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Characterization and Classification of Soils in the Southern Plateau and Hills Region of Utkoor Mandal of Narayanpet District, Telangana State, India

S. K. Kumawat [a], Karamvir [a], Manoj Kumar Singh [a], Deep Narayan Roy [a], Sumit Raizada [a], Monika [a], Ravi Gautam [a], Y. Suresh Kumar [a], A. William Mariya Joseph [a], Sanjay A. Dhale [a], Milind Wadodkar [a], R. L. Meena [a], N. S. Gahlod [a], Kumar Rajeev [a] and S. K. Tripathi [a*]

[a] Soil and Land Use Survey of India, IARI Buildings, PUSA, Delhi-110012, India.

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

Accurate soil characterisation and classification are essential for understanding soil variability and supporting sustainable land-use and nutrient-management decisions. A detailed soil characterisation and classification study was conducted in Utkoor Mandal, Narayanpet District, Telangana State, India, to evaluate the morphological, physical, chemical, and taxonomic properties of soils developed under a semi-arid tropical

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**Corresponding author: E-mail: sktripathi.slusi@gov.in;*

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environment. Ten representative pedons distributed across upper pediplains, lower pediplains, alluvial plains, and stream banks were examined using standard field and laboratory procedures. Pedon depth ranged from 37 to 107 cm, and the soils displayed cambic (Bw), gleyed (Bng), vertic (Bss), and transitional (AC) subsurface horizons, indicating different stages of profile development. Textural classes ranged from gravelly sandy loam to clay, with clay generally increasing with depth. Soil pH ranged from 7.0 to 9.85, while electrical conductivity ranged from 0.05 to 0.57 dS m^{-1}, indicating neutral to strongly alkaline but non-saline conditions. Organic carbon ranged from 0.06 to 0.50%, and cation exchange capacity ranged from 3.6 to 24.0 cmol(p^+) kg^{-1}. Based on USDA Soil Taxonomy, the pedons were classified as Entisols, Inceptisols, and Vertisols, represented by Typic Ustorthents, Typic Haplustepts, Typic Halaquepts, and Typic Haplusterts. The observed variation was associated with differences in parent material, physiography, drainage, and pedogenic processes. The findings provide baseline soil information for land capability assessment, site-specific nutrient management, soil-resource mapping, and sustainable land-use planning in the study area.

Keywords: Soil characterisation; soil classification; pedons; soil morphology; Entisols; Inceptisols; Vertisols; semi-arid tropics; soil–landscape relationships.

1. Introduction

Soil is the most important basic natural resource determining the ultimate sustainability of any agricultural system. Modern agriculture requires precise information on biophysical and climatic resources for sustainable land-use planning. Soil properties are basic attributes that directly influence its response to any specified use (Bhattacharyya *et al.*, 2024). The life-support system of a country and the socioeconomic development of its people depend on natural resources (Meena *et al.*, 2014). Soil characterisation and classification are important for understanding the nature of soil resources (Sahoo *et al.*, 2019). Data generated from profile characteristics serve as a benchmark for periodically monitoring and evaluating likely changes in soil characteristics under different cropping systems. Sustainable management of soil resources in agroclimatic zones requires the timely monitoring of important soil properties and their responses to changes in land management. Soil classification also helps to organise knowledge, facilitates the transfer of experience and technology from one location to another, and enables the comparison of soil properties (Weil & Brady, 2017). A reliable database on soil properties and related site characteristics is essential for advising current and potential land users on the most appropriate use of the land. The resulting spatial soil information assists farmers, planners, and researchers in optimising productivity while maintaining long-term soil health and environmental sustainability. Recent evidence from semi-arid districts also indicates that soil texture, pH, moisture, and organic carbon vary with environmental setting and depth, supporting the need for site-specific soil assessment (Yadav & Ram, 2025).

The integration of remote sensing and geographic information system (RS and GIS) techniques has improved the accuracy and efficiency of soil resource mapping and spatial analysis in heterogeneous landscapes (Sahu *et al.*, 2015). Thus, soil survey and mapping have evolved from simple resource inventory preparation into a comprehensive decision-support framework that integrates field observations, laboratory analyses, and spatial data (Arunkumar *et al.*, 2024). Owing to the consistent variability and heterogeneity of soil and land resources within Telangana, a systematic study of soil characteristics is required. The present study involved a detailed soil survey at a 1:10,000 scale in Utkoor Mandal, Narayanpet District, Telangana State, situated in the Southern Plateau and Hills agroclimatic zone (Zone X). The investigation was conducted under the National Soil Mapping Programme (NSMP), implemented by the Soil and Land Use Survey of India (SLUSI).

Geospatial soil assessment can combine field and laboratory observations with GIS, GPS, remote sensing, and terrain information to improve the spatial interpretation of soil properties and land suitability (AbdelRahman & Afifi, 2024; Deogade *et al.*, 2024; Kalaiselvi *et al.*, 2024). However, detailed information linking soil morphology, physicochemical variability, taxonomic classes, and landscape position at a 1:10,000 scale remains limited for Utkoor Mandal, restricting locally specific soil-resource planning.

This article, therefore, examines the concepts, methodologies, technological advancements, and applications of soil survey and mapping and highlights their role in sustainable land-resource management and climate-resilient agriculture. Accordingly, this study aimed to characterise the morphological, physical, and chemical properties of representative soils in Utkoor Mandal, classify them according to USDA Soil Taxonomy, and delineate soil mapping units by integrating field, laboratory, and remote-sensing information.

2. Materials and Methods

2.1 Description of Study Area

The study was conducted in Utkoor Mandal of Narayanpet District, Telangana State, situated between 16°32′40″ and 16°43′44″ N latitudes and 77°25′80″ and 77°38′47″ E longitudes. The region experiences a semi-arid tropical climate characterised by distinct wet and dry seasons. The average annual rainfall is 727 mm, occurring over approximately 52 rainy days. The south-west monsoon contributes 76% of the normal annual rainfall, the north-east monsoon contributes 16%, and the remaining 8% is received from January to May. The mean annual temperature is 27°C. Summer begins in March and reaches its peak in May, with an average maximum temperature of 40.5°C. Winter begins in late November and lasts until early February, with the lowest average temperature of 15.6°C recorded in January. The district forms a contiguous part of the Mysore Plateau and is characterised by erosional topography, with a general slope towards the south and north-east. According to USDA Soil Taxonomy (2014), the study area is characterised by an *Ustic* soil moisture regime and an *Iso-hyperthermic* soil temperature regime, reflecting the prevailing semi-arid tropical climate, distinct seasonal moisture availability, and consistently high soil temperatures throughout the year.

2.2 Geology and Vegetation Type of Study Area

The study area is underlain predominantly by granitic formations, with granite-gneiss and recent alluvial deposits occurring locally. Physiographically, the landscape comprises upper pediplains with very gently to moderately sloping terrain (1-10% slope), lower pediplains, alluvial plains, and stream banks characterised by very gently sloping terrain (1-3% slope). Spatial variability in parent material and physiographic setting has strongly influenced soil genesis, drainage conditions, and the distribution of soil properties across the landscape. The soil-site characteristics of the representative pedons are presented in Table 1. The natural vegetation of the study area is dominated by babul (*Acacia nilotica*), banyan (*Ficus benghalensis*), mango (*Mangifera indica*), tamarind (*Tamarindus indica*), and neem (*Azadirachta indica*). Agriculture is the predominant land use, with rice (*Oryza sativa*) and maize (*Zea mays*) cultivated extensively under irrigated conditions, whereas cotton (*Gossypium spp.*), pulses, and oilseed crops are grown mainly in the rainfed uplands. The interaction of climatic conditions, parent material, physiography, and irrigation availability has strongly influenced pedogenic processes, resulting in distinct soil-landscape relationships and diverse agricultural production systems across the study area.

2.3 Field Survey and Mapping

The detailed soil survey was conducted using high-resolution Resourcesat-2 LISS-IV False Colour Composite (FCC) satellite imagery and enlarged Survey of India (SOI) toposheet quadrants at a working scale of 1:10,000, generated from the original 1:50,000-scale maps. The satellite imagery was interpreted to identify physiographic features and delineate preliminary soil-landscape units. These preliminary boundaries were subsequently verified and refined through intensive field investigations. Land-use/land-cover (LULC) mapping was conducted through visual interpretation of the satellite imagery based on image elements such as tone, texture, pattern, shape, association, and site characteristics. Slope, hillshade, and 10 m contour maps were generated from the Cartosat-1 Digital Elevation Model (DEM; 30 m spatial resolution). These terrain derivatives were integrated to prepare the landform map, which served as the basis for the soil survey and mapping.

A detailed soil survey was conducted through systematic field traverses across the major physiographic units of the study area. Representative soil profile pits (pedons) and auger observations were selected to capture spatial variability in soils associated with differences in landform, slope, drainage, parent material, and landscape position. Based on the physiography-soil relationship, ten georeferenced representative pedons were excavated, each representing a distinct physiographic unit. The pedons were morphologically described in the field following the standard procedures of the Soil Survey Manual and Keys to Soil Taxonomy (All India Soil and Land Use Survey Organization, 1970; Soil Survey Staff, 2014). Morphological characteristics recorded for each genetic horizon included horizon designation and boundary, soil depth, matrix colour using the Munsell Soil Color Charts, texture, structure, dry, moist, and wet consistence, root abundance and distribution, pore size and abundance, coarse fragments, mottles, concretions, cutans, and other diagnostic pedogenic features relevant to soil genesis and classification. These observations formed the basis for subsequent laboratory analyses, soil classification, and delineation of soil mapping units.

2.4 Laboratory Analysis

Horizon-wise soil samples were collected from each representative pedon, air-dried under laboratory conditions, gently crushed, and passed through a 2 mm sieve before analysis. The processed samples were analysed for routine physical and chemical properties following standard laboratory procedures. Soil pH and electrical conductivity were measured in a soil-to-water (1:2.5) suspension using a glass electrode and conductivity meter, respectively (Jackson, 1973). Soil organic carbon content was estimated using the wet oxidation method of Walkley and Black (1934). Calcium carbonate content was estimated using the rapid titration method (Puri, 1949). Cation exchange capacity (CEC) was determined by the neutral 1 N ammonium acetate extraction method (pH 7.0), using the centrifuge extraction procedure described by Thomas (1982). Exchangeable sodium percentage (ESP) was calculated as the ratio of exchangeable sodium to cation exchange capacity and expressed as a percentage.

Based on the physiography-soil relationship, ten representative soil pedons were identified across the study area: P1 (Amarchenta), P2 (Chitanur), P3 (Golpalle), P4 (Gurrampalli), P5 (Jaklur), P6 (Kolampalli), P7 (Kondadoddi), P8 (Narayanpet), P9 (Peddapurle), and P10 (Vetugudla). These pedons were morphologically characterised in the field and subsequently classified according to the Keys to Soil Taxonomy (Soil Survey Staff, 2014). Field morphological observations and laboratory analytical data were integrated with remote-sensing information to delineate homogeneous soil mapping units, which formed the basis for preparing the final soil map of the study area.

3. Results and Discussion

3.1 Physiographic Characteristics

The study area was stratified into four major physiographic units, namely upper pediplains, lower pediplains, alluvial plains, and stream banks, which exhibited shallow to moderately weathered landscapes. These units were further subdivided according to slope gradient and erosion intensity to represent landscape heterogeneity. Based on the physiography-soil relationship, ten representative pedons were selected for detailed morphological characterisation: P1 (Amarchenta), P2 (Chitanur), P3 (Golpalle), P4 (Gurrampalli), P5 (Jaklur), P6 (Kolampalli), P7 (Kondadoddi), P8 (Narayanpet), P9 (Peddapurle), and P10 (Vetugudla). Their soil-site characteristics are summarised in Table 1.

Table 1. Landscape characteristics

Pedons	Series	Latitude	Longitude	Parent Material	Physiography	Slope	Drainage	Land Use
P1	Amarchenta	16°39'51" N	77°33'11" E	Granite	Upper pediplains	B: Very gently (1-3%)	Well	Double crop cultivation
P2	Chitanur	16°39'31" N	77°26'50" E	Granite gneiss	Lower pediplains	B: Very gently (1-3%)	Moderately well	Double crop cultivation
P3	Golpalle	16°36'10" N	77°31'46" E	Alluvium	Alluvial plains	B: Very gently (1-3%)	Imperfectly	Double crop cultivation
P4	Gurrampalli	16°32'51" N	77°32'28" E	Granite	Upper pediplains	C: Gently (3-5%)	Well	Single crop cultivation
P5	Jaklur	16°39'44" N	77°30'16" E	Granite	Lower pediplains	B: Very gently (1-3%)	Moderately well	Double crop cultivation
P6	Kolampalli	16°41'11" N	77°31'52" E	Granite	Upper pediplains	B: Very gently (1-3%)	Moderately well	Single crop cultivation
P7	Kondadoddi	16°42'39" N	77°30'15" E	Alluvium	Stream banks	B: Very gently (1-3%)	Moderately well	Double crop cultivation
P8	Narayanpet	16°37'54" N	77°36'24" E	Granite	Upper pediplains	B: Very gently (1-3%)	Moderately well	Double crop cultivation
P9	Peddapurle	16°36'47" N	77°30'25" E	Granite	Upper pediplains	B: Very gently (1-3%)	Imperfectly	Double crop cultivation
P10	Vetugudla	16°42'16" N	77°33'23" E	Granite	Upper pediplains	D: Moderately (5-10%)	Well	Single crop cultivation

Table 2. Morphological characteristics

Pedon & Horizons	Depth (cm)	Colour (Moist)	Soil Texture	Structure (Size)	Structure (Grade)	Structure (Type)	Consistency (Dry)	Consistency (Moist)	Consistency (Wet)	Efferve scence	Pores	Root distribution
P1: Amarchenta												
Ap	0-18	7.5YR4/4	Sandy loam	m	1	sbk	dl	mvfr	wso,wpo	e0	fvf-ff	vff-ff
Bw1	18-34	7.5YR3/4	Sandy clay loam	m	2	sbk	dsh	mfr	wss,wps	e0	fvf-ff	vff-ff
Bw2	34-56	5YR3/4	Sandy clay loam	m	2	sbk	-	mfr	wss,wps	e0	fvf-ff	-
Bw3	56-82	5YR3/4	Sandy clay loam	m	2	sbk	-	mfr	wss,wps	e0	fvf-ff	-
C	82-88	Weathered parent materials										
P2: Chitanur												
Ap1	0-14	10YR3/2	Clay	m	2	sbk	dvh	mvfi	wvs,wvp	e0	fvf	vff
Bw1	14-32	10YR3/2	Clay	m	2	sbk	dvh	mvfi	wvs,wvp	e0	fvf	vff
Bw2	32-59	10YR3/2	Clay	m	2	sbk	-	mvfi	wvs,wvp	e0	fvf	-
Bw3	59-82	10YR3/2	Clay	m	2	sbk	-	mvfi	wvs,wvp	e0	fvf	-
Bw4	82-101	10YR3/2	Clay	m	2	sbk	-	mvfi	wvs,wvp	e0	-	-
P3: Golpalle												
Ap1	0-16	10YR3/2	Sandy loam	m	1	sbk	dl	mvfr	wso,wpo	es	fvf-ff	vff
Ap2	16-37	10YR3/3	Sandy loam	m	2	sbk	dsh	mvfr	wso,wpo	es	fvf-ff	vff-ff
B1	37-58	10YR3/3	Sandy clay loam	m	2	sbk	-	mfr	wss,wps	e	fvf-ff	vff
B2	58-87	10YR4/3	Sandy clay loam	m	2	sbk	-	mfr	wss,wps	e	fvf-ff	-
B3	87-105	10YR4/4	Sandy clay loam	m	2	sbk	-	mfr	wss,wps		fvf-ff	-
P4: Gurrampalli												
AP	0-11	7.5YR4/4	Gravelly sandy loam	f	1	sbk	dl	mvfr	wso,wpo	e0	fvf	vff
AC1	11-23	7.5YR4/3	Gravelly sandy loam	m	1	sbk	dsh	mvfr	wso,wpo	e0	ff-cm	vff
AC2	23-37	7.5YR4/3	Gravelly sandy loam	m	1	sbk	-	mvfr	wso,wpo	e0	ff-cm	-
C	37-60	Weathered parent materials										
P5: Jaklur												
Ap1	0-14	10YR4/2	Sandy clay loam	m	2	sbk	dsh	mfi	wss,wps	es	fvf-ff	vff-ff
Ap2	14-32	10YR4/2	Sandy clay	m	2	sbk	dh	mfi	ws,wp	es	fvf-ff	vff
Bw1	32-58	10YR4/3	Sandy clay	m	2	sbk	-	mfi	ws,wp	es	fvf-ff	-
Bw2	58-79	10YR4/3	Sandy clay	m	2	sbk	-	mfi	wvs,wvp	es	fvf-ff	-
Bw3	79-102	10YR4/3	Clay	m	2	sbk	-	mfi	wvs,wvp	es	fvf-ff	-
P6: Kolampalli												
Ap1	0-11	10YR4/2	Gravelly sandy clay loam	m	1	sbk	ds	mfr	wss,wps	e0	fvf-ff	vff-ff
Bw1	11-27	10YR4/4	Gravelly sandy clay loam	m	1	sbk	-	mfr	wss,wps	e0	fvf-ff	vff

Pedon & Horizons	Depth (cm)	Colour (Moist)	Soil Texture	Structure (Size)	Structure (Grade)	Structure (Type)	Consistency (Dry)	Consistency (Moist)	Consistency (Wet)	Effervescence	Pores	Root distribution
Bw2	27-48	10YR4/3	Gravelly sandy clay loam	m	1	sbk	-	mfr	wss,wps	e0	fvf-ff	-
C	48-52	Weathered parent materials										
P7: Kondadoddi												
A	0-12	10YR5/2	Sandy loam	m	2	sbk	dl	mvfr	wso,wpo	e	fvf	vff
Bng1	12-46	10YR4/2	Sandy clay loam	m	3	sbk	dsh	mfr	wss,wps	e	fvf	vff
Bng2	46-78	10YR4/2	Sandy clay loam	c	3	sbk	-	mfr	wss,wps	e	ff	-
Bng3	78-107	10YR4/2	Sandy clay loam	c	3	sbk	-	mfr	wss,wps	e	ff	-
P8: Narayanpet												
Ap1	0-15	7.5YR4/4	Gravelly sandy clay loam	m	1	sbk	ds	mfr	wss,wps	e0	fvf-ff	vff-ff
Ap2	15-37	7.5YR4/4	Gravelly sandy clay loam	m	2	sbk	dsh	mfr	wss,wps	e0	fvf-ff	vff-ff
AC1	37-59	7.5YR4/4	Gravelly sandy clay loam	m	1	sbk	-	mfr	wss,wps	e0	fvf-ff	vff
AC2	59-81	7.5YR4/3	Gravelly sandy clay loam	m	1	sbk	-	mfr	wss,wps	e0	fvf-ff	-
AC3	81-104	7.5YR4/3	Gravelly sandy clay	m	2	sbk	-	mfi	ws,ws	e0	fvf-ff	-
P9: Peddapurle												
Ap1	0-14	10YR3/2	Sandy clay loam	m	2	sbk	dh	mfr	wss,wps	es	fvf-ff	vff
Ap2	14-32	10YR3/2	Clay loam	m	2	sbk	dh	mfi	ws,wp	es	fvf-ff	vff
Bss1	32-58	10YR3/2	Clay	m	2	abk	-	mvfi	wvs,wvp	es	fvf-ff	vff
Bss2	58-79	10YR3/2	Clay	m	2	abk	-	mvfi	wvs,wvp	es	fvf-ff	-
Bss3	79-102	10YR3/2	Clay	m	2	abk	-	mvfi	wvs,wvp	es	fvf-ff	-
P10: Vetugudla												
Ap	0-10	7.5YR4/6	Gravelly sandy loam	f	1	sbk	dl	mvfr	wso,wpo	e0	fc-ff	vff-ff
Bw1	10-27	7.5YR4/6	Gravelly sandy loam	f	1	sbk	dsh	mvfr	wso,wpo	e0	fc-ff	vff-ff
Bw2	27-39	7.5YR4/6	Gravelly sandy clay loam	f	1	sbk	-	mfr	wss,wps	e0	fc-ff	vff
C	39-59	Weathered parent materials										

Table 3. Physical and physico-chemical characteristics

Pedon & Horizons	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	pH (1:2.5)	EC (dsm^{-1})	OC (%)	CaCO3 (%)	CEC cmol (p+) kg^{-1}	BS (%)
P1: Amarchenta										
Ap	0-18	57.00	26.00	17.00	7.20	0.20	0.33	0.50	15.00	81.60
Bw1	18-34	49.00	20.00	31.00	7.60	0.20	0.32	0.50	16.00	78.56
Bw2	34-56	51.00	20.00	29.00	7.80	0.20	0.23	0.50	17.00	75.00
Bw3	56-82	51.00	20.00	29.00	7.60	0.20	0.21	1.00	18.00	80.67
C	82-88	Weathered parent materials								
P2: Chitanur										
Ap1	0-14	34.60	8.00	57.40	8.10	0.25	0.32	0.00	19.70	94.92
Bw1	14-32	34.60	10.00	55.40	8.10	0.30	0.30	0.00	20.50	96.20
Bw2	32-59	32.60	12.00	55.40	8.20	0.30	0.25	0.00	21.90	90.27
Bw3	59-82	30.60	12.00	57.40	8.20	0.32	0.19	0.00	23.00	91.00
Bw4	82-101	30.60	10.00	59.40	8.20	0.33	0.19	0.00	24.00	95.54
P3: Golpalle										
Ap1	0-16	63.00	18.00	19.00	7.90	0.32	0.30	4.00	11.20	95.09
Ap2	16-37	57.00	24.00	19.00	8.10	0.39	0.25	4.50	11.20	89.29
B1	37-58	59.00	18.00	23.00	8.20	0.41	0.20	4.50	12.50	93.44
B2	58-87	57.00	16.00	27.00	8.20	0.39	0.20	5.00	12.90	93.80
B3	87-105	55.00	16.00	29.00	8.15	0.38	0.20	5.00	12.80	94.53
P4: Gurrampalli										
Ap	0-11	73.20	12.00	14.80	7.20	0.05	0.31	0.00	3.60	83.06
AC1	11-23	73.20	12.00	14.80	7.00	0.09	0.33	0.00	4.00	75.25
AC2	23-37	75.20	12.00	12.80	7.10	0.10	0.25	0.00	4.00	86.75
C	37-60	Weathered parent materials								
P5: Jaklur										
Ap1	0-14	47.20	18.00	34.80	8.15	0.25	0.49	4.00	15.00	91.67
Ap2	14-32	45.20	18.00	36.80	8.20	0.31	0.50	4.50	15.60	93.91
Bw1	32-58	45.20	14.00	40.80	8.25	0.40	0.40	5.00	16.20	95.68
Bw2	58-79	45.20	12.00	42.80	8.55	0.41	0.20	7.50	16.90	93.96
Bw3	79-102	43.20	12.00	44.80	8.60	0.41	0.20	7.50	17.10	94.33
P6: Kolampalli										
Ap1	0-11	71.00	8.00	21.00	7.30	0.15	0.35	0.00	11.00	94.55
Bw1	11-27	67.00	12.00	21.00	7.60	0.16	0.25	0.00	11.00	90.00
Bw2	27-48	63.00	14.00	23.00	7.60	0.17	0.20	0.00	11.20	88.84
C	48-52	Weathered parent materials								
P7: Kondadoddi										
A	0-12	75.72	10.98	13.30	9.55	0.49	0.17	1.13	11.46	90.05

Pedon & Horizons	**Depth (cm)**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**pH (1:2.5)**	**EC (dsm^{-1})**	**OC (%)**	**CaCO3 (%)**	**CEC cmol (p+) kg^{-1}**	**BS (%)**
Bng1	12-46	61.98	13.89	24.13	9.85	0.57	0.06	1.26	16.25	69.11
Bng2	46-78	58.49	13.73	27.78	9.25	0.49	0.08	0.78	17.06	67.06
Bng3	78-107	60.24	9.86	29.90	9.27	0.47	0.08	0.90	18.61	56.60
P8: Narayanpet										
Ap1	0-15	65.00	14.00	21.00	7.30	0.10	0.35	0.00	13.00	96.15
Ap2	15-37	65.60	12.00	22.40	7.50	0.15	0.25	0.00	14.50	92.41
AC1	37-59	59.60	16.00	24.40	7.60	0.15	0.22	0.00	14.00	94.00
AC2	59-81	57.60	14.00	28.40	7.60	0.11	0.22	0.00	15.00	88.80
AC3	81-104	51.60	12.00	36.40	7.50	0.11	0.20	0.00	15.00	88.80
P9: Peddapurle										
Ap1	0-14	46.00	24.00	30.00	8.20	0.25	0.30	5.50	19.50	93.59
Ap2	14-32	42.00	22.00	36.00	8.50	0.31	0.20	6.00	21.10	96.07
Bss1	32-58	36.00	20.00	44.00	8.50	0.32	0.20	7.50	21.50	93.49
Bss2	58-79	32.00	20.00	48.00	8.60	0.33	0.15	7.50	22.40	88.39
Bss3	79-102	30.00	22.00	48.00	8.60	0.34	0.15	8.00	22.50	94.53
P10: Vetugudla										
Ap	0-10	73.00	12.00	15.00	7.50	0.09	0.26	0.00	10.00	97.50
Bw1	10-27	67.00	14.00	19.00	7.60	0.10	0.25	0.00	11.00	91.91
Bw2	27-39	65.00	12.00	23.00	7.80	0.10	0.20	0.00	11.50	90.61
C	39-59	Weathered parent materials								

Table 4. Taxonomic classification of soils in the study area up to family level

Pedons	**Series**	**Mineral**	**Soil Taxonomy**				
			Order	**Sub order**	**Great group**	**Sub group**	**Family**
P1	Amarchenta (AM)	Mixed	Inceptisols	Ustepts	Haplustepts	Typic Haplustepts	Fine-loamy
P2	Chitanur (CH)	Mixed	Inceptisols	Ustepts	Haplustepts	Typic Haplustepts	Fine
P3	Golpalle (GL)	Mixed	Inceptisols	Ustepts	Haplustepts	Typic Haplustepts	Fine-loamy
P4	Gurrampalli (GP)	Mixed	Entisols	Orthents	Ustorthents	Typic Ustorthents	Loamy-skeletal
P5	Jaklur (JK)	Mixed	Inceptisols	Ustepts	Haplustepts	Typic Haplustepts	Fine-loamy
P6	Kolampalli (KP)	Mixed	Inceptisols	Ustepts	Haplustepts	Typic Haplustepts	Fine-loamy
P7	Kondadoddi (KD)	Mixed	Inceptisols	Aquepts	Halaquepts	Typic Halaquepts	Fine-loamy
P8	Narayanpet (NP)	Mixed	Entisols	Orthents	Ustorthents	Typic Ustorthents	Loamy-skeletal
P9	Peddapurle (PP)	Montmorillonitic	Vertisols	Usterts	Haplusterts	Typic Haplusterts	Fine
P10	Vetugudla (VG)	Mixed	Inceptisols	Ustepts	Haplustepts	Typic Haplustepts	Fine-loamy

3.2 Morphological Characteristics

Soil morphology, or pedomorphic features, was studied primarily under field conditions. Soil morphology was evaluated through in situ examination of representative pedons (Table 2). The pedons were excavated to depths ranging from 37 to 107 cm. The soils were moderately deep to very deep and moderately well to well drained, except for Pedons P3 and P9, which exhibited imperfect drainage. Pedons P2, P3, P5, P7, P8, and P9 were classified as very deep soils (>100 cm); Pedon P1 was classified as deep, whereas Pedons P4, P6, and P10 were moderately deep. Variation in soil depth was attributed to differences in elevation, slope, topography, and geomorphic processes characteristic of semi-arid regions. Similar variations in soil depth across landforms in semi-arid environments have been reported by Supriya *et al.* (2019). Most pedons supported double-crop cultivation, indicating favourable soil and site conditions for intensive agriculture. In contrast, Pedons 4, 6, and 10 were under single-crop cultivation, likely reflecting limitations associated with soil properties, water availability, or other site-specific constraints. Slight to strong effervescence with dilute (10%) HCl was observed in Pedons 3, 5, 7, and 9, indicating the presence of calcareous parent material that became more pronounced with depth, whereas the remaining pedons showed no effervescence because of negligible $CaCO_3$ content. Soil depth varied according to location and topographic setting. Horizon boundaries ranged from clear to diffuse in distinctness and from smooth to wavy in topography. The surface horizons of all pedons were designated as Ap because of disturbance by mechanical means such as tillage. The subsurface Bw horizons in Pedons 1, 2, 5, 6, and 10 exhibited alteration of the parent material from its original condition, as evidenced by structural development and the presence of a cambic horizon (Bw). This diagnostic horizon reflects incipient pedogenic processes, including changes in soil structure, colour, and consistency, that distinguish it from the unaltered parent material beneath. The subsurface Bng horizon in Pedon 7 exhibited features characteristic of gleying, including mottling and discolouration resulting from periodic water saturation and reducing conditions. The horizon showed structural alteration of the parent material, with weak to moderate development of soil aggregates. The presence of the Bng horizon indicates impeded drainage and fluctuating groundwater conditions, which have contributed to the development of gleyic properties and the accumulation of iron and manganese concretions. The subsurface Bss horizon in Pedon 9 was characterised by pronounced slickensides, indicating substantial shrink-swell activity associated with high clay content. These features reflect pedogenic processes typical of Vertisols, in which repeated wetting and drying cycles produce shear planes, wedge-shaped aggregates, and polished surfaces. The presence of the Bss horizon denotes strong vertic properties, confirming the influence of expansive clays and seasonal moisture fluctuations on soil morphology and structural development. In Pedon 3, representing the alluvial plains, the subsurface B1, B2, and B3 horizons exhibited moderate alteration of the parent material. The B1 horizon showed weak structural development and friable consistency, whereas the B2 horizon displayed clearer pedogenic features, including a subangular blocky structure and slight clay accumulation. The B3 horizon showed transitional characteristics, with partially weathered material retaining features of the original alluvium. Collectively, these horizons indicate incipient soil development under semi-arid conditions, with progressive changes in structure and texture with depth. In Pedons 4 and 8, the subsurface AC horizons exhibited transitional characteristics between the altered B horizons and the underlying parent material. These horizons showed partial weathering, limited structural development, and retention of lithological features from the parent rock. The AC horizons thus represent an intermediate stage of soil formation, marking the gradual transition from pedogenic modification to unaltered substratum. All ten pedons exhibited horizon boundaries that were clear to gradual in distinctness and smooth in topography. These boundary features reflect uniform transitions between horizons, indicative of stable soil-forming processes under semi-arid conditions. In Pedons 1, 4, 8, and 10, the surface horizons exhibited moist colours ranging from 7.5YR 4/4 to 7.5YR 4/6, while the subsurface horizons ranged from 7.5YR 3/4 to 7.5YR 4/3 and 7.5YR 4/6. In Pedon 1, the subsurface horizons ranged from 7.5YR 3/4 to 5YR 3/4. These chromatic variations reflect differences in organic matter content and moisture regime, with darker hues in the subsurface horizons indicating greater accumulation of finer materials and reduced aeration than in the surface layers. In Pedons 2, 3, 5, 6, 7, and 9, the surface horizons exhibited moist colours ranging from 10YR 3/2 to 10YR 5/2, while the subsurface horizons varied between 10YR 3/2 and 10YR 4/2. These hues, generally in the brown to greyish-brown range, reflect medium organic carbon content at the surface and the increasing influence of mineral composition and drainage conditions with depth. The chromatic variation indicates semi-arid pedogenic processes, in which lighter surface colours correspond to aeration and organic inputs, while subsurface colours suggest reduced conditions and the accumulation of finer-textured material. This wide variation in soil colour was due to differences in chemical and mineralogical composition, as well as the textural make-up of the soils, which were influenced by topographic position and moisture regime (Srinivasan *et al.*, 2020). Textural classes varied from sandy loam to sandy clay. These variations were caused by the nature of the parent material, in situ weathering, clay translocation, and the age of soil development. The textural classes of the pedons ranged from gravelly sandy loam to sandy clay loam in the surface horizons and from gravelly sandy loam to clay in the subsurface horizons. These variations were attributed to the nature of the parent material (granite, granite-gneiss, and alluvium), the degree of in situ weathering, the translocation and illuviation of clay, and the relative age of soil development. Coarser textures in the surface horizons reflect depositional processes and limited pedogenic modification, whereas finer clayey textures in the subsurface horizons indicate advanced soil development, clay migration, and accumulation under semi-arid conditions. The dominant soil structures were subangular blocky and angular blocky. The angular and subangular blocky structures were attributed to the presence of a larger clay fraction (Devi *et al.*, 2015). Consistency ranged from loose to very hard under dry conditions, from very friable to very firm under moist conditions, and from non-sticky and non-plastic to very sticky and very plastic under wet conditions. Very sticky and very plastic consistency may be due to the high clay content of the soil (Sarkar *et al.*, 2001), whereas very friable, non-sticky, and non-plastic consistency might be due to negligible or very small amounts of expanding clay minerals (Sireesha & Naidu, 2013). The pore-size distribution in most pedons was dominated by few very fine to few fine pores throughout the surface and subsurface horizons. However, Pedon 4 exhibited few fine to common medium pores, whereas Pedon 10 was characterised by few coarse to few fine pores throughout the profile (Nimmo *et al.*, 2023). Root distribution in most pedons was characterised by very few very fine to few fine roots throughout the surface and subsurface horizons.

3.3 Physical and Chemical Characteristics

The sand content of the pedon horizons ranged from 30.00 to 75.72 per cent (Table 3). In general, total sand content decreased with depth. All ten pedons had relatively high sand contents, which might be attributed to the dominance of physical weathering (Dinesh & Grewal, 2017). Silt content ranged from 8.00 to 26.00 per cent and generally showed an irregular trend with depth in all pedons. The irregular distribution of silt with depth might be due to variations in the weathering of parent material or in situ formation. The clay fraction in the studied pedons exhibited considerable variability, ranging from 12.80 to 59.40 per cent. A consistent pedogenic trend was observed in most pedons, with clay content increasing progressively with soil depth, except in Pedon 4. Among the studied pedons, Pedon 4 had the lowest clay content, ranging from 12.8 to 14.8 per cent, whereas Pedon 2 had the highest clay content, ranging from 55.4 to 59.4 per cent. The increase in clay content with depth in most pedons may be attributed to the illuviation of finer clay particles from the surface horizons to the subsurface horizons during pedogenesis. Similar observations have been reported in earlier studies (Himabindu *et al.*, 2018; Sharma *et al.*, 2011). Variation in soil texture among the profiles may be attributed to differences in parent material and the intensity of weathering processes, which influence the distribution and accumulation of soil separates during pedogenesis.

Soil pH ranged from 7.0 to 9.85, indicating neutral to strongly alkaline conditions across the studied pedons. Electrical conductivity values ranged from 0.05 to 0.57 dS m^{-1}, confirming that all soils were non-saline (Table 3). Soil pH generally increased with depth, likely because of the downward movement and accumulation of basic cations in the subsurface horizons, together with the depletion of exchangeable bases from the surface through crop uptake. In addition, the release of organic acids during organic matter decomposition in the surface horizons may have contributed to the relatively lower pH of the upper layers. Organic carbon (OC) content ranged from 0.17 to 0.49 per cent in the surface horizons and from 0.06 to 0.50 per cent in the subsurface horizons. Despite minor variation among pedons, OC generally decreased with increasing soil depth, consistent with the reduced incorporation of plant residues and root-derived carbon in the lower horizons. The relatively higher OC content in the surface horizons was primarily associated with greater biomass inputs and litter accumulation, whereas the predominantly warm climatic conditions of the study area promoted rapid decomposition and mineralisation of organic matter, contributing to the overall low OC status of the soils. These findings agree with those reported by Vasundhara *et al.* (2020). The cation exchange capacity (CEC) of the studied pedons ranged from 3.6 to 19.70 cmol(p^+) kg^{-1} in the surface horizons and from 4.0 to 24.0 cmol(p^+) kg^{-1} in the subsurface horizons. The relatively higher CEC values observed in the subsurface horizons were primarily attributed to increased clay accumulation, indicating a strong positive relationship between CEC and clay content. This trend reflects the greater abundance of negatively charged exchange sites associated with clay minerals in the finer-textured horizons. Similar relationships between CEC and clay content have been reported by Hegde *et al.* (2020). Base saturation (BS) in the studied pedons ranged from 56.60 to 97.50 per cent, indicating moderate to very high occupancy of the soil exchange complex by the basic cations Ca^{2+}, Mg^{2+}, K^+, and Na^+. The observed variability in BS among the pedons reflects differences in parent material, mineralogical composition, topographic position, drainage conditions, weathering intensity, and land-use practices, which collectively regulate the retention and leaching of exchangeable base cations. Pedons with relatively lower BS values indicate greater depletion of base-forming cations through leaching and weathering, whereas higher BS values suggest greater retention of exchangeable bases and relatively higher inherent soil fertility. Thus, base saturation serves as an important indicator of soil weathering, nutrient status, and pedogenic development. Sharma *et al.* (2011) reported similar observations and suggested that variation in base saturation primarily reflects the degree of base leaching during soil-forming processes.

3.4 Soil Classification

Five factors are responsible for soil formation: climate, parent material, relief, organisms, and time. Their interaction and relative dominance give rise to particular soil types within an area (Weil & Brady, 2017). Based on morphological characteristics and physicochemical properties, the typifying pedons were classified to the family level according to the Keys to Soil Taxonomy (Table 4). Entisols represent the least developed soils and are characterised by minimal pedogenic horizon differentiation and the absence of diagnostic subsurface horizons. These soils possess only an ochric epipedon as the diagnostic surface horizon. In the present study, Pedons 4 and 8 were classified in the order Entisols because they lacked a diagnostic subsurface horizon indicative of advanced pedogenesis. The occurrence of an ustic soil moisture regime further supported their classification within the suborder Orthents, specifically Ustorthents. Based on particle-size class, mineralogy, soil temperature regime, and other family-level characteristics, both pedons were classified as loamy-skeletal, mixed, isohyperthermic, Typic Ustorthents according to the Keys to Soil Taxonomy (Soil Survey Staff, 2014).

Pedons 1, 2, 3, 5, 6, and 10 were classified as Inceptisols at the order level because of the presence of a cambic (Bw) horizon in the subsurface, indicating weak pedogenic horizon development. At the great-group level, these pedons were placed in Haplustepts because of the ustic soil moisture regime, which is characteristic of seasonally dry tropical environments. Based on particle-size class, mineralogy, soil temperature regime, and other family-differentiating characteristics, Pedons 1, 3, 5, 6, and 10 were classified as fine-loamy, mixed, isohyperthermic, Typic Haplustepts, whereas Pedon 2 was classified as fine, mixed, isohyperthermic, Typic Haplustepts. The isohyperthermic soil temperature regime is characterised by a mean annual soil temperature exceeding 22°C and a seasonal variation of less than 5°C. In contrast, Pedon 7 was classified as fine-loamy, mixed, isohyperthermic, Typic Halaquepts. It was classified under the suborder Aquepts because prolonged saturation resulted in aquic conditions and redoximorphic features. The great group Halaquepts was assigned owing to the occurrence of a salic horizon or a substantial accumulation of soluble salts within the soil profile. Pedon 9 was classified as a Vertisol because of the presence of a diagnostic vertic horizon characterised by wide and deep seasonal cracks, well-developed slickensides, wedge-shaped aggregates, and a high content of expanding 2:1 clay minerals. The absence of other diagnostic subsurface horizons placed the pedon in the great group Haplusterts, while its typical expression of the great group justified its classification as Typic Haplusterts. At the family level, it was classified as fine, montmorillonitic, isohyperthermic, Typic Haplusterts, indicating a fine particle-size class and the dominance of montmorillonitic clay minerals with pronounced shrink-swell properties. These findings are consistent with observations reported in previous studies (Weil & Brady, 2017; Karthika *et al.*, 2023; Vasu *et al.*, 2023).

4. Conclusion

The soils of the study area exhibited considerable variability in their morphological, physicochemical, and taxonomic characteristics, reflecting the combined influence of parent material, topography, drainage conditions, and pedogenic processes under a semi-arid tropical environment. The soil pedons ranged from moderately deep to very deep and displayed diagnostic horizons such as cambic (Bw), gleyed (Bng), vertic (Bss), and transitional (AC) horizons, indicating different stages of soil development. Soil texture varied from gravelly sandy loam to clay, with a general increase in clay content with depth due to clay illuviation. The soils were neutral to strongly alkaline and non-saline, while organic carbon generally decreased with depth. Cation exchange capacity increased with clay content, highlighting the important role of clay minerals in nutrient retention. Based on USDA Soil Taxonomy, the soils were classified into the orders Entisols, Inceptisols, and Vertisols. At the subgroup level, these orders were represented by Typic Ustorthents, Typic Haplustepts, Typic Halaquepts, and Typic Haplusterts. These taxonomic classes reflect variability in soil-forming processes and environmental conditions across the landscape. Overall, the study provides a comprehensive understanding of soil genesis and spatial variability and generates valuable baseline information for soil resource inventories, land capability assessment, site-specific nutrient management, sustainable land-use planning, and the long-term conservation of soil resources in semi-arid agroecosystems.

5. Limitation

The study was based on ten representative pedons selected across the principal physiographic units of Utkoor Mandal. Consequently, the findings describe the sampled soil–landscape units and may not capture all fine-scale spatial variability within the mandal. The cross-sectional assessment also does not represent seasonal or long-term changes in soil properties. Future studies should therefore include denser spatial sampling and repeated assessments across seasons to improve the resolution and temporal reliability of soil-resource information.

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Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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