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Research Article

Characterization and Mapping of Soil-Landscape for Site-Specific Soil Management in Ayiba Watershed, Northern Highlands of Ethiopia

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The characterization of soil landscapes is becoming increasingly important for making decisions regarding site-specific agriculture systems and soil management. This study was initiated for the purpose of identifying landscape-scale spatial soil variation using a toposequence model so that site-specific fertilization could be achieved. According to the finding, the soils were shallow to very deep in depth, moderately acidic to moderately alkaline in soil reaction, nonsaline in salinity, and clay to sandy loam in texture. The soils were found very low to low levels in most soil nutrients, very low to very high levels of base saturation, and deficient in zinc but have adequate levels of iron, copper, and manganese. The soil exchange complex was mainly dominated by Ca and Mg where the order of occurrence was Ca > mg > K > Na. The CEC values were in high to very high range. Following the field survey and soil analytical results, five main reference soil groups of the World Soil Resource Base—Leptosols (56%), Luvisols (8.5%), Fluvisols (14.4%), Vertisols (13%), and Cambisol (8.2%)—were identified and mapped. Leptosols cover the largest landmass of the watershed and mostly found at the summit and hill back slopes. On the other hand, Luvisols, Fluvisols, Vertisols, and Cambisols were found on the middle and foot slopes. According to the findings, the variation in soil source indicating that topography is the primary pedogenic element in the formation of the soil in the watershed that was under research. Therefore, having local-scale-specific soil information can assist the site-specific application of soil nutrients and amendments based on spatial variability which is tailored to the soil requirements.

1. Introduction

Soils are a nonrenewable source and comprise a vital component of the world's stock of natural capital with a prolonged forming process. Soil takes 100s to 1000s years to form a 1 cm of soil and erode in a relatively short time due to improper use or poor management with little opportunity for regeneration [1, 2]. Hence, soil scientists strongly recommend understanding the soil beneath our feet, managing it properly, and avoiding destroying the essential building block of our environment and food security. The soil is perhaps the most difficult, underrated, and little understood matrix [3, 4]. There is a saying by the legendary Italian artist Leonardo Da Vinci to explain our nuanced understanding of soil resources, i.e., "we know more about the movement of celestial bodies than about the soil underfoot" [5].

The main ecological functions of soils have grouped into the following three major categories: (i) regulatory and support functions; (ii) provision functions; and (iii) information, culture, leisure, and religion functions [6–8]. Soil is essential for supporting food production (producing about 95% of humanity's food supply) and providing ecosystem services. However, like other habitats and ecosystems, the soil is under increasing pressure due to anthropocentric activities [1] to the extent that a new geologic epoch, the Anthropocene, has been proposed [9]. Thus, the soil capital is threatened in Ethiopia and elsewhere due to rapid population growth, higher food demand, land use competition, massive vegetation clearing, desertification, overuse, and mismanagement. These caused it to exceed its capacity to perform, as manifested by land degradation [4, 10]. About 30% of the world's soils are currently degraded [11]. All of the world's topsoil could become unproductive within 60 years if current loss rates continue [12].

Consequently, defining the spatial distribution of soils and their features can improve natural resources management, forecast soil attributes in nonsampled sites, and improve sampling designs in agroecological and environmental studies. Given the importance of soil in ecosystems and human existence, soil health must be assessed, especially on field crop farms that dominate agricultural landscapes like Ethiopia. To feed a growing population and reduce agriculture's environmental impact, ecosystem services and agricultural productivity must be balanced [13]. Since agricultural soils are in danger, site-specific farming relies on spatial variability analysis and interpretation [14, 15]. Various studies on soil properties also confirmed that topographic position largely governs the change in types, characteristics, and distribution of soils [16, 17].

Local and regional planning, economic forecasting, food security, and environmental preservation depend on natural resource distribution data. Research also showed that precision agriculture's management zones are dependent on soil fertility variability [18]. Over the last few decades, landscape monitoring and assessment of spatial patterns has expanded as understanding of soil types and qualities is crucial for agricultural production and other land-use decisions [19]. Hence, soil characterization, classification, and mapping are crucial stages and building blocks in natural resources assessment tools for comprehending the soil landscape, classifying it, and acquiring the greatest understanding of the environment [20, 21]. In addition to soil-forming components, soil characterization describes color, texture, structure, consistence, voids, cutans, roots, cementations, nodules/concretions, rock fragments/stones, faunal activity, and horizon boundary of each generic soil horizon [22, 23].

However, according to the World Soil Information Service (WoSIS), Ethiopia has just 1712 soil profiles (WoSIS) [24]. More profile numbers will be researched than the WoSIS reported, but only a portion is accessible in a consistent format for the international community. Another lag is that no vernacular language Ethiopian soil classification system was established. This causes several soil use issues. Geospatially explicit soil-landscape resource data is scarce or dispersed across the nation [19]. Hence, beneficiaries need current site-specific soil knowledge from a local or watershed soil research for sustainable soil use. Moreover, the United Nations pledged to achieve sustainable development goals (SDGs) by 2030, and regional land use analyses are essential to achieving these goals. Study showed that soil resource information is essential for soil use planning and sustainable fertility control [25, 26].

Ethiopia is known as the "soil museum" since it has 19 of the 28 main soil classes on the FAO-UNSECO soil map of the World. However, our knowledge of Ethiopia's soil resources is limited. The soil resources were mapped at 1 : 2,000,000, which were too coarse and topographically not detailed enough to provide practical information for soil fertility decisions at site-specific spatial scales [27]. Previous soil surveys lacked essential soil data to manage soils according to their local variations (i.e., watershed or farm-scale). The soil classification systems and maps are the final steps of the soil survey; asserting soils by similar characteristics and/or properties; and making the knowledge accessible to policy-makers, farmers, and the scientific community [28]. Soil maps, which can be effectively produced with statistical models in digital soil mapping (DSM), contain vital information on the spatial distribution of soil properties used in fields such as water and land management and climate studies [29]. Currently, Mendes and Demattê [30] and Hartemink and Bockheim [31] explained that soil maps at regional and farm levels are essential for the best management of agricultural practices.

Site-specific nutrient management can address nutrient shortages and avoid excessive or inadequate application, which reduces environmental pollution and optimizes crop productivity and soil nutrient losses, benefiting the environment and farmers. Therefore, to address emerging concerns and maintain sustainable land use for current and future generations, precise and scientific soil data with a high-resolution soil map is needed for site-specific fertilizer recommendation and agricultural production intensification. Hence, this study was designed to generate meaningful soil classification aimed for site-specific fertilization to improve land utilization, productivity, and soil management in the southern Tigray of Ayiba watershed, northern Ethiopia using the FAO-WRB legends [22, 32]. We assess the agricultural landscape and contribute to an overall picture of its environmental quality by addressing the following specific objectives:

(i) To provide detailed morphological, physical, and chemical properties of the soils in the Ayiba mountainous landscape

(ii) To classify the soils according to the FAO-WRB soil classification system and develop a soil map of the watershed to enable soil-specific farm-scale management interventions

2. Materials and Methods

2.1. Site Description: Location, Climate, Soil, Land Use, and Husbandry. The research was conducted in southern Tigray's Ayiba watershed (4099.14 ha). It is part of the Denakil River basin and 106 kilometers from Mekelle, the Tigray capital, on the way to Addis Ababa through Maychew. Ayiba watershed lies between 12°51′18″–12°54′36″N and 39°29′24″–39°35′24″E (Figure 1). The elevation spans from 2722 to 3944 meters above

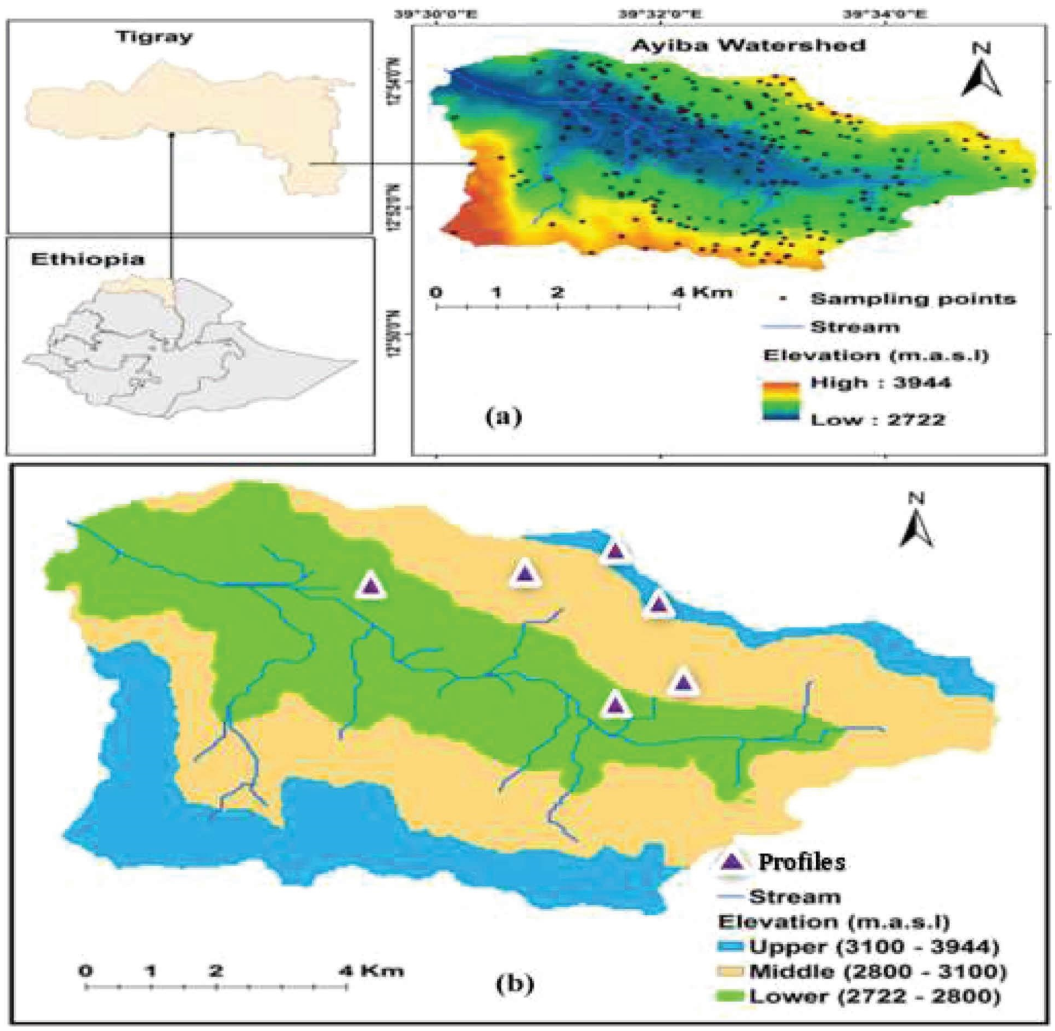


Figure 1: Location map of the Ayiba watershed [33].

sea level (m.a.s.l.) with rugged environment and steep upper and middle slopes. High mountainous relief hills, severely dissected plateaus, and valley bottoms characterize the study area's landform [27, 34]. In the study of watershed's geomorphological environment, basaltic parent material deposition down the slope caused landslides within the toposequence, which are crucial for soil distribution [27, 34, 35]. In similar geomorphological settings, Van de Wauw et al. [36] identified the following two essential mass movements: (a) large-scale landslides that move basaltic parent material downslope and (b) flows of vertic clays deposited at the foot of the sandstone cliff or similar secondary flows at the foot of large-scale landslides.

The watershed is generally characterized as tepid to cool semiarid climatic condition with extended 270–300 days of dry periods and 50–60 days of the rainy season and highland agroecological zone with a rainfall bimodally distributed [27, 34, 37]. The main rainy season, "*Keremti*" (summer: June to September), is preceded by a short rainy season, "*Belgi*" (spring: February to May), predominantly derived from the Indian Ocean [27, 38, 39]. According to the 20 years of weather data obtained from four nearby weather stations (Bora, Maychew, Wedisemero, and Korem), the mean monthly rainfall is 72.88 mm, with total annual precipitation of 853 mm. August is the peak period for main rain season and April is the peak for the slight rain season. The area's mean minimum and maximum monthly temperatures are 7.1 and 25.6°C, respectively, with a mean temperature of 16.8°C (Figure 2). The dotted area on the left and right sides designates the dry season. The area's annual potential evapotranspiration (PET) is about 1411 mm [27].

The study watershed's native woods and flora had been abandoned for more than 50–100 years, like other northern highland Ethiopia [41, 42]. Very tiny sections of remaining natural trees near churches are kept by psychic divining capacity. Since ancient times, religion has taught that "any disturbance to the nature and spirit around the holly Church (e.g., removing a tree and leaving animal for grazing or browsing) will bring a terrible consequence" (personal communication with local elders and priests, 2018). Demand for wood products for energy and construction and pressure from other land uses, agriculture, and cattle grazing to support the rapid population growth cause deforestation and forest degradation. Consequently, limiting deforestation and

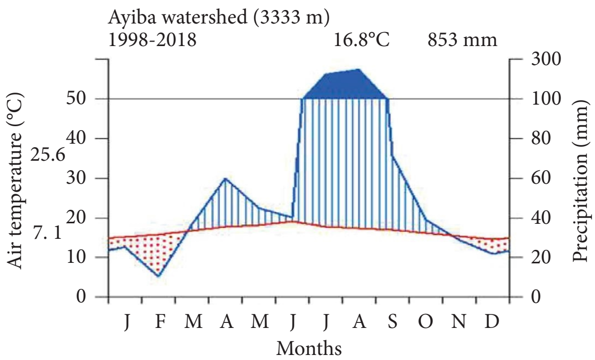


Figure 2: Climatic diagram of the Ayiba watershed from 1998 to –2018 [40].

expanding reforestation are predicted to make economic sense and assist agriculture and rural livelihood.

Farming relies on mixed crop-livestock systems [27]. Grain, legume, and certain vegetable and fruit crops are grown in the research region [27, 43]. Wheat, barley, and teff provide most of the study area's staples. For yield and rotation, legume crops such fava bean, field pea, Ethiopian pea, and lentils are grown. In the region, teff-wheat-legumes are rotated. Chickpea is also sown after harvesting using residual moisture. Besides, farmers in the watershed also raise onions, peppers, cabbages, and apples [35, 43]. Natural pasture is the primary source of animal feed in the area [44].

Regarding demography, there are no actual data which describe the study area in specific, but based on the 2022 Central Statistical Agency of Ethiopia (CSA) data, Alaje Woreda (second administrative level in Ethiopia), which include the study area and other 21 kebelles (first administrative level in Ethiopia), has a total population of 130,287 with a population density of 77.6 persons per square kilometer [45].

2.2. Profile Site Selection and Field Description. The watershed's soil variability was surveyed using the free-soil survey (traverse survey) approach. Before the field survey, a team of experts conducted a transect walk to identify major soil units and locate profile sampling sites. Local farmers, elders, and extension experts provided basic land information before soil sample collection. About 249 auguring was done to find mapping units and profile pit sites. The necessary soil survey facilities and formats such as the FAO guidelines for soil profile description [22], WRB soil classification manual [32], Munsell color chart, GPS, soil profile, and auger description sheets were collected and prepared before fieldwork.

Slope maps were produced from a digital elevation model (DEM), and a catena was physically picked from the north sloping land escarpment to the south valley floor, comprising landform components ranging from crest/summit to foot slope/toe slope (Figure 3(a)). Then, the selected toposequence was stratified into the following three landscape positions: upper (crest + shoulder), middle (back slope), and foot (toe slope + depressions) slope positions, and two profiles were opened at each (Figure 3(b)). Profiles were opened to a depth of 2+ m (unless soil depth is limited or is impracticable due to stoniness) with dimensions of 2 m × 1.5 m on a site that was representative of each landscape position. All profiles were geo-referenced, and general site information and soil description were recorded (Table S3). Profiles were defined and sampled according to established protocols to explore soil morphological, physical, and chemical parameters and morphological descriptions were done *in situ* [22, 32, 46].

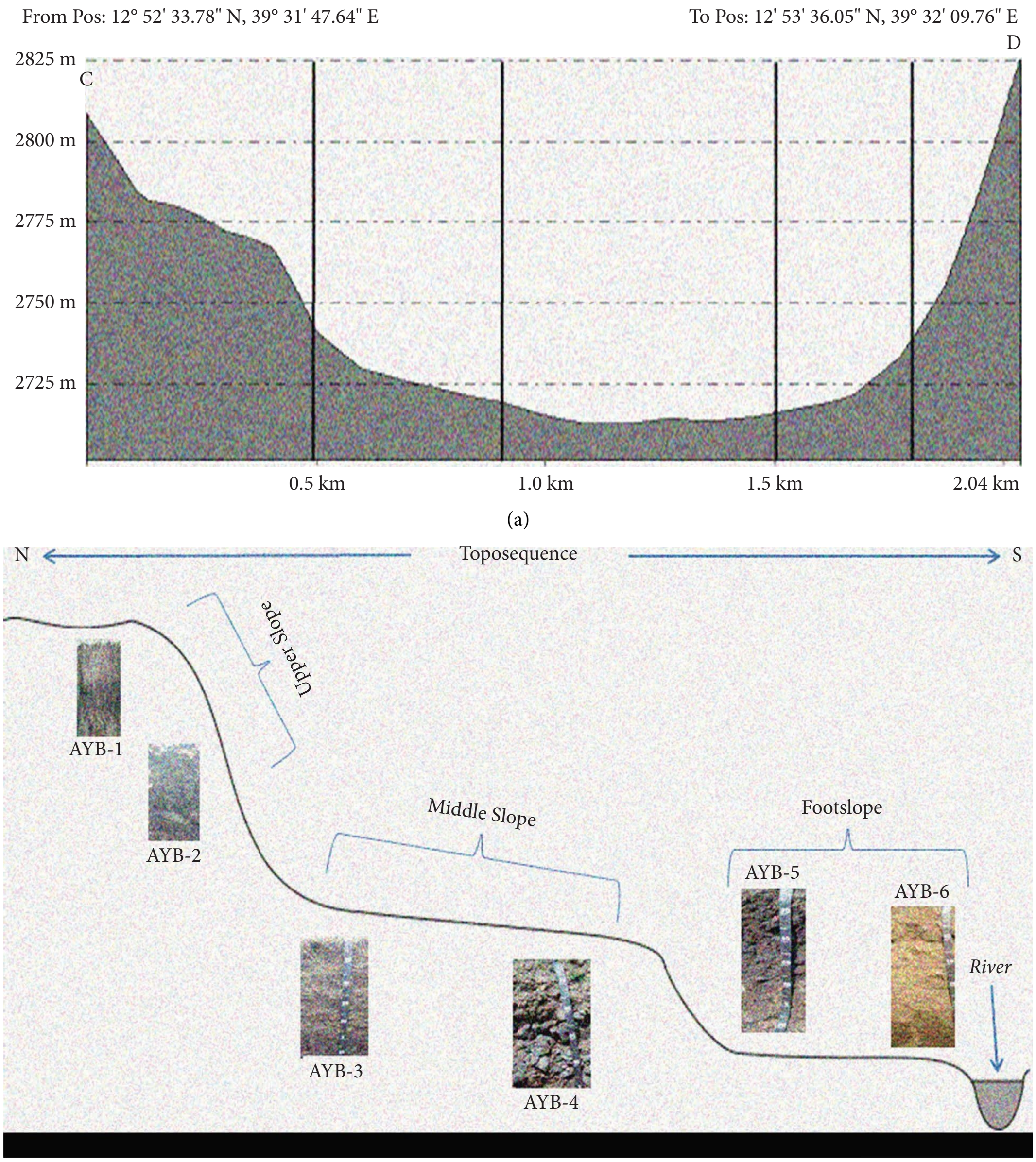
2.3. Soil Sampling and Analysis. Soil samples were collected using a soil auger. Then, disturbed and undisturbed soil samples were collected from each generic horizon (starting with the lowest horizon and working to the uppermost to avoid contamination) for the physicochemical laboratory analysis. Table 1 shows laboratory soil parameter measurement methods, and Table S1 was used for interpretation. The lab analysis was done at Tigray Soil Laboratory Center, Mekelle (Ethiopia), and Plant Nutrition Laboratory, Environmental Science Resources, Zhejiang University, Hangzhou (China).

2.4. Soil Classification and Mapping. Based on the morphological, physical, and chemical properties, the watershed soils were classified into different units (major soils) following the World Reference Base for soil resources [32]. Soils identical in landforms, parent material, relief, topography, and morphology were considered similar and accorded a similar mapping unit and their extent was described following IUSS Working Group WRB [62].

2.5. Statistical Data Analysis and Software Used. Average soil parameters value for each profile is computed and presented as mean ± standard error. Finally, the Ayiba watershed soil map was created using GIS software (version 10.5).

3. Result

3.1. Profile Site and Soil Morphological Characteristics. The profiles showed slope, drainage, and water erosion variances. The opening profiles were placed in a slope gradient range of slightly sloping to very steep (Table S2). The upper and middle terrain has most of the sloping to very steep slope gradient classifications (Figure 4 and Table S2). All profiles were well-drained except AYB-5 (Table S2). All Profile sites demonstrated a variety of water erosion processes, including sheet, rill, and gully formation (Figure 5 and Table S2). Land use, widespread and intensive farming, and plant removal have accelerated erosion at all profiles and their surrounding landscapes. Profiles AYB-1 and 3 were opened on basaltic and colluvial grassland soil while profiles AYB-2, 4, 5, and 6 were opened on annual rainfed field cropping sites with different land-use histories and soils formed from colluvium and alluvium basaltic origins (Table S2). Rainfed agricultural land, grassland, plantation forest, and barren ground dominated the upper and intermediate slopes (eroded sites), whereas cultivated land and



(b)

Figure 3: (a) Cross profile CD dissected plateau of the Ayiba watershed and (b) conceptual toposequence model showing landscape position and profiles opened at the upper slope, middle slope, and foot slope, respectively.

grassland dominated the watershed's foot slope. Our preceding articles contain information regarding the land use classification of the study watershed (https://doi.org/10.1155/2020/8816248 and https://doi.org/10.1016/j.heliyon.2021.e06770).

Table 2 and Table S4 provide morphological properties of each horizon's color, texture, structural distinction, etc. The soil depth ranged from 53 cm (shallow) at the top to 100+ cm (very deep) at the middle and foot slope. As rock debris rolls down due to gravity, AYB-1 was the shallowest profile, indicating limited soil-forming processes. In this study, dry and moist soils had a color hue of 2.5–10 YR, a value of 2–5, and chroma of 1–4. All profiles had soil colors ranging from black to greyish brown (dry) to black to yellowish brown (moist). Due to organic matter darkening, A- and B-horizon boundaries were visible. Over toposequence, field soil texture by feel varies; accordingly, profiles AYB-1, 2, and 5 had clay-dominated surfaces, while profiles AYB-3, 4, and 6 had sandy loam dominant. Surface horizons AYB-1 and 3 were slightly damp, but AYB-2, 4, 5, and 6 were dry, which may be related to soil organic matter and clay variance. By distinctness-topography, profiles 1 to 6 had clear-smooth, clear-wavy, clear-smooth, and diffuse-smooth horizon borders (Table 3).

All soils have friable surfaces but strong subsoils (Table S4). In the upper and middle catena, profiles 1 to 4 displayed weak to moderate surface structure and weak to strong subsurface structure. The surface horizon of AYB-5

Table 1: Soil parameters and methods used to determine in this study.

Soil parameters	Extraction method	References
Particle size distribution†	Modified hydrometer method	Beretta et al. [47]
Soil bulk density (ρd)	Core method	Blake and Hartge [48]
Soil aggregate stability (SAS)	Wet sieving method	Kemper and Rosenau [49]
Water retention capacity (FC, PWP, AWC)	Pressure plate apparatus	Schoonover and Crim [50]
Soil pH (H_2O-1 : 2.5 and 1 M KCl) and EC	Potentiometric method	Mclean [51]; Rhoades [52]
Soil organic carbon (SOC)	LOI methods	George et al. [53]; Heiri et al. [54]
Total nitrogen (TN)	Micro-kjeldahl digestion	Bremner [55]
Available phosphorus (av.P)	Olsen method	FAO [56]
Available sulfur (av.S)	Mehlich-III	Mehlich [57]
Available boron (av.B)	Mehlich-III (hot water extraction)	Johnson and Fixen [58]
Soil micronutrients (Zn, Cu, Mn, and Fe)	DTPA extraction	Lindsay and Martens [59]
Ex. Bases (Ca^{2+}, Mg^{2+}, Na^+, and K^+)	Ammonium acetate (pH-7)	Rhoades [52]
Soil CEC (cation exchange capacity)	Ammonium acetate (pH-7)	Van Reeuwijk [60]
Soil $CaCO_3$ (calcium carbonate equivalent)	Rapid titration method	Van Reeuwijk [60]

†Soil textural classes were read from the textural triangle [61], EC: electric conductivity, $\rho s = 2.65\ g{\cdot}cm^{-3}$, %SAS is the percentage of wet stable aggregate (soil aggregate stability), M_{A+S} is the mass of wet stable aggregate plus the mass of sand (g), M_S is the mass of sand (g), and M_T is the mass of the soil sample (g).

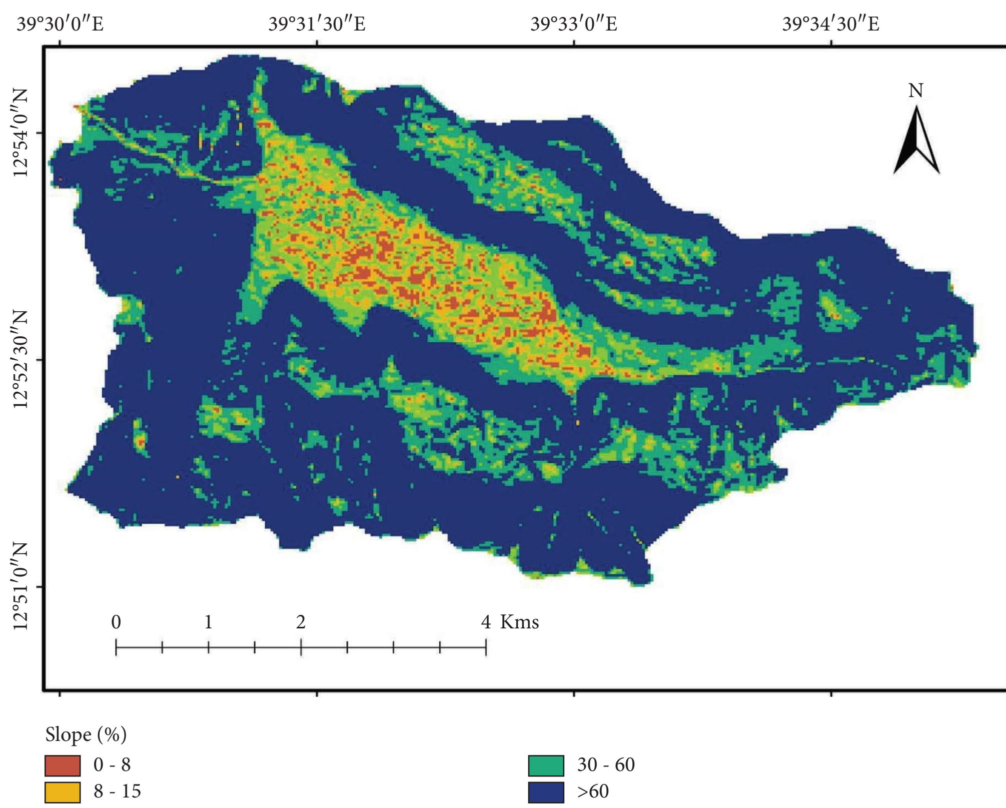


Figure 4: Spatial slope map of the Ayiba watershed, Northern Ethiopia.

was lumpy and hard due to tillage disturbance. Soil structure in AYB-6 was weak to moderate grade, massive to crumbly kind, and fine to medium size. In terms of type and size, all profiles were massive to crumbly and very fine to medium textured. Subsurface soil morphology goes from subangular blocky to poorly developed coarse blocky. All soils exhibited varied consistency in dry, moist, and wet conditions, mostly following friable on the surface and becoming firm in the subsoil (Table S4). The field $CaCO_3$ (using 1 N HCl solution) was noneffervescent except for AYB-5 in its bottom levels, which created few bubbles.

3.2. Soil Physical Characteristics of the Profiles

3.2.1. Soil Particle Size Distribution and Clay Contrast Index. Sand, silt, and clay particle sizes varied from 18– to 68%, 14–53%, and 6–68% along the toposequence. As a result, soil texture ranged from clay to sandy loam, depending on

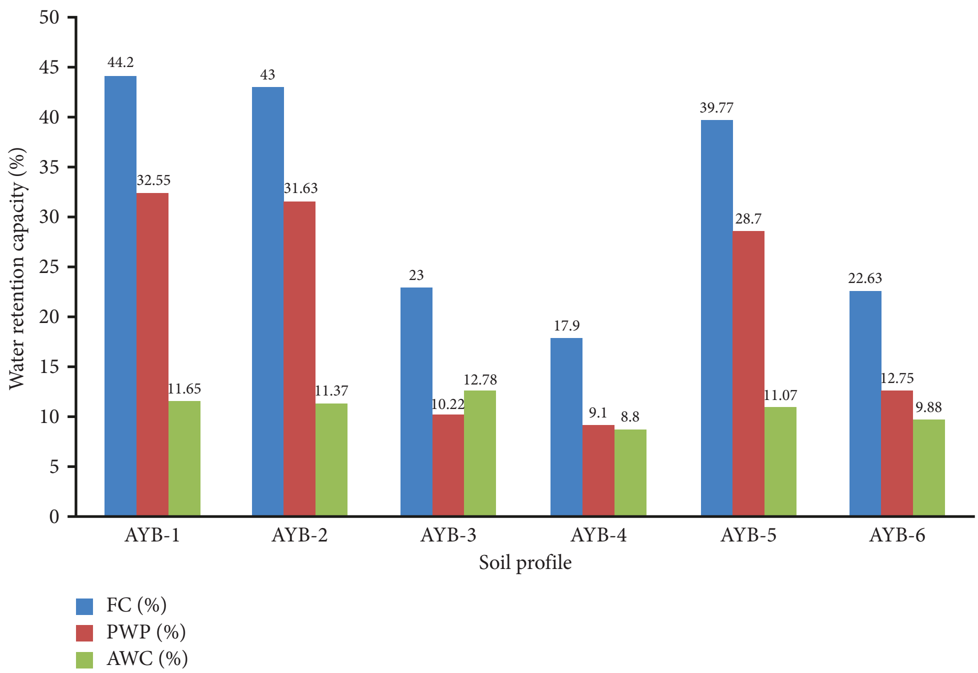


FIGURE 5: The average water retention capacity (FC: field capacity, PWP: permanent wilting point, and AWC: available water content) of the studied soil profiles (AYB: Ayiba).

topography (Table 2). Clay dominates soil particle size fractions, followed by sand and silt. Except for AYB-3, percentages of sand and clay decrease and increase with depth in geomorphic units. Erosion selectively removes clay and silt from the surface layer because sand is less transportable than finer soil fractions. In this investigation, we also observed seasonal water logging at the foot slope, which may promote structural B-horizon deterioration and clay particle dispersion down with the water table front.

The silt/clay ratio ranged from 0.21 to 4.33 along with the topography, and the ratio ranges from 0.29 to 4.33 in the A-horizons and from 0.21 to 2.94 in the B-horizons and decreases with depth. The highest value of the silt/clay ratio was recorded in the A_h-horizon (4.33) of profile 4, followed by the Bw-horizon (2.94) of profile 3, and the lower was recorded at the lower subsoils of AYB-2 (Table 2). The clay contrast index (CCI) ranged from 0.40 to 0.95, with the highest at AYB-1 and the lowest at AYB-3. Higher CCI indicates lower textural differentiation, while lower CCI indicates higher textural differentiation in the profiles. Accordingly, the clay enrichment of the profiles was found in the following decreasing order: AYB-1 (0.95) < AYB-2 (0.89) < AYB-5 (0.85) < AYB-6 (0.80) < AYB-4 (0.75) < AYB-3 (0.40) (Table 2). AYB-1 to 4 are located on the middle and upper topography, mainly manifested by sloping to a steep slope gradient (Figure 3), intensively cultivated land with free grazing experiences, which all induced erosion on the site and lower clay content by removing the upper horizon.

3.2.2. Bulk Densities, Total Porosity, and Water Retention Capacity. The A-horizons of profiles 1 and 4 have surface bulk densities (BDs) of 1.13 and 1.46 $g{\cdot}cm^{-3}$, respectively. In contrast, profile 2's Bt-horizon has 1.27 $g{\cdot}cm^{-3}$ subsoil BD, and profile 5's Bc-horizon had 2.32 $g{\cdot}cm^{-3}$ (Table 2). The soil horizons' BD was found increased with depth. The soil water content at field capacity (1/3 bar) ranged from 17.9 to 44.2%, at the permanent wilting threshold (15 bar) from 9.1 to 32.55%, and available water content (AWC) from 8.8 to 12.78% across soils of the terrain (Figure 5). The FC and PWP water content of surface soils was found to be higher than that of subhorizon soils. AWC decreased but was uneven in the lower subsoil of profile 3, possibly due to textural change after the 4^{th} layer. The AWC ranged between 10–12 and 9–15(v %) in surface and subsurface soils, respectively.

3.3. Chemical Characteristics of the Studied Soils

3.3.1. Soil pH, Soil EC, and Soil Calcium Carbonate Content. The soil pH ranges from 7.14 to 8.31 (pH-H_2O) and 6.31 to 7.27 (pH-KCl). In all soil horizons, pH (H_2O) exceeded pH (KCl) and delta pH (ΔpH) values, and the difference between pH (KCl) and pH (H_2O) showed that soils have net negative charges and will keep positively charged ions on exchange site colloidal particles. The soils are found in the range of neutral to moderately alkaline for pH-H_2O and the range of moderately acidic to neutral soil reaction for pH-KCl [63] in nature. The average soil electric conductivity (EC) values also ranged from 0.19 (AYB-4) to 0.35 (AYB-3), with AYB-1 to 6 ranging from 0.15 to 0.52 $mS{\cdot}cm^{-1}$ (Table 4). The EC was low for all horizons. Hence, all profiles' soils were nonsaline, showing that salinity's effect on crop growth and yield restriction is minor or negligible [63]. Percolation and drainage of liberated bases may explain the low EC. Calcium carbonate ($CaCO_3$) concentration in surface soils

Table 2: Soil physical properties were analyzed for the studied profiles along the toposequence.

Profile	Horizon	Depth (cm)	Particle size distribution (%)			Textural class	SCR	CCI	BD ($g{\cdot}cm^{-3}$)	TP (%)
			Sand	Silt	Clay					
AYB-1	Ah	0–27	14.3	32.0	53.7	Clay	0.6	0.95	1.26	52.5
	B	27–53+	32.0	11.3	56.7	Clay	0.2		1.36	48.6
	Average	—	23.15	21.65	55.2	Clay	0.4		1.31	50.55
AYB-2	Ap	0–20	31.3	15.3	53.3	Clay	0.29	0.89	1.32	50.2
	Bt	20–80	29.7	11.0	59.3	Clay	0.19		1.32	50.2
	BC	80–110	27.3	16.7	56.0	Clay	0.30		1.33	49.2
	C	110–168+	16.7	24.3	59.0	Clay	0.43		1.36	49.8
	Average	—	26.25	16.83	56.9	Clay	0.30	—	1.33	49.85
AYB-3	Aa	0–20	60.0	25.7	14.3	Sandy loam	1.80	0.40	1.26	52.3
	B	20–45	57.3	33.3	9.3	Sandy loam	3.58		1.41	46.9
	2B	45–80	51.3	33.3	15.3	Sandy loam	2.18		1.42	46.4
	3B	80–128	42.7	34.4	23.0	Loam	1.50		1.43	46.2
	Bw	128–180+	34.3	56.0	9.70	Silty loam	5.77		1.47	44.4
	Average	—	49.12	36.54	14.32	Sandy loam	2.97		1.40	47.24
AYB-4	Ap	0–35	54.3	12.1	13.7	Sandy loam	0.88	0.75	1.26	52.3
	BC	90–140+	74.3	15.7	10.3	Sandy loam	1.52		1.5	43.5
	Average	—	64.3	13.90	12.00	Sandy	1.20	—	1.38	47.90
AYB-5	Ap	0–23	32.7	19.7	47.7	Clay	0.44	0.85	1.64	38.1
	Bit	23–80	19.7	32	48.3	Clay	0.68		1.6	39.6
	Bc	80–110+	14.7	29	56.3	Clay	0.53		1.6	39.6
	Average	—	22.37	26.9	50.77	Clay	0.55		1.61	39.1
AYB-6	Ap	0–20	71.3	13.0	15.7	Sandy loam	0.86	0.80	1.41	46.7
	A	20–50	58.7	26.3	15.0	Sandy loam	1.76		1.39	47.5
	A2	50–80	57.7	25.3	17.0	Sandy loam	1.5		1.41	46.8
	Bw	80–165+	57.0	24.3	18.7	Sandy loam	1.31		1.43	46.2
	Average	—	61.18	22.23	16.6	Sandy loam	1.36		1.41	46.80

SCR: silt to clay ratio, CCI: clay contrast index, BD: bulk density, and TP: total porosity.

ranged from 0.35 (AYB-3) to 0.63% (AYB-6), whereas in subsurface soils it ranged from 0.62 to 1.14% (Table 4). The field measurement of carbonates with 10% HCl showed no audible or visible effervescence across the soil depth except for AYB-5's subsurface.

3.3.2. The SOC, TN, and C/N Ratio Analysis. Soil organic carbon (SOC) and total nitrogen (TN) were recorded higher in the surface soils and significantly (Table 5) decreased with soil depth with average values ranging between 0.78 and 2.53% and 0.10 and 0.21%, respectively. In comparison, the SOC of subsurface layer soils ranged from 0.62% on the middle slope of degraded grassland (AYB-3) to 1.87% on the upper slope of the exclosure grassland (AYB-1). The TN content of the surface horizons was higher than the subsurface soil horizons, and it followed a similar pattern to that of SOC in all the studied profiles, implying a strong relation between SOC and TN in the soil system. The amount of SOC and TN was relatively high (3.19 and 0.25%, respectively) at the upper slope position of the surface horizons, which might be attributed and correlated to the biomass turnover of the grass.

The C/N ratio of the surface soils along the toposequence in the study area ranged from 4.51 to 12.78, while in subsoil horizons, it ranged from 5.44 to 14.04 with an average range of 6.15 to 12.61 (Table 5). In the buried horizons of AYB-5 and 6, the C/N ratio was slightly higher than in the rest of the horizons, which might be probably due to the long-accumulated/sediment undecomposed material rich in carbon in the soil. In almost all profiles, the C/N ration demonstrates a decreasing or increasing systematic variation with depth, suggesting the existence of similar conditions of mineralization in the recognized horizon (Table 5).

3.3.3. Soil Available P, S, B, Exchangeable Base, CEC, and Base Saturation Analysis. The surface horizons of all profiles had high available phosphorus (av. P) content due to higher organic matter content, phosphorus-containing fertilizer application on cultivated fields, and reduced free iron oxide and exchangeable Al^{3+}. The soils' available P content decreased with profile depth in all profiles, but spatially the trend was inconsistent. The available P content of the profile ranged from 3.14 $mg{\cdot}kg^{-1}$ at the bottom layer of AYB-3 to 23.47 $mg{\cdot}kg^{-1}$ at the surface layer of AYB-1 (Table 5). Topsoil available P is usually greater than that in the subsoil due to sorption of the artificially added P on the soil surface and its gradual desorption, greater biological activity and higher addition and accumulation of organic materials on the surface soil than in the subsoils.

Regarding sulfur (S) and boron (B), the result obtained for both follows the trend of av. P (Table 5). In this study, the average available S content in the studied soil profiles ranged

Table 3: Morphological description of the six profiles studied.

Profile	Horizon	Depth (cm)	Munsell soil color matrix test: Color code (dry)	Soil color description	Color code (moist)	Soil color description	HB[24] dist/top	Field texture[25]	Moisture status[57]
AYB-1	A_h	0–27	2.5YR2.5/1	Black	7.5YR2.5/2	Black	C/S	Clay	SM
	B	27–53	10YR3/2	Brown	10YR2/1	Black	C/S	Sandy clay	Dry
	R	53+	—	—	—	—	C/S	—	—
AYB-2	A_p	0–20	2.5YR2.5/1	Black	5YR2.5/1	Black	C/S	Clay	Dry
	Bt	20–80	7.5YR2.5/1	Black	10YR2/1	Black	C/W	Clay	Very dry
	B_C	80–110	7.5YR3/1	Very dark gray	7.5YR3/1	Very dark gray	C/S	Clay	Very dry
	C	110–168+	7.5YR3/4	Dark brown	7.5YR3/4	Dark brown	C/S	Sandy clay	Very dry
AYB-3	Aa	0–20	5YR3/1	Very dark gray	7.5YR2.5/1	Black	C/S	Sandy loam	SM
	B	20–45	10YR3/2	Brown	10YR3/1	Very dark gray	C/S	Sandy loam	Dry
	2B	45–80	5YR4/1	Dark gray	5YR2.5/1	Black	C/S	Sandy loam	Very dry
	3B	80–128	10YR4/2	Dark grayish brown	10YR2/1	Black	C/S	Loamy sand	—
	Bw	128–180+	10YR4/1	Dark gray	7.5YR3/1	Very dark gray	C/S	Silt loam	Very dry
AYB-4	Ap	0–35	10YR5/1	Gray	10YR5/1	Gray	G/S	Sandy loam	Very dry
	Rc	35–90	—	—	—	—	G/S	—	—
	Bc	90–140	10YR5/2	Greyish brown	10YR5/4	Yellowish brown	G/S	Sandy	Very dry
	RC	140+	—	—	—	—	G/S	—	—
AYB-5	Ap	0–23	5YR2.5/1	Black	5YR2.5/1	Black	D/S	Clay	SM
	Bit	23–80	5YR2.5/1	Black	5YR2.5/1	Black	D/S	Clay	Dry
	Bc	80–110	7.5YR4/1	Dark gray	7.5YR3/1	Very dark gray	D/S	Silt loam	Very dry
	CR	110+	—	—	—	—	D/S	—	—
AYB-6	Ap	0–20	10YR5/2	Greyish brown	10YR4/1	Dark gray	D/S	SCl loam	Dry
	A	20–50	7.5YR4/1	Dark gray	7.5YR3/1	Very dark gray	D/S	Sandy loam	Very dry
	A2	50–80	10YR4/2	Dark grayish brown	10YR3/1	Very dark grayish	D/S	Sandy loam	Very dry
	Bw	80–165+	10YR3/2	Brown	10YR3/2	Brown	D/S	Sandy loam	Very dry

[24, 25, 57] The tables used for soil description from the FAO [22] guideline and the symbols used (if) are in accordance with it. SM: slightly moist and HB dist/top: horizon boundary by distinctness/topography (C/S: clear/smooth, C/W: clear/wavy, G/S: gradual/smooth, and D/S: diffuse/smooth).

Table 4: Soil reaction, electrical conductivity, and $CaCO_3$ of the soil profiles.

Profile	Horizon	pH (H_2O)	pH (KCl)	−ΔpH	EC ($mS \cdot cm^{-1}$)	$CaCO_3$ (%)
AYB-1	Ah	7.72	6.59	1.16	0.17	0.38
	Bw	7.84	7.12	0.69	0.26	0.62
	Average	7.78	6.86	0.93	0.22	0.50
AYB-2	Ap	7.59	6.48	1.10	0.23	0.42
	Bt	7.82	6.90	0.93	0.15	0.63
	Bc	7.98	7.04	0.94	0.31	0.75
	C	8.21	7.14	1.07	0.32	0.91
	Average	7.9	6.89	1.01	0.25	0.68
AYB-3	Aa	7.73	7.17	0.56	0.23	0.35
	B	7.69	6.85	0.84	0.27	0.62
	2B	7.95	6.83	1.12	0.31	0.73
	3B	8.14	7.15	0.99	0.42	0.91
	Bw	8.31	7.27	1.04	0.52	1.02
	Average	7.96	7.05	0.91	0.35	0.73
AYB-4	Ap	7.14	6.31	0.83	0.22	0.47
	Bc	7.77	6.78	0.99	0.16	0.67
	Average	7.46	6.55	0.91	0.19	0.57
AYB-5	Ap	7.26	6.31	0.95	0.09	0.54
	Bit	7.69	6.59	1.10	0.13	0.74
	Bc	7.79	6.86	0.93	0.21	1.43
	Average	7.58	6.59	0.99	0.14	0.90
AYB-6	Ap	7.61	6.65	0.96	0.26	0.41
	A	7.85	6.83	1.02	0.22	0.54
	A2	7.95	7.12	0.83	0.37	0.63
	Bw	8.17	7.27	0.90	0.49	0.85
	Average	7.90	6.97	0.93	0.34	0.61

from 0.67 $mg \cdot kg^{-1}$ in profile 2 to 0.80 $mg \cdot kg^{-1}$ in profile 5 (Table 5). The highest and lowest av. S was recorded in AYB-6 of Ap and Bw horizons, respectively. While, av. B was found in the range of 0.19 $mg \cdot kg^{-1}$ soil in the Bw horizon of AYB-1 to 0.77 $mg \cdot kg^{-1}$ soil in the Ap horizon of AYB-6, with an average range of 0.24 to 0.77 $mg \cdot kg^{-1}$ soil across the landscape.

In the studied soil profiles, the result revealed that the content of exchangeable Ca^{2+} was the dominant exchangeable base, followed by Mg^{2+} along the toposequence. Exchangeable basic cations are found in the range 0.07–0.49, 0.22–2.12, 2.46–10.20, and 4.46–27.10 across the landscape for Na, K, Mg, and Ca, respectively (Table 6). Generally, the abundance of cations occupying the exchange site followed the order of $Ca^{2+} > Mg^{2+} > K^{+} > Na^{+}$ throughout the profiles, which was found in how a productive agricultural soil should contain these basic cations. The percent base saturation (PBS) of the soil of the study area varied from 18.7 to 99.4%. Soil horizons in AYB-2 and 6 were recorded as high-value PBS compared to others. Regarding cation exchange capacity (CEC), the overall CEC of the studied soils ranged from 28.7 to 54.52 $cmol_{(+)}\ kg^{-1}$ soil along the toposequence (Table 6). The lowest and highest values were recorded in the topsoil of AYB-2 (cultivated land) and AYB-3 (grassland).

3.3.4. Extractable Micronutrients (Fe, Cu, Zn, and Mn). In the studied soil profiles, the mean values of extractable micronutrients (i.e., Fe, Cu, Zn, and Mn) in different soil depths are presented in Table 7.

The contents of available micronutrients varied with soil depth and showed a decreasing trend with increasing depth. However, their trend with topographic position is inconsistent. The contents of extractable Fe, Cu, Zn, and Mn in the studied profiles ranged from 11.42 to 21.10, 1.15 to 3.79, 0.15 to 1.16, and 3.93 to 12.88 $mg \cdot kg^{-1}$ soil, respectively. The extractable micronutrients followed the order of Fe > Mn > Cu > Zn in their concentration in all profiles across the landscape. The result showed that the surface soil layers had higher contents of available micronutrients than the subsurface soil layers. Mean values of the surface layers' extractable micronutrients were significantly varied compared to the subsurface layers (Table 7). In contrast, the mean difference among profiles along the toposequence was insignificant.

3.4. Soil Classification and Mapping. Based on the morphological, physical, and chemical analysis, the studied soil profiles were classified using FAO/WRB legend [32, 62]. Therefore, following the field survey and soil analytical results, five main reference soil groups of the World Soil Resource Base—Leptosols, Luvisols, Fluvisols, Vertisols, and Cambisols—were identified and mapped (Table 8). These soil sources showed that parent material, climate, geography, biotic, and land use/land cover changes determine regional and local soil kinds and characteristics [64]. Previous study by Gebremeskel et al. [65] also reported that prominent soils in the area are Cambisols, Fluvisols, Leptosols, Vertisols, and Regosols. As described the soil extent following IUSS

Table 5: The studied soil profiles are SOC, TN, and C/N ratio, available P, S, and B.

Profile	Horizon	SOC (%)	TN (%)	C/N ratio	Av. P (mg·kg^{-1} soil)	Av. S (mg·kg^{-1})	Av. B (mg·kg^{-1} soil)
AYB-1	Ah	3.19	0.25	12.78	23.47	0.74	0.29
	Bw	1.87	0.17	11.03	16.71	0.77	0.19
	Average	2.53	0.21	11.91	20.09	0.76	0.24
AYB-2	Ap	1.53	0.14	10.95	18.38	0.74	0.82
	Bt	1.13	0.12	9.76	11.93	0.69	0.35
	Bc	0.90	0.11	8.68	8.08	0.62	0.31
	C	0.76	0.09	8.46	6.70	0.61	0.21
	Average	1.08	0.12	9.46	11.27	0.67	0.42
AYB-3	Aa	2.15	0.25	8.72	17.97	0.84	0.98
	B	1.26	0.17	7.37	10.15	0.88	0.77
	2B	0.81	0.13	6.43	7.07	0.76	0.62
	3B	0.71	0.13	5.44	5.39	0.61	0.48
	Bw	0.62	0.08	7.84	3.14	0.49	0.46
	Average	1.11	0.15	7.16	8.74	0.72	0.66
AYB-4	Ap	0.92	0.21	4.51	11.72	0.73	0.44
	Bc	0.64	0.09	7.78	7.62	0.83	0.38
	Average	0.78	0.15	6.15	9.67	0.78	0.41
AYB-5	Ap	1.62	0.18	8.81	15.80	0.86	0.75
	Bit	1.33	0.16	8.33	13.38	0.85	0.65
	Bc	0.99	0.10	10.25	9.81	0.79	0.54
	Average	1.31	0.15	9.13	12.99	0.83	0.64
AYB-6	Ap	1.9	0.16	11.64	17.95	0.96	1.14
	A	1.38	0.11	12.59	15.56	0.69	0.70
	A2	1.0	0.08	12.17	9.88	0.63	0.65
	Bw	0.83	0.06	14.04	5.14	0.51	0.58
	Average	1.28	0.10	12.61	12.13	0.70	0.77

Working Group WRB [62], the soil landscape was found Leptosols dominated (Table 8, Figure 6) as it covers >50% of the total landmass mainly occurred in the middle and upper landscape positions, followed by others as associated soils occurred in the middle and foot slopes. Another study by Nyssen et al. [66] in Tigray highland stated that Leptosols and bare rock are found on the steepest slopes (>40%), which is concurrent with our result.

4. Discussion

4.1. Profile Site and Soil Morphological Characteristics. The slope, parent materials, and land use types are the major contributing factors to the differences in site characteristics. Effects of land use, extensive and intensive farming, and removal of vegetation cover have amplified the erosion process, which was observed at all profiles and their surrounding landscapes. Debie et al. [67] also confirmed that accelerated soil erosion by water is a critical problem in Ethiopia's soil landscape. For instance, Ibrahim et al. [68] reported upper topography was well-drained while the middle and valley bottom was poorly drained, and soils in the lower topographic locations were saturated with moisture longer than upper slope soils. Likewise, previous research findings also highlighted that erosion intensity might depend on slope class, topographic position, and land use [69, 70]. Schaetzl [70] reported that slope controls the movement of matter and energy downslope. It has minimal summit position and an erosional, transportational, and depositional effect on the shoulder, middle, and foot slope positions.

Soil color can vary with soil profile depth and landscape location [71]. The soil's mineralogy and chemical composition, organic matter and clay concentration, drainage condition, and redoximorphic reactions may influence the soil color matrix within and between profiles. The extent of oxidation, hydration, and diffusion of iron oxides in soils determines the yellow and brown colors, which are largely caused by goethite and magnetite, respectively [71]. For instance, the darker color indicates the presence of higher decomposed organic matter (*humus*). As a result, most surface layers have a darker color than subsurface horizons. Others reported similar results in Ethiopia and China [72, 73]. The subsurface horizon (<80 cm) soil color of the foot slope was dark grey to brown, suggesting that soils comprised fine-textured colluvial and alluvial materials. In harmony with this work, Tunçay and Dengiz [74] reported a similar result in Turkey's central Black Sea Region.

Soil structure, which refers to how particles of soil are grouped by physical, chemical, and biological processes, is most usefully described in terms of grade (degree of aggregation), class (average size), and type of aggregates (form). The robust structure formed in the subsurface horizons is due to the overlying layers, reduction in organic matter, high clay accumulation, and reduction in plant root abundance, as was also discussed by a previous study [72]. From A-horizon down to the bedrock R-horizon the structure changes from massive to crumbly structure with depth. All the six profiles showed weak grade granular type soil structure in the A-horizon due to relatively high organic

Table 6: Exchangeable bases (Na, Mg, K, and Ca) and CEC of the studied soil profiles along the toposequence.

Profile	Horizon	Exchangeable bases ($cmol_{(+)}$ kg^{-1})				Teb ($cmol_{(+)}$ kg^{-1})	CEC ($cmol_{(+)}$ kg^{-1})	PBS (%)	ESP (%)
		Na	K	Mg	Ca				
AYB-1	Ah	0.23	0.35	5.18	17.60	23.40	36.80	63.50	0.98
	Bw	0.36	0.47	8.44	22.50	31.70	48.20	66.20	1.14
	Average	0.30	0.41	6.81	20.05	27.55	42.50	64.85	1.06
AYB-2	Ap	0.07	0.27	5.62	17.72	23.68	28.70	82.17	0.32
	Bt	0.17	0.30	5.67	24.71	30.84	38.72	79.70	0.54
	Bc	0.30	1.03	5.86	24.81	32.00	40.73	78.70	0.95
	C	0.34	1.16	8.87	28.17	38.54	44.40	99.40	0.87
	Average	0.22	0.69	6.51	23.85	31.27	38.14	84.99	0.67
AYB-3	Aa	0.12	0.44	5.44	6.23	12.20	54.52	22.50	0.96
	B	0.13	0.98	6.24	7.56	14.90	48.40	30.70	0.90
	2B	0.13	1.11	6.42	8.77	16.40	40.96	40.10	0.31
	3B	0.15	1.24	7.69	9.85	18.90	37.6	50.30	0.80
	Bw	0.17	2.12	8.11	15.30	25.70	35.64	72.10	0.68
	Average	0.14	1.18	6.78	9.54	17.62	43.42	40.14	0.73
AYB-4	Ap	0.24	0.47	2.46	5.47	8.64	46.20	18.70	0.53
	Bc	0.16	0.68	2.57	5.57	8.99	40.60	22.10	0.40
	Average	0.20	0.58	2.52	5.52	8.82	43.40	20.40	0.47
AYB-5	Ap	0.07	0.22	9.38	4.46	14.10	51.60	27.40	0.47
	Bit	0.11	0.32	9.69	9.81	19.90	50.70	39.30	0.54
	Bc	0.14	0.36	10.20	14.20	24.89	39.62	63.30	0.59
	Average	0.11	0.3	9.76	9.49	19.63	47.31	43.33	0.53
AYB-6	Ap	0.13	0.22	3.50	21.30	25.20	44.60	56.60	0.52
	A	0.22	0.28	5.67	23.78	30.00	41.70	71.80	0.75
	A2	0.25	0.49	8.16	25.90	34.80	38.50	90.40	0.73
	Bw	0.29	0.57	9.66	27.10	37.70	38.20	98.60	0.76
	Average	0.22	0.39	6.75	24.52	31.93	40.75	79.35	0.69

matter content, and the gravel content was observed to be higher in the parent material layer [75, 76].

The sticky to very sticky/plastic to very plastic consistency in surface and subsurface horizons indicated low organic matter content and hard to work with these soils. On the other hand, soils with very sticky and very plastic consistency revealed that smectite clays in the soils are high [77, 78]. Dinssa and Elias [72] and Ayalew et al. [79] reported a similar result in the soils of Bako Tibe district and Yigossa watershed, Ethiopia. In northern Ethiopia, Nyssen et al. [66] also analyzed those mass movements in many landscapes that transported materials from their *in situ* upland basaltic over the lower-lying sedimentary rocks, raising the chance for clay soil to develop. Available water for plant roots is strongly affected by stoniness [66], and the soil texture becomes fine with an increase in plant root components [73].

4.2. Soil Physical Characteristics of the Profiles. Soil texture, the most stable physical attribute, affects soil structure, consistency, soil moisture regime and infiltration rate, runoff rate, erodibility, workability, permeability, root penetrability, and fertility. The fine earth fraction soil texture distribution shows a dramatic textural change between surface and subsurface horizons, where clay increases and sand-sized particles decrease. Lessivage and illuviation vertically translocate clay from surface to subsurface, increasing clay content with depth. Likewise, others have reported in different parts of Ethiopia [25, 80, 81]. According to Hazelton and Murphy [82] rating the general abundance of the particle distribution was found in low to medium sand, low silt, and very high clay at upper slope profiles; high to very high sand, low to medium silt, and low clay at middle slope profiles; and low to very high sand, low to medium silt, and low to high clay at foot slope profiles. The variation indicates that topography influences the pattern of soil particle distribution over the landscape [21].

The decreasing or increasing pattern in soil fractions with depth indicated the existence of soil water erosion from *in situ* formation or accumulation and weathering of primary minerals in B-horizons. For instance, the increase in clay content with depth indicates clay migration or probably shows the presence of active eluviation-illuviation pedogenic processes. In contrast, the seasonal water erosion effect and redoximorphic features could explain the decrease at the surface horizon. Clay translocation and enrichment fulfilled requirements for the argic subsurface horizon development [32, 61]. The variation in soil development may be due to unstable landscape features (rugged and sloppy) where pedogenesis trends are often altered.

The water logging at the foot slope, which may probably cause deterioration of structured B-horizon and dispersion of clay particles down with water table front, was similarly reported by Choudhury et al. [83]. Other authors Li and Lindstrom [84] correspondingly explained that water erosion has the potential to modify the spatial patterns of soil properties on hilly landscapes. Our result is also consistent

Table 7: Micronutrient availability in the studied soil profiles along the toposequence.

Profile	Horizon	Extractable micronutrients (mg·kg^{-1} soil)			
		Fe	Cu	Zn	Mn
AYB-1	Ah	17.78	3.74	0.56	9.78
	Bw	17.21	3.46	0.34	5.49
	Average	17.35	3.6	0.45	7.64
AYB-2	Ap	17.2	3.79	1.16	9.50
	Bt	17.0	3.03	0.78	7.97
	Bc	13.4	2.65	0.63	6.35
	C	13.0	1.58	0.17	4.95
	Average	15.13	2.76	0.69	7.19
AYB-3	Aa	19.64	3.73	1.03	8.77
	B	17.30	2.92	0.97	6.97
	2B	14.28	2.88	0.49	4.58
	3B	12.35	2.69	0.41	4.12
	Bw	11.71	2.07	0.33	3.93
	Average	15.06	2.85	0.65	5.67
AYB-4	Ap	16.47	3.79	0.72	7.85
	Bc	14.51	2.98	0.44	4.38
	Average	15.49	3.39	0.58	6.12
AYB-5	Ap	19.88	3.64	0.39	12.88
	Bit	18.48	2.48	0.24	9.91
	Bc	14.83	2.41	0.16	8.36
	Average	17.64	2.84	0.26	10.38
AYB-6	Ap	21.10	3.35	0.81	8.32
	A	18.20	2.95	0.50	6.02
	A2	16.90	2.10	0.29	5.67
	Bw	11.42	1.15	0.24	5.38
	Average	16.9	2.39	0.46	6.35

Table 8: Classification of soils studied at the Ayiba watershed according to the FAO-WRB system.

Pedon ID	WRB soil unit	Area covered		Result[1]
		(ha)	%	
AYB-1&4	*Leptosols*	2295.93	56.01	Dominant soil
AYB-2	*Luvisols*	346.97	8.46	Associated soil
AYB-3	*Fluvisols*	588.98	14.37	Associated soil
AYB-5	*Vertisols*	531.48	12.97	Associated soil
AYB-6	*Cambisols*	335.80	8.19	Associated soil

AYB: Ayiba watershed; [1]world reference base [62].

with the justification of Ellerbrock and Gerke [85]. They revealed that soil particles could be transported along slope gradient during erosion, accumulate in the foot slope position (depressions), and form colluvial soil. Likewise, others also observed a decrease in fine fractions in the steeper slope due to the selective removal of fine particles by water erosion [86, 87].

Contrary to our result, Uwitonze et al. [88] reported that particle size distribution did not show a clear trend with depth, and Amanuel et al. [34] described clay content as higher on the top and declining with depth. The clay deposition in the subsurface is episodic, possibly in conjunction with the wet and dry cycle climate experience, regarding the eluviation-illuviation pedogenic processes. According to this idea, fine-grained deposits may be converted into typical loess due to weathering and soil-forming processes.

The silt/clay ratio of the subsoil is lower than the surface horizons, and the higher percentage in the surface layers reflects the annual alluvial enrichment of the surface through deposition by annual floods. Such a result suggests the presence of weatherable mineral reserves in the soil [89]. The result agrees with the report of other findings in Nigeria and Ethiopia [90–92]. According to Asamoa [93] and Egbuchua and Ojobor [94]; the silt/clay ratio below 0.15 indicates that such soils are of old parent material, while those above 0.15 are of young parent materials. Therefore, in our case study, all the profiles along the toposequence recorded far above 0.15, confirming that the soils are young with weatherable reserve materials and have not gone through ferralitic pedogenesis, which was in accord with other findings [90, 95, 96].

The variations in degrees of clay enrichment were related to slope positions and land use. The relatively small differences between the highest and lowest amounts of clay contents in the foot slope position are attributed to active pedoturbation through the shrink-swell phenomenon. While the high clay enrichment ratio in the upper position of AYB-1 is probably due to minimum erosion occurrences mainly happened splash and sheet erosion in which its severity is highly correlated to rainfall intensity and longevity. Crusting is more severe in coarse and medium-textured soils than in fine-textured soils, and soils with an organic matter of less than 1% are more prone to crusting [71].

The relatively lower BD values obtained at the surface soil horizons may be attributed to the structural aggregation of the soils due to relatively high organic matter content and congelifraction. This facilitates the development of porous soil structure with low rooting impedance [97, 98], which is common in high latitudes and altitudes [99]. Besides, soil compaction resulting from intensive cultivation and overgrazing might have caused higher bulk density values in the cultivated and free grazing land uses compared to others. Soil type may be a possible reason for high bulk density and low porosity. Compaction affects nearly all soil properties and functions, affecting roots' growth, distribution, function, and crop productivity. Correspondingly, others reported an increase in soil strength further down the soil profile [77, 100, 101].

The ideal BD for plant growth ranges from <1.10 g·cm^{-3} for clay to <1.6 g·cm^{-3} for sands [50]. Thus, following the aforementioned critical values for root penetration, some are expected to be limited and affected, while the rest are in a reasonable range. Per the rating system of the effect of BD on soil condition [82], profiles at upper, middle, and foot slope topography are too compact to very compact, very open to satisfactory, and very available to excessively compact, respectively. The bulk densities in the studied area were moderate in the upper and middle landscape, whereas low to very high in the foot slope landscape. The good record shows that BD is not expected to impede root penetration and water movement restriction in these soils.

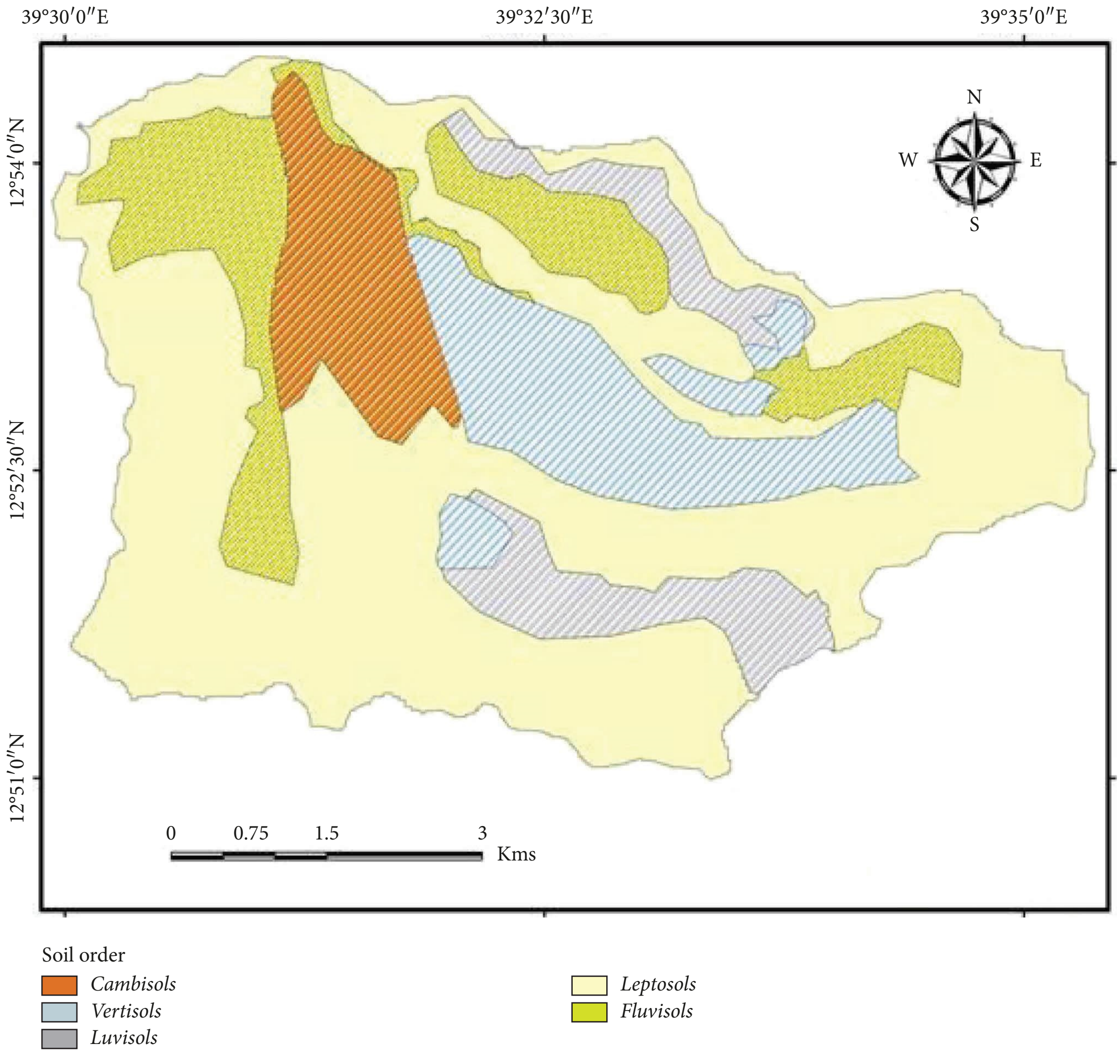


FIGURE 6: Spatial soil map of Ayiba watershed according to WRB system.

Nevertheless, the BD values of the studied soils are favorable for crop production since the values are within the range that favors the growth of crops in tropical soils. However, profile 5 (Vertisols) were recorded with relatively high BD (≥1.6 g·cm^{-3}), which might be due to the smectite/montmorillonitic group of clay minerals which show cracks between hard clods when dry and are difficult to till. Such soils need corrective management like manuring, cover crop, and other agronomical recommended field management to Vertisols soil types. Bulk density values exceeding 1.8 g·cm^{-3} indicated the likely presence of duripans or fragipans [102]. In addition, the total porosity also almost lay within the usual range of 30% to 70% [82]. Hence, most soils in the Ayiba watershed have an acceptable range of total porosity values for crop production.

Farmers must prioritize soil water holding capacity for plant usage since water content is crucial to soil physical dynamic processes and high water retention capacity allows soils to keep more water, which plants can utilize during water shortages [103]. Soil that stores large amounts of water without waterlogging problems can keep plants alive and well for prolonged periods during droughts. According to Hazelton and Murphy [82]; available soil water holding capacity (%v) for a soil profile is rated as low (<10), medium (10–20), and high (>20). Hence, the AWC at the upper slope was found medium, while low to medium in the mid and foot slopes. Soils that fall below the stated ideal range are probably due to high bulk density caused by intensive cultivation, unrestricted grazing, and low organic matter content due to the complete removal of crop residue.

4.3. Chemical Characteristics of the Studied Soils

4.3.1. Soil pH, EC, and $CaCO_3$. The lowest pH reading was found in the upper horizon soils at each site, with higher pH values at depth which might be due to the movement of cations from surface soil to subsurface soil. Similar results were also observed and reported by others [76, 77, 92, 104], who confirmed that an increment in soil pH down horizon might indicate the presence of vertical movements of exchangeable bases, which is caused by decreased in organic matter content with depth. All soil pH records documented at the study site are favorable for most crops per the pH scale stated by EthioSIS [63] and Hazelton and Murphy [82]. The low EC may also be due to free drainage conditions, favoring the removal of released bases by percolation and drainage. The variation in soil pH is probably attributed to the nature of the parent material, leaching of basic cations, and presence of $CaCO_3$ and exchangeable Na as discoursed by Deressa et al. [69] and Shalima and Anil [105].

The higher concentration of $CaCO_3$ at the subsurface than at the surface horizons might be ascribed to the effect of leaching and parent material which was in accord with the result of others in Ethiopia and else [16, 106–108]. Regarding the rating of $CaCO_3$, there is no clear and precise rating for the contents of free carbonates, but values of over 40% can be considered highly calcareous [109]. In addition, FAO [22] also stated that soil horizons having a $CaCO_3$ content of >15% within 100 cm from the soil surface qualifies for a calcic horizon and such high carbonate contents affect both physical and chemical properties of soils. In the current study, the level of $CaCO_3$ is recorded far <15%, which is a very low rate.

4.3.2. SOC, TN, and C/N. The results obtained regarding SOC and TN are similar with others [25, 68] who quantified SOC and TN that showed significant variation in depth. The values are under the category of low to very low rate for SOC and medium to very low rate for TN according to the rating of EthioSIS [63]; and this coincides with the amounts usually present in arid climates due to the rapid rate of mineralization. The low SOC and TN in most profiles could be ascribed to the removal of vegetation at the expense of cultivation and complete removal of crop residue mainly for livestock feed, limited use of organic fertilizer sources, unrestricted grazing, and rigorous cultivation, which was similar to the result observed in other studies [25, 89, 108]. As a result, the low SOC and TN content recorded on most soils cannot sustain crop production for a long time. Thus, the organic matter content has to be substantially enhanced through effective crop residue management and organic fertilizers.

In each profile, the C/N ratio was less variable than SOC and TN concentrations indicating the C/N ratio may be more stable than its elements. Likewise, in agreement with our finding, others like Yitbarek et al. [81] in the Abobo area, western Ethiopia, and Yimer [110] in the central rift valley area of Ethiopia also reported a similar result. Although the decomposition rate was not measured, a higher C/N ratio signifies moderate stress in the microbial decomposition of organic matter and N-mineralization [89]. According to Gebreselassie [111]; the optimum range of the C/N ratio is about 10 : 1 to 12 : 1, which provides nitrogen over microbial needs. Yerima and Van Ranst [112] also classified the C/N ratio as low (<10), medium (around 20), and high (>50). Accordingly, the C/N ratio of the surface soils across the topography may be considered below the optimum range in all soils for microbial needs except at AYB-1 and 6. Sakin et al. [113] found the C/N ratio of arable soils much lower than 10, which might indicate N input from external sources, mainly from fertilizers and deposits. On the other hand, prolonged intensive farming also led to a continuous increase in soil nitrogen [114, 115].

4.3.3. Available P, S, and B. The lower P content in the subsurface horizons could be ascribed to the fixation of P by clay minerals and oxides of Iron and Aluminum. The overall profile means av. P content was found in harmony with the result observed in other studies [108, 116, 117]. Based on the ratings of EthioSIS [63]; the average av. P content was found in the low to medium category. Phosphorus deficiency in Ethiopian soils is well documented as a result of depletion and slow recycling due to a fixation on the inherent low occurrence [116, 118]. Moreover, the low content of av. P could be attributed to fixation by Ca content as Ca–P (Ca bounded)—the significant inorganic P fraction in alkaline soils [119]. Mulugeta also showed that P concentration decreased with profile depth due to clay and Ca fixation in the subsurface soil.

The S and B in agriculture are now gaining importance because their role in increasing crop production is recognized. Available S is the primary source of S taken up by most crops. The source is the SOM via the microbial pool or directly from animal residues, atmospheric inputs, or fertilizers [120]. Whereas B, usually present in soil solution as a nonionized molecule (H_3BO_3), is an essential trace element desired for the physiological functioning of higher plants. B deficiency is considered a nutritional disorder that adversely affects the metabolism and growth of plants because B is involved in the multi-structural and functional integrity of the entire plant system. The difference between deficiency and toxicity limits is very narrow; hence, B requires judicious fertility management [121, 122]. Das and Purkait [121] also emphasized that site-specific and crop-specific nutrient management should be taken care of while dealing with B soils under divergent geographical and climatic zones.

Generally, the av. S and B contents of the studied soil profiles decreased with profile depth and were found in very low and very low to low, respectively [63]. Similarly, Dinssa and Elias [72] reported very low to low B distribution in the Bako Tribe of western Ethiopia. The pH is retained as the main factor affecting B adsorption in agricultural soils [123], as well as soil texture, soil moisture, parent material, clay nature and content, Al and Fe (hydr)oxides, clay minerals, calcium carbonate, and organic matter and interrelationship with other elements affect the B concentration in soil [124, 125]. For instance, Wójcik [126] reported high B deficiency on coarse texture soils and recommended the application of calcium nitrate or ammonium nitrate would be appropriate to keep B more available to plants.

4.3.4. Exchangeable Bases, PBS, and CEC. Few nutrients flow readily in the soil solution. Most are freely exchangeable on mineral and organic surfaces, which act as a storehouse both for nutrient cations and anions. For instance, clay minerals, notably illitic and montmorillonitic kinds, contain large negatively charged surfaces on which cations like Ca^{2+},

Mg^{2+}, and K^+ are adsorbed and shielded from leaching [127]. According to FAO [127]; a deviation from the order of $Ca^{2+} > Mg^{2+} > K^+ > Na^+$ might cause plant ion-imbalance problems, thus our result showed appropriate basic cation distribution in the studied soils. The prevalence of Ca^{2+} followed by Mg^{2+}, K^+, and Na^+ in the exchange site of soils is favorable for plant production [128]. The result might be related to the parent material from which the soils developed and their differential attraction to the soil's exchange complex. The extent of exchangeable base distribution was not consistent along the toposequence. However, soil depth showed an increasing trend for all exchangeable bases. The studied soils were very low to medium in Na, low to very high in K and Ca, and medium to very high in Mg, following the rate suggested for exchangeable bases by EthioSIS [63]. Other previous studies also reported similar findings in Ethiopia's agroecological settings [116, 129].

This study also observed a trend of increasing percent base saturation (PBS) with depth, possibly due to the leaching of bases from the overlying layers and subsequent accumulation in the subsurface horizons. The PBS was also recorded very low to very high along the toposequence [63, 82]. The high base saturation of the soil was consistent with high contents of exchangeable bases (chiefly Ca^{2+} and Mg^{2+}), as reported similarly by others [25, 89, 129, 130].

The result of CEC was found qualified in the range of high to very high rating [63, 82, 127], which corresponds to clay content, organic carbon content, and type of clay mineral present. The high CEC result revealed that the soils of the studied profiles had good nutrient retention. Moreover, the high CEC values imply that the soil has high buffering capacity against the induced changes. Most studies also showed a direct relationship between organic matter, clay content, and CEC [25, 81, 128]. Many previous studies confirmed that deforestation, intensive cultivation, land-use change, and the nature of the topographic position led to a decline in CEC [81, 131–133].

4.3.5. Soil Micronutrients. The accumulation of organic matter on topsoil or chemical fertilizer inputs and ongoing movement of micronutrients from root depth (via absorption by plants and subsequent litterfall) may explain why surface soils have more micronutrients than subsurface soils. A drop in the subsurface horizon's extractable micronutrient level suggests phytomining and redeposition with organic matter. Organic matter reduces oxidation and precipitation loss, and its chelating agents, depending on their solubility potential, increase micronutrient availability. Prior studies also indicated the highest micronutrient concentration in the top soil, decreasing down the profile [134–139]. These scientists found that surface soil organic matter closely correlates with accessible micronutrients. Yitbarek et al. [81] similarly found texture and organic matter content affected extractable micronutrients. Sharma et al. [140] also found that extractable micronutrients rose with organic carbon content, CEC, and pH and decreased with sand, calcium carbonate, and pH. Increased soil pH converts micronutrients to insoluble forms, reducing their availability [141].

According to the critical interpretative values for extractable micronutrients set by EthioSIS [63]; the mean values for extractable Fe, Cu, Zn, and Mn in all profiles were rated as high, medium, low, and high, respectively. Accordingly, none of the soils studied is deficient in Fe, Cu, and Mn; however, Zn deficiency is observed along the toposequence. Low Zn availability is attributed to high calcium carbonate content (>15%) in neutral to alkaline soils of semiarid/arid regions, low OM in sandy soils, waterlogging conditions, precipitation or adsorption of zinc with various soil components depending on soil pH, organic matter, pedogenic oxides, and redox potential [142, 143]. Although chemical fertilizers (e.g., DAP to supply P) were successful in nutrient supply for intensive agriculture, their uneven application caused micronutrient deficit. Zn is vital for plant and human growth and development; hence the Zn deficiency problem is developing daily [144].

5. Conclusion and Recommendation

In the research area, low soil fertility and inadequate management practices limit agricultural productivity. Hence, thorough soil knowledge is essential to understand functional diversity across landscapes to improve soil fertility. Accordingly, this study was initiated to characterize soil and produced a soil-landscape map of the Ayiba area for more sustainable soil use and production systems. The study involved soil profile description and understanding of soil-landscape relations. Based on soil morphological, physical, and chemical studies, shallow soils (Leptosols) dominate on the plateau and steepest slope. This study discovered soils with very low to low SOC, av.S, and av.B; low to medium TN and av.P; and high to very high CEC. Most soil properties were better in lower topographic positions than upper and middle topographic positions. Hence, increasing soil organic matter using organic fertilizers like farm yard manure and lowering crop waste removal can improve agricultural soil fertility. In addition, to reduce soil erosion, the site management plan should include terracing, slope reduction, runoff velocity limiting, and drainage.

This study also proposed using site-specific information to manage soil resources, such as applying inorganic fertilizers and maintaining soils over various landscapes to boost agricultural yields. Soil test based application of fertilizers blended with deficient nutrients at recommended rates would help to maintain a warehouse of nutrient available for plants, and keeping the soil pH at scales which suits for most nutrients (e.g., 5.5 - 7.0) as most nutrients are available to plants in such a range, and make the nutrient water soluble and thus available to restock the warehouse as plants remove the nutrient for growth. If controlled grazing, forestry, and perennial crop production are used to control the huge percentage of unsuitable soils in the middle and upper terrain, the Ayiba watershed offers great production potential. For instance, Vertisols and Cambisols were used to assess site-soil-specific fertilizer management using wheat as a test crop and NPSZnB blended fertilizer as a trial fertilizer (readers can refer to our published manuscript at https://doi.org/10.7717/peerj.13344). The new approach yielded the highest yield, showing that different soil types respond differently. However, for full-scale extension services soil-specific fertilization, researching on the other soil types of the area is important. The laboratory resource scarcity was the basic obstacle of this research work. In addition, the analysis of some samples was delayed as a result of the lockdown that was implemented as a response to the worldwide COVID-19 pandemic.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest or personal relationships that could have influenced the work reported in this paper.

Authors' Contributions

WS was involved in conceptualization, methodology, formal analysis, investigation, data curation, writing the original draft, and visualization. **EE and GG** were involved in conceptualization, methodology, supervision, fund acquisition, writing the review, and editing the manuscript. **GL** was involved in formal analysis, visualization, and editing. **WT** was involved in methodology, formal analysis, data curation, and visualization and editing.

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Supplementary Materials

Table S1: Critical levels used for classifying soil fertility analytical results. Table S2: Characteristics of the toposequence around studied pedons. Table S3: Some site characteristics of the studied profiles along the toposequence of Ayiba watershed, northern Ethiopia. Table S4: Morphological description of the six profiles studied. (*Supplementary Materials*)

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