East African Journal of Sciences (2023) Volume 17(2): 109-122

Characterizing and Classifying Soils of Sentele Watershed, Hadiya Zone, Southern Ethiopia

Getachew Beyene[1*], Nigussie Dechassa[2], Lemma Wogi[3], and Alemayehu Regassa[4]

[1]Department of Natural Resources Management, Wachemo University, Hossaina, Ethiopia
[2]School of Plant Sciences, Haramaya University, Dire Dawa, Ethiopia
[3]Department of Natural Resources Management, Jimma University, Jimma, Ethiopia
[4]School of Natural Resources Management and Environmental Sciences, Haramaya University, Dire Dawa, Ethiopia

Abstract

Background: Soil morphological, physical, and chemical characteristics are vital for determining suitable land use and increasing crop productivity under certain environmental conditions. Thus, this study was carried out to characterize and classify the soils of the Sentele Watershed in southern Ethiopia.

Materials and Methods: The preliminary boundary of the Watershed and soil mapping units (SMU) was defined using a topographic map (1:50,000). Four soil pedons were dug, and soil samples were collected from the pedons and taken to the laboratory for testing soil physical and chemical parameters. The soil pedons were described using FAO soil description guideline.

Results: The soils in the Watershed range from intermediately deep to deep (70 to >200 cm), with varying colors (dark brown to reddish-brown); varying structures (sub-angular to blocky); moderate to well-drained; and the texture varying from loam, clay loam, and clay. The pH of the soil ranges from 5.6 to 6.4, from moderately acidic to slightly acidic. The soil OC contents vary from medium to very high (1.12–4.9%), medium to high TN contents (0.135–0.484%), and very low to medium contents of AP (8.9–30.1) mg kg^{-1} soil. The soils have moderate to high CEC (23.8–34.2 cmol $_{(+)}$ kg $soil^{-1}$). Ca and Mg are the dominant exchangeable cations, followed by K and Na. The soils belong to Rhodic Luvisols, Silandic Andosols, Rhodic Nitisols, and Vertic Luvisols.

Conclusion: The four pedons of the various land mapping units have varied soil morphological, physical, and chemical characteristics. Crop yield is limited by moderate to slight acidity, available phosphorus, and boron. The soils were categorized into one of four classification groups: Chromic Luvisols, Silandic Andosols, Rhodic Nitisols, and Vertic Luvisols. The results show that soils must be used for sustainable agricultural production based on their classification and the potential and limitations they have.

Keywords: Andosols; Luvisols; Nitisols; Pedons; Soil horizons; Soil mapping units

1. Introduction

Understanding characteristics of soils and interpreting them adequately is required for using and managing agricultural soils in particular (Delgado and Gomez, 2016). Soil classification is vital for the convenient use of soil resources (Nortcliff, 2006). Due to variations in soil properties, sound scientific knowledge of soil characterization and classification is very important. This is because different soils have different properties due to differences in morphological, physical and chemical, and mineralogical properties. Alemu Lelago and Tadele Buraka (2018) reported that characterizing and classifying soils of a given area is important to determine its potential and limitation for sustainable agricultural production.

Some soil characterization works have been done in Ethiopia (Alemayehu Kiflu, 2015; Alemayehu Kiflu *et al*., 2016; Teshome Yitbarek *et al*., 2015). However, most of the soil characterization works have been confined to a few areas or are small-scale in nature and could not provide adequate information. This means that limited attention has been paid to the information base, including soil characterization, classification, and land suitability evaluation for specific crop production (Shimelis Damene *et al*., 2007).

Therefore, to understand the properties and evaluate the fertility status of soils of Sentele Watershed in southern Ethiopia and enhance sustainable land utilization, it is necessary to characterize and classify the soils by generating data required to produce efficient soil classification schemes. The question to be answered by this research was whether soils of Sentele Watershed are uniform in physical and chemical as well as morphological properties to suit a similar agricultural land use pattern or whether they differ in these characteristics to warrant characterizing and classifying them for producing crops optimally that suit their specific physical and chemical characteristics. This research, was, therefore, conducted to characterize and classify the soils of the Sentele Watershed located in the Hadiya Zone of southern Ethiopia.

*Corresponding Author: gechbeye1260@yahoo.com

ISSN 1993-8195 (Online), ISSN 1992-0407(Print)

2. Materials and Methods

2.1. Description of the Study Watershed

The study was conducted at the Sentele Watershed in Southern Nations, Nationalities, and Peoples' Regional (SNNPR) State in Ethiopia (Figure 1). The total area of the study Watershed covers about 1883 ha and is located at the coordinates between 7º36'30" to 7º39'30" N latitude and 37º48'00" to 37º50'30" E longitude at the altitudes ranging from 2270 to 2680 meters above sea level (Getachew Beyene *et al.*, 2022).

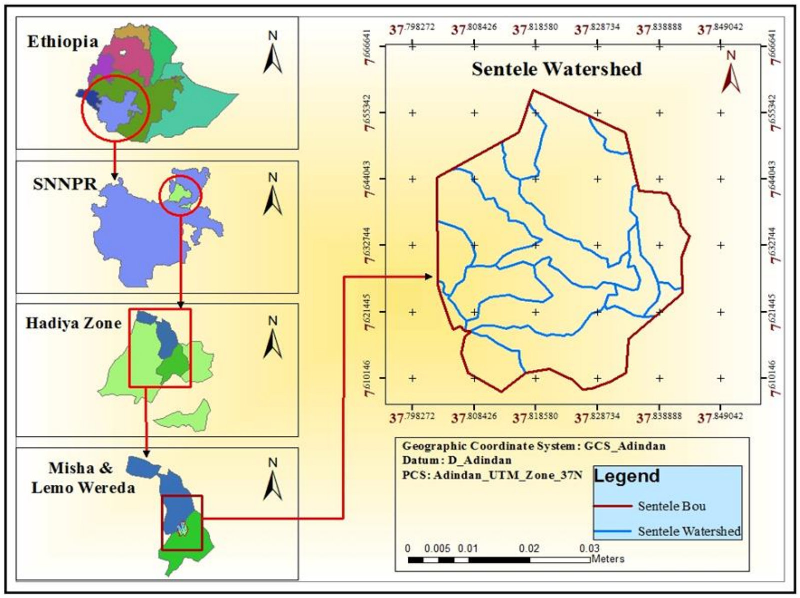

Figure 1. Location Map of Sentele Watershed.

The study Watershed constitutes various land uses, including cultivated land, grazing land, fallow land, Eucalyptus plantations, and homesteads. The average temperature of the study Watershed is 16 °C, with the mean minimum and means maximum temperatures of 9.2 °C and 22.8 °C, respectively (Figure 2). The geology of the study area is made up of Phanerozoic Quaternary Period volcanic with associated sediments revealing basaltic ignimbrite parent material (Kazmin, 1973).

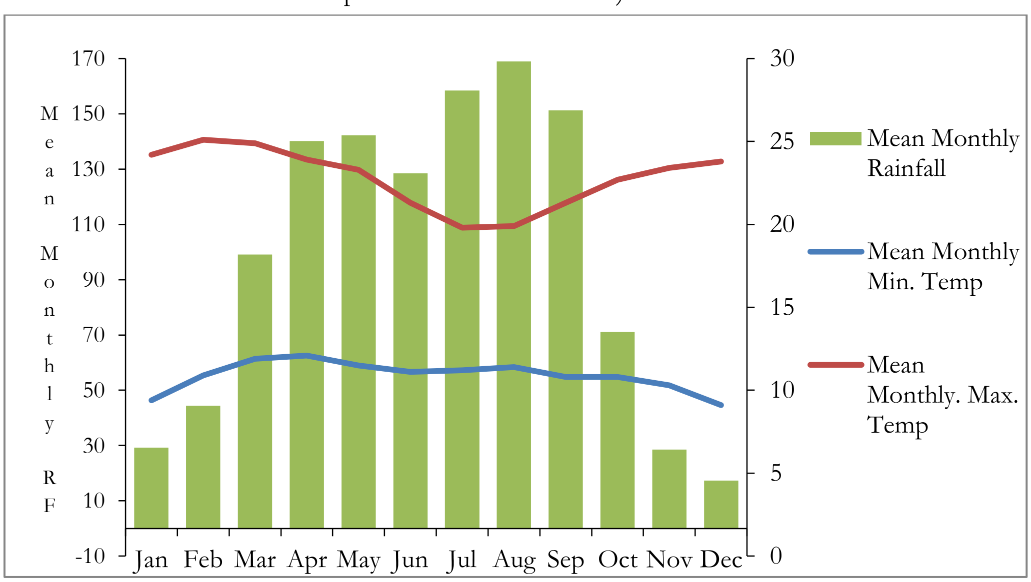

Figure 2. Mean monthly rainfall (RF), mean monthly minimum temperature and mean monthly maximum temperature.

2.2. Study Site Selection, Pedon Description, and Soil Sampling

A topographic map (1:50,000) of the study area which was obtained from the Ethiopia Mapping Agency and used to define the preliminary boundary of Watershed and soil mapping units (SMU), as well as select temporary sampling sites. Digital elevation model (DEM) was used to get general information about the study Watershed. The Global Positioning System (GPS) was used to record the boundary points, and Landsat ETM+ SLC-off Images were used to develop a soil map. Before opening pedons, a field visit was made to have a general overview of the variation in the land units of the study Watershed and to determine representative pedon opening sites and Watershed boundaries. Based on the information gathered, the selected Watershed was classified into four different land mapping units using land use, landform, elevation, topographic position and slope class, vegetation, soil morphological characteristics (soil color, structure, drainage, and texture), rock outcrops, and topographic maps. To determine variations in soil depth and textural characterization, a soil observation was carried out using 'Edelman Auger'. A total of four standard pedons, one on each land mapping unit was opened having a 2 m width, a 1.5 m length, and a 2 m+ depth (unless soil depth was limited by underlying stones). The opened pedons were described according to FAO (2006) and were geo-referenced using the Global Positioning System (GPS) receiver (MODEL GARMIN 12 L). The elevation was measured using an altimeter. The soil horizons were differentiated for each pedon and the pedons were designated as SE/LD/LA/P1, SE/MD/LE/P2, SE/MD/LE/P3, and SE/MD/SA/P4. Soil samples from each horizon were collected for laboratory analysis and carefully labeled and bagged. A total of 15 disturbed and composited soil samples which were made from five to ten subsamples of the same horizon were collected from each of the exposed genetic soil horizons of the pedons representing the identified land mapping units for laboratory analysis, and 15 undisturbed soil samples were taken with a core sampler for determination of bulk density. Soil color (moist) was determined by Munsell Soil Color Company (1994).

2.2.1. Preparing soil samples and laboratory analysis

The soil samples were collected and air-dried on plastic trays in a properly ventilated room, ground, and sieved to pass through a 2 mm sieve. However, for determining organic carbon (OC) and total nitrogen (TN) contents, a 0.5 mm sieve was used. Soil particle size distribution was analyzed using the Bouyoucos hydrometer method (Bouyoucos, 1962), and the soil textural names were determined based on the USDA textural triangle (Jones, 2001). Bulk density was determined using the core sampler method of Blake and Hartge (1986). The average soil particle density (2.65 g cm^{-3}) was used for estimating total porosity. The total porosity was computed as shown by (Landon, 1991):

$$f\% = \left[1 - \frac{pb}{ps}\right] * 100 \quad (1)$$

Where, $[f(\%)]$= total porosity, Pb = bulk density, and ps = particle density which was assumed to be 2.65 g cm^{-3}.

The soil pH (pH-H_2O) and potassium chloride (1M KCl) were determined in a 1:2.5 soil: liquid ratio potentiometrically using a combined glass electrode and pH meter as described by Carter and Gregorich (2008). Soil organic carbon (OC) was determined following the wet digestion method procedure of Walkley and Black (1934). The content of soil organic matter (%) was estimated by multiplying the OC content by the factor of 1.724. The content of total nitrogen (TN) was determined through the Kjeldahl digestion, distillation, and titration method as described by de la Paz Jimenez *et al.* (2002). Available soil phosphorus content was determined by using the Bray II solution method (Bray and Kurtz, 1945). Cation exchange capacity (CEC) and exchangeable bases (Ca, Mg, K and Na) were determined by saturating the soil with neutral 1M ammonium acetate (NH4OAc) at (pH 7) (Reeuwijk, 2002). Exchangeable Ca and Mg in the extracts were analyzed using the atomic absorption spectrophotometer (Moss, 1961), while Na and K were determined by flame photometry (Chapman, 1965). CEC of the clay fraction was estimated from the measured CEC soil (cmol (+) kg^{-1}, OM, and percentage of clay (Baize, 1993). The available micronutrient contents of the soil (Zn, Fe, Mn, and Cu) were extracted by the diethylenetriamine pentaacetic acid (DTPA) method and all of these nutrients were determined by atomic absorption spectrophotometer (Houba *et al.*, 1989). Boron concentration in soils was determined using the azomethine-H spectrophotometric method (John *et al.*, 1975).

$$CEC_{Clay} = \left[CEC_{Soil} - \left(\frac{\%OM * 2}{\%Clay} \right) \right] * 100 \quad (2)$$

Where, % clay is the clay content of the soil and CEC soil is the cation exchange capacity measured in fine earth (less than 2 mm) in cmol $_{(+)}$ kg^{-1} (Reeuwijk, 2002). Based on cation exchange capacity and extractable acidity percentages, the base saturation (%BS) of the soil was calculated as shown by Hazelton and Murphy (2016).

$$\%BS = \left[\frac{(Bases)}{(CEC-7)} \right] * 100 \quad (3)$$

Where, BS (%) is base saturation, Bases are the sum of NH4OAc extractable bases, and CEC-7 is the cation exchange capacity in NH4OAc at pH 7 (Soil Survey Laboratory Methods Manual, 1996).

2.2.2. Soil classification

The soils were classified into different Reference Soil Groups following the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015) soil classification system according to their physical, chemical, and mineralogical properties. Finally, a soil map of the study Watershed was produced using ArcGIS version 10.5.

2.3. Data Analysis

The data obtained from the laboratory analysis were subjected to simple linear correlation analysis to check functional relationships between selected physical and chemical properties of the soils with the help of SAS technology software.

3. Results and Discussions

3.1. Morphological Properties of Soil Pedons

The depth of the studied pedons was found to be greater than 200 cm except for one pedon located at the summit of the studied Watershed, which has a shallow depth due to an impenetrable 70 cm layer. All pedons have well-developed morphological characteristics and A to Bt horizon sequences. The soils in SE/LD/LA/P1 and SE/MD/SA/P4 are characterized by Ap, Bt1, Bt2, and Bt3 horizons; the soils in SE/MD/LE/P2 consist of Ah, Bw1, and Bw2 horizons with an impenetrable layer (R) which makes them moderately deep; soils in SE/MD/LE/P3 are characterized by an Ap, Ap1, Bt1 and Bt2 horizons. There were differences in solum thickness which increased with increasing depth. Slickensides and deep cracks were noticed in pedons SE/LD/LA/P1 and SE/MD/SA/P4 mainly in the lower part of the pedons (Table 1). The dark color in the surface horizons of all opened pedons may be due to the presence of high content organic matter. This result agrees with the previously reported findings in Jalingo Metropolis of north-east Nigeria and Gobeya sub-Watershed in northern Ethiopia (Seid Mohammed *et al.*, 2017). The authors reported that the dark color on the surface of the horizon was attributable to organic matter deposits. The darkness of the soil color decreased with increasing soil depth almost in all pedons. The red to reddish-brown color trends may be attributed to the drainage condition of the surface soil.

The variation in soil color within a pedon and among the pedons could be attributed to differences in soil organic matter content (Buol *et al.*, 2011). Organic matter influence soil color, due to the formation of organic mineral complexes. The degree of soil darkness depends on the composition of humic acids. Vodyanitskii and Savichev (2017) indicated that organic matters neutralize the effect of white, red, and yellow soil pigments.

Table 1. Morphological characteristics of soil pedons of Sentele Watershed in Southern Ethiopia during the 2018 main cropping season.

Pedon	Horizon	Depth (cm)	Color (Moist)	Structure	Consistency (moist)	Drainage	Boundary
SE/LD/LA/P1	Ap	0–23	Dark brown (7.5 YR 3/3)	SA	Friable	WD	cs
	Bt1	23–72	Dark reddish-brown (5YR 3/4)	SB	Very friable	WD	gs
	Bt2	72–129	Reddish-brown (5YR 5/4)	AB	Friable	MD	dw
	Bt3	129–200+	Dark reddish-brown (5YR 3/3)	SA	Firm	MD	gs
SE/MD/LE/P2	Ah	0–20	Very dark brown (7.5 YR 2.5/2)	SB	Very friable	WD	cs
	Bw1	20–50	Dark red-brown (5YR 3/2)	SB	Friable	WD	cs
	Bw2	50–70	Dark reddish-brown (5YR 3/3)	SB	Friable	WD	dw
	R	70+	–	–	–	–	–
SE/MD/LE/P3	Ap	0–24	Dark brown (7.5 YR 3/2)	AB	Firm	WD	ds
	Ap1	24–74	Dark red-brown (5 YR 3/2)	SA	Friable	WD	dw
	Bt1	74–120	Dark reddish-brown (5 YR 3/4)	SB	Friable	MD	dw
	Bt2	120–200+	Dark reddish-brown (2.5 YR ¾)	SA	Firm	MD	cs
SE/MD/SA/P4	Ap	0–25	Dark brown (7.5 YR 3/2)	AB	Friable	WD	cs
	Bt1	25–69	Dark reddish-brown (5YR 2.5/3)	AB	Friable	WD	dw
	Bt2	69–117	Dark reddish-brown (2.5YR 3/3)	AB	Friable	WD	dw
	Bt3	117–200+	Dark red (2.5YR 3/6)	SA	Firm	MD	ds

Note*: SA = Sub-angular and angular blocky; SB = Sub-angular blocky; AB = Angular blocky; WD = Well-drained, MD = moderately drained; cs = clear smooth; gs = gradual smooth; dw = diffuse wavy; and ds = diffused smooth.*

3.2. Soil Physical Properties

The results in Table 2 reveal that the surface horizons have loam to clay loam texture. Due to clay illuviation in all pedons, clay contents increased with the increase in soil depth. Similar findings were reported by Aruleba and Ajayi (2013) who reported that the dominance of clay particles at the lower depths showed illuviation of soil clays. Therefore, the increasing clay and decreasing sand and silt contents with the increasing pedon depths in all pedons indicate that the sub-soil horizons could be identified as argic subsurface horizons (Bt) (IUSS Working Group WRB, 2015). The general characteristics of the soil in the Watershed are high clay and low silt contents. Overall, all pedons had comparable texture as they were formed from the same parent material under similar ecological conditions. Soils in all pedons have high structural stability and, therefore, show low soil particle detachment due to the dominance of the finer texture size.

The bulk density (BD) values ranged from 0.91 to 1.34 g cm^{-3} with a mean value of 1.17 g cm^{-3}. There was an increasing bulk density with the soil depth gradually from surface to subsurface horizons. The increase in soil depth could be attributed to the decrease in OM content from the surface to the subsurface horizons. The highest bulk density under the pedon of the cultivated land unit could be attributed to compaction that may have occurred due to cultivation and low content of carbon. However, the lowest bulk density under the pedon of grassland land could be attributed to the presence of higher OM content, structural aggregation, and root penetration of soils. Verifying the above suggestions, Pearson`s correlation analysis indicated that OM and BD were strongly negatively related with a correlation coefficient of –1.000** (Table 6). This result agrees with the previously reported findings of Endalkachew Fekadu *et al.* (2018) who reported that cultivation seriously impaired soil properties and resulted in a significant decrease in soil organic matter, aggregate stability, and hydraulic conductivity. Soils that are free from compaction have no limitations in bulk density and do not hinder penetration and proliferation of roots of crops (Hazelton and Murphy, 2016). Consistent with this suggestion, bulk densities above 1.75 g cm^{-3} for sandy soil or 1.46 to 1.63 g cm^{-3} for silty and clayey soils cause hindrance to root penetration (de Geus, 1973 as cited in Landon, 1991).

The silt: clay ratio of the soils ranged from 0.28 to 0.97 across the pedons with a mean value of 0.58. This ratio is one of the indices used to assess the rate of weathering and determine the relative stage of development of a given soil (Rech *et al.*, 2001). The ratio of silt to clay was very much higher at the surface and decreased through pedon depth. Thus, the higher silt: clay ratio and its decline with increasing depth show the movement of clay materials from the upper horizon to the lower horizon and that sub-soils are more weathered than the topsoil as suggested by Karuma *et al.* (2015).

The total porosity of the surface and sub-surface layers of the pedons ranged from 50.9 to 65.7% and 49.4 to 61.1%, respectively (Table 2). This could be due to natural compaction, change in soil particle size distribution and increase of soil bulk density, and decrease in OM content and thus the formation of less aggregation of soil particles and management effects. The surface layers encompass comparatively higher OM, which makes the soil loose and porous, thereby leading to increased porosity (Celik, 2005). This finding is in agreement with that of Mulugeta Debele *et al.* (2018) who reported that total porosity decreased with increasing soil depth as a result of management effect, limited penetration by roots of crops into sub-surface layers, and decreasing OM content. Accordingly, total pore space and BD showed an inverse relationship in all pedons. The soils of the studied Watershed had an overall average total pore space of 57.8%, which is typical for well granulated, medium to fine-textured soils in good condition for plant growth. This is because sandy soils having above 40% pore space and clay soils having above 50% pore space do not restrict root growth (Harrod, 1975).

Table 2. Selected physical properties of soils in the different horizons of the pedons in Sentele Watershed, Southern Ethiopia, during the 2018 main cropping season.

Pedon	Horizon	Depth (cm)	Particle size distribution (%)			Texture class	Silt:Clay	BD (g cm^{-3})	TP (%)
			Sand	Silt	Clay				
SE/LD/LA/P1	Ap	0–23	44.5	27.3	28.2	L	0.97	1.08	59.2
	Bt1	23–72	33.5	27.1	39.4	CL	0.69	1.17	55.8
	Bt2	72–129	24.1	22.1	53.8	C	0.41	1.26	52.5
	Bt3	129–200+	19.4	20.3	60.3	C	0.34	1.21	54.3
SE/MD/LE/P2	Ah	0–20	33.4	30.3	36.3	CL	0.83	0.91	65.7
	Bw1	20–50	32.2	28.7	39.1	CL	0.73	1.03	61.1
	Bw2	50–70	32.5	28.2	39.3	CL	0.72	1.11	58.1
	R	70+	–	–	–	–	–	–	–
SE/MD/LE/P3	Ap	0–24	36.3	27.3	36.4	CL	0.75	1.28	51.7
	Bt1	24–64	26.2	24.7	49.1	C	0.50	1.32	50.2
	Bt2	64–120	22.8	22.0	55.2	C	0.40	1.34	49.4
	Bt3	120–200+	20.4	17.2	62.4	C	0.28	1.15	56.6
SE/MD/SA/P4	Ap	0–25	30.4	32.6	37.0	CL	0.88	1.06	60.0
	Bt1	25–69	26.1	23.1	50.8	C	0.45	1.13	57.4
	Bt2	69–117	25.3	20.1	54.6	C	0.37	1.22	54.0
	Bt3	117–200+	28.3	19.5	52.2	C	0.37	1.30	50.9

Note: *C = Clay; L = Loam; CL = Clay loam; and TP = Total porosity.*

3.3. Chemical Properties

3.3.1. Soil pH

The pH-$_{Water}$ (H_2O) values of the soils in the pedons range from 5.6 to 6.41, which are in the category of moderate acidity to slight acidity according to the rating of Murphy (1968). In the pedon, SE/MD/LE/P2, the values of pH increased with soil depth and the trend of increase was irregular for the rest of the pedons. The highest pH value (6.41) was observed at the depth of 72 to 129 cm for the sub-surface horizon of SE/LD/LA/P1 whereas the lowest (5.6) pH value was observed at SE/MD/LE/P3 for steep cultivated land use (Table 3). This could be due to the continuous removal of basic cations and leaching of bases and clay particles from the exposed cultivated land in addition to the possible release of H^+ by the nitrification of NH_4^+ sourced from chemical fertilizers and legume roots during N_2 fixation on most surface layers of a cultivated field. The range of slight and moderate acidity can have special advantages for enhanced mobilization of soil nutrients and their uptake by plants (FAO, 2006), and, therefore, there was no limitation for crop production in terms of soil reaction (pH).

3.3.2. Organic carbon

The organic carbon (OC) content in the surface layers of the studied pedons range from 2.94 to 4.9% (Table 3). According to the rating of Berhanu Debele (1980), as cited by Tekalign Tadesse *et al.* (1991), these contents of organic carbon are in the category of medium to high. The organic carbon content of the sub-surface soils of the studied pedons ranges from 1.12 to 4.6% (Table 3). According to the rating of the same authors (ibid), this range of organic carbon is in the category of low to high.

Generally, the OC content decreased with depth for all pedons. This could be attributed to the addition of compost (farmyard manure) and presence of dead roots, and plant residues on the top soil whereas such addition were low or absent in the deeper soil pedons. The higher OC content was recorded for the grassland pedon which might be a result of the contribution from the decomposition of live grassroots and deposits of organic materials from grass leaves as suggested by Buol *et al.* (2011). Organic carbon was significantly ($P \leq 0.01$) and positively correlated with total nitrogen content ($r = 0.760^{**}$) at $p < 0.01$ (Table 6) indicating that the soil OM is the main source of nitrogen. This suggestion is consistent with the observation of Murage *et al.* (2000) who inferred that organic carbon is a surrogate of improved soil quality through improved soil nitrogen contents. The lowest OC content was observed in the pedon located on the cultivated land, which could be due to the rapid decomposition rate of organic matter and mineralization of organic matter under intense cultivation (Sheleme Beyene, 2011).

The contents of total nitrogen in the studied soils ranged from 0.135% to 0.484%, which falls in the category of high to very high according to the rating of Berhanu Debele (1980) as cited by Tekalign Tadesse *et al.* (1991). The content of total nitrogen decreased with depth in all pedons followed by that of the OC showing the strong relationship between OC and TN. This may be attributed to the fact that carbon is the main source of nitrogen (Allotey *et al.*, 2008), and here was high accumulation organic matter in the surface horizons. Similar findings were reported by Seid Mohammed *et al.* (2017) who observed that a decrease in total nitrogen was parallel to a decrease in the contents of organic matter. Similar to the OC trend observed in land use, higher total nitrogen content was recorded in grassland use followed by fallow land use. Topographically, a higher TN content was recorded on summits and a lower TN content was recorded on the middle slope of the cultivated land. The difference in the content of TN could be attributed to the effect of variation in the land use system and slope of the specific land uses, which were 3% for the summit and 27% for the cultivated land.

The carbon to nitrogen ratio (C:N) of the soils on the surface ranges from 10.1 to 15.0 with a mean of 11.6, while that in the sub-surface soil ranges from 8.3 to 16.7 with a mean of 11.3 (Table 3). All Pedons showed an irregular distribution with depth. The range of 24:1 carbon to nitrogen ratio is the perfect balance necessary to select crop types and keep a cropping sequence on the right path toward sustainability (USDA NRCS, 2011). The organic matter with a high carbon to nitrogen ratio (>20 to 30) locks up nitrogen as it decomposes, decreasing the availability of nitrogen for the crop in the short term (Hoyle, 2013).

The contents of available phosphorus in all studied pedons range from 17.8 to 30.1 mg kg^{-1} for the surface horizons and from 8.9 to 28.8 mg kg^{-1} (Table 3). According to the rating of Ryan *et al.* (2001), it was very low to medium, and the values decreased as depth increased except for SE/MD/LE/P2. The relatively higher phosphorus content on the surface of all pedons could be attributed to the relatively higher OM content as a result of the incorporated farmyard manure, and application of phosphorus fertilizers. Similar results were reported by Mulugeta Debele *et al.* (2018) who found that available phosphorus contents decreased as the soil depth increased. Thus, phosphorus could be a deficient nutrient for crop production in the soils along with some other nutrients. Therefore, phosphorus application is recommended through regular monitoring. On the other hand, available phosphorus was significantly and positively correlated with OC ($r = 0.677^{**}$, $P < 0.01$) (Table 6). The positive correlation between OC and phosphorus imply an increase in soil organic carbon, and also an increase in soil available phosphorus.

Table 3. Selected chemical properties of the soils in the different horizons in Sentele Watershed, southern Ethiopia, during the 2018 main cropping season.

Horizons	Horizon	Depth (cm)	pH (H_2O)	OC (%)	TN (%)	C: N	Av. P Mg kg soil^{-1}
SE/LD/LA/P1	Ap	0–23	6.20	4.1	0.365	11.2	25.6
	Bt1	23–72	6.29	2.64	0.244	10.8	23.8
	Bt2	72–129	6.41	2.31	0.195	11.9	15.8
	Bt3	129–200+	5.71	1.83	0.155	11.8	10.5
SE/MD/LE/P2	Ah	0–20	5.64	4.9	0.484	10.1	30.1
	Bw1	20–50	5.83	4.2	0.478	8.8	24.5
	Bw2	50–70	5.93	4.6	0.446	10.3	28.8
	R	70+	–	–	–	–	–
SE/MD/LE/P3	Ap	0–24	5.70	2.94	0.196	15.0	17.8
	Bt1	24–64	6.23	2.8	0.168	16.7	12.3
	Bt2	64–120	5.63	1.6	0.146	11.0	9.90
	Bt3	120–200+	5.70	1.12	0.135	8.3	8.90
SE/MD/SA/P4	Ap	0–25	5.60	4.35	0.428	10.2	13.1
	Bt1	25–69	5.86	3.6	0.298	12.1	6.0
	Bt2	69–117	5.79	2.95	0.239	12.3	5.0
	Bt3	117–200+	6.08	1.74	0.165	10.5	3.7

3.3.3. Cation exchange capacity and percent base saturation (PBS)

The cation exchange capacity (CEC) of the soils varies across the land units and the depth of the pedons (Table 4). The values of CEC of soils increased with depth which may be due to leaching and retention of more cations (FAO, 2008). There was a significant and positive correlation between CEC and clay particles ($r = 0.579^*$) at $p < 0.05$ (Table 6). This is consistent with Sparks' (2003) hypothesis that negative charges that form on organic matter and clay minerals, which are pH-dependent, attract positive charges by electrostatic forces. CEC of the clay is greater than the CEC of the soil because the clay fraction has negatively charged sites which adsorb and hold positively charged cations by electrostatic (McKnzie *et al.*, 2004). Thus, soils with high amounts of clay and/or organic matter typically have a higher cation exchange capacity (CEC), which can bind more cations such as calcium or potassium than siltier or sandy soils (McCauley *et al.*, 2017). The CEC in the studied pedons was rated as moderate to high CEC (Landon, 1991), and therefore, the high CEC values indicate higher clay content and organic matter (FAO, 2006). Soils with medium to high CEC (15–40) cmol $_{(+)}$ kg soil^{-1} have high clay or humus contents as well as high water-holding capacity and a greater capacity to hold plant nutrients (Landon, 1991).

The percentage of base saturation (PBS) ranges between 56.9% and 88.9%, with a mean value of 70.9% (Table 4). The PBS generally showed an inconsistent trend with the increase in soil depth except for pedon SE/MD/LE/P3 which showed a decreasing trend with the increase in soil depth. The PBS of surface soil horizons ranges from 73.3% to 88.9% with a mean value of 80.5%, whereas in the PBS of sub-surface layers range from 56.9 to 75.9 with a mean value of 67.4%. According to the rating by Maria and Yost (2006), the PBS in all pedons is rated as high. Soils with a PBS of > 50% are regarded as fertile soils, whereas soils with PBS of < 50% are regarded as having low fertility (FAO, 1999).

3.3.4. Exchangeable bases

The number of exchangeable bases (Ca^{++}, Mg^{++}, $K^{+,}$ and Na^{+}) is presented in Table 4. The trend of distribution of calcium and magnesium shown as an irregular pattern with soil depth and the highest contents of Ca and Mg were observed in the subsurface layer of SE/MD/LE/P2. Both exchangeable calcium and magnesium were rated as high (FAO, 2006) in both surface and subsurface horizons. The ratio of Ca: Mg of the soils range from 2.7 to 3.9 with an average value of 3.1. Ca:Mg ratios should be between 3.0 and 5:1 (Landon, 1991). However, the average Ca: Mg ratio in Pedon SE/LD/LA/P1 was less than 3.0:1, which might lead to P inhibition and Ca insufficiency (Yates, 1964). This profile might have a high magnesium level throughout. Similarly, Naseem *et al.* (2012) showed that a high magnesium supply contributes to the soil's low Ca: Mg value and lowers Ca inflow rates. The content of K in the soils was rated as medium to high (FAO, 2006), and the content of Na was rated as low to medium (Hazelton and Murphy, 2016). The distribution trend of potassium generally increased within the increase in soil depth and sodium showed an irregular pattern with soil depth and the contents in the soil at the optimal level for most crops (FAO, 2006).

Table 4. Exchangeable bases, cation exchange capacity, CEC clay, calcium to magnesium ratio (Ca: Mg), and PBS (Percent base saturation) of Sentele Watershed.

Pedon	Horizon	Depth (cm)	Exch. base (cmol (+) kg^{-1}				CEC (cmol/kg)		Ca:	BS
			Ca	K	Mg	Na	Soil	Clay	Mg	(%)
SE/LD/LA/P1	Ap	0–23	15.9	0.9	5.0	0.15	24.7	86.8	3.2	88.9
	Bt1	23–72	14.6	1.0	5.4	0.12	29.4	74.2	2.7	71.6
	Bt2	72–129	15.8	1.1	5.4	0.14	29.8	55.2	2.9	75.3
	Bt3	129–200+	14.1	1.0	5.2	0.15	32.7	54.1	2.7	62.5
SE/MD/LE/P2	Ah	0–20	16.2	1.1	5.2	0.11	30.4	82.2	3.1	74.4
	Bw1	20–50	13.8	1.1	4.4	0.14	31.3	79.3	3.1	62.1
	Bw2	50–70	17.4	1.2	6.3	0.16	33.6	84.7	2.8	74.6
	R	70+	–	–	–	–	–	–	–	–
SE/MD/LE/P3	Ap	0–24	14.9	0.9	4.4	0.13	23.8	65	3.4	85.4
	Bt1	24–64	15.6	0.9	4.8	0.17	28.3	57.3	3.1	75.9
	Bt2	64–120	14.2	0.4	3.9	0.11	29.1	52.6	3.6	64.0
	Bt3	120–200+	13.5	1.0	4.8	0.16	34.2	54.8	2.8	56.9
SE/MD/SA/P4	Ap	0–25	14.2	0.6	4.2	0.12	26.1	69.7	3.4	73.3
	Bt1	25–69	13.4	0.8	3.4	0.13	28.7	56.1	3.9	61.8
	Bt2	69–117	15.5	1.0	5.4	0.15	29.6	53.9	2.9	74.5
	Bt3	117–200+	14.3	1.2	4.6	0.14	32.3	61.7	3.1	62.7

3.3.5. Extractable micronutrients

The available micronutrient concentrations were shown to be in the following order: Fe > Mn > Cu > Zn > B (Table 5). Soil organic matter, pH, redox potential, soil texture, and mycorrhizae are the key factors influencing soil micronutrient content (Kumar *et al.*, 2016). According to Jones (2003)'s nutrient critical values, the concentration of iron and manganese is high, copper (Cu) and zinc (Zn) are medium, and B is low to adequate. This suggests that soil boron concentration was relatively insufficient, despite adequate soil Fe, Cu, Zn, and Mn levels. When compared to other land uses, grassland land had a higher concentration of extractable micronutrients in the soil, which could be attributed to the organic matter content. According to Hartz (2007), crop response to fertilizer is unlikely for Fe, Mn, Zn, and Cu concentrations larger than 10.0, 3.0, 1.5, and 1.0 mg kg^{-1}, respectively. As a result, the soils in the watershed do not lack these micronutrients. However, the B concentration is insufficient for the majority of crops grown in the area.

Table 5. Content of exchangeable micronutrients in the soils of Sentele Watershed.

Pedon	Horizon	Depth (cm)	Fe mg kg soil^{-1}	Cu mg kg soil^{-1}	Zn mg kg soil^{-1}	Mn mg kg soil^{-1}	B mg kg soil^{-1}
SE/LD/LA/P1	Ap	0–23	48.9	1.6	2.3	48.94	0.3
	BA	23–72	52.4	2.4	1.6	18.74	0.5
	Bt1	72–129	51.5	2.7	1.8	37.24	0.8
	Bt2	129-200+	69.8	2.8	1.9	36.94	0.8
SE/MD/LE/P2	Ah	0–20	73.2	2.4	2.4	46.36	0.2
	Bw1	20–50	70.4	2.3	1.2	51.84	0.5
	Bw2	50–70	78.6	2.6	1.8	24.01	0.4
	R	70+	–	–	–	–	–
SE/MD/LE/P3	Ap	0–24	48.4	1.5	2.2	39.80	0.4
	Ap1	24–64	58.3	1.7	1.6	11.16	0.6
	Bt1	64–120	60.4	1.8	1.6	47.44	0.2
	Bt2	120–200+	67.9	1.9	1.4	38.04	0.6
SE/MD/SA/P4	Ap	0–20	59.6	2.2	2.1	50.69	0.8
	Bt1	20–69	56.7	2.1	1.8	44.38	0.6
	Bt2	69–117	52.2	2.4	1.8	29.83	0.4
	Bt3	117–200+	74.8	2.6	1.4	16.64	0.2

Table 6. Correlation properties of soils.

	BD	TP	pH	OC	Sand	Silt	Clay	TN	AV. P	Ca	K	Mg	Na	CEC	PBS
BD	1	1.0**	.274	–.759**	–.429	–.605**	.541*	–.868**	–.625**	–.141	–.226	–.130	.228	–.066	–.051
TP		1	–.274	.760**	.427	.604**	–.539*	.868**	.623**	.142	.226	.129	–.227	.065	.052
pH			1	–.094	.219	–.085	–.104	–.176	.143	.329	.384	.352	.333	–.063	.307
OC				1	.665**	.854**	–.801**	.943**	.677**	.474*	.121	.137	–.168	–.296	.460*
Sand					1	.701**	–.951**	.585*	.690**	.420	.129	.128	–.158	–.578*	.730**
Silt						1	–.888**	.808**	.733**	.341	–.101	.038	–.385	–.473*	.510*
Clay							1	–.730**	–.764**	–.419	–.039	–.099	.270	.579*	.693**
TN								1	.700**	.346	.172	.143	–.224	–.083	.237
Av. P									1	.580*	.303	.475*	–.143	–.100	.476*
Ca										1	.381	.754**	.231	–.057	.681**
K											1	.655**	.445*	.507*	.010
Mg												1	.408	.376	.320
Na													1	.313	.027
CEC														1	.731**
PBS															1

3.4. Classification of the Soils

From the morphological and soil analytical data discussed, the soils in pedon SE/LD/LA/P1 have higher clay content in the sub-surface than in the topsoil characterized by the presence of argic property of the horizon. Also, the argic horizon has high CEC and high base saturation which fulfills the criteria of Luvisols. The presence of reddish color on the subsurface qualifies the soil as chromic. Therefore, according to the IUSS Working Group WRB (2015), the soils are classified as Chromic Luvisols, and cover an area of 492.6 ha (Figure 3).

Pedon SE/MD/LE/P2 was characterized by intermediate soil depth (0−70 cm) on the summit of the Watershed with a gentle slope (3−5%). The sub-surface had 30 cm thickness with more than10% clay fraction. After 70 cm depth, the pedon has continuous hard rocks and generally pH_{water} value of above 5, uncultivated surface rich with organic matter meeting the criteria for Silandic properties and the requirement of Andosols originating from the pumice parent material. The thick, dark-colored horizon at or near the soil surface that was typically associated with short-range-order minerals, the presence of andic properties with a dark brown colored surface, and a Munsell color value or chroma of > 2 (moist) qualifies the pedon as a Fulvic additional qualifier. Therefore, the soil in this pedon could be classified according to the IUSS Working Group WRB (2015) as Silandic Andosols (Fulvic), with a total distribution of 417.8 ha (Figure 3).

For pedon SE/MD/LE/P3, the sub-surface horizon has more than 30 cm thickness with more than 30% clay fraction, moderate to blocky angular structures with many shiny ped faces; silt/clay ratio <0.4 meetings the criteria for Nitic subsurface horizon. The pedons has a diffused boundary between the surface and the subsurface layers; without ferric, plinthic, or Vertic horizons, no gleyic color patterns start within 100 cm of the surface meeting the requirements for Nitisols. Furthermore, the subsurface layer started at 28 cm and has high iron content; dark reddish brown (2.5YR 2.5/3) color. Therefore, according to the IUSS Working Group WRB (2015), the soils are classified as Rhodic Nitisols, and it covers an area of 527.2 ha (Figure 3).

Pedon SE/MD/SA/P4 (middle slope) has a slope gradient of 2586 masl, a view to the north-east, and a mountain with a gradient of 10–30%. The soils were deep (above 200 cm) and prone to erosion from water. Surface and subterranean drainage are both adequate. The parent material is, of course, basaltic ignimbrite with Phanerozoic quaternary volcanic and related deposits. In the argic horizons, had shiny surfaces that shrink-swell and cracks (slickensides) that close and open on a periodic basis, which might match the Vertic prefix qualifier criterion. The pedon is a humic suffix qualifier because it contains more than 1% soil organic carbon to a depth of 50 cm below the mineral soil surface. As a result, the pedon's soils were identified and classified.as Vertic Luvisols (Humic) by the IUSS Working Group WRB (2015) and they cover an area of 445.4 ha (Figure 3).

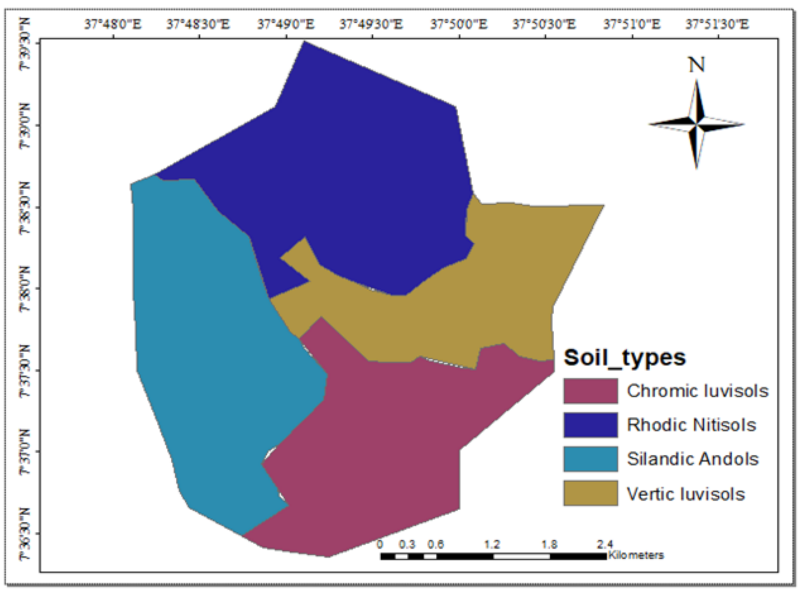

Figure 3. Soil map of study Watershed.

4. Conclusion

The results of this study have revealed that the pedons are well-drained in the upper horizons, have sub-angular to angular blocky structures, with dark brown (7.5 YR 3/3), dark reddish-brown (5YR 3/4), and reddish-brown (5YR 5/4) colors. The surface soils have loamy and clayey loam textures, whilst the sub-surface soils have clayey loam and clay texture. The increasing trend of clay content across the depth of all pedons indicates a prominent movement of clay materials down the pedons forming the argic horizons. The soils have moderately acidic reaction, medium to high CEC, and medium to very high OC. The important nutrients, namely, N, K, Ca, and Mg were shown to be adequately available for uptake by crop plants except phosphorus, which is deficient. Following the legend of IUSS Working Group WRB (2015), four soil types have been identified as Chromic Luvisols, Silandic Andosols (Fulvic), Rhodic Nitisols, and Vertic Luvisols (Humic). This implies that soil characteristics and types are influenced by land use variations. Therefore, the results of the study imply that four types of soil are available in the Watershed, which have varying physical and chemical properties and should be used for the production of specific crops that fit them. In addition, the soils also need site-specific management practices. Further research needs to be conducted to generate additional information on site-specific soil physical and chemical properties for profitable cultivation of specific crops in the Watershed.

5. Acknowledgments

The authors are grateful to Wachemo University for facilitating the study and financial support, and the Ministry of Education (MoE) for proving research funds for this research.

6. References

Alemayehu Kiflu. 2015. Characterization of Agricultural Soils in CASCAPE Intervention Woredas in Southern Nations Nationalities and People Region (SNNPR).

Alemayehu Kiflu, Sheleme Beyene and Schoenau, J. 2016. Characterization of problem soils in and around the south-central Ethiopian Rift Valley. *Journal of Soil Science and Environmental Management,* 7(11): 191–203.

Alemu Lelago and Tadele Buraka. 2018. Soil classification and agricultural potentials of soils of Tembaro. *Journal of Environmental Science*, 10(6): 75–91.

Allotey, D.F.K., Asiamah, R.D., Dedzoe, C.D. and Nyamekye, A.L. 2008. Physico-chemical properties of three salt-affected soils in the lower Volta Basin and management strategies for their sustainable utilization. *West African Journal of Applied Ecology*, 12(1). DOI: 10.4314/wajae.v12i1.45776.

Aruleba, J.O. and Ajayi, A.S. 2013. Classification, characterization, and suitability evaluation of the savanna soils of Oyo North of Nigeria. Developments in soil classification, land use planning and policy implications: Innovative thinking of soil inventory for land use planning and management of land resources. Pp.285–303.

Barthès, B. and Roose, E. 2002. Aggregate stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels. *Catena*, 47(2): 133–149.

Berhanu Debele. 1980. The physical criteria and their rating proposed for land evaluation in the highland region of Ethiopia. Land Use Planning and Regulatory Department, Ministry of Agriculture, Addis Ababa, Ethiopia.

Blake, G.R. and Hartge, K.H. 1986. Bulk density. Pp. 363–575. *In*: Klute, A. (ed.). Methods of soil analysis: Part 1 Physical and Mineralogical Methods. The American Society of Agronomy, USA.

Bouyoucos, G.J. 1962. Hydrometer method improved for making particle size analyses of soils 1. *Agronomy journal*, 54(5): 464–465.

Bray, R.H. and Kuntz, L.T. 1945. Determination of Total Organic and Available Forms of Phosphorus in Soils. *Soil Science*, (59): 39–45.

Buol, S.W., Southard, R.J., Graham, R.C. and McDaniel, P.A. 2011. *Soil genesis and classification*. John Wiley and Sons, New Jersey. Pp. 544.

Carter, M.R. and Gregorich, E.G. 2003. *Soil sampling and methods of analysis*. 2nd edition. Canadian Society of Soil Science, Canada. Pp. 1262.

Celik, I. 2005. Land-use effects on organic matter and physical properties of soil in a southern Mediterranean highland of Turkey. *Soil and Tillage research*, 83(2): 270–277.

Chapman, H.D., editor. 1965. *Cation-exchange capacity. Methods of soil analysis: Part 2 Chemical and Microbiological Properties*. The American Society of Agronomy, USA. Pp. 891–901.

De Geus, J.G. 1973. *Fertilizer Guide for the Tropics and Subtropics*. 2nd edition. Centre d'Etude de l'Azote, Switzerland. Pp. 774.

de la Paz Jimenez, M., de la Horra, A., Pruzzo, L. and Palma, M.R. 2002. Soil quality: a new index based on microbiological and biochemical parameters. *Biology and Fertility of Soils*, 35: 302–306.

Delgado, A. and Gómez, J.A. 2016. *The soil. Physical, Chemical and Biological Properties*. Pp. 15–26. *In*: Villalobos, F.J. and Fereres, E. (eds.). Principles of Agronomy for Sustainable Agriculture. Springer, Berlin.

Endalkachew Fekadu, Kibebew Kibret, Bobe Bedadi and Asmare Melese. 2018. Characterization and classification of soils of yikalo subwatershed in lay gayint district, northwestern highlands of Ethiopia. *Eurasian Journal of Soil Science*, 7(2): 151–166.

FAO (Food and Agricultural Organization).1999. World Reference Base for Soil Resource. World Soil Resources Report, 84. Rome, Italy

FAO (Food and Agricultural Organization). 2006. *Guidelines for Soil Description*. 4th edition. Rome, Italy. Pp. 109.

FAO (Food and Agricultural Organization). 2006. Plant nutrition for food security: A guide for integrated nutrient management. FAO Fertilizer and Plant Nutrition Bulletin 16, Rome, Italy.

FAO (Food and Agricultural Organization). 2008. Guide to laboratory establishment for plant nutrient analysis. FAO Fertilizer and Plant Nutrition Bulletin 19, Rome, Italy.

Getachew Beyene, Nigussie Dechassa, Alemayehu Regassa, Lemma Wogi. 2022. Land suitability assessment for apple (*Malus domestica*) production in Sentele watershed in Hadiya zone, southern Ethiopia. *Applied and Environmental Soil Science*, https://doi.org/10.1155/2022/4436417.

Harrod, M.F. 1975. *Field Experience on Light Soils*. *In*: Proceedings of a Conference on Soil physical conditions and crop production. Agricultural Development and Advisory Service, UK. Pp. 505.

Hartz, T.K. 2007. Soil testing for nutrient availability: Procedures and interpretation for California vegetable crop production. Department of Plant Sciences, Davis, CA, USA. Pp. 1–7.

Hazelton, P. and Murphy, B. 2016. *Interpreting Soil Test Results*: *What Do All The Numbers Mean*?. CSIRO Publishing, Clayton, Australia. Pp. 134.

Houba, V.J.G., Van der Lee, J.J., Novozamsky, I. and Walinga, I. 1989. *Soil and Plant Analysis: A Series of Syllabi. Part 5 Soil Analysis Procedures.* Department of Soil Science and Plant Nutrition, Wageningen Agricultural University, Netherlands.

Hoyle, F. and Fairbanks, M. 2013. *Managing Soil Organic Matter: A Practical Guide*. 1st edition. Grains Research and Development Corporation (GRDC), Department of Agriculture and Food Western Australia, Australia. Pp. 111.

IUSS Working Group WRB. 2015. World reference base for soil resources 2014 International soil classification system for naming soils and creating legends for soil maps Update 2015.

John, M.K., Chuah, H.H. and Neufeld, J.H. 1975. Application of improved azomethine-H method to the determination of boron in soils and plants. *Analytical Letters*, 8(8): 559–568.

Jones, J.B. 2001. *Laboratory Guide for Conducting Soil Tests and Plant Analysis*. Rutledge, Oxfordshire, UK.

Jones, J.B. 2003. *Agronomic Handbook: Management of Crops, Soils, and Their Fertility*. CRC Press, Boca Raton, FL, USA. Pp. 450.

Karuma, A.N., Gachene, C.K., Msanya, B.M., Mtakwa, P.W., Amuri, N. and Gicheru, P.T. 2015. Soil morphology, physico-chemical properties and classification of typical soils of Mwala District, Kenya. *International Journal of Plant & Soil Science*, 4(2): 156–170.

Kazmin, V. 1973. Geological map of Ethiopia (scale 1: 2,000,000). *Geological Survey of Ethiopia*, Addis Ababa, Ethiopia.

Kumar, A., Choudhary, A.K., Pooniya, V., Suri, V.K. and Singh, U. 2016. Soil factors associated with micronutrient acquisition in crops – Biofortification perspective. *Biofortification of Food Crops*, 159–176.

Landon J.R. 1991. Booker tropical soil manual: A handbook for soil survey and agricultural land evaluation in the Tropics and Subtropics. Longman UK Limited, Essex, UK. Pp. 474.

Maria, R.M. and Yost, R. 2006. A survey of soil fertility status of four agroecological zones of Mozambique. *Soil Sciences*, 171(11): 902–914.

McCauley, A., Jones, C. and Jacobsen, J. 2009. Soil pH and organic matter. *Nutrient Management Module*, 8(2): 1–12.

McKenzie, N., Jacquier, D., Isbell, R. and Brown, K. 2004. Australian Soils and Landscapes: *An illustrated Compendium*. CSIRO Publishing, Clayton, Australia.

Moss, P. 1961. Limits of interference by iron, manganese, aluminum and phosphate in the EDTA determination of calcium in the presence of magnesium using Cal-red as indicator. *Journal of the Science of Food and Agriculture*, 12(1): 30–34.

Mulugeta Debele, Bobe Bedadi, Sheleme Beyene and Muktar Mohammed. 2018. Characterization and Classification of Soils of Muger Sub-Watershed, Northern Oromia, Ethiopia. *East African Journal of Sciences,* 12(1): 11–28.

Munsell, S.C.C. 1994. Macbeth Division of Kollmorgen Instruments. New Windsor, New York, USA.

Murage, E.W., Karanja, N.K., Smithson, P.C. and Woomer, P.L. 2000. Diagnostic indicators of soil quality in productive and non-productive smallholders' fields of Kenya's Central Highlands. *Agriculture, Ecosystems and Environment*, 79(1): 1–8.

Murphy, H.F. 1968. A Report on fertility status and other data on some soils of Ethiopia. Experimental Station Bulletin No. 44. Hailesilassie College of Agriculture, Oklahoma State University, Stillwater. Pp. 551.

Naseem, S., Hamza, S. and Bashir, E. 2012. Assessment of geochemistry of soils for agriculture at Winder, Balochistan, Pakistan. *Water quality, soil and managing irrigation of crops, InTech-Open Access Publisher, Croatia.* Pp.73–94.

Rech, J.A., Reeves, R.W. and Hendricks, D.M. 2001. The influence of slope aspect on soil weathering processes in the Springerville volcanic field, Arizona. *Catena*, 43(1): 49–62.

Nortcliff, S. 2006. *Classification Need for the System*. Pp. 227–229. *In*: Lal, R. (ed.). Encyclopedia of Soil Science.

Ryan, J., Estefan, G. and Rashid, A. 2001. *Soil and Plant Analysis Laboratory Manual*. 2nd edition. Internationl Center for Agricultural Research in the Dry Areas (ICARDA). Aleppo, Syria. Pp. 177.

Seid Mohammed, Kibebew Kibret and Muktar Mohammed. 2017. Characterization and Classification of Soils along Toposequence of Gobeya Sub-Watershed, South Wello Zone, Ethiopia. *Asian Journal of Soil Science and Plant Nutrition*, 2(4): 1–17.

Sheleme Beyene. 2011. Characterization of soils along a toposequence in Gununo area, southern Ethiopia. *Journal of Science and Development*, 1(1): 31–41.

Shimelis Damene, Mohamed Assen and Abayneh Eyasu. 2007. Characteristics and classification of the soils of Tenocha-Wenchacher micro-catchment, South-west Shewa, Ethiopia. *Ethiopian Journal of Natural Resources,* 9(1): 37–62.

Soil Survey Laboratory Methods Manual. 1996. Soil survey Investigator Report No. 42 Version 3.0, USDA.

Sparks, D.L., Singh, B. and Siebecker, M.G. 2022. *Environmental Soil Chemistry*. Elsevier, Amsterdam, Netherlands.

Tekalign Tadesse, Haque, I. and Aduayi, E.A. 1991. Soil, plant, water, fertilizer, animal manure and compost analysis manual. Available at https://hdl.handle.net/10568/4448.

Teshome Yitbarek, Abdeta Jembere and Habtamu Kerebeh. 2018. Characterization and classification of soils of Wolkite University research sites, *Eurasian Journal of Soil Science*, 7(4): 292–299.

Reeuwijk, L.P., editor. 2002. Procedures for Soil Analysis. International Soil and Reference Information Centre, Wageningen, Netherlands. Pp. 119.

USDA NRCS. 2011. C:N Ratios in Cropping Systems. USDA Natural Resources Conservation Service Soils. Available at https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd331820.pdf. Accessed on 4/5/2022.

Vodyanitskii, Yu.N. and Savichev, A.T. 2017. The influence of organic matter on soil color using the regression equations of optical parameters in the system CIE-*L*a*b**. *Annals of Agrarian Science,* 15(3): 380–385.

Walkley, A. and Black, I.A. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science,* 37: 29–38.

Yates, R.A. 1964. Yield depression due to phosphate fertilizer in sugarcane. *Australian Journal of Agricultural Research*, 15(4): 537–547.