International Journal of Energy and Environmental Science
2026, Vol. 11, No. 4, pp. 76–94
https://doi.org/10.11648/j.ijees.20261104.12

Research Article

Soil Resource Characterization, WRB Classification and Mapping of Guto Gida District, Western Oromia, Ethiopia

Amanuel Tadesse Warke*, Chalsissa Takele Sori, Temesgen Chimdessa Deressa, Bikiltu Regasa Sori, Mintesinot Desalegn Eshetu, Amanuel Kejela

Oromia Agricultural Research Institute, Nekemte Soil Research Center, Oromia, Ethiopia

Abstract

Accurate and spatially explicit information on soil properties is essential for sustainable land-use planning and the development of site-specific soil management strategies. This study aimed to characterize, classify, and map the soil resources of the Guto Gida district in Western Oromia, Ethiopia. A semi-detailed soil survey was conducted, delineating 28 Soil Mapping Units (SMUs). Twenty representative pedons were described in the field for morphological attributes and analyzed in the laboratory for key physicochemical properties. The soils were predominantly deep to very deep (>150 cm), except for Leptosols occurring on steep dissected landscapes. Morphologically, most pedons exhibited reddish to reddish-brown hues (2.5YR–5YR), reflecting well-drained conditions and the presence of iron oxides. Soil texture was largely dominated by clay, and low silt: clay ratios (<0.35) indicated advanced weathering and clay translocation. Soil reaction (pH-H_2O) ranged from strongly acidic (4.66 in SMU 26) to slightly acidic (6.36 in SMU 23), with substantial portions of the landscape affected by acidity, as evidenced by high exchangeable acidity values reaching up to 10.49 cmolc kg^{-1}in SMU 27. Organic carbon and total nitrogen contents were generally low to moderate, while available phosphorus was critically low (<10 ppm) in most pedons due to the strong P-fixing capacity of the clay-rich, acidic soils. Based on the World Reference Base for Soil Resources (WRB, 2022), the soils were classified into eight Reference Soil Groups: Nitisols (41.59%), Alisols (14.73%), Cambisols (15.37%), Lixisols (13.95%), Leptosols (4.54%), Luvisols (3.53%), Acrisols (2.89%), and Regosols (0.88%). Overall, soil acidity and nutrient depletion constitute the major limitations to agricultural productivity in the district. Integrated Soil Fertility Management (ISFM), encompassing liming, organic matter enhancement, and site-specific fertilization, is recommended for the strongly acidic Alisols and Acrisols, whereas targeted soil and water conservation strategies are critical for the sloping landscapes dominated by Nitisols and Lixisols.

Keywords

Guto Gida, Soil Acidity, Soil Characterization, Soil Classification, Soil Mapping

*Correspondence: Amanuel Tadesse Warke (amanueltadesse2021@gmail.com)

Received: 8 July 2026; **Accepted:** 21 July 2026; **Published:** 10 August 2026

1. Introduction

Soil is a finite and non-renewable natural resource that supports terrestrial ecosystem functioning and determines the long-term sustainability of agricultural production systems. In Sub-Saharan Africa and particularly within the intensively cultivated Ethiopian highlands, rapid population growth has accelerated pressure on land resources, resulting in continuous cultivation, nutrient mining, and widespread soil degradation [19, 27]. The combined influence of parent material, climate, topography, vegetation, and time has produced a highly heterogeneous soil landscape in Ethiopia, making site-specific soil characterization indispensable for sustainable land management [9].

Ethiopia's economy remains heavily dependent on rainfed agriculture, which supports the livelihoods of more than 80% of its population. However, the country faces severe challenges associated with land degradation. Recent assessments estimate that more than 80% of Ethiopia's land area is affected by soil erosion, nutrient depletion, and declining organic matter [14, 47]. Soil erosion alone contributes to an annual loss of approximately one billion tons of topsoil, undermining agricultural productivity and food security [12, 15]. In this context, sustainable agricultural intensification is widely recognized as essential for meeting future food demands requires precise, spatially explicit information on soil resources in order to guide appropriate land use and management interventions [17, 35].

Soil characterization encompasses the systematic assessment of physical, chemical, and biological attributes that define soil functionality and classification [2]. Properties such as texture, aggregate structure, bulk density, pH, organic matter, cation exchange capacity (CEC), and essential nutrient concentrations (N, P, K) strongly determine soil fertility, water-holding capacity, and crop response [23]. Accurate characterization is therefore fundamental for identifying soil constraints and designing effective soil fertility management strategies.

Soil classification provides a structured framework for grouping soils based on diagnostic horizons, properties, and materials. Globally recognized classification frameworks include the USDA Soil Taxonomy [37, 39] and the World Reference Base for Soil Resources (WRB) [21]. These systems standardize communication among soil scientists and enable the transfer of scientific knowledge across regions. Soil mapping, which delineates the spatial distribution of soil types, is a crucial complement to classification. Advances in digital soil mapping (DSM) have enabled the integration of field observations with remote sensing, digital elevation models (DEMs), climate surfaces, geologic maps, and machine learning algorithms to generate high-resolution soil maps that are essential for precision agriculture and site-specific land management [29, 45, 48].

Despite Ethiopia's long history of soil surveys, high-resolution, district-level soil maps remain limited. Many existing maps were produced at small scales (e.g., 1:1,000,000 or 1:250,000), making them insufficient for local planning and tailored land management interventions [9, 20]. The Guto Gida District in East Wollega Zone is characterized by diverse topography, high agricultural potential, and mixed farming systems. However, scientifically robust, spatially explicit soil studies for the district are scarce. The absence of detailed soil information constrains effective land capability assessment, fertilizer recommendations, soil conservation planning, and sustainable agricultural intensification efforts.

This study was therefore undertaken to fill this critical knowledge gap by generating a comprehensive characterization, classification, and spatial mapping of the soil resources of Guto Gida District following internationally accepted soil survey standards. The outputs of this study provide essential baseline datasets for researchers, policymakers, development planners, extension officers, and farmers, contributing to improved decision-making for sustainable land and soil resource management.

Accordingly, the specific objectives of this study were:

To characterize the key morphological, physical, and chemical properties of the dominant soils across the Guto Gida District.

2. Materials and Methods

2.1. Description of the Study Area

Guto Gida district is situated in the East Wollega Zone of the Oromia Regional State, Western Ethiopia, about 331 km west of the capital, Addis Ababa. Geographically situated between approximately 9°00′00″ to 9°30′00″ N latitude and 36°20′00″ to 36°50′00″ E longitude. The district covers a considerable area in East Wollega Zone of Oromia National Regional State, western Ethiopia, and is located about 328 km west of Addis Ababa. The topography is highly diverse, ranging from gently undulating plains in the central and southern parts to dissected highlands and steep slopes in the northern and eastern fringes, with some valley bottoms along major rivers. Elevations generally vary from 1,350 to 2,450 meters above sea level and bordered by the districts of Digga and Sasigga in the west, Wayu Tuka in the east, Gida Ayana and Limu in the north, and Leka Dulecha in the south. The district's many agroecological zones, which range from warm weather in low-altitude regions (like Uke FA) to cooler weather in higher-altitude regions (like Negasa FA), provide an environment that is favorable for growing a variety of crops. The predominant crops in the area are maize, Tef, sorghum, wheat, and horticultural crops. The area's economy depends on a mixed cropping system and livestock rearing agricultural production system.

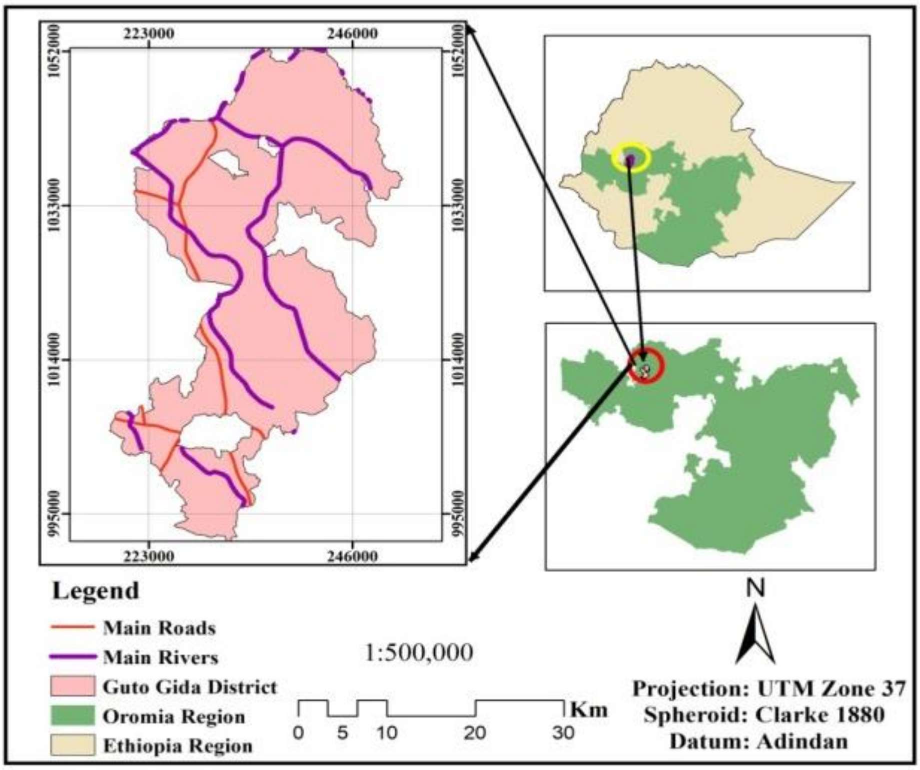

Figure 1. Map the of the study area.

2.2. Climate

The climatic condition of the area includes highland (dega) (0.26%), midland (woynadega) (46.74%) and lowland (bereha) (53%) with the mean annual rainfall ranging from 1800- 2200 mm and average temperature 16°C to 31°C. The area receives bimodal rainfalls that were long rainy season (June to September) and short rainy season (March, April and May).

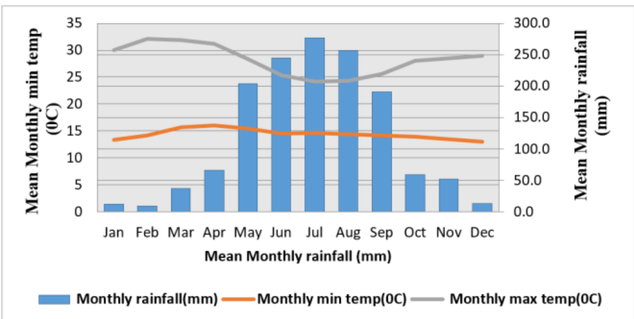

Figure 2. Mean monthly rainfalls and maximum and minimum temperature of Guto Gida district.

2.3. Land Use and Land Cover

In Guto Gida District, land use and land cover are predominantly characterized by farmland, which occupies the largest proportion of the district. Other important land use categories include settlement areas, bare land, and forest land. The dominance of agricultural land reflects the strong dependence of the local community on crop production and mixed farming systems for their livelihood [31, 42].

A land use and land cover change study conducted between 1990 and 2020 revealed substantial changes in the district's landscape. Forest cover declined significantly from 12.1% in 1990 to 2.6% in 2020, indicating severe deforestation over the study period. In contrast, farmland and settlement areas expanded considerably. These changes were mainly driven by socio-economic pressures such as population growth, agricultural expansion, and increasing demand for settlement land. Consequently, the district experienced considerable landscape fragmentation and environmental degradation [24, 25].

2.4. Soil Genesis

The soil genesis in Guto Gida district is primarily influenced by high rainfall and the local topography, leading to the formation of heavily leached, acidic soils, generally classified as Nitisols. Because of the differences in topography, soils grown on extremely steep terrain and soils developed on flat terrain are not the same. On extremely steep terrain, a very shallow soil, or Leptosols, is clearly anticipated due to the parent material's minimal interaction with moisture or precipitation. The steepness prevents water from penetrating since it flows off the surface. Consequently, there is less chemical weathering, which results in poorly developed soil. Conversely, soils on level terrain are typically deeper and more developed. The kind, nature, and characteristics of the soils are also influenced by the parent materials from which they originate. For instance: 1) If the other soil-forming elements remain constant, soil formed from fine-grained, basic volcanic rock (basalt) and soil formed from the parent material of sandstone will not have the same chemical and physical characteristics, such as texture, color, soil reactivity, etc. 2) Soils from wet regions with healthy vegetation differ greatly from those from arid regions with little vegetation and moisture. The size of the particles has shrunk with comparatively little change in composition under arid conditions when physical forces predominate. Minerals that require water for synthesis are less common than the original fundamental minerals. Only slight chemical action occurs in conjunction with physical changes brought on by temperature variations and wind. As a result, the soils found in arid areas resemble their parent materials quite closely a bit [34].

As was previously mentioned, it is evident that the district soils vary depending on how their genesis is impacted by the importance of the soil-forming elements. The district receives the most rainfall each year, which hastened the parent rocks' chemical weathering and led to the creation of older, more deeply weathered soils including Nitisols, Acrisols, and Lixisols. Conversely, the district's steep and extremely steep regions have comparatively shallower soils due to topographic constraints that prevent the parent material from interacting with precipitation or moisture, resulting in the formation of Leptosols and Cambisols, which have limited depth and profile development

2.5. Research Design and Procedures

2.5.1. Pre-field Survey

Before beginning the fieldwork, office tasks such as creating soil mapping units were completed by using ArcGIS 10.8 to overlay Ethiopia's geomorphological soil and slope classes (Figure 3). Global Mapper 30.2 software was used to create the slope classes from a digital elevation model (DEM) with a resolution of 30 meters. All predetermined auger observations and profile pit locations were found and downloaded to a Google Earth map and global positioning system (GPS) for the final fieldwork. This stage involved gathering and preparing the necessary formats and instruments for soil surveys. These included the WRB soil classification manual [21], Munsell soil color charts, GPS, sheets outlining soil profiles and augers, and FAO guidelines for auger and soil profile descriptions [12].

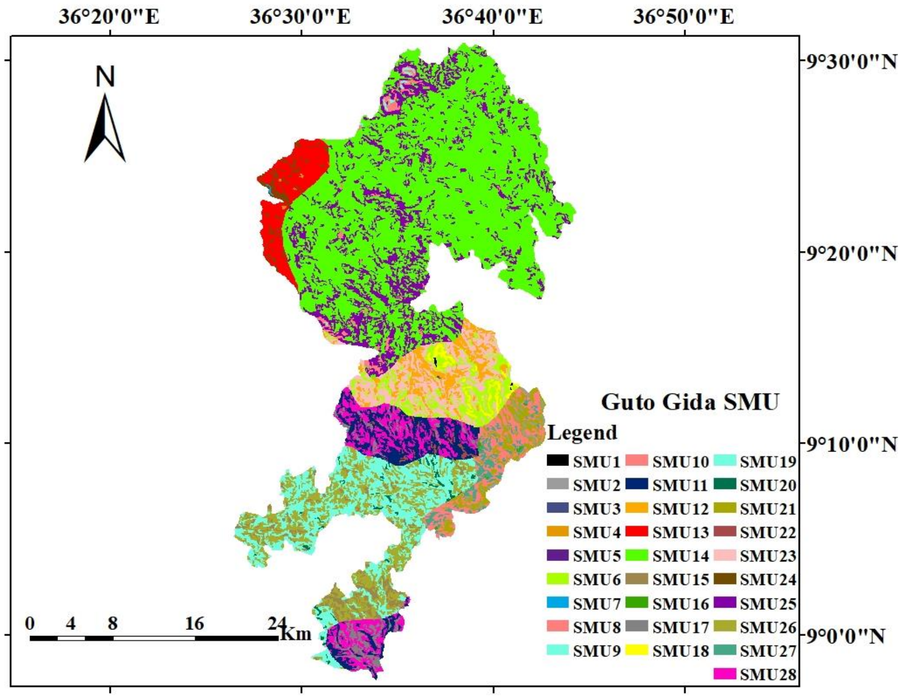

Figure 3. Soil mapping units of the Guto Gida district.

2.5.2. Field Survey

In the field, soil profiles and auger observations were used to describe and sample the soil. Utilizing traverses that crossed several physiographic units within each Soil Map Unit (SMU), reconnaissance surveys were carried out utilizing generated base maps and a free survey methodology. For each SMU, at least ten auger observations were made. Elevation, landform, slope, micro-topography, land use, vegetation, parent material, rock outcrops, stoniness, surface cracking and crusting, erosion status, drainage, and flooding conditions were all recorded at each location in accordance with FAO criteria [11-13]. Soil morphological properties such as depth, color, texture, structure, horizon development, and stoniness were also measured. Additionally, one soil profile pit with dimensions of 1.5 m × 2 m was excavated to a depth of 2 m in each soil mapping unit (SMU). These profiles were used to provide a comprehensive field description and to collect samples from genetic horizons for physical and chemical analysis. Pedogenetic variables were recorded for each pit, and a preliminary classification was assigned using the World Reference Base (WRB). In total, 87 soil samples were collected, air-dried, and sieved for standard laboratory analysis.

2.5.3. Post-Field Survey

Sample preparation, laboratory analysis, and final soil classification and mapping were the main post-field tasks. After being collected in the field, soil samples were brought to the lab, allowed to air dry, and then sieved using a 2 mm screen. Standard laboratory procedures were followed in the analysis of specific physical and chemical parameters. The World Reference Base for Soil Resources [21] was used to modify the original field classifications based on the analytical data. A final soil map for end users was created by mapping the spatial distribution of soils through the correlation of soil parameters with landscape features.

2.6. Soil Sample Preparations and Analyses

Following conventional protocols, 87 disturbed soil samples were air-dried, crushed to fit through a 2 mm filter, and prepared for physicochemical analysis. The Bouyoucos hydrometer method [4] was used to determine soil texture, and the soil texture triangle was used to assign textural classes. The method described by [43] was used to assess soil pH potentiometrically in a 1:2.5 soil-to-water solution. The wet oxidation method was used to measure organic carbon [46]. Exchangeable bases (Ca^{2+}) and Mg^{2+}) were analyzed using the EDTA titration method, Exchangeable potassium (K^+) and sodium (Na^+) were extracted with a 1 M ammonium acetate (NH_4OAc) solution at pH 7.0 [43]. Total exchangeable acidity was determined by saturating the soil samples with a 1 M KCl solution, followed by titration with 0.02 M NaOH, as described by [43]. Finally, Percent Base Saturation (PBS) was calculated as the ratio of the sum of exchangeable bases to the Cation Exchange Capacity (CEC), expressed as:

$$PBS = \frac{(Na+Ca+Mg+K)*100}{CEC}$$

Table 1. *Soil laboratory analysis methods.*

S.N	Soil Parameter		Unit	Methods (Extraction/Analysis)
1	Particle size distribution		%	Hydrometer
2	Bulk density		$gmcm^{-3}$	Core sampling
3	Soil pH		pH meter	Soil: H_2O ratio 1:2.5/Potentiometric
4	OC		%	Wet-Oxidation (Walkley-Black)/Titration
5	TN		%	Kjeldahl /Titration
6	Available P		$mgkg^{-1}$	Olsen’s/Spectrophotometric
7	Exchangeable bases	Na, K	$Cmol_{(+)}kg^{-1}$	Ammonium Acetate/Flame photometer
		Ca, Mg	$Cmol_{(+)}kg^{-1}$	EDTA method
8	CEC		$Cmol_{(+)}kg^{-1}$	Ammonium Acetate/Distillation-Titration
9	Exchangeable Acidity (Al, H)		$Cmol_{(+)}kg^{-1}$	KCl/Titration

2.7. Statistical Data Analysis

Descriptive statistics and other statistical analysis were performed. To ascertain the spatial variability of soil parameters, geostatistical analyses was carried out using the dissolve technique with the ArcGIS 10.8 software package. This study's conceptual model, a discrete model of spatial variation, is predicated on the idea that the landscape can be separated into discrete polygons of "natural" soil bodies.

3. Results and Discussion

3.1. Site Characteristics of Soil Mapping Units in the Study Area

The soil mapping units (SMUs) of Guto Gida district show clear variation in elevation, slope, topographic position, drainage, and land use, all of which strongly influence soil formation and distribution. Elevation ranges from 1360 to 2250 m a.s.l, indicating a transition from lower foot-slope landscapes to higher back- and shoulder-slope areas. Slope gradients vary from nearly level (0–2%) in SMU4 and SMU5 to very steep (32–60%) in SMU20 and SMU21, showing the presence of both depositional and erosional environments. Nearly level foot slopes typically accumulate sediments and favor deeper soils, whereas steep back-slopes promote runoff and soil loss, often limiting soil depth.

Most SMUs are well drained, indicating good water percolation and aeration, with the exception of moderately drained units (SMU9 and SMU17) where foot-slope positions slow subsurface flow. Land use corresponds strongly with terrain. Gentle and moderately sloping areas (SMU4, SMU5, SMU12, and SMU13) are mainly cultivated, while steep slopes and erosion-prone zones (SMU8, SMU20, and SMU28) are used for mining or fallow. Higher elevation units such as SMU21 and SMU26 support plantation lands, and SMU9 is used mainly for extensive grazing as shown in Table 2 Overall, topography is the dominant factor controlling soil distribution, drainage conditions, and land-use suitability across the district.

Overall, the spatial arrangement of topography, slope gradient, and land-use types indicates that the pedological environment of Guto Gida district is shaped by strong topographic control, which governs moisture distribution, soil erosion intensity, drainage patterns, and land-use suitability.

Table 2. Selected site characteristics of soil mapping units in Guto Gida district.

SMU	Locations		Elevation (m a.s.l)	Slope (%)	Slope form	Slope Position	Drainage class	Land use
	Latitude (N)	Longitude (E)						
4	9.41044	36.52250	1361	0-2	LL	Foot Slope	Well drained	Fallow
5	9.35564	36.53124	1372	0-2	LL	Foot Slope	Well drained	Cultivation
6	9.26167	36.52124	1553	16-32	CV	Toe Slope	Well drained	Mining
8	9.27559	36.51475	1515	16-32	VV	Shoulder Slope	Well drained	Mining
9	9.02446	36.54021	2032	16-32	LL	Foot Slope	Moderately drained	Extensive grazing
10	9.10729	36.61888	2248	16-32	VL	Back Slope	Well drained	Shrub land
11	9.00798	36.53165	1994	16-32	VL	Back Slope	Well drained	Cultivation
12	9.26332	36.51887	1576	2-8	VL	Foot Slope	Well drained	Cultivation
13	9.30705	36.49262	1413	2-8	CL	Back Slope	Well drained	Cultivation
14	9.33229	36.51145	1379	2-8	LC	Back Slope	Well drained	Cultivation
15	9.02701	36.53368	2060	2-8	VL	Foot Slope	Well drained	Cultivation
17	9.00206	36.54334	1982	2-8	LL	Foot slope	Moderately drained	Cultivation
20	9.01346	36.52963	2027	32-60	VV	Back Slope	Moderately drained	Cultivation
21	9.11639	36.63938	2138	32-60	VV	Foot Slope	Well drained	Plantation Land
23	9.26470	36.51823	1570	8-16	VL	Back Slope	Well drained	Cultivation
24	9.34377	36.48190	1378	8-16	CC	Foot Slope	Well drained	Cultivation
25	9.28313	36.51340	1444	8-16	CC	Foot Slope	Well drained	Cultivation
26	9.10406	36.50373	2020	8-16	VC	Back Slope	Well drained	Plantation Land
27	9.10099	36.61122	2195	8-16	VC	Back Slope	Well drained	Cultivation
28	8.975885	36.559283	1922	8-16	LC	Back Slope	Well drained	Fallow

3.2. Morphological Properties of Soils

Field morphology across pedons shows well-developed B horizons (argic/Bt with clay accumulation) in many SMUs (e.g., Bt1–Bt4 horizons), consistent with clay accumulation and strong subsoil structure. Many topsoils are 20–40 cm thick with granular to sub angular blocky structure; subsoil structures ranged from strong sub angular blocky to very fine platy and massive in some horizons (detailed in Table 3).

3.2.1. Colors

The dominant soil colors were reddish-brown to dark red (hues 2.5YR and 5YR). For instance, the subsoil of SMU 14 (Nitisols) and SMU 5 exhibited colors of 2.5YR 3/6 (moist). This vivid redness is attributed to the presence of unhydrated iron oxides (hematite), which form under conditions of good drainage and high aeration [9]. The colors of surface horizons at dry were red, dark reddish brown, dark reddish gray, yellow red, dark red, brown, dusky red, very dusky red, mostly at moist the color was changed to dark reddish brown and three of them changed to very dusky red, and other changed to dusky red, dark brown, brown and black. Whereas the color of the subsurface horizon at dry and moist varied from reddish black (2.5YR 2.5/1) to dark red (10R 3/6) (Table 3). The surface horizons were darker as compared to subsurface horizons that mainly could be due to accumulation and decomposition of organic materials and specific process of mineralization that related to addition process of organic matter to the soil.

3.2.2. Structure

The subsurface horizons (Bt) of many pedons (e.g., SMU 5, 14, 28) displayed strong angular to sub-angular blocky structures with shiny ped faces. This "nutty" structure is diagnostic of *Nitic* horizons, which break into polyhedral elements with shiny cutans, characteristic of Nitisols in the Ethiopian highlands. The structure of the surface horizons ranged from weak (WE) to strong (ST) in grade. Very fine (VF) to coarse (CO) sizes and dominated by granular (GR) angular blocky (AB) in its type (Table 3).

3.2.3. Soil Depth

Most soils (SMU 4, 5, 9, 14, 28) were very deep (>200 cm), indicating a long period of weathering and stability. Conversely, SMU 6 and SMU 21 were shallow (<50-60 cm), classified as *Leptosols*, located on steep slopes (16-60%) where erosion exceeds soil formation. Fourteen soil-mapping units had soil depths ≥200 cm, five of soil mapping units had <200 cm depth. Twelve of soil mapping units had a Bt horizon, four of soil mapping unit has a C horizon (SMU 4, 6, 20 and 23) as well as one soil map unit was registered as regosol (SMU,8) (Table 3).

3.2.4. Consistency

The consistency of the soil of the study area at dry ranges from loose (LO) to very hard VHA) but in most case it has hard consistency due high clay content of soil and also at moist friable (FR) and firm (FI). It was non sticky (NST) to very sticky (VST) consistency at wet (Table 3). This change in consistency associated with a change in texture. The root abundance decreased with depth, many at surface and mostly few roots at lower horizons. The horizon boundaries characterized by clear, gradual, diffuse and smooth topography in different soil mapping units (Table 3).

Table 3. *Morphological description of soil map units (SMU) of Guto Gida district.*

SMU	Depth (cm)	Horizon	Color		Structure grade/size/ Type	Consistency			Root abundance/ Size	Boundary Distinct/ Topography
			Dry	Moist		Dry	Moist	Wet		
	0-26	Ah	2.5YR3/3	5YR3/3	MO/F/GR	SO	FR	SST/NPL	M/F-M	C/S
GG4	26-66	Bt1	2.5YR5/6	2.5YR3/6	ST/F/GR	HA	FR	ST/SPL	F/VF	D/S
	60-95	Bt2	10R5/8	2.5YR3/6	ST/VF/AB	VHA	FI	ST/PL	F/VF	D/S
	95-130	Bt3	10R4/6	10R 3/6	ST/VF/AB	VHA	FI	VST/PL	N	D/S
GG5	0-29	Ap	2.5YR2.5/4	7.5R2.5/4	MO/FI/AB	SO	FR	NST/NPL	ME/CO	G/S
	29-66	Bt1	10R3/4	7.5R2.5/3	ST/FI/AB	SHA	FR	SST/SPL	F/VF	D/S
	66-100	Bt2	10R4/8	10R4/6	ST/VF/AB	SHA	FR	SST/SPL	F/VF	D/S
	100-132	Bt3	10R3/6	10R4/6	ST/VF/AB	HA	FI	ST/PL	N	D/W
	132-200+	Bt4	2.5YR4/6	10R4/6	ST/VF/AB	EHA	FI	VST/PL	N	D/W
	0-26	Ah	7.5YR4/3	10YR2/1	WE/FI/GR	SHA	FR	ST/PL	F/VF	C/W
GG6	26-50	BC	7.5YR3/3	5YR2.5/1	WE/FI/GR	SHA	FI	ST/PL	N	D/S

SMU	Depth (cm)	Horizon	Color		Structure grade/size/ Type	Consistency			Root abundance/ Size	Boundary Distinct/ Topography
			Dry	Moist		Dry	Moist	Wet		
	0-30	Ah	7.5R2.5/4	5YR2.5/2	MO/CO/GR	LO	VFR	NST/SPL	M/ME	D/S
GG9	30-70	AB	7.5R3/3	7.5R2.5/3	MO/FI/GR	SO	VFR	SST/SPL	C/F	C/S
	70-110	Bt1	2.5YR3/3	2.5YR3/4	WE /FI/GR	SHA	FR	ST/PL	F/VF	C/S
	110-145	Bt2	2.5YR3/4	7.5R3/6	ST/VF/AB	HA	FI	ST/PL	N	D/S
	145-200+	Bt3	2.5YR4/4	7.5R3/4	ST/VF/AB	HA	FI	ST/PL	N	NB
	0-40	Ah	2.5YR3/4	7.5R2.5/3	MO/FI/GR	SHA	FR	SST/SPL	M/C	G/S
	40-88	Bt1	5YR3/3	2.5YR3/4	ST/FI/AB	HA	FR	SST/SPL	F/VF-F	D/S
GG10	88-109	Bt2	2.5YR5/6	10R3/4	ST/FI/AB	HA	FR	ST/PL	VF/VF	D/S
	109-148	Bt3	2.5YR2.5/1	10R4/4	ST/FI/AB	HA	FI	ST/PL	N	D/S
	148-200+	Bt4	2.5YR4/4	2.5YR2.5/1	ST/FI/AB	HA	FI	ST/PL	N	NB
	0-30	Ah	2.5YR4/4	2.5YR3/2	MO/CO/GR	LO	VFR	NST/NPL	M/F	C/S
GG11	30-60	Bt1	10R3/6	2.5YR3/2	SO/FI/AB	SO	VFR	SST/SPL	F/VF	C/S
	60-95	Bt2	10R4/4	2.5YR3/4	SHA/FI/AB	SHA	FR	ST/PL	VF/VF	G/S
	95-127	Bt3	7.5YR2.5/3	5YR4/3	SHA/FI/AB	SHA	FR	ST/PL	N	D/S
	127-200+	Bt4	10R3/3	5YR3/3	SHA/VF/AB	HA	FI	VST/VPL	N	NB
	0-27	Ap	5YR3/2	7.5R2.5/4	SHA/ME/AB	SHA	VFR	NST/NPL	F/VF	D/S
GG12	27-50	B1	5YR4/6	2.5YR3/4	MO/FI/AB	HA	VFR	NST/SPL	VF/VF	D/S
	50-80	B2	10R4/8	2.5YR4/6	MO/VF/AB	HA	FR	SST/SPL	N	G/W
	80-110	B3	10R4/4	2.5YR4/4	MO/VF/AB	HA	FR	SST/SPL	N	D/S
	110-200+	B4	10R4/6	2.5YR4/6	MO/VF/AB	HA	FR	SST/SPL	N	NB
GG13	0-24	Ap	2.5YR4/6	2.5YR3/2	ST/FI/AB	SHA	VFR	ST/NPL	M/F	C/S
	24-44	AB	10R3/6	2.5YR4/6	ST/FI/AB	SHA	FR	SST/SPL	C/F	C/S
	44-66	Bt1	10R4/6	2.5YR4/6	ST/ME/AB	HA	FR	ST/PL	F/VF	D/S
	66-90	Bt2	10R3/6	2.5YR3/6	ST/ME/AB	VHA	FI	ST/PL	N	D/S
	90-200+	Bt3	10R3/6	2.5YR3/6	ST/ME/AB	VHA	VFI	VST/PL	N	D/S
	0-13	Ap	7.5YR4/4	7.5YR3/3	ST/ME/SAB	SHA	FR	ST/SPL	M/VF	D/S
GG14	13-30	AB	2.5YR3/6	2.5YR4/3	ST/CO/SAB	HA	FI	SST/SPL	F/VF	D/S
	30-60	Bt1	10R4/6	2.5R4/6	ST/CO/SAB	HA	FI	ST/PL	N	D/S
	60-200+	Bt2	2.5YR4/6	2.5YR4/6	MO/FI/SAB	HA	FI	ST/PL	N	D/W
	0-16	Ap	7.5YR3/3	2.5YR2.5/2	WE/FI/GR	SHA	VFR	NST/NPL	M/VF	D/S
GG15	16-35	AB	2.5YR2.5/3	7.5R2.5/3	WE/FI/GR	SHA	VFR	NST/NPL	F/VF	C/W
	35-74	Bt1	2.5YR4/2	7.5R2.5/3	WE/FI/GR	SHA	FR	SST/SPL	N	C/W
	74-102	Bt2	2.5YR4/4	2.5YR2.5/4	WE/FI/GR	HA	FI	SST/SPL	N	D/S
	102-135	Bt3	10R3/4	5YR4/6	WE/FI/GR	HA	FI	SST/PL	N	D/S
	135-200+	Bt4	2.5YR3/6	2.5YR4/4	ST/FI/GR	VHA	FI	ST/PL	N	NB
	0-23	Ah	7.5YR4/6	7.5R3/3	MO/FI/AB	SHA	VFR	SST/SPL	M/VF	G/S
GG17	23-45	AB	10R3/3	5YR3/4	MO/FI/AB	SHA	FR	SST/SPL	F/VF	D/S

SMU	Depth (cm)	Horizon	Color		Structure grade/size/ Type	Consistency			Root abundance/ Size	Boundary Distinct/ Topography
			Dry	Moist		Dry	Moist	Wet		
	45-93	Bt1	2.5YR4/4	7.5YR3/4	ST/ME/AB	HA	FR	ST/PL	F/VF	D/W
	93-112	Bt2	2.5YR3/6	5YR3/4	ST/ME/AB	HA	FR	ST/PL	N	G/S
	112-200+	Bt3	10R4/6	2.5YR3/6	MO/ME/AB	HA	FI	ST/PL	N	D/S
GG20	0-13	Ap	2.5YR3/4	5YR3/4	ST/ME/AB	LO	LO	SST/SPL	M/F	G/S
	13-23	AB	2.5YR3/4	2.5YR3/4	ST/ME/AB	SO	VFR	ST/SPL	M/VF	C/S
	23-42	B	10R3/4	2.5YR3/6	ST/ME/AB	SO	VFR	ST/SPL	C/VF	G/S
	42-60	BC	10R3/4	2.5YR3/6	ST/ME/AB	SO	VFR	SST/SPL	F/VF	C/S
GG21	0-14	Ap	10R3/2	7.5YR3/3	ST/FI/GR	HA	FR	NST/NPL	M/C	C/S
	14-19	Bt2	2.5YR4/6	2.5YR3/4	ST/FI/AB	HA	FI	SST/SPL	M/C	D/S
	19-25	Bt3	2.5YR4/4	7.5YR4/4	ST/FI/AB	HA	FI	SST/SPL	M/F	C/S
GG23	0-29	Ap	10YR 4/3	2.5YR2.5/2	WE/CO/GR	SO	LO	SST/SPL	M/C	C/S
	29-50	AB	5YR 4/4	10R3/4	WE/CO/GR	SO	VFR	SST/SPL	M/C	C/S
	50-75	AB	5YR 5/6	7.5R3/6	WE/CO/AB	SHA	FR	ST/SPL	F/F	D/S
	75-100	BC	2.5YR 4/6	7.5R3/6	WE/CO/AB	SHA	FR	ST/PL	F/F	D/W
	0-25	Ap	5YR3/4	7.5R2.5/3	MO/ME/GR	SO	FR	NST/NPL	M/F	C/W
GG24	25-55	AB	2.5YR4/6	7.5YR3/6	MO/ME/SAB	SHA	FR	SST/SPL	F/VF	C/S
	55-100	B1	10R4/6	5YR3/4	ST/ME/SAB	SHA	FR	SST/SPL	F/VF	D/S
	100-150	B2	10R3/6	2.5YR3/6	ST/MO/AB	HA	FI	ST/PL	N	D/S
	150-200+	B3	7.5R3/4	2.5YR4/4	ST/MO/AB	HA	FI	ST/PL	N	NB
	0-20	Ap	5YR4/3	5YR3/2	ST/FI/GR	HA	FI	ST/PL	M/F	C/S
	20-40	AB	2.5YR3/4	7.5R3/6	ST/FI/GR	SO	FI	SST/PL	F/VF	C/S
GG25	40-59	Bt1	5YR4/2	10R5/8	MO/FI/AB	SO	FR	SST/SPL	N	D/S
	59-93	Bt2	5YR3/4	10R5/8	MO/VF/AB	SO	FR	SST/SPL	N	G/S
	0-13	Ah	5YR4/6	5YR5/4	WE/FI/GR	LO	FR	NST/NPL	M/VF	G/S
GG26	13-36	AB	2.5YR2.5/4	5YR3/2	WE/FI/GR	SO	FR	NST/NPL	F/VF	C/W
	36-75	Bt1	5YR4/6	2.5YR3/4	ST/FI/AB	SHA	FR	SST/SPL	N	C/W
	75-122	Bt2	5YR4/6	2.5YR4/4	ST/VF/AB	HA	FI	ST/PL	N	C/S
	122-200+	Bt3	2.5YR3/6	2.5YR4/6	ST/VF/AB	HA	FI	ST/PL	N	NB
	0-24	Ap	7.5YR4/4	2.5YR2.5/4	ST/ME/GR	HA	FR	ST/PL	M/F	G/S
GG27	24-55	ABt1	5YR3/4	2.5YR2.5/4	ST/ME/GR	SHA	FR	ST/PL	M/F	D/S
	55-80	Bt2	7.5R4/6	2.5YR3/6	SHA/ME/AB	SHA	FR	ST/PL	N	D/S
	80-143	Bt3	2.5YR4/6	2.5YR4/6	SHA/MO/AB	SHA	VFR	ST/SPL	N	D/W
	143-200+	Bt4	7.5R4/6	2.5YR4/6	SO/MO/AB	SO	VFR	ST/SPL	N	NB
	0-12	Ah	5YR4/6	2.5R3/3	MO/VF/GR	SHA	FR	SST/SPL	M/F	G/S
GG28	12-23	AB	2.5YR5/6	2.5YR3/4	MO/VF/GR	SHA	FR	SST/SPL	M/VF	G/S
	23-38	Bt1	2.5YR4/6	2.5YR4/4	MO/VF/AB	SHA	FR	ST/SPL	C/VF	C/S
	38-60	Bt2	2.5YR4/6	5R3/4	ST/VF/AB	HA	FI	ST/PL	F/VF	D/S

SMU	Depth (cm)	Horizon	Color		Structure grade/size/ Type	Consistency			Root abundance/ Size	Boundary Distinct/ Topography
			Dry	Moist		Dry	Moist	Wet		
	60-95	Bt3	2.5YR3/6	2.5YR3/4	ST/VF/AB	HA	FI	ST/PL	VF/VF	D/S
	95-200+	Bt4	5YR4/4	10R3/4	ST/VF/AB	HA	FI	ST/PL	N	NB

Where: SMU = soil mapping unit, SO = soft, SHA = slightly hard, MO= moderate, CO=Common, FR=friable, WE = Weak, ST = strong, ME = medium, FI = Fine, M = medium, GR = Granular, AB= Angular blocky, SAB=Strong Angular Blocky, PL= platy, VF= very fine, F = Fine, C= Clear, S= smooth, NB = no boundary, D = diffuse, G = gradual, SB=sub-angular blocky, SST=slightly sticky, SPL= slightly plastic, FR=Friable, FI=Firm

3.3. Soil Physical Properties of the Study Area

3.3.1. Bulk Density (BD) and Total Porosity

Bulk density is an indicator of soil compaction and its values across the soil mapping units (SMUs) ranged from 0.91 ± 0.16 g cm^{-3} in SMU6 to 1.35 ± 0.06 g cm^{-3} in SMU25, indicating substantial variation in soil compaction and structural development. SMUs with lower BD particularly SMU6 (0.91 ± 0.16 g cm^{-3}), SMU27 (1.06 ± 0.10 g cm^{-3}), and SMU10 (1.04 ± 0.08 g cm^{-3}) generally reflect relatively higher organic matter content or well-developed aggregation, which enhances pore space and improves aeration [5, 18, 36]. In contrast, SMU25 exhibited the highest BD (1.35 ± 0.06 g cm^{-3}), falling near the critical threshold (>1.40 g cm^{-3}) that can restrict root elongation and reduce infiltration [6, 22]. Moderately high bulk densities in SMU11 (1.28 ± 0.11 g cm^{-3}) and SMU24 (1.17 ± 0.10 g cm^{-3}) suggest greater clay content or compaction within subsoil Bt horizons, consistent with their field-observed clayey textures (≥74% clay, Table 4). The predominance of clayey horizons in most SMUs explains the relatively narrow BD range (1.02–1.28 g cm^{-3}), since clay-rich soils naturally exhibit lower particle density and higher micro porosity [38].

Porosity showed an inverse relationship with BD, varying from 49.06 ± 2.29% in SMU25 to 65.66 ± 5.87% in SMU6. The highest porosity in SMU6 (65.66%), SMU27 (60.0%), and SMU10 (60.68%) is consistent with their lower BD values and improved aggregation in surface horizons. Conversely, SMU25 (49.06%) and SMU11 (51.62%) displayed the lowest porosities, reflecting compaction, high clay content, and reduced structural stability [30]. Values above 60%, as observed in SMUs 6, 10, 12, 20, and 27, indicate highly porous soils favorable for root aeration and water movement. Porosity < 50% (e.g., SMU25) signals restricted pore geometry, often linked to high compaction or sodicity [12, 22].

3.3.2. Moisture Content (%)

Moisture content exhibited wide variability, ranging from 12.93 ± 7.63% in SMU25 to 33.42 ± 3.17% in SMU10 and 33.37 ± 4.63% in SMU12. SMUs with higher clay proportions such as SMU10 (51.6% clay) and SMU9 (72.8% clay) demonstrated higher moisture retention due to greater micro porosity and adsorptive capacity of clay minerals [18]. Exceptionally high moisture content in SMU21 (39.7 ± 12.31%) and SMU27 (32.9 ± 7.49%) also indicates strong water-holding capacity from the dominance of clayey horizons. In contrast, SMU25 (12.93%) and SMU23 (16.78%) showed relatively low moisture, consistent with their lighter textures (e.g., SMU23: 38.5% sand; SMU25: 36.0% sand).

3.3.3. Texture

Sand content was highly variable (15.60–48.00%), with the highest mean observed in SMU6 (48.00 ± 5.66%) and SMU23 (38.50 ± 8.70%), reflecting coarser textures and improved drainage (Table 4). Conversely, the lowest sand content was recorded in SMU24 (14.80 ± 11.54%), SMU5 (16.00 ± 2.45%), and SMU9 (18.40 ± 3.58%), which corresponded to highly developed clay-rich subsoils. Silt contents were generally low across all SMUs (8.8–28.0%). The highest silt values were found in SMU6 (28.0 ± 2.83%), SMU10 (21.6 ± 5.90%), and SMU23 (21.0 ± 4.76%), contributing to their loam or clay loam classifications. Low silt contents (<10%) in SMU9, SMU24, SMU25 suggest dominance of either sand or clay, which affects workability. Clay content was extremely high across most SMUs, ranging from 24.0 ± 8.49% in SMU6 to 76.0 ± 12.41% in SMU24 (Table 4). SMUs 4, 5, 9, 11, 13, 14, 15, 17, 20, 24, and 28 exhibited clay contents exceeding 60%, characteristic of Bt horizons with pronounced illuviation. High clay content improves moisture retention but increases shrink–swell behavior [3, 32]. Textural classes were predominantly clay, with occasional clay loam and sandy clay loam in SMUs such as SMU6, SMU21, SMU23, and SMU28 (Table 4). These differences imply contrasting hydrological behavior: Clayey SMUs (the majority) exhibit high water retention, slow infiltration, and high shrink–swell potential. Soils with coarser textures show better drainage, lower water-holding capacity, and improved aeration.

3.3.4. Silt to Clay Ratio (Si:C)

The Si:C ratio is a standard index for soil weathering. Ratios<0.20 often indicate intense weathering and clay accumulation, while values > 0.50 suggest moderate weathering. The Si:C ratio ranged from 0.13 ± 0.04 in SMU24 and 0.13 ± 0.08 in SMU9 to as high as 1.27 ± 0.57 in SMU6(Table 4). SMUs with low Si:C (<0.20) SMU4, SMU5, SMU9, SMU11, SMU13, SMU14, SMU24 show strong clay illuviation and advanced pedogenic weathering. SMUs with moderate Si:C (0.30–0.60) SMU10, SMU15, SMU17, SMU21, SMU23 indicate mixed particle-size development. SMU6 (1.27 ± 0.57) showed the highest Si:C ratio, reflecting a much coarser, less weathered profile, consistent with its classification as a Leptosols (Tables 6).

Table 4. *Descriptive Statistics (Mean±standard deviation) of soil physical properties of soil mapping units of the study area.*

SMU	Horizons	Bulk density	Porosity	Moisture content	Sand	Silt	Clay	Si:C
SMU4	4	1.03 ± 0.04	61.32 ± 1.46	25.14 ± 5.16	20.50±6.61	13.5±3.42	66.0±8.49	0.21±0.08
SMU5	5	1.1 ± 0.04	58.34 ± 1.52	28.0 ± 3.2	16.00±2.45	12.8±5.22	71.2±7.56	0.19±0.11
SMU6	2	0.91 ± 0.16	65.66 ± 5.87	23.82 ± 4.47	48.00±5.66	28.0±2.83	24.0±8.49	1.27±0.57
SMU9	5	1.1 ± 0.05	58.64 ± 1.72	32.6 ± 3.58	18.40±3.58	8.8±5.4	72.8±8.32	0.13±0.08
SMU10	5	1.04 ± 0.08	60.68 ± 3.2	33.42 ± 3.17	26.80±9.76	21.6±5.9	51.6±14.45	0.49±0.31
SMU11	5	1.28 ± 0.11	51.62 ± 4.27	29.38 ± 2.33	22.00±2.00	12.0±3.74	66.0±4.69	0.19±0.06
SMU12	5	1.0 ± 0.03	62.19 ± 1.26	33.37 ± 4.63	25.60±10.81	12.4±6.84	62.0±17.38	0.26±0.28
SMU13	5	1.04 ± 0.11	60.83 ± 4.04	26.43 ± 4.18	15.60±5.55	12.0±4.69	72.4±9.32	0.18±0.1
SMU14	4	1.03 ± 0.08	61.23 ± 3.15	23.71 ± 9.21	18.00±1.63	13.0±4.76	69.0±6.0	0.19±0.09
SMU15	6	1.16 ± 0.11	56.42 ± 4.07	25.2 ± 9.47	20.33±3.88	16.67±9.52	63.0±11.58	0.3±0.23
SMU17	5	1.13 ± 0.08	57.36 ± 3.08	30.32 ± 2.93	22.00±4.24	16.0±5.83	62.0±9.8	0.28±0.15
SMU20	4	1.02 ± 0.08	61.42 ± 3.15	25.09 ± 4.94	28.00±4.90	11.0±2.0	61.0±4.16	0.18±0.03
SMU21	3	1.12 ± 0.09	57.74 ± 3.29	27.83 ± 12.31	33.33±11.02	22.0±5.29	44.67±15.28	0.57±0.33
SMU23	4	1.11 ± 0.13	58.02 ± 4.92	16.78 ± 4.69	38.50±8.70	21.0±4.76	40.5±13.3	0.61±0.36
SMU24	5	1.17 ± 0.1	55.92 ± 3.73	28.79 ± 3.1	14.80±11.54	9.2±1.79	76.0±12.41	0.13±0.04
SMU25	4	1.35 ± 0.06	49.06 ± 2.29	12.93 ± 7.63	36.00±16.57	9.5±1.0	54.5±16.6	0.19±0.07
SM26	5	1.0 ± 0.11	62.26 ± 4.05	29.1 ± 13.38	29.20±8.44	23.6±6.23	47.2±13.97	0.56±0.26
SMU27	5	1.06 ± 0.1	60.0 ± 3.88	32.9 ± 7.49	21.20±12.21	19.6±3.29	59.2±15.14	0.37±0.2
SMU28	6	1.07 ± 0.1	59.81 ± 3.64	25.59 ± 7.42	21.67±10.23	17.33±6.15	61.0±16.24	0.33±0.24

3.4. Extent and Status of Soil Chemical Properties of Soil Mapping Units

The chemical data for soils under different SMUs in Guto Gida reveal substantial spatial heterogeneity in soil acidity, organic matter, nutrient availability, cation exchange capacity (CEC), and base saturation (PBS), which together has important implications for soil fertility, crop suitability, and land-use management.

3.4.1. Soil Reaction (pH) and Exchangeable Acidity (EA)

The data presented in Tables 6 and 7 indicate that the soils in the study area range from strongly acidic to moderately acidic. As shown in Table 6, the pH (H_2O) values across the pedons varied, with the lowest surface value observed in SMU26 (pH 4.66) and the highest in SMU23 (pH 6.36). The descriptive statistics in Table 5 reveal a relatively low standard deviation across most Soil Mapping Units (SMUs), suggesting a consistent acidification trend across the landscape. The prevalence of acidic conditions (pH<5.5 in SMU4, SMU10, and SMU11) is likely attributable to the leaching of basic cations (Ca^{2+}, Mg^{2+}) induced by high rainfall, a characteristic feature of tropical highland soils [1, 33].

Furthermore, the concomitant rise in exchangeable acidity, particularly in SMU10 (Mean EA = 5.6 cmol(+) kg^{-1}) and SMU27 (Mean EA = 7.9 cmol(+) kg^{-1}), suggests the potential presence of toxic levels of aluminum (Al^{3+}), which can inhibit root growth and restrict phosphorus availability [10]. This shows that continuous cultivation without adequate liming contributes to significant soil acidification. High EA in SMU27 indicates accumulation of exchangeable H^+/Al^{3+}, which may exacerbate acidity-related constraints, such as Al toxicity, reduced root growth, and P fixation [44]. This constraint suggests that SMU27 soils are likely to be constrained by acidity, requiring liming or other amelioration if used for acid-sensitive crops; whereas SMU23 and other neutral-to-slightly-acid soils may be more suitable for general cropping without liming.

3.4.2. Soil Organic Carbon (OC) and Total Nitrogen (TN) Distribution

The distribution of Soil Organic Carbon (OC) followed a consistent decline from surface to subsurface horizons across all pedons. For instance, in SMU4, OC content decreased from 1.72% in the Ah horizon to 0.86% in the Bt2 horizon. According to the descriptive statistics in Table 5, SMU23 and SMU6 exhibited the highest organic matter reserves, with mean organic matter (OM) values of 4.6±2.44% and 4.2±1.7%, respectively. These values classify the soils as having moderate to high organic matter status based on the ratings by [40]. However, other units such as SMU13 and SMU20 displayed considerably lower mean OC contents (0.8±0.60% and 1.0±0.2%, respectively), indicating a rapid mineralization rate or insufficient biomass return. The Total Nitrogen (TN) levels closely mirrored the OC trends, with SMU6 recording the highest mean TN (0.21±0.10%), emphasizing the reliance of this ecosystem on organic matter mineralization as the primary source of nitrogen fertility.

3.4.3. Phosphorus Availability (Av.P)

Available Phosphorus (Av.P) demonstrated extreme variability within the study site, highlighting a complex fertility landscape. While the majority of the SMUs were critically deficient in phosphorus, SMU23 was a distinct outlier. As shown in Table 5, the Ap horizon of SMU23 recorded an exceptionally high Av.P value of 41.79 ppm, resulting in a high mean value of 14.4±19ppm. This anomaly is likely attributable to site-specific anthropogenic management, such as the recent application of phosphatic fertilizers or the accumulation of organic waste near homesteads. In contrast, SMU14 and SMU5 exhibited very low mean Av.P values of 0.6±0.70 ppm and 0.6±0.90ppm, respectively (Table 5). In these acidic SMUs (pH < 5.5), the low phosphorus availability is scientifically consistent with P-fixation mechanisms, where soluble phosphates precipitate with iron and aluminum oxides/hydroxides, rendering them unavailable to plants [5]. This suggests that P-deficiency is a binding constraint for the majority of the district, necessitating liming or P-fertilization strategies.

3.4.4. Cation Exchange Capacity (CEC)

The Cation Exchange Capacity (CEC) results indicate a wide variation in the soil's ability to retain nutrients across the study area. As presented in Table 5, the mean CEC values ranged from a low of 12.2 ± 4.0 cmol(+)kg^{-1} in SMU5 to a high of 30.8 ± 5.2 cmol(+)kg^{-1} in SMU23. The relatively high CEC values observed in SMU23 and SMU6 (29.6 ± 3.8 cmol(+)kg^{-1}) suggest the dominance of high-activity 2:1 lattice clays (such as smectites) or a significant contribution from soil organic matter. In contrast, SMU14 and SMU25 exhibited lower mean CEC values of 12.4 ± 3.5 and 13.5 ± 5.7 cmol (+) kg^{-1} respectively, characteristic of soils dominated by low-activity Kaolinitic clays often found in highly weathered tropical environments [5, 8]. Furthermore, the vertical distribution of CEC within the pedons generally showed a declining trend with depth, paralleling the distribution of organic carbon. For instance, in SMU23, the CEC decreased from 37.60 cmol (+) kg^{-1} in the surface Ap horizon to 25.10 cmol (+) kg^{-1} in the subsurface B horizon. Similarly, in SMU4, the CEC dropped from 17.12 cmol (+) kg^{-1} in the Ah horizon to 16.14 cmol (+) kg^{-1} in the Bt3 horizon. This trend highlights the critical role of organic matter in providing negatively charged exchange sites in the surface layers of these soils.

The exchangeable bases followed the typical order of abundance Ca > Mg > K > Na in most mapping units, although severe depletion was evident in specific pedons. Calcium (Ca) and Magnesium (Mg): While Calcium was generally dominant, its levels varied drastically. SMU23 recorded the highest mean Ca value of 13.3 ± 7.4 cmol (+) kg^{-1} (Table 5). However, the data result reveals critical depletion in other units; specifically, in SMU10, the exchangeable Ca and Mg levels dropped to 0.00 cmol(+)kg^{-1} throughout the subsurface horizons (Bt1 through Bt4). Similarly, SMU26 showed 0.00 cmol (+) kg^{-1} for Magnesium in the Ah, AB, and Bt1 horizons. This complete exhaustion of basic cations is indicative of intense leaching conditions driven by acidity.

Potassium (K): Potassium availability was generally low across the district. As shown in Table 5, SMU14 and SMU10 recorded mean K values of only 0.09 ± 0.04 and 0.13 ± 0.02 cmol(+)kg^{-1}, respectively, which are below the critical level of 0.38 cmol(+)kg^{-1} required for optimal plant growth [26, 41]. The notable exception was SMU23, which exhibited a high mean K concentration of 1.39 ± 0.27 cmol (+) kg^{-1}, likely reflecting anthropogenic fertilizer inputs. Sodium (Na): Exchangeable sodium was negligible across all profiles. The highest mean value was observed in SMU4 (0.3 ± 0.05 cmol (+) kg^{-1}), confirming that these soils are non-sodic and free from sodium toxicity hazards.

3.4.5. Percentage Base Saturation (PBS)

The Percentage Base Saturation (PBS) values effectively delineated the soils into leached (dystric) and saturated (eutric) categories. Dystric Status: A significant portion of the study area exhibited very low base saturation, correlated with the high exchangeable acidity previously discussed. Table 6 reports that SMU26, SMU10, and SMU27 possess mean PBS values of 17.7 ± 11.5%, 23.5 ± 2.7%, and 24.2 ± 5.9%, respectively. In the subsurface layers of SMU26, the PBS dropped as low as 8.33% in the Bt1 horizon. These values are well below the 50% threshold, classifying these soils as strongly dystric and indicating that the exchange complex is dominated by Aluminum and Hydrogen ions [16]. Eutric Status: Conversely, SMU11 exhibited a remarkably high mean PBS of 107.2 ± 29.7% (Table 6), with the Bt2 horizon reaching 134.63%. Values exceeding 100% typically suggest the presence of soluble salts or carbonates that were dissolved during the laboratory extraction process, rather than cations solely adsorbed to clay surfaces. SMU5 also showed high saturation, with a mean PBS of 77.3 ± 17.1%, indicating higher inherent fertility compared to the rest of the district.

3.4.6. Cation Exchange Capacity of the Clay (CECc)

The Cation Exchange Capacity of the clay fraction (CECc) serves as a diagnostic indicator of the dominant clay mineralogy within the soil mapping units. According to the classification by [7], CECc values less than 20 cmol(+)kg^{-1} clay indicate a dominance of low-activity clays (such as Kaolinite), values between 20 and 40 cmol(+)kg^{-1} indicate mixed mineralogy, and values exceeding 40 cmol(+)kg^{-1} suggest the presence of high-activity 2:1 clays (such as Smectites or Vermiculite). The results in Table 5 reveal a significant heterogeneity in clay mineralogy across the Guto Gida district.

(i). Low Activity Clays (Kaolinitic)

Several mapping units exhibited low CECc values, indicative of highly weathered soils. Specifically, SMU5 and SMU14 recorded mean CECc values of 17.6 ± 7.5 cmol(+)kg^{-1} and 18.2 ± 5.9 cmol(+)kg^{-1} clay, respectively(Table 5). These values fall below the 20 cmol (+) kg^{-1} threshold, suggesting that the clay fraction is dominated by Kaolinite and sesquioxides (Iron and Aluminum oxides). This low clay activity explains the lower general CEC and nutrient retention capacity observed in these specific units, implying that nutrient management must focus on preventing leaching losses.

(ii). High Activity Clays (Smectitic/Mixed)

In sharp contrast, SMU6 and SMU23 exhibited exceptionally high CECc values. SMU6 recorded a mean CECc of 134.6 ± 63.6 cmol (+) kg^{-1} clay, while SMU23 recorded 87.4 ± 48.6 cmol (+) kg^{-1} clay (Table 5). In the Ah horizon of SMU6 peaked at 179.56 cmol (+) kg^{-1} clay. Such high values are characteristic of Smectitic mineralogy, which possesses a high shrink-swell potential and high nutrient holding capacity. However, extremely high values (>100) may also suggest the influence of amorphous materials or the contribution of organic matter to the exchange complex, which can inflate the calculated CECc relative to the actual clay content [26].

(iii). Mixed Mineralogy

Other units, such as SMU4 and SMU12, displayed intermediate mean CECc values of 25.2 ± 4.5 and 26.9 ± 18.9 cmol(+)kg^{-1} clay, respectively. This suggests a mixed mineralogy, likely composed of an intergrade of Illite, Chlorite, and Kaolinite.

Table 5. Descriptive Statistics (Mean ± standard deviation) of soil Chemical properties of soil mapping units of the study site.

SMU	Horizons	pH	Ex.Ac	OC (%)	OM (%)	TN (%)	AP (ppm)	Ca (cmolkg^{-1})	Mg	K	Na	CEC	CECc	PBS (%)
SMU4	4	5.3 ± 0.3	1.0 ± 1.3	1.5 ± 0.4	2.5±0.8	0.13±0.00	0.7 ± 0.3	7.6 ± 1.3	2.3 ± 0.8	0.15 ± 0.03	0.3 ± 0.05	16.3 ± 0.8	25.2 ± 4.5	62.8 ± 10.9
SMU5	5	5.4 ± 0.2	1.0 ± 0.3	1.6 ± 1.5	2.8±2.5	0.14±0.10	0.6 ± 0.9	7.4 ± 2.3	1.7 ± 1.4	0.10 ± 0.03	0.1 ± 0.08	12.2 ± 4.0	17.6 ± 7.5	77.3 ± 17.1
SMU6	2	5.3 ± 0.0	0.6 ± 0.2	2.5 ± 1.0	4.2±1.7	0.21±0.10	0.3 ± 0.1	13.8 ± 3.3	4.6 ± 2.4	0.17 ± 0.03	0.2 ± 0.03	29.6 ± 3.8	134.6 ± 63.6	62.5 ± 11.1
SMU9	5	5.2 ± 0.1	3.0 ± 1.7	1.2 ± 0.4	2.0±0.8	0.10±0.00	2.5 ± 1.4	7.3 ± 0.3	1.9 ± 0.5	0.13 ± 0.02	0.1 ± 0.07	16.3 ± 2.0	22.7 ± 3.7	59.1 ± 8.8
SMU10	5	5.1 ± 0.3	5.6 ± 0.9	1.5 ± 0.8	2.6±1.5	0.13±0.10	7.0 ± 2.5	5.0 ± 1.3	0.0 ± 0.0	0.13 ± 0.02	0.0 ± 0.01	21.6 ± 3.8	47.4 ± 25.8	23.5 ± 2.7
SMU11	5	4.9 ± 0.1	1.3 ± 0.8	1.0 ± 0.2	1.6±0.3	0.08±0.00	2.1 ± 1.4	11.0 ± 1.0	3.8 ± 2.2	0.15 ± 0.02	0.2 ± 0.11	14.4 ± 1.8	21.8 ± 2.2	107.2 ± 29.7
SMU1	5	5.1 ±	1.9 ±	1.3 ±	2.2±1.	0.11±0.	0.9 ±	5.0 ±	0.3 ±	0.25 ±	0.1 ±	14.3 ±	26.9 ±	38.9 ±

SMU	Hori-zons	pH	Ex.Ac	OC (%)	OM (%)	TN (%)	AP (ppm)	Ca (cmolkg^{-1})	Mg	K	Na	CEC	CECc	PBS (%)
2		0.2	0.3	0.9	6	10	1.1	1.7	0.6	0.27	0.08	4.9	18.9	5.8
SMU13	5	5.4 ± 0.1	0.7 ± 0.3	0.8 ± 0.6	1.4±1.0	0.07±0.10	0.7 ± 0.9	7.1 ± 2.5	2.3 ± 1.6	0.26 ± 0.36	0.1 ± 0.04	15.3 ± 9.3	21.7 ± 13.4	73.3 ± 26.2
SMU14	4	5.8 ± 0.3	0.5 ± 0.3	1.5 ± 0.6	2.6±1.0	0.13±0.00	0.6 ± 0.7	6.2 ± 1.9	1.4 ± 1.3	0.09 ± 0.04	0.1 ± 0.03	12.4 ± 3.5	18.2 ± 5.9	63.1 ± 73.7
SMU15	6	5.3 ± 0.1	2.0 ± 1.3	1.4 ± 0.6	2.5±1.1	0.13±0.10	1.7 ± 0.8	7.4 ± 1.6	2.7 ± 1.6	0.51 ± 0.27	0.1 ± 0.05	14.8 ± 4.6	23.5 ± 7.3	75.2 ± 16.5
SMU17	5	5.5 ± 0.1	3.1 ± 1.6	1.4 ± 0.8	2.3±1.4	0.12±0.10	1.0 ± 0.7	7.1 ± 2.0	1.9 ± 1.6	0.29 ± 0.03	0.2 ± 0.19	19.0 ± 2.9	31.7 ± 9.9	49.7 ± 15.3
SMU20	4	5.4 ± 0.1	3.8 ± 1.1	1.0 ± 0.2	1.7±0.4	0.09±0.00	2.5 ± 0.6	7.6 ± 1.2	2.2 ± 0.4	0.13 ± 0.03	0.2 ± 0.25	23.7 ± 2.3	39.0 ± 4.6	42.6 ± 1.5
SMU21	3	5.4 ± 0.0	4.5 ± 0.6	2.1 ± 0.9	3.7±1.5	0.18±0.10	0.5 ± 0.3	6.3 ± 0.5	0.7 ± 0.5	0.16 ± 0.04	0.0 ± 0.01	28.9 ± 0.3	71.4 ± 29.2	24.6 ± 1.9
SMU23	4	6.0 ± 0.4	0.4 ± 0.2	2.7 ± 1.4	4.6±2.4	0.23±0.10	14.4 ± 19	13.3 ± 7.4	5.8 ± 5.2	1.39 ± 0.27	0.1 ± 0.06	30.8 ± 5.2	87.4 ± 48.6	63.6 ± 28.4
SMU24	5	5.3 ± 0.2	0.6 ± 0.2	1.1 ± 0.7	1.9±1.2	0.09±0.10	3.8 ± 2.4	6.3 ± 0.9	1.3 ± 1.1	0.30 ± 0.39	0.0 ± 0.03	18.1 ± 2.7	24.9 ± 8.6	43.5 ± 6.2
SMU25	4	5.5 ± 0.6	1.9 ± 2.8	1.0 ± 0.5	1.7±0.8	0.09±0.00	5.1 ± 2.3	6.1 ± 3.4	1.6 ± 2.1	0.31 ± 0.21	0.0 ± 0.02	13.5 ± 5.7	25.2 ± 8.2	68.4 ± 52.0
SM26	5	4.8 ± 0.1	4.4 ± 2.4	2.6 ± 0.4	4.5±0.6	0.22±0.00	3.8 ± 1.5	4.0 ± 1.6	0.7 ± 1.5	0.13 ± 0.08	0.1 ± 0.06	28.7 ± 5.2	66.6 ± 25.8	17.7 ± 11.5
SMU27	5	5.1 ± 0.3	7.9 ± 1.6	1.2 ± 0.8	2.0±1.4	0.10±0.10	7.1 ± 2.6	6.3 ± 1.7	0.2 ± 0.4	0.16 ± 0.06	0.1 ± 0.12	27.6 ± 2.6	50.8 ± 21.0	24.2 ± 5.9
SMU28	6	5.2 ± 0.2	3.9 ± 0.6	1.6 ± 0.6	2.7±1.0	0.14±0.00	5.5 ± 3.2	7.0 ± 1.6	0.6 ± 1.0	0.11 ± 0.03	0.0 ± 0.00	23.8 ± 2.2	41.8 ± 12.6	32.4 ± 6.6

pH=Power of Hydrogen, EA = Exchangeable acidity, OC = Organic carbon, TN = Total Nitrogen, A.P = Available Phosphorus, CEC = Cation exchange capacity, CECc = Cation exchange capacity of Clay, PBS = Percentage base saturation

3.5. Soil Classification and Mapping

The soils of the study area were classified following the *World Reference Base for Soil Resources* (WRB) diagnostic criteria, based on both morphological observations and detailed physicochemical analyses [21, 28]. Diagnostic horizons, properties, and materials were identified from field descriptions and laboratory results, and these were used to assign each Pedon to its respective Reference Soil Group (RSG) through the WRB key.

According to the classification outcomes, eight major RSGs were identified within the study area: Nitisols, Alisols, Cambisols, Lixisols, Leptosols, Luvisols, Acrisols, and Regosols. The areal distribution of these soil groups shows that Nitisols are the dominant soil type, covering 41.59% of the landscape (Figure 4). This dominance reflects the deep weathering, strong structural development, and favorable chemical conditions typical of Nitisols in humid tropical environments. Alisols (15.73%) and Cambisols (15.37%) constitute the next most extensive soil groups, indicating substantial areas with moderate weathering and acidic subsurface horizons enriched with exchangeable aluminum (Figure 5).

Lixisols, accounting for 13.95%, are associated with leached subsurface horizons and low-activity clays, while Leptosols (4.54%) represent shallow soils formed over hard rock or strongly eroded landscapes. Luvisols, covering 3.53%, reflect zones with clay accumulation and higher base saturation relative to surrounding soil types. Acrisols (2.89%) occur in more strongly leached and acidic areas, while Regosols, representing 0.83%, are weakly developed soils typically associated with young parent materials or unstable geomorphic surfaces (Figure 5). The total area covered by soil mapping was 93,181.61 ha (98.48%). The remaining 1.52% of the study area was not included in the soil classification due to field inaccessibility caused by security-related restrictions and absence of accessible roads, which hindered ground trothing and soil sampling in those locations These distributions collectively illustrate the geomorphic, climatic, and pedogenic variability within the study area.

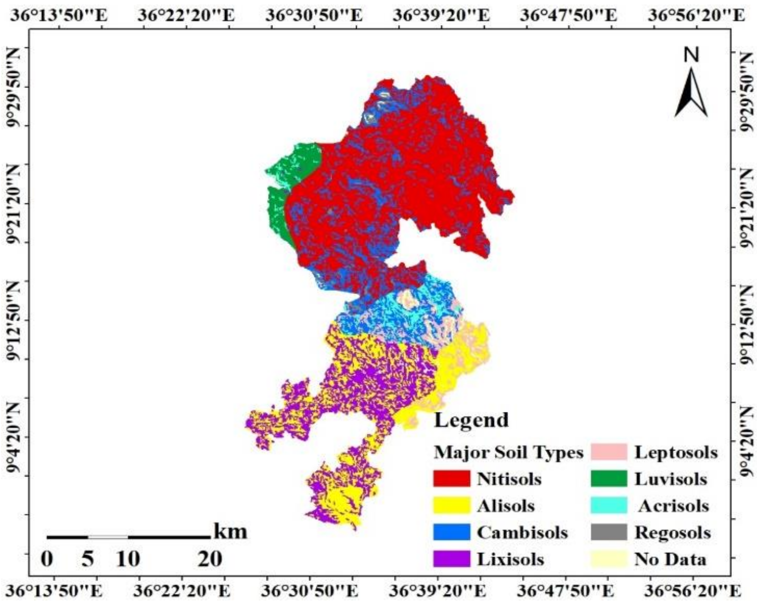

Figure 4. Map of major soil types of Guto Gida district.

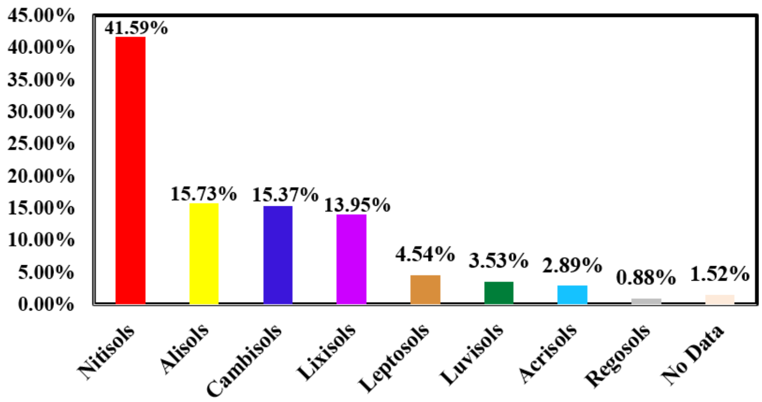

Figure 5. Distribution of major soil types by area coverage in Guto Gida district.

Table 6. Soil classification according to WRB (2022).

SMUs	Soil type (WRB system of soil classification)	Area	
		Hectare	%
SMU4	Eutric Haplic Lixisols (Mollic)	34.72	0.04
SMU5	Eutric Rhodic Haplic Nitisols (Clayic, Mollic)	349.88	0.37
SMU6	Eutric Leptic Leptosols (Lithic, Mollic, Skeletic)	2638.36	2.79
SMU8	Stagnic Regosols (Raptic)	829.78	0.88
SMU9	Eutric Lixisols (Clayic, Mollic)	8154.28	8.62
SMU10	Dystric Haplic Alisols (Clayic)	2431.31	2.57

SMUs	Soil type (WRB system of soil classification)	Area	
		Hectare	%
SMU11	Eutric Lixisols (Clayic, Mollic)	3559.8	3.76
SMU12	Dystric Haplic Rhodic Acrisols (Clayic)	2164.38	2.29
SMU13	Eutric Haplic Luvisols (Clayic, Mollic)	3336.05	3.53
SMU14	Dystric Rhodic Nitisols (Clayic)	39004.7	41.22
SMU15	Eutric Haplic Lixisols (Clayic)	1451.9	1.53
SMU17	Dystric Haplic Alisols (Clayic)	1165.86	1.23
SMU20	Dystric Haplic Alisols (Clayic)	420.96	0.44
SMU21	Eutric Leptic Leptosols (Clayic)	1658.42	1.75
SMU23	Eutric Haplic Cambisols (Clayic)	4055.49	4.29
SMU24	Dystric Rhodic Acrisols (Clayic, Mollic)	573.61	0.61
SMU25	Dystric Cambisols (Clayic)	10490.5	11.09
SMU26	Hyperdystric Rhodic Alisols (Clayic)	6291.2	6.65
SMU27	Dystric Alisols (Clayic)	940.29	0.99
SMU28	Dystric Profondic Alisols (Clayic)	3630.12	3.84
	Total	93181.61	98.48

Table 7. Person correlation matrix among measured soil chemical properties.

	BD	pH	OC	Av.P	CEC	CEC clay	Ex. A	Av.P	Na+	K+	Ca2+	Mg2+	PBS
BD	1.000**,*												
pH	0.070	1.000***											
OC	-0.260*	0.039	1.000***										
Av.P	-0.027	0.174	0.354***	1.000***									
CEC	-0.319**	-0.103	0.450***	0.426***	1.000***								
CEC clay	-0.299**	0.045	0.612***	0.445***	0.790***	1.000***							
Ex. A	-0.186	-0.398***	-0.052	-0.198	0.447***	0.176	1.000***						
Av.P	-0.027	0.174	0.354***	1.000***	0.426***	0.445***	-0.198	1.000***					
Na+	-0.033	-0.098	-0.116	-0.100	-0.145	-0.064	-0.103	-0.100	1.000***				
K+	0.103	0.371***	0.409***	0.438***	0.233*	0.312**	-0.295**	0.438***	-0.039	1.000***			
Ca2+	0.035	0.322**	0.348***	0.428***	0.219*	0.443***	-0.378***	0.428***	0.141	0.481***	1.000***		
Mg2+	0.140	0.333**	0.362***	0.413***	0.103	0.347***	-0.477***	0.413***	0.138	0.528***	0.867***	1.000***	
PBS	0.298**	0.300**	0.022	-0.053	-0.529***	-0.221*	-0.583***	-0.053	0.191	0.208*	0.586***	0.641***	1.000***

4. Conclusions and Recommendations

The soil characterization, classification, and mapping of the Guto Gida district revealed clear spatial variability in soil properties across Soil Mapping Units (SMUs). Most soils are deep, well-developed, and clay-dominated, with well-expressed argic (Bt) horizons in several SMUs, indicating advanced weathering, clay translocation, and long-term pedogenic development typical of tropical highland environments. Soil physical properties such as low bulk density (0.80–1.28 g cm^{-3}) and high porosity (51.7–69.8%) reflect generally good structure and favorable conditions for root growth and water movement.

Topography strongly influenced soil formation and distribution, where foot- and back-slope positions showed deeper and better-developed profiles, while upper slope positions exhibited signs of erosion and weak horizon development. Land use also affected surface soil conditions, with cultivated areas showing slight compaction compared to fallow and grazing lands.

Overall, the soils of the district are pedologically mature, structurally well-developed, and generally suitable for agriculture, but they are constrained by acidity risks, clay-related drainage limitations, and erosion susceptibility on sloping lands. The resulting soil maps provide a solid basis for sustainable land management and agricultural planning in the district.

Implement Soil Acidity Management Programs: Because many Alisols-type soils develop high acidity and low base saturation, future chemical analysis (CEC, PBS, exchangeable acidity, pH) should guide targeted liming. Areas with strongly acidic Bt horizons should undergo periodic pH monitoring and application of agricultural lime or dolomitic lime to improve nutrient availability and crop productivity.

Adopt Erosion Control Measures on Steep Slopes (SMUs 6, 20, 21, 27, 28): SMUs located on steep gradients (32–60%) require immediate conservation measures such as: contour plowing**,** terracing**,** grass strips and buffer zones**,** controlled grazing. These practices will minimize soil loss, surface sealing, and horizon truncation, thereby preserving soil fertility.

Promote Soil Organic Matter Enrichment across All Cultivated SMUs: Despite favourable structure, long-term cultivation areas (e.g., SMUs 5, 12, 13, 14, 24) are likely to have declining organic carbon levels. Incorporating organic amendments is recommended, including: compost and manure, green manure crops, crop residue retention, improving organic matter improves water retention, cation exchange capacity, and aggregate stability.

Site-Specific Fertilizer Recommendation Based on Soil Classes: Since clay-rich Alisols tend to fix phosphorus and exhibit low base saturation, fertilizer regimes should include: phosphorus sources (DAP, TSP, organic P) balanced NPK based on crop type micronutrients (particularly Zn and B) where required Developing a SMU-based fertilizer guide will substantially improve input use efficiency.

Sustainable Land Use Planning: The soil map generated from this study should serve as a guiding tool for allocating land to appropriate uses: Deep, well-drained clay soils (SMUs 4, 5, 9, 10, 11) are highly suitable for cereals, pulses, and perennial crops. Moderately drained grazing areas (SMU 9, 17) should be managed as controlled grazing systems. Steep slopes (SMU 20, 21, 27) recommended for agroforestry, perennial crops, or protection forestry.

Abbreviations

EC	Electrical Conductivity
GPS	Global Positioning System
GIS	Geographical Information System
HDPE	High-density Polyethylene
HTM	Human-transported Material
ISO	International Organization for Standardization
Meq	Milliequivalent
PVC	Polyvinyl Chloride
PBS	Percentage Base Saturation
RSG	Reference Soil Group
SMU	Soil Mapping Unit
USDA	United States Department of Agriculture
UTM	Universal Transverse Mercator
WRB	World Reference Base for Soil Resources

Acknowledgments

The authors gratefully acknowledge the financial support provided by the Oromia Agricultural Research Institute and the logistical assistance of the Nekemte Soil Research Centre during field data collection and laboratory analyses. We extend our sincere appreciation to the Bedelle Agricultural Research Center for its valuable support by assigning Mr. Amanuel Kejela from the Soil Survey Team to assist with the field data collection. His technical expertise, dedication, and contribution throughout the data collection process were highly appreciated and contributed significantly to the successful completion of this study.

Author Contributions

Amanuel Tadesse Warke: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing

Chalsissa Takele Sori: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing

Temesgen Chimdessa Deressa: Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation

Bikiltu Regasa Sori: Data curation, Investigation, Visualization, Writing – review & editing

Mintesinot Desalegn Eshetu: Formal Analysis, Software, Writing – review & editing

Amanuel Kejela: Data curation, Investigation, Methodology, Resources, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Aleminew, A. and Alemayehu, M., 2020. Soil fertility depletion and its management options under crop production perspectives in Ethiopia: A review. *Agricultural Reviews*, *41*(2), pp. 91-105.

[2] Arshad, M. A. and Coen, G. M., 1992. Characterization of soil quality: Physical and chemical criteria. *American Journal of Alternative Agriculture*, *7*(1-2), pp. 25-31.

[3] Basma, A. A., Al-Homoud, A. S., Malkawi, A. I. H. and Al-Bashabsheh, M. A., 1996. Swelling-shrinkage behavior of natural expansive clays. *Applied Clay Science*, *11*(2-4), pp. 211-227. https://doi.org/10.1016/S0169-1317(96)00009-9

[4] Bouyoucos, G. J., 1927. The hydrometer as a new method for the mechanical analysis of soils. Soil Science, 23(5), pp. 343-354.

[5] Brady, N. C. and Weil, R. R., 2017. The Nature and Properties of Soils, 15th Edn (eBook).

[6] Buol S., Hole F., McCracken J., and Southard R. 2003. Soil genesis and classification, 5thed. Iowa State Press, USA. pp. 126-327.

[7] Buol, S. W., Southard, R. J., Graham, R. C., & McDaniel, P. A. (2011). Soil Genesis and Classification (6th ed.). John Wiley & Sons.

[8] Daniels, W. L. (2016). The Nature and Properties of Soils, 15th EditionRay R. Weil and Nyle C. Brady. Pearson Press, Upper Saddle River NJ, 2017. 1086 p. $164.80. Also available as eText for $67.99. *Soil Science Society of America Journal*, *80*(5), 1428. https://doi.org/10.2136/sssaj2016.0005br

[9] Elias E (2016) Soils of the Ethiopian Highlands: Geomorphology and Properties. CASCAPE Project, ALTERA, Wageningen University and Research Centre (Wageningen UR). The Netherlands.

[10] Fageria, N., & Baligar, V. (2008). Chapter 7 Ameliorating soil acidity of tropical oxisols by liming for sustainable crop production. In *Advances in agronomy* (pp. 345–399). https://doi.org/10.1016/s0065-2113(08)00407-0

[11] FAO (Food and Agricultural Organization). 1994. World reference base for soil resources, by ISSS–ISRIC–FAO. Draft. Rome/Wageningen, the Netherlands.

[12] FAO (Food and Agricultural Organization). 2006. Guidelines for soil description, 4th edn. Food and Agriculture Organization of the United Nations, Rome 92-5-105521-1, p. 109.

[13] FAO, 2017. Voluntary Guidelines for Sustainable Soil Management. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. 16p. Available at [Access date: 06.01.2018]: http://www.fao.org/3/a-bl813e.pdf

[14] Gashu, K. and Muchie, Y., 2018. Rethink the interlink between land degradation and livelihood of rural communities in Chilga district, Northwest Ethiopia. *Journal of Ecology and Environment*, *42*(1), p. 17.

[15] Gebreselassie, S., Kirui, O. K., Mirzabaev, A. (2016). Economics of Land Degradation and Improvement in Ethiopia. In: Nkonya, E., Mirzabaev, A., von Braun, J. (eds) Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development. Springer, Cham. https://doi.org/10.1007/978-3-319-19168-3_14

[16] Hazelton, P., & Murphy, B. (2007). Interpreting soil test results: What do all the numbers mean (2nd ed.). CSIRO Publishing.

[17] Hengl, T., Mendes de Jesus, J., Heuvelink, G. B., Ruiperez Gonzalez, M., Kilibarda, M., Blagotić, A., Shangguan, W., Wright, M. N., Geng, X., Bauer-Marschallinger, B. and Guevara, M. A., 2017. SoilGrids250m: Global gridded soil information based on machine learning. *PLoS one*, *12*(2), p. e0169748.

[18] Hillel, D., 2013. *Fundamentals of soil physics*. Academic press.

[19] Hurni, H., Abate, S., Bantider, A., Debele, B., Ludi, E., Portner, B., Yitaferu, B. and Zeleke, G., 2010. 12 Land Degradation and Sustainable Land Management in the Highlands of Ethiopia. *Global change and sustainable development*, p. 187.

[20] Hurni, H., Kebede, T. and Gete, Z., 2005. The implications of changes in population, land use and land management for surface runoff in the Upper Nile Basin of Ethiopia. Mountain Research and Development, 25(2), pp. 147–154. https://doi.org/10.1659/0276-4741(2005)025[0147:TI-OCCI]2.0.CO;2

[21] IUSS Working Group WRB. 2022. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria.

[22] Jahn, R., Blume, H. P., Asio, V. B., Spaargaren, O. and Schad, P., 2006. Guidelines for soil description. FAO.

[23] Javed, T., *et al.,* 2022. Soil properties and their role in crop productivity: A review. Journal of Soil Science and Plant Nutrition, 22, pp. 1–15. https://doi.org/10.1007/s42729-021-00684-3

[24] Kindu, M., Schneider, T., Teketay, D., & Knoke, T. (2015). Changes of ecosystem service values in response to land use/land cover dynamics in Munessa-Shashemene landscape of the Ethiopian highlands. *Science of the Total Environment*, 547, 137–147. https://doi.org/10.1016/j.scitotenv.2015.12.127

[25] Lambin, E. F., Geist, H. J., & Lepers, E. (2003). Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources*, 28, 205–241. https://doi.org/10.1146/annurev.energy.28.050302.105459

[26] Landon, J. R. (2014). Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics. Routledge.

[27] Lemenih, M., 2004. *Effects of land use changes on soil quality and native flora degradation and restoration in the highlands of Ethiopia* (No. 306).

[28] Lufega, S. M., Msanya, B. M., 2017. Pedological characterization and soil classification of selected soil units of Morogoro District, Tanzania. International Journal of Plant and Soil Science 16(1): 1-12.

[29] Ma, Y., Minasny, B. and McBratney, A. B., 2019. Digital soil mapping using machine learning algorithms: A review. Geoderma, 338, pp. 1–12. https://doi.org/10.1016/j.geoderma.2018.09.026

[30] Marshall, T. J., Holmes, J. W. and Rose, C. W., 1996. *Soil physics*. Cambridge university press.

[31] Meshesha, D. T., Tsunekawa, A., & Haregeweyn, N. (2016). Dynamics and hotspots of soil erosion and management scenarios of the Central Rift Valley of Ethiopia. *International Journal of Sediment Research*, 31(3), 257–268. https://doi.org/10.1016/j.ijsrc.2016.05.002

[32] Mulugeta Debele and Sheleme, Beyene, 2010. Characterization and classification of soils along the top sequence of Kindo Koye Watershed in Southern Ethiopia. East African Journal of Sciences, 4(2), pp. 65-77.

[33] Weil, R.R., Brady, N.C. and Weil, R.R., 2017. The nature and properties of soils (Vol. 1104). New York: Pearson.

[34] Schaetzl, R. J. and Thompson, M. L., 2015. *Soils*. Cambridge university press.

[35] Schulte, R. P. O., Creamer, R. E., Donnellan, T., Farrelly, N., Fealy, R., O'Donoghue, C. and O'hUallachain, D., 2014. Functional land management: A framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. Agricultural Systems, 129, pp. 45–58. https://doi.org/10.1016/j.agsy.2014.06.002

[36] Seifu, W. and Elias, E., 2018. Soil quality attributes and their role in sustainable agriculture: a review. *International Journal of Plant & Soil Science*, *26*(3), pp. 1-26.

[37] Shi XZ, Yu DS, Warner ED, Sun WX, Petersen GW, Gong ZT, Lin H (2005). Cross-reference system for translating between genetic soils classifications of China and soil taxonomy. Soil Science Society of America Journal 70(1): 78-83.

[38] Shukla, M. K; Lal, R; Ebinger, M. Soil Quality Indicators For Reclaimed Minesoils In Southeastern Ohio. Soil Science 169(2): P 133-142, February 2004. https://doi.org/10.1097/01.Ss.0000117785.98510.0f

[39] Soil Survey Staff. 2014. Kellogg Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42, Version 5.0. R. Burt and Soil Survey Staff (ed.). U.S. Department of Agriculture, Natural Resources Conservation Service.

[40] Tekalign, M. (1991). Soil fertility and plant nutrition research in Ethiopia. International Institute of Tropical Agriculture (IITA).

[41] Teshome Yitbarek, Sheleme Beyene and Kibebew Kibret, 2016. Characterization and Classification of Soils of Abobo Area, Western Ethiopia Hindawi Publishing Corporation Applied and Environmental Soil Science Volume 2016, 16 pages http://dx.doi.org/10.1155/2016/4708235

[42] Tolessa, T., Senbeta, F., & Kidane, M. (2017). The impact of land use/land cover change on ecosystem services in the central highlands of Ethiopia. *Ecosystem Services*, 23, 47–54. https://doi.org/10.1016/j.ecoser.2016.11.010

[43] Van Reeuwijk, L. P., 2002. Procedures for soil analysis: Wageningen International Soil Reference and Information Centre, Technical Paper, (9).

[44] von Uexküll, H. R., Mutert, E. Global extent, development and economic impact of acid soils. Plant Soil 171, 1–15 (1995). https://doi.org/10.1007/BF00009558

[45] Wadoux, A. M. J. C., Minasny, B. and McBratney, A. B., 2020. Machine learning for digital soil mapping: Applications, challenges and suggested solutions. Earth-Science Reviews, 210, p. 103359. https://doi.org/10.1016/j.earscirev.2020.103359

[46] Walkley, A. and Black, I. A. (1934) An Examination of the Degtjareff Method for Determining Soil Organic Matter and a Proposed Modification of the Chromic Acid Titration Method. Soil Science, 37, 29-38. http://dx.doi.org/10.1097/00010694-193401000-00003

[47] Zerssa, G., Feyssa, D., Kim, D. G. and Eichler-Löbermann, B., 2021. Challenges of smallholder farming in Ethiopia and opportunities by adopting climate-smart agriculture. *Agriculture*, *11*(3), p. 192.

[48] Zhu, A. X., Hudson, B., Burt, J., Lubich, K. and Simonson, D., 2001. Soil mapping using GIS, expert knowledge, and fuzzy logic. *Soil Science Society of America Journal*, *65*(5), pp. 1463-1472.