Research Article

Characterization and Classification of Soils of Abobo Area, Western Ethiopia

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Knowledge of the kinds and properties of soils is critical for making decisions with respect to crop production and other land use types. A field survey and soil morphological description and laboratory analysis were carried out to describe, characterize, and classify the soils of Abobo area, western Ethiopia. Seven representative pedons (A-1 to A-7) were opened and described across the study area. The results revealed variation in morphological, physical, and chemical properties of the soils. The soils are clay loam to clayey in texture with bulk density values ranging from 1.12 to 1.32 g cm⁻³ and basic infiltration rate varying from slow to moderate (0.4 to 3.3 cm hr⁻¹). They were moderately acidic to neutral in pH (5.5 to 7.1) and had very low to medium organic carbon (OC) (0.27 to 2.98%). Four soil types, Haplic Cambisols, Vertic Luvisols, Mollic Leptosols, and Mollic Vertisols, were identified in the area based on World Reference Base. Generally, the properties of the soils differed along the transect indicating their variation in productive potential and management requirements for specific agricultural use.

1. Introduction

Knowledge of the kinds and properties of soils is critical for decisions making with respect to crop production and other land use types. It is through precise measurement and full understanding of the nature and properties of soils as well as proper management of the nutrient and moisture requirements that one can maximize crop production to the allowable potential limits [1]. In order to evaluate the quality of our natural resources and their potential to produce food, fodder, fiber, and fuel for the present and future generations, detailed information on soil properties is required.

Assessment of soil for land use planning is increasingly important due to increasing competition for land among many land uses and the transition from subsistence to market based farming in many countries [2]. High quality soil classification, therefore, is the basis for efficient land suitability evaluation, planning, and management. Soil classification is important in identifying the most appropriate use of soil,

estimating production, extrapolating knowledge gained at one location to other often relatively little known locations, and providing a basis for future research needs [3]. Soil characterization is required to classify soil and determine chemical and physical properties not visible in field examination [4].

Since the early works of Dokuchaev, there has been belief in the dependence of soil properties on soil processes, which depend in turn on soil-forming factors. The five soil-forming factors can combine in almost endless ways to give rise to many kinds of soil individuals. It is impossible to remember their names, let alone their properties; hence there is need to organize soils information by classification systems [5]. Landscape position influences runoff, drainage, erosion and soil depth, and thereby soil formation and development. Different soil properties such as pH, OC, sand, and clay contents and distribution are highly correlated with landscape positions [6, 7].

Agriculture has been the mainstay of Ethiopian economy for centuries and will remain the same for the coming many years [8]. However, reliable soils data, which are the prerequisite for the design of appropriate land use systems and soil management practices, are not adequately available. Most of the studies undertaken so far were localized mostly to areas close to major transportation networks and some of the available data are not currently used, as they are 20–30 years old [9].

All the previous studies conducted in Gambella, the present study area, were at small scale [10, 11]. National and regional small-scale studies seem to be inadequate in providing basic soil data that can help to manage soils according to local variability [12]. This study was therefore initiated and carried out in Abobo area of Gambella region to characterize and classify the soils of the area in detail.

2. Materials and Methods

2.1. Description of the Study Area. The study area, Abobo district, is located at 42 km south of Gambella town and about 808 km west of Addis Ababa. It lies between 07°50'47" to 08°01'59"N and 34°28'59" to 34°34'37"E with altitude ranging from 446 to 490 meters above sea level (masl) and slope from flat (0.2–0.5%) to gently sloping (2–5%).

The climate of the region is influenced by the tropical monsoon, which is characterized by high rainfall in the wet period from May to October and little rainfall during the dry period from November to April [11]. The average annual rainfall is 955.5 mm, whereas the mean minimum and mean maximum monthly temperatures range from 16.2 to 21.2°C and 32.1 to 38.2°C, respectively. The region is drained by a number of perennial rivers including, Baro, Alwero, Gillo, Akobo, and their tributaries.

The geology of Abobo is characterized by undifferentiated Pleistocene Holocene deposits. Granite, gneisses, schist, sandstone, and basalt are the rock types existing in the region [13]. The major soils of Abobo District include Dystric and Eutric Plinthosols, Dystric and Chromic Cambisols, Eutric Vertisols, and Planosols, where Cambisols occur at the upper slope north of Abobo while Plinthosols and Vertisols exist at the middle and lower slopes, respectively [11].

The Abobo district encompasses forest land, woodland, shrub land, grassland, and cultivated land occupying 143,086, 75,227, 5,793, 62,997, and 19,854 hectares (ha), respectively [14]. The forest cover is continuously declining due to settlement and agricultural expansion. The major crops grown by farmers include maize (*Zea mays* L.), sorghum (*Sorghum bicolor*), groundnut (*Arachis hypogaea*), and sesame (*Sesamum aestivum*), whereas cotton (*Gossypium* sp.) and rice (*Oryza sativa* L.) are cultivated by state farms and investors operating in and around the study area.

2.2. Field Work. Prior to the start of the field soil descriptions, the boundaries of the *kebeles* (the smallest administrative unit) along the transect were delineated using digital map of Gambella region, and the soils within each *kebele* were thoroughly examined and differentiated based on observable site and soil characteristics such as slope, soil depth, and

texture following free survey method [15]. The approach was to traverse the landscape along selected transects (north to south) by auger inspection at enough points to identify the existing soils type and their boundaries.

The study area was categorized into seven soil units after inspecting 189 auger samples. A representative soil pedon, 1.5 × 2 m, was opened in each identified soil unit and described in situ following the Guidelines for Field Soil Description [16]. General site information and soil description were recorded and samples were collected from every identified horizon. Core samples were collected at different points across each horizon. Infiltration rates were measured in triplicate in each identified soil unit using double ring infiltrometer [17]. The rate was measured by observing the fall of water within concentric cylinders (28 and 53 cm diameter with 24 cm height) driven 10 cm vertically into the soil surface layer.

Based on the morphological properties and the laboratory analysis, the soils of the study area were classified according to WRB [18] and Soil Taxonomy [19].

2.3. Laboratory Analysis. The samples collected from identified horizons of all pedons were air-dried and ground to pass through 2 mm sieve. For the determinations of total N and OC, a 0.5 mm sieve was used. Analyses of the physicochemical properties were carried out following standard laboratory procedures.

Bulk and particle densities were determined by core sampling [20] and pycnometer [21] methods, respectively. Particle size distribution was determined by Bouyoucos hydrometer method [22]. Total porosity was computed from the measurements of soil dry bulk density (ρ_b) and soil particle density (ρ_p) as

$$\text{Porosity} = 1 - \left(\frac{\rho_b}{\rho_p} \right). \quad (1)$$

Water retention at field capacity (FC) and permanent wilting point (PWP) was measured by employing pressure plate extraction methods [23]; and available water content (AWC) was computed by subtracting values of permanent wilting point from that of field capacity.

Soil pH and electrical conductivity were measured using a 1:2.5 soil to water ratio [24], whereas OC was determined by wet digestion method [25]. Total N was determined by Kjeldahl wet digestion and distillation method [26], available P by the modified Olsen method [27], and available K using sodium acetate extractant [28]. The CEC and exchangeable bases were extracted by 1M ammonium acetate (pH 7) method [29]. In the extract, exchangeable Ca and Mg were determined by atomic absorption spectrophotometer (AAS) and exchangeable K and Na by flame photometer. Available micronutrients (Fe, Mn, Zn, and Cu) of the soil were extracted by diethylene triamine pentaacetic acid (DTPA) method as described in Tan [21] and determined using AAS. Calcium carbonate and gypsum contents were determined following acid neutralization method [30] and Nelson procedure [31], respectively.

TABLE 1: Site characteristics and land use/cover of the study area.

Pedons	Coordinates		Altitude (masl)	Land form ¹	SP ²	PM ³	Slope (%)	Land use/cover
	Latitude	Longitude						
A-1	08°01'35"	034°33'42"	490	GS	UP	B	2	Maize farm
A-2	07°59'54"	034°33'25"	479	VGS	MS	B	1	Sesame farm
A-3	07°55'34"	034°33'36"	469	VGS	MS	B	1	Cotton farm
A-4	07°58'25"	034°33'18"	468	VGS	MS	B	1	Fallow land
A-5	07°56'36"	034°32'25"	462	NF	MS	A	0.5	Maize farm
A-6	07°53'45"	034°29'54"	455	NF	MS	B	0.5	Maize farm
A-7	07°48'34"	034°31'40"	446	F	LS	A	0.2	Forest land

¹F = flat; NF = nearly flat; VGS = very gently sloping; GS = gently sloping; ²SP = slope position; MS = middle slope; UP = upper slope; LS = lower slope; ³PM = parent materials; B = basalt; A = alluvium.

The following parameters were computed from the result of the chemical analysis:

- (i) Organicmatter (%)
= Organic carbon (OC) * 1.724,
- (ii) $\frac{\text{Carbon}}{\text{nitrogen ratio}} = \frac{\text{OC}}{\text{Total N}}$,
- (iii) CEC of clay (cmol_c/kg)
= $\left[\frac{\text{CEC of soil}}{\text{percentage of clay}} \right] * 100$,
Exchangeable sodium percentage (%)
= $\left[\frac{\text{Exchangeable Na}}{\text{CEC}} \right] * 100$,
 $\frac{\text{Calcium}}{\text{magnesium ratio}} = \frac{\text{Exchangeable Ca}}{\text{exchangeable Mg}}$,
- (iv) Percent base saturation (%)
= $\left[\text{Exchangeable Ca} + \text{Mg} + \text{K} + \frac{\text{Na}}{\text{CEC}} \right] * 100$.

2.4. Statistical Analysis and Mapping. General Linear Model (GLM) procedure [32] version 9.2 was employed to analyze the correlation among soil parameters. The soils map of the study area was prepared by employing ArcGIS 9.3.

3. Results and Discussion

3.1. Characteristics of the Study Area. The site characteristics of the pedons indicated that the study area was situated on level to gentle sloping (Table 1) and the pedons represented different physiographic position: Pedon Abobo- (A-) 1 (upper slope), Pedons A-2, A-3, A-4, A-5, and A-6 (middle slope), and Pedon A-7 lower slope of the terrain. The pedons were also representatives of different land use/cover: maize farm (A-1, A-5, and A-6), sesame farm (A-2), cotton farm (A-3), fallow land (A-4), and forest land (A-7). All the pedons were

well drained, except Pedon A-7, which was on lower slope positions and imperfectly drained.

In the upper and middle slope classes, slight sheet erosion was observed, whereas deposition was prevalent in the lower slope area. Furthermore, the existing land use/cover at the area has also contributed to the erosion process. Cultivated land, which is highly exposed to rainfall impact, was in the upper slope soils of the terrain. Removal of surface soil from this land use affected the soil profile development in comparison with the middle and lower slope soils. Erosion of materials from O or A horizons of upslope and their deposition on lower slopes are common phenomena, contributing to a textural differentiation with finer-textured soils in the lower landscape positions [33]. Due to repeated deposition of soluble materials the lower slope would have relatively higher exchangeable bases content in comparison with middle and upper slopes.

3.2. Morphological Properties of the Soils. The pedons exhibited differences in sequence of horizons; whereas Pedon A-6 consisted of only one genetic soil horizon (Ap), the others consisted of 3-4 horizons (Table 2). The pedon (A-1) at the upper part of the site had relatively shallower (18 cm) surface horizon compared to that of others due to removal of surface materials. This is attributed to slope, which contributes to greater translocation of surface materials down slope through surface erosion and movement of soil [34]. Variation in soil depth, particle size distribution, structure, and color could also be due to the difference in parent material [35].

The color of surface horizons varied from brown (7.5YR 4/4) to dark yellow brown (10YR 4/4) and dark brown (7.5YR 3/4) to dark yellowish brown (10YR 3/4) when they were dry and moist, respectively, whereas the color of the subsurface horizons varied from reddish brown (2.5YR 4/4) to gray (2.5Y 6/1) and reddish brown (2.5YR 4/3) to gray (2.5Y 5/1) at respective moisture levels (Table 2). The color differences between surface and subsurface layers reflect biological processes, notably those influenced by the soil organic matter. In line with this, many authors reported that the surface horizons have darker color than the corresponding subsurface horizons as a result of relatively higher soil OM contents [7, 36]. Pedons A-1, A-2, A-3, and A-4 had bright-colored (red, reddish brown, and yellowish red) subsoils, which might be

TABLE 2: Selected morphological properties of the pedons.

Pedon	Horizon	Depth (cm)	Boundary ¹	Color		Moist	Texture (Feel method) ²	Structure ³	Consistency ⁴	Coarse fragment (%)
A-1	Ap	0–18	GS	10YR 3/6	10YR 3/6	10YR 3/3	CL	MO, VM, GR	SHA, FR, ST, SPL	—
	Bw1	18–25	GS	2.5YR 4/6	2.5YR 4/6	2.5YR 4/4	CL	MO, VM, AB	SHA, FR, ST, SPL	—
	Bw2	25–35	GS	2.5YR 4/8	2.5YR 4/8	2.5YR 4/6	C	MO, FM, AB	SHA, FR, ST, PL	—
	CB	35–110	—	2.5YR 4/6	2.5YR 4/6	2.5YR 4/6	C	MO, FM, AB	SHA, FR, ST, PL	47
A-2	A	0–18	GS	10YR 4/3	10YR 4/3	10YR 3/2	CL	MO, FM, GR	SHR, FR, ST, PL	—
	Ad	18–27	CS	10YR 4/3	10YR 4/3	10YR 3/2	CL	MO, FM, AB	SHA, FR, ST, PL	—
	Bt1	27–37	CS	2.5YR 4/4	2.5YR 4/4	2.5YR 4/3	C	MO, ME, AB	SHA, FR, ST, PL	—
	Bt2	37–50	GS	2.5YR 4/6	2.5YR 4/6	2.5YR 4/5	C	MO, ME, AB	SHA, FR, ST, PL	—
	BC	50–80	—	2.5YR 4/6	2.5YR 4/6	2.5YR 4/5	C	MO, ME, AB	SHA, FR, ST, PL	21
A-3	Ap	0–22	CS	7.5YR 3/3	7.5YR 3/3	7.5YR 3/3	CL	MO, FM, GR	SHA, FR, ST, PL	—
	A	22–33	CS	7.5YR 3/3	7.5YR 3/3	7.5YR 3/2	C	MO, ME, AB	HA, FR, VST, VPL	—
	Bt1	33–45	GS	5YR 4/6	5YR 4/6	5YR 4/4	C	MO, ME, AB	HA, FR, VST, VPL	—
	Bt2	45–63	GS	5YR 4/4	5YR 4/4	2.5YR 4/3	C	MO, ME, AB	HA, FR, VST, VPL	—
	BC	63–85	—	5YR 4/6	5YR 4/6	5YR 4/4	C	MO, ME, AB	HA, FR, VST, VPL	19
A-4	Ap	0–10	CS	10YR 3/6	10YR 3/6	10YR 3/3	CL	WE, FI, GR	SHA, FR, ST, PL	—
	A	10–19	CS	10YR 3/4	10YR 3/4	10YR 3/3	C	ST, FM, SB	VHA, FI, ST, PL	—
	Bt1	19–37	GS	7.5YR 4/4	7.5YR 4/4	7.5YR 3/3	C	ST, FM, AB	VHA, FI, ST, PL	—
	Bt2	37–75	GS	5YR 4/6	5YR 4/6	5YR 3/4	C	ST, FM, AB	HA, FI, ST, PL	—
	BC	75–85	—	5YR 4/6	5YR 4/6	5YR 4/4	C	ST, FM, AB	SHA, FR, TS, PL	23
A-5	Ap	0–17	GS	10YR 3/7	10YR 3/7	10YR 3/1	C	MO, MC, AB	HA, FR, ST, PL	—
	A	17–55	GS	10YR 5/2	10YR 5/2	10YR 3/2	C	ST, CO, AB	VHA, FI, ST, PL	—
	Bss1	55–116	GS	2.5Y 5/2	2.5Y 5/2	2.5Y 4/2	C	ST, CO, AB	VHA, VFI, ST, PL	—
	BCss2	116–150	—	10YR 5/2	10YR 5/2	10YR 3/2	C	VST, CO, AB	VHA, VFI, ST, PL	—
	Ap	0–20	—	10YR 4/3	10YR 4/3	10YR 3/2	L	MO, FM, GR	SHA, FR, ST, PL	—
A-7	A	0–29	CS	10YR 3/2	10YR 3/2	10YR 2/1	C	MO, FM, AB	SHA, FR, ST, PL	—
	Bss1	29–48	GS	10YR 4/4	10YR 4/4	10YR 3/4	C	ST, VC, AB	EHA, EFI, VST, VPL	—
	Bss2	48–105	GS	10YR 3/6	10YR 3/6	10YR 3/2	C	ST, ECAB	EHA, EFI, VST, VPL	—
	BCss	105–150+	—	2.5Y 6/1	2.5Y 6/1	2.5Y 5/1	C	ST, EC, PR	EHA, EFI, VST, VPL	—

¹ CS = clear and smooth; GS = gradual and smooth.² CL = clay loam; C = clay.³ WE = weak; ST = strong; MO = moderate; VST = very strong; FI = fine; FM = fine and medium; VM = very fine to medium; MC = medium and coarse; ME = medium; CO = coarse; VC = very coarse; EC = extremely coarse; GR = granular; SB = subangular blocky; AB = angular blocky; PR = prismatic.⁴ SHA = slightly hard; VHA = very hard; HA = hard; EHA = extremely hard; ST = sticky; SST = slightly sticky; VST = very sticky; PL = plastic; SPL = slightly plastic; VPL = very plastic; FR = friable; FI = firm; EFI = extremely firm.

TABLE 3: Particle size distribution and textural classes of soils of Abobo area.

Pedon	Horizon	Depth (cm)	Particle size distribution (%)			Textural class
			Sand	Silt	Clay	
A-1	Ap	0–18	37	28	35	Clay loam
	Bw1	18–25	33	31	36	Clay loam
	Bw2	25–35	30	33	37	Clay loam
	CB	35–110	35	30	35	Clay loam
A-2	A	0–18	20	29	51	Clay
	Ad	18–27	20	27	53	Clay
	Bt1	27–37	17	26	57	Clay
	Bt2	37–50	23	12	65	Clay
	BC	50–80	26	21	53	Clay
A-3	Ap	0–22	26	17	57	Clay
	A	22–33	28	20	52	Clay
	Bt1	33–45	25	14	61	Clay
	Bt2	45–63	24	14	62	Clay
	BC	63–85	36	14	50	Clay
A-4	Ap	0–10	25	28	47	Clay
	A	10–19	23	25	52	Clay
	Bt1	19–37	17	13	70	Clay
	Bt2	37–75	15	10	75	Clay
	BC	75–85	22	15	63	Clay
A-5	Ap	0–17	21	24	55	Clay
	A	17–55	23	18	59	Clay
	Bss1	55–116	27	14	59	Clay
	BCss2	116–150	24	15	61	Clay
A-6	Ap	0–20	35	32	33	Clay loam
A-7	A	0–29	35	18	47	Clay
	Bss1	29–48	31	15	54	Clay
	Bss2	48–105	27	8	65	Clay
	BCss	105–150+	21	11	68	Clay

due to oxidized Fe indicating good drainage conditions of the soils.

The surface horizons had granular and angular blocky structures with varied grade and size, whereas the subsurface horizons had moderate to very strong and fine to extremely coarse angular blocky and prismatic structures (Table 2). Generally, the size of the peds increased with depth and peds get larger and more block-like as was also reported by previous study [37]. Many of the peds were held together by coatings (cutans) of material that had been translocated into this horizon. Organic matter and microbial exudates serve to form and temporally stabilize the granular aggregates [38], although physical disruption of surface horizons reduces the microbial activity and aggregate stability as the stabilizing organic compounds are decomposed.

The dry consistence of the surface soil was slightly hard, except Pedon A-5, which had hard consistence (Table 2), whereas the moist and wet consistencies were friable and sticky/plastic, respectively. Likewise, the subsurface horizons had slightly hard to extremely hard (dry), friable to extremely firm (moist), and slightly sticky/plastic to very sticky/very plastic (wet) consistence. Generally, friable consistence

indicates the composition of different size of particles, the presence of organic materials, and microbiological activities in the soil. It was pointed out that the friable consistence observed in the surface soils of the pedons could be attributed to the higher soil OM contents of the layers [7]. The friable consistency of the soils indicates that the soils are workable at appropriate moisture content [36].

3.3. Physical Properties

3.3.1. Particle Size Distribution. The particle size determination showed that the soils of the study area are clay texture, except for the upper (A-1) and middle (A-6) slopes, which are clay loam (Table 3). The clay content varied from 33 to 59% in the surface horizons and generally increased with depth.

The textural differentiation might be caused by an illuvial accumulation of clay, predominant pedogenetic formation of clay in the subsoil, destruction of clay in the surface horizon, selective surface erosion of clay, upward movement of coarser particles due to swelling and shrinking, biological activity, and a combination of two or more of these different processes [18].

TABLE 4: Bulk density (ρ_b), particle density (ρ_p), total porosity (TP), water content, and available water content (AWC) of soils of Abobo area.

Pedon	Horizon	Depth (cm)	ρ_b (g cm ⁻³)	ρ_p (g cm ⁻³)	TP (%)	Water content (volume %)		AWC (volume %)
						FC	PWP	
A-1	Ap	0–18	1.20	2.42	50.41	42	25	17
	Bw1	18–25	1.22	2.42	49.59	39	23	16
	Bw2	25–35	1.32	2.52	47.62	40	26	14
	CB	35–110	—	—	—	—	—	—
A-2	A	0–18	1.21	2.48	51.21	40	24	16
	Ad	18–27	1.27	2.48	48.79	39	26	13
	Bt1	27–37	1.29	2.51	48.61	40	26	16
	Bt2	37–50	1.29	2.50	48.40	38	23	15
	BC	50–80	—	—	—	—	—	—
A-3	Ap	0–22	1.20	2.44	50.82	47	29	18
	A	22–33	1.21	2.44	49.59	43	28	15
	Bt1	33–45	1.23	2.43	49.38	41	24	17
	Bt2	45–63	1.25	2.41	48.13	41	23	18
	BC	63–85	—	—	—	—	—	—
A-4	Ap	0–10	1.20	2.45	51.02	44	28	16
	A	10–19	1.23	2.39	48.53	36	24	12
	Bt1	19–37	1.27	2.42	47.52	44	26	18
	Bt2	37–75	1.31	2.46	46.75	41	29	12
	BC	75–90	—	—	—	—	—	—
A-5	Ap	0–17	1.20	2.50	52.00	42	27	15
	A	17–55	1.24	2.44	49.18	44	31	13
	Bss1	55–116	1.25	2.38	47.48	41	29	12
	BCss2	116–150	—	—	—	—	—	—
A-6	Ap	0–20	1.20	2.53	52.57	35	19	16
A-7	A	0–29	1.12	2.37	52.74	39	23	16
	Bss1	29–48	1.21	2.31	47.84	45	31	14
	Bss2	48–105	1.25	2.32	46.12	49	34	15
	BCss	105–150+	—	—	—	—	—	—

—: not determined; FC: field capacity; PWP: permanent wilting point.

In the surface horizons of the pedons, silt and sand contents varied from 17 to 32% and 20 to 37%, respectively, whereas their respective values varied from 8 to 33% and 15 to 36% in the subsurface horizons. Negative and significant ($r = -0.78$, $p < 0.001$) correlation was observed between clay and sand indicating that removal of clay results in accumulation of sand (Table 10).

3.3.2. Bulk, Particle Density, Total Porosity, and Soil Water Retention. The bulk and particle density values of the surface horizons ranged from 1.12 to 1.21 and 2.37 to 2.53 g cm⁻³, respectively (Table 4). Relatively higher (1.21 g cm⁻³) surface horizons bulk density was recorded for the cultivated land, which could be attributed to compaction created due to cultivation. An increase in soil bulk density by 21.42% was observed due to deforestation and subsequent cultivation [39].

The total pore space in the surface layer ranged from 52 to 53 (Table 4). The values were within the range (40 to 60%) of clay texture total porosity [40] and showed decreasing trend with soil depth. This could be related to the distribution of organic matter content and natural compaction of the subsurface soils by the load of surface soils [41]. As the soil OM contents decreased, the soils would be less aggregated and the bulk density would be increased. As a result, the total porosity would be decreased. The correlation analysis revealed highly negative and significant ($r = -0.92$, $p < 0.001$) relationship between bulk density and total porosity (Table 10).

Following the general relationship of soil bulk density to root growth, the root-restricting bulk densities for clay are greater than 1.47 g cm⁻³ [42] and for clay loam greater than 1.75 g cm⁻³ [43]. Thus, the soils of the study area were not compacted to the extent of restricting root growth.

TABLE 5: Infiltration characteristics of soils of Abobo area.

Nearby pedon	Coordinates		Basic infiltration rate (cm hr ⁻¹)	Categories
	Latitude	Longitude		
A-1	08°01'35.1"	034°33'42.0"	3.3	Moderate
A-2	07°59'54.7"	034°33'25.9"	1.1	Moderately slow
A-3	07°54'02.1"	034°33'31.8"	2.0	Moderate
A-4	07°57'05.0"	034°33'10.0"	1.7	Moderately slow
A-5	07°54'36.9"	034°32'12.9"	0.5	Moderately slow
A-6	07°52'49.0"	034°29'54.9"	2.1	Moderate
A-7	07°51'23.5"	034°29'02.7"	0.4	Slow

The soil water content at field capacity (33 kPa) varied from 35 to 49% for clay loam and clay textural classes, respectively (Table 4), whereas at permanent wilting point, it varied from 19 to 34% for the same soil textural classes. The available water content ranged from 12 to 18% and the values were influenced by organic matter and clay contents within the horizons.

3.3.3. Infiltration. Basic infiltration rate varied from 0.4 (clayey soil of A-7) to 3.3 cm hr⁻¹ (clay loam texture of Pedon A-1) showing that the relatively higher sand content in Pedon A-1 contributed to the highest infiltration rate, whereas the expansive clay decreased the infiltration rate in case of Pedon A-7 (Table 5). Infiltration rates were initially high in all pedons, perhaps due to the large suction gradients and progressively approached final steady state. The decrease of infiltrability from an initially high rate can in some cases result from gradual deterioration of soil structure and the partial sealing of the profile by the formation of a surface crust [44]. It can also result from the detachment and migration of pore-blocking particles, from swelling of clay, as well as from entrapment of air bubbles or the bulk compression of the air originally present in the soil, if it is prevented from escaping during its displacement by incoming water.

The soils of the study area could be categorized under slow, moderately slow, and moderate infiltration rate [17]. The author concluded that soils having average infiltration rates less than 0.1 cm hr⁻¹ are usually considered nonirrigable for crops other than rice indicating that the soils of the area are suitable for irrigation.

3.4. Chemical Properties

3.4.1. Soil pH, Electric Conductivity, Calcium Carbonate, and Gypsum Contents. The results revealed that the pH (H₂O) of the surface soil ranged from 5.5 to 7.1, whereas the subsurface pH values were between 5.7 and 6.7 (Table 6) indicating that the soils are moderately acidic to neutral [45]. In the range of pH 5.5 to 7, hydroxyl aluminum polymers predominate among acids soil components, exchangeable acidity is virtually absent, and only none exchangeable and titratable acidity are present in measurable quantities [46]. Although potential acidity depends on the equilibrium pH of the soil suspension [47], exchangeable aluminum normally occurs in significant amounts only at soil pH values less than about 5.5.

Considering the optimum pH for many plant species to be 5.5 to 6.8 [48] and absence of free exchangeable Al in this range, the pH of the soils in study area could be considered as suitable for most crop production.

The pH (KCl) values ranged from 4.7 to 6.4 and 4.9 to 5.9 for surface and subsurface horizons, respectively (Table 6). The pH measurements in KCl were lowered by 0.5 to 1.3 units compared to pH measurements in H₂O. Increasing the neutral salt concentration to 0.1 or 1 M can lower the measured soil pH as much as 0.5 to 1.5 units compared to in distilled water suspensions [46], because H and Al cations on or near soil colloid surfaces can be displaced by exchange with soluble cations. If a higher reading is obtained in salt solution than in water, this almost invariably indicates poor nutrient availability and the likelihood of strong phosphate fixation [17].

Electrical conductivity (EC) values of the pedon varied from 0.05 to 0.24 dS m⁻² and in accordance with the EC rating, the soils of the study area were nonsaline [49]. Similarly, the calcium carbonate (CaCO₃) content within the pedons varied from 0.13 to 0.39%, whereas the gypsum (CaSO₄·2H₂O) content was trace throughout the soil profiles. Thus, the soils were low in both calcium carbonate [17] and gypsum contents [50]. The EC and CaCO₃ contents showed irregular pattern in most of the pedons with increasing depth, indicating low degree of leaching process in the area. However, Pedons A-5 and A-7 showed increasing trained in CaCO₃ content with depth.

3.4.2. Organic Carbon, Total Nitrogen, Carbon to Nitrogen Ratio, Available Phosphorus, and Potassium. The organic carbon (OC) content ranged from 1.32 to 2.98% in the surface layers of all pedons and could be categorized under low to medium [51]. The values decreased with increasing depth in all pedons (Table 7). Generally, the low to medium content of soil OC is attributed to the warmer climate, which enhances rapid rate of mineralization [41]. Relatively higher OC (2.98%) for surface layers was recorded in fallow land (Pedon A-4) while the lowest (1.32%) was recorded in cultivated cotton state farm (Pedon A-3). The difference could be attributed to the rapid decomposition and mineralization of organic matter under cultivation practices [34, 52]. Furthermore slash and burn, which is a common practice in the area during field preparation, might have also contributed to the depletion of soil OC.

TABLE 6: Soil pH, electrical conductivity, and calcium carbonate.

Pedon	Horizon	Depth (cm)	pH (1:2.5)		Δ pH	EC (dS m ⁻¹)	CaCO ₃ (%)
			(H ₂ O)	(KCl)			
A-1	Ap	0–18	6.0	5.1	0.9	0.10	0.23
	Bw1	18–25	6.1	5.6	0.5	0.10	0.19
	Bw2	25–35	6.0	5.3	0.7	0.08	0.15
	CB	35–110	6.3	5.6	0.7	0.08	0.24
A-2	A	0–18	6.5	5.8	0.7	0.15	0.25
	Ad	18–27	6.7	5.9	0.8	0.10	0.17
	Bt1	27–37	6.1	5.4	0.7	0.07	0.20
	Bt2	37–50	6.3	5.6	0.7	0.07	0.35
	BC	50–80	6.4	5.7	0.7	0.05	0.31
A-3	Ap	0–22	6.7	5.9	0.8	0.23	0.28
	A	22–33	6.5	5.7	0.8	0.21	0.25
	Bt1	33–45	6.3	5.6	0.7	0.14	0.23
	Bt2	45–63	6.3	5.5	0.8	0.09	0.25
	BC	63–85	6.0	5.3	0.7	0.09	0.27
A-4	Ap	0–10	6.6	5.8	0.8	0.16	0.29
	A	10–19	6.0	5.4	0.6	0.10	0.21
	Bt1	19–37	6.3	5.6	0.7	0.09	0.14
	Bt2	37–75	6.1	5.2	0.9	0.06	0.17
	BC	75–90	6.2	5.5	0.7	0.06	0.13
A-5	Ap	0–17	5.5	4.7	0.8	0.11	0.16
	A	17–55	5.7	4.9	0.8	0.08	0.15
	Bss1	55–116	6.1	5.0	1.1	0.06	0.22
	BCss2	116–150	6.5	5.8	0.7	0.06	0.27
A-6	Ap	0–20	7.1	6.4	0.7	0.24	0.39
A-7	A	0–29	6.1	5.1	1.0	0.15	0.19
	Bss1	29–48	6.1	5.3	0.8	0.13	0.21
	Bss2	48–105	6.6	5.3	1.3	0.07	0.29
	BCss	105–150+	6.8	5.9	0.9	0.16	0.31

The total N content of the surface soils ranged 0.11 to 0.24%, which could be rated as low to medium [51]. Similar to OC, total N content decreased with depth in all pedons (Table 7). Soils with less than 0.07% total N have limited N mineralization potential, while those having greater than 0.15% total N would be expected to mineralize a significant amount of N during the succeeding crop cycle showing that most of the soils have good potential of N mineralization [53]. A strong positive correlation ($r = 0.92$, $p < 0.001$) was observed between soil OM and total N indicating the main source of N in the soils is organic matter (Table 10).

The carbon to nitrogen ratio (C:N) showed numerically narrow variation among the pedons and irregular pattern with increasing depth. This is in contrast to the findings of previous study [54] where C:N ratio varied markedly due to change in land use and decreased consistently with increasing depth. Generally, most of the values were found between 10:1 and 13:1, showing optimal range of mineralization.

The available phosphorus content of the pedons ranged from 0.22 in subsoil of Pedon A-7 to 108.3 mg kg⁻¹ in surface layer of Pedon A-6 (Table 7), which could be categorized from very low to very high [55]. Relatively the maximum available

P was recorded in pedon where the pH was neutral (7.1), the pH value where P fixation is low. P-Olsen between 12 and 18 mg kg⁻¹ is considered as sufficient [56] and hence the available P in surface horizons of all pedons was in sufficient range, except Pedon A-7. It was also reported that soil P is more available in warm soil than in cool soil [53]. Therefore, P availability in the soils might have been favored by the warm climatic condition of the study area along with the preferred pH range. Available P values declined with increasing depth which could be attributed to decrease in soil OM, as was also asserted by their positive significant ($r = 0.71$, $p < 0.01$) correlation (Table 10). The increase in clay content with depth could have also contributed to decrease available P, although this was not confirmed by the correlation analysis.

The available potassium content of the soils of all the pedons varied from 113 to 1155 mg kg⁻¹ (Table 7) and could be categorized from medium to very high [55]. The highest available K (1155 mg kg⁻¹) was recorded in the surface horizon of Pedon A-4, whereas the smallest value (115 mg kg⁻¹) was in Pedon A-5 and the values generally decreased with depth. High values of available K in 0–40 cm depth compared to those in 40–120 cm depth were observed and were attributed

TABLE 7: Organic carbon, total nitrogen, carbon to nitrogen ratio, available P, and available K contents of soils of Abobo area.

Pedon	Horizon	Depth (cm)	OC (%)	TN (%)	C : N	Available P (mg kg ⁻¹)	Available K (mg kg ⁻¹)
A-1	Ap	0–18	2.64	0.20	13	25.34	295
	Bw1	18–25	1.72	0.13	13	17.28	285
	Bw2	25–35	0.84	0.05	16	6.09	301
	CB	35–110	0.56	0.04	13	7.15	274
A-2	A	0–18	1.98	0.18	11	47.84	780
	Ad	18–27	1.19	0.08	15	22.50	750
	Bt1	27–37	0.61	0.05	12	10.26	581
	Bt2	37–50	0.52	0.04	13	16.37	473
	BC	50–80	0.31	0.02	15	9.20	330
A-3	Ap	0–22	1.32	0.11	12	50.00	700
	A	22–33	0.75	0.07	11	31.35	615
	Bt1	33–45	0.63	0.05	13	14.20	439
	Bt2	45–63	0.42	0.03	14	10.86	201
	BC	63–90	0.27	0.03	9	8.11	134
A-4	Ap	0–10	2.98	0.24	12	88.40	1155
	A	10–19	2.79	0.21	13	60.35	1079
	Bt1	19–37	1.52	0.11	13	33.12	754
	Bt2	37–75	0.80	0.07	11	8.38	180
	BC	75–85	0.60	0.05	12	6.79	236
A-5	Ap	0–17	1.94	0.14	14	16.28	115
	A	17–55	1.28	0.16	8	11.35	150
	Bss1	55–116	0.76	0.05	15	6.08	115
	BCss2	116–150	0.44	0.03	14	7.43	123
A-6	Ap	0–20	2.59	0.23	11	108.32	755
A-7	A	0–29	2.10	0.20	10	4.92	210
	Bss1	29–48	1.40	0.11	13	2.37	186
	Bss2	48–105	0.48	0.04	12	0.22	130
	BCss	105–150+	0.28	0.02	14	1.44	145

to the difference in weathering rate [57]. Potassium removal from primary minerals requires hydronium ion, which dissociates from organic and inorganic acids in the soil solution [4]. Obviously, the supply of hydronium is relatively higher in the surface horizon due to the relatively higher contents of organic matter and root activities, which release CO₂. The dissolution of CO₂ forms H₂CO₃ and ultimately hydronium ion. This process might have resulted in higher available K in surface than subsurface layers. Relatively the highest available K (1155 mg kg⁻¹) was recorded in surface horizon of Pedon A-4 where the OC was highest (2.98%).

3.4.3. Cation Exchange Capacity, Exchangeable Bases, and Base Saturation. The overall cation exchange capacity (CEC) of the soils ranged between 20.66 and 44.70 cmol_c kg⁻¹ (Table 8), which is medium to very high [58]. The smallest value was recorded under Pedon A-6, which was under continuous maize cultivation, whereas the highest value was recorded under Pedon A-7 of forest land. Previous studies indicated that deforestation and subsequent cultivation led to decline in CEC [39, 59, 60]. On the other hand, the CEC clay varied from 36.70 to 77.96 cmol_c kg⁻¹ suggesting greater proportions of 2:1 clay mineral, most probably

montmorillonite and/or illite with more nutrient reserves. Soils with low CEC are more likely to develop deficiencies in potassium (K⁺), magnesium (Mg²⁺), and other cations while high CEC soils are less susceptible to leaching of these cations [61]. Generally, CEC is a very important soil property influencing soil structure stability, nutrient availability, soil pH, and the soil's reaction to fertilizers and other ameliorants [58]. Generally, the soils of the study area had good nutrient retention and buffering capacity due to the high status of CEC.

The results revealed that the contents of exchangeable Ca and Mg varied from 10.24 to 29.12 and 3.76 to 8.98 cmol_c kg⁻¹, respectively, whereas exchangeable K varied from 0.29 to 2.95 cmol_c kg⁻¹. In accordance with the ratings of [62] the soils are categorized under high to very high with respect to Ca and Mg contents and low to very high in terms of K. The contents of exchangeable Ca and Mg (29.12 and 8.98 cmol_c kg⁻¹, resp.) were highest under Pedon A-7 of forest land, whereas the lowest values (10.24 and 3.76 cmol_c kg⁻¹, resp.) were recorded under Pedons A-4 and A-6 of cultivated lands. These differences could be due to crop uptake and recycling of nutrients under cultivated and forest lands, respectively.

TABLE 8: Exchangeable bases (Ca, Mg, K, and Na), cation exchange capacity (CEC), calcium to magnesium ratio (Ca : Mg), and percent base saturation (BS) of the soils.

Pedon	Depth (cm)	Exchangeable bases $\text{cmol}_c \text{ kg}^{-1}$					CEC $\text{cmol}_c \text{ kg}^{-1}$		ESP (%)	Ca : Mg	PBS (%)
		Ca	Mg	K	Na	TEB*	Soil	Caly			
A-1	0–18	12.50	5.70	0.75	0.11	13.07	25.54	72.97	0.4	2.19	75
	18–25	13.57	8.61	0.78	0.14	16.21	23.92	66.44	0.6	1.59	96
	25–35	11.02	4.34	0.71	0.16	20.37	24.13	65.22	0.7	2.54	68
	35–110	13.35	6.11	0.75	0.16	20.37	26.40	75.43	0.6	2.18	77
A-2	0–18	14.63	6.52	1.99	0.09	23.23	25.71	50.41	0.3	2.24	90
	18–27	15.01	6.07	1.76	0.10	22.87	25.02	47.21	0.4	2.47	91
	27–37	15.62	5.96	1.42	0.08	23.08	26.01	45.63	0.3	2.62	89
	37–50	13.20	7.01	1.57	0.10	21.88	25.96	39.94	0.4	1.88	84
	50–80	13.74	6.68	0.98	0.13	21.53	25.44	48.00	0.5	2.06	85
A-3	0–22	18.48	5.61	1.79	0.13	25.93	26.47	46.44	0.5	3.29	98
	22–33	16.36	5.61	1.63	0.26	23.86	27.32	49.67	0.9	2.92	87
	33–45	17.24	4.31	1.41	0.19	23.15	28.65	46.97	0.7	4.00	81
	45–63	18.61	5.01	0.98	0.18	24.77	29.34	47.32	0.6	3.71	84
	63–85	19.25	5.50	1.02	0.21	25.98	28.17	56.34	0.7	3.5	92
A-4	0–10	18.41	8.64	2.95	0.13	29.96	36.64	77.96	0.4	2.13	82
	10–19	16.27	8.03	1.87	0.15	26.32	34.12	65.61	0.4	2.03	77
	19–37	13.01	7.66	2.05	0.12	22.84	35.47	50.67	0.3	1.70	64
	37–75	10.24	7.36	0.46	0.11	18.18	27.53	36.70	0.4	1.39	66
	75–90	11.12	8.00	0.51	0.15	19.78	28.84	45.77	0.5	1.39	68
A-5	0–17	15.80	6.89	0.40	0.13	23.22	31.14	56.62	0.4	2.29	75
	17–55	14.98	6.54	0.37	0.24	22.13	30.79	52.19	0.8	2.29	72
	55–116	18.61	6.27	0.29	0.30	25.48	33.24	56.34	0.9	2.97	77
	116–150	20.23	5.97	0.31	0.35	26.86	34.11	55.92	1.3	3.39	79
A-6	0–20	12.81	3.76	1.93	0.11	18.61	20.66	62.61	0.5	3.41	90
A-7	0–19	20.33	3.90	0.54	0.22	28.99	35.08	74.73	0.6	5.21	83
	19–48	25.97	8.44	0.41	1.13	35.95	37.38	69.22	3.0	3.08	96
	48–105	28.38	8.77	0.33	1.35	38.83	44.70	67.69	3.0	3.24	87
	105–150+	29.12	8.98	0.33	1.41	39.84	43.56	64.06	3.2	3.24	91

*TEB = total exchangeable bases.

The exchange complex was found to be dominated by Ca followed by Mg, K, and Na, which could be considered as appropriate for plant growth. Cations in productive agricultural soils are present in the order $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+ > \text{Na}^+$ and deviations from this order can create ion-imbalance problems for plants [46]. Ca:Mg ratio of the pedons did not reveal deficiency for both cations [58]; however, all of the pedons were categorized under low (1 to 4) availability for Ca, except surface horizon of Pedon A-7, which could be categorized under balanced availability. The approximate optimum range of Ca : Mg ratio for most crops is between 3 : 1 and 4 : 1 [17]. If it is less than 3:1, P uptake may be inhibited.

The exchangeable Na accounted only for 0.3 to 3.2% of the exchangeable cations, with lowest and highest values in Pedons A-2 and A-7, respectively (Table 8). The Na content throughout the profiles of all pedons was low indicating the absence of sodicity problem. Additionally, the percent base saturation of the pedons ranged from 64 to 98% (Table 8), which could be categorized under high to very high contents [58]. Relatively lower percent base saturation (75%) in the

surface soils was observed under Pedons A-1 and A-5 of maize farms. The reason might be the depletion of bases due to continuous cultivation of maize. It was concluded that deforestation and conversion of forest land to agricultural uses resulted in significant change in percent base saturation [59]. The highest value ($39.84 \text{ cmol}_c \text{ kg}^{-1}$) of total exchangeable bases was recorded under lower slope Pedon A-7 of forest land, whereas the smallest value ($13.07 \text{ cmol}_c \text{ kg}^{-1}$) was recorded under Pedon A-1 of upper slope cultivated land. The difference was attributed by the combined effect of slope position and land use.

3.4.4. Micronutrients. The contents of available micronutrients in the pedons generally decreased with increasing depth. The soils of the study area were found to be high in Fe (10.36 to 36.58 mg kg^{-1}), medium to high in Mn and Zn (10.33 to 42.18 and 0.63 to 4.75 mg kg^{-1} , resp.), and low to medium in Cu (1.48 to 4.23 mg kg^{-1}) contents [55] (Table 9). Fertilizer response is unlikely for values greater than 10.0, 3.0, 1.5, and 1.0 for Fe, Mn, Zn, and Cu, respectively [53]. Accordingly,

TABLE 9: Available micronutrient contents of the soil of Abobo area.

Pedon	Horizon	Depth (cm)	Micronutrients (mg kg ⁻¹)			
			Fe	Mn	Zn	Cu
A-1	Ap	0–18	28.87	42.18	4.75	3.86
	Bw1	18–25	24.91	38.21	3.05	3.59
	Bw2	25–35	17.43	27.46	1.21	3.17
	CB	35–110	19.55	35.13	0.63	2.10
A-2	A	0–18	24.03	41.23	4.64	4.23
	Ad	18–27	25.61	34.51	4.13	3.00
	Bt1	27–37	20.35	29.06	2.07	3.34
	Bt2	37–50	20.12	19.45	1.13	2.51
	BC	50–80	18.22	21.76	1.10	2.76
A-3	Ap	0–22	18.46	38.81	4.59	3.75
	A	22–33	16.53	14.94	3.41	2.97
	Bt1	33–45	12.97	10.65	2.25	3.18
	Bt2	45–63	14.26	13.21	1.13	2.37
	BC	63–85	12.66	10.33	1.11	1.48
A-4	Ap	0–10	24.07	41.46	3.62	3.30
	A	10–19	23.03	38.15	2.92	2.68
	Bt1	19–37	15.97	31.09	1.57	2.59
	Bt2	37–75	12.35	25.95	0.99	2.55
	BC	75–90	13.95	27.83	0.76	1.76
A-5	Ap	0–17	36.58	40.94	2.42	3.93
	A	17–55	31.44	28.16	1.86	3.58
	Bss1	55–116	20.75	19.93	1.37	3.22
	BCss2	116–150	18.26	20.74	0.98	1.76
A-6	Ap	0–20	19.26	34.00	4.73	3.57
	A	0–19	29.61	40.52	1.64	2.15
A-7	Bss1	19–48	22.82	22.67	1.35	2.26
	Bss2	48–105	12.71	15.21	1.12	2.44
	BCss	105–150+	10.36	13.19	0.89	1.55

the soils of the study are not deficient in Fe, Mn, and Zn, whereas the lower values of available Cu in some of the pedons indicate the potential deficiency of the element with continuous cropping. Previous findings have also indicated Cu deficiency in Ethiopian soils as a wide spread problem [36, 41].

The contents of Fe and Mn were relatively highest in Pedons A-5 and A-1, respectively. Numerically, wide variation was not observed in Mn contents among the surface horizons of the pedons. The highest values of Zn (4.75 mg kg⁻¹) and Cu (4.23 mg kg⁻¹) were observed in surface horizons of Pedons A-1 and A-2, respectively, whereas the corresponding lowest values (1.64 and 2.15, resp.) were recorded in Pedon A-7. Relatively higher values of available micronutrients were expected under forest land use as compared to the cultivated lands. However, the reverse situation was observed in this study. The difference probably is due to texture; finely textured soils high in clay are abundant in micropores in which organic matter can find physical protection from microbial decomposition, which is a potential source of micronutrients. Contrary to this study, significantly higher ($p < 0.01$) values of micronutrients were observed in the natural and plantation forests than

cultivated land [63]. Positively significant ($r = 0.80$, $p < 0.01$) correlation was observed between Mn and soil OM (Table 10).

3.5. Classification of Soils of Abobo Area. The soils of the study area were classified according to WRB [18] and Soil Taxonomy [19], which is presented in Figure 1. The morphological properties in the field description and the physicochemical analysis results of the samples collected from every identified horizon were used for the classifications.

3.5.1. Soil Classification Based on WRB Legend. All pedons had well-structured dark surface horizons having color values of 3 when moist and 5 or less when dry with one unit less than the parent material in both cases. The surface layers of the pedons contain more than 0.6 percent organic carbon, base saturation (by 1 M NH₄OAc) of 50 percent or more throughout the horizon (Table 8) fulfilling the diagnostic criteria for mollic horizon, except Pedons A-1 and A-4, which failed to fulfill the horizon thickness requirement. The subsurface horizon of Pedon A-1 had redder hue, higher value, and chroma as well as higher clay content than the overlying and underlying layers. The layer was greater than

TABLE 10: Correlation matrix for linear relationships between soil parameters of Abobo area.

	Sand	Silt	Clay	ρ_b	TP	AWC	pH	OM	TN	Av.P	Ca	Mg	CEC	Fe	Mn	Zn	CU
Sand	1.00																
Silt	0.31	1.00															
Clay	-0.78***	-0.84***	1.00														
ρ_b	0.15	0.02	-0.10	1.00													
TP	-0.28	0.14	0.07	-0.92***	1.00												
AWC	-0.31	0.11	0.11	-0.60*	0.61*	1.00											
pH	0.24	0.15	-0.24	0.21	-0.21	0.07	1.00										
OM	0.25	0.57*	-0.52*	-0.35	0.33	0.19	0.07	1.00									
TN	0.34	0.53*	-0.55*	-0.33	0.30	0.14	0.13	0.96***	1.00								
Av. P	0.12	0.47	-0.38	-0.11	0.19	0.19	0.5*	0.71**	0.71**	1.00							
Ca	0.21	0.32	0.09	-0.11	-0.20	0.06	0.21	0.08	-0.02	-0.14	1.00						
Mg	0.06	0.65*	-0.46	-0.31	0.39	0.18	-0.04	0.79***	0.75**	0.46	-0.25	1.00					
CEC	-0.06	-0.51*	0.37	-0.09	-0.20	-0.07	-0.12	-0.002	0.01	-0.21	0.73**	-0.17	1.00				
Fe	0.11	0.43	-0.35	-0.36	0.38	0.06	-0.44	0.57*	0.59*	0.07	-0.06	0.68**	-0.05	1.00			
Mn	0.06	0.65*	-0.46	-0.31	0.39	0.18	-0.04	0.80***	0.75**	0.63*	-0.25	0.43	-0.17	0.68**	1.00		
Zn	0.02	0.51*	-0.35	-0.50*	0.59*	0.38	0.31	0.57*	0.55*	0.63*	-0.24	0.58*	-0.44	0.32	0.58*	1.00	
CU	-0.36	0.33	-0.01	-0.63*	0.78***	0.55	-0.23	0.26	0.20	0.200	-0.35	0.40	-0.39	0.36	0.40	0.58*	1.00

* Significant at $p \leq 0.05$, ** $p \leq 0.01$, and *** $p \leq 0.001$. ρ_b = bulk density; TP = total porosity; AWC = available water content; OM = organic matter; TN = total nitrogen; Av. P = available phosphorus; CEC = cation exchange capacity.

FIGURE 1: Soil map of the study area.

TABLE 11: Diagnostic horizons, properties, quantifiers, and soil types of Abobo area according to WRB.

Pedon	Diagnostic horizon		Diagnostic properties	Soil type
	Surface	Subsurface		
A-1	—	Cambic	—	Haplic Cambisols (eutric)
A-2	Mollic	Argic	Vertic	Vertic Luvisols (hypereutric)
A-3	Mollic	Argic	Vertic	Vertic Luvisols (hypereutric)
A-4	—	Argic	Vertic	Vertic Luvisols (hypereutric)
A-5	Mollic	Vertic	Vertic	Mollic Vertisols (hypereutric)
A-6	Mollic	—	—	Mollic Leptosols (eutric)
A-7	Mollic	Vertic	Vertic	Mollic Vertisols (hypereutric)

15 cm in thickness with clay loam in texture and moderately developed structure. The layer was therefore qualified for cambic horizon and the pedon was classified as Cambisols. The pedon also had base saturation (by 1 M NH_4OAc) of 50 percent or more throughout the profile qualifying for eutric, but without any noticeable prefix qualifier. Thus, the pedon was classified as Haplic Cambisols (eutric) (Table 11).

Pedons A-2, A-3, and A-4 had subsurface horizons with distinct higher clay content than the overlying horizons,

qualifying for argic subsurface diagnostic horizon. Consequently, the three pedons were classified under Luvisols. The soils also exhibited vertic properties and had base saturation (by 1 M NH_4OAc) of 50 percent or more throughout between 20 and 100 cm from the soil surface and 80 percent or more in some layer within 100 cm of the soil surface, qualifying vertic prefix and hypereutric suffix qualifiers. Finally, the three pedons were classified as Vertic Luvisols (hypereutric). On the other hand, Pedons A-5 and A-7 possessed subsurface

TABLE 12: Diagnostic horizons and soil types of Abobo area according to Soil Taxonomy.

Pedon	Diagnostic horizon		Subgroup
	Surface	Subsurface	
A-1	Mollic	Cambic	Typic Haplustepts
A-2	Mollic	Argillic	Vertic Haplustalfs
A-3	Mollic	Argillic	Vertic Haplustalfs
A-4	Mollic	Argillic	Vertic Haplustalfs
A-5	Mollic	Vertic	Typic Haplusterts
A-6	Mollic	—	Lithic Ustorthents
A-7	Mollic	Vertic	Typic Haplusterts

horizon having greater than 30% clay throughout, wedge-shaped structure with cracks that open and close periodically, and thickness of 25 cm or more, which qualify them for vertic diagnostic horizons. Thus, the two pedons are classified as Mollic Vertisols (hypereutric). The qualifier hypereutric was used for the second level classification due to their high percentage of base saturation. The remaining pedon (A-6) had shallow depth with extremely gravelly subsurface. As a result, the pedon was classified as Leptosols. The pedon had mollic horizon, base saturation (by 1 M NH_4OAc) of 50 percent or more, and therefore classified as Mollic Leptosols (eutric).

3.5.2. Soil Classification Based on Soil Taxonomy. All the soil profiles had thick (18 to 55 cm) surface horizons, having moist color of 10YR 3/4 and darker, weak to moderately strong structure. The organic carbon content of the surface horizons of the pedons ranged from 1.19 to 2.98% with percent base saturation of greater than 50 (by 1 M NH_4OAc). Thus, all the pedons possessed mollic epipedon. The subsurface horizon of Pedon A-1 had higher chroma, higher value, redder hue, or higher clay content than the underlying and overlying horizons, qualifying cambic subsurface diagnostic horizon, and it was classified as Inceptisols. It was classified under Ustepts due to its ustic moisture regime and the pedon was further classified as Haplustepts and Typic Haplustepts (Table 12).

Pedons A-2, A-3, and A-4 had an argillic horizon and hence categorized under the order Alfisols [19]. The pedons were further grouped under Ustalfs at suborder level due to their ustic soil moisture regime and Haplustalfs and Vertic Haplustalfs, at great group and subgroup levels, respectively, due to their vertic properties.

Pedons A-5 and A-7 had 30 percent and more clay and exhibit slicken sides and cracks that open and close periodically. Thus, the pedons were classified under Vertisols. If not irrigated during the year, the cracks remained opened for 90 or more cumulative days per year, qualifying it for Usterts suborder, and Haplusterts and Typic Haplusterts at great group and subgroup, respectively. Pedon A-6 had shallow depth with extremely gravelly subsurface and classified as Entisols and Orthents suborder. The pedon further classified as Ustorthents suborders due to its ustic moisture regime. The pedon had also a lithic contact within 50 cm of the mineral soil surface and hence classified as Lithic Ustorthents.

4. Conclusion

Field study was carried out to characterize and classify soils of Abobo area, western Ethiopia. The soils were thoroughly examined and differentiated along north-south transect based on observable site and soil characteristics including slope, soil depth, and texture following free survey method. Seven representative pedons (A-1 to A-7) were opened and described across the study area. The results of the study revealed variation in morphological, physical, and chemical properties of the soils across the study area, which indicate their variation in productive potential and management requirements for specific agricultural use.

Four soil types, Haplic Cambisols (eutric), Vertic Luvisols (hypereutric), Mollic Leptosols (eutric), and Mollic Vertisols (hypereutric), were identified according to WRB and with their Soil Taxonomy equivalent to Typic Haplustepts, Vertic Haplustalfs, Lithic Ustorthents, and Typic Haplusterts, respectively. Therefore, using the soils according to their potential and suitability and by applying the required management would optimize agricultural production in a sustainable manner. Special emphasis should also be given to soil OM management as it plays a major role in soil physical, chemical, and biological quality. Additionally, integrated soil fertility management should be implemented in the area to optimize and sustain crop production.

Competing Interests

The authors declare that they have no competing interests.

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