positions, primarily due to differences in the degree of soil development under various topographic conditions. The soils ranged from very shallow to very deep, were slightly to strongly alkaline, and exhibited organic carbon levels ranging from very low to high. They were also slightly to strongly calcareous, with Exchangeable Sodium Percentage (ESP) varying from low to high. The exchangeable cations followed the order $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$. Nutrient availability decreased with increasing soil depth, alkalinity, and calcareousness. Factors such as soil depth, pH, $CaCO_3$ content, and hydraulic conductivity were identified as major yield-limiting constraints. Taxonomically, the soils were classified into Entisols, Inceptisols, and Vertisols. At the family level, they were further categorized as: Fine, Smectitic, Isohyperthermic, Typic Ustorthents, Fine, Smectitic, Isohyperthermic, Typic Haplustepts, Fine, Smectitic, Isohyperthermic, Calcic Haplustepts, Fine, Smectitic, Isohyperthermic, Typic Haplusterts, Very Fine, Smectitic, Isohyperthermic, Calcic Haplusterts These findings provide valuable insights for soil classification and management, aiding in the development of strategies to optimize land use and agricultural productivity.

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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