CHARACTERIZATION AND CLASSIFICATION OF SOILS FOR SELECTED SITES IN SOUTHERN ETHIOPIA †

[CARACTERIZACIÓN Y CLASIFICACIÓN DE SUELOS PARA SITIOS SELECCIONADOS EN EL SUR DE ETIOPÍA]

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SUMMARY

Background: Soils in southern Ethiopia are under intensive cultivation, and low soil fertility is a major problem. However, very little is known about soil types and their inherent nature to support specific decisions on soil managements. **Objective:** To characterize and classify soils for three selected agricultural sites in southern Ethiopia. **Methodology:** The field morphological description and laboratory analysis were carried out to characterize, and classify the soils of Kokate, Hawassa, and Alage in southern Ethiopia. A representative soil profile (2 m x 2 m x 2 m) was open at each site, for soil profile description. For each profile, soil samples were collected for each of the genetic horizons identified, and the samples were analyzed for their soil physicochemical properties. **Results:** The results showed that the surfaces of Kokate, Hawassa, and Alage were strongly acidic, neutral, and moderately alkaline, respectively. The surface soil of Kokate had clay texture, a high content of micronutrients, cation exchange capacity and moderate base saturation, low soil organic carbon, and available phosphorus. The surface soil of Hawassa had loam texture, high base saturation, cation exchange capacity, and low levels of soil organic carbon, available phosphorus, and micronutrients. The surface soil of Alage had silt clay loam texture, high base saturation, cation exchange capacity, sodium content, and low soil organic carbon content, available phosphorus, and micronutrients. Based on WRB, the soils of Kokate, Hawassa, and Alage were classified as Vertic Luvisols with an argic diagnostic subsurface horizon, Haplic Cambisols with a cambic diagnostic subsurface horizon, and Calcaric Fluvisols with fluvic diagnostic material, respectively. **Implications:** The differences may suggest that site-specific soil fertility management is desired, and the results may provide basic information to design soil management options to improve land productivity. **Conclusions:** The present study showed three soil types and revealed their low nutrient content and different soil pH.

Key words: Soil horizons; soil characterization; soil classification; soil profile; soil properties; soil types.

RESUMEN

Antecedentes: Los suelos del sur de Etiopía están bajo cultivo intensivo y la baja fertilidad del suelo es un problema importante. Sin embargo, se sabe muy poco sobre los tipos de suelo y su naturaleza inherente para respaldar decisiones específicas sobre el manejo del suelo. **Objetivo**: Caracterizar y clasificar suelos de tres sitios agrícolas seleccionados en el sur de Etiopía. **Metodología:** Se realizó la descripción morfológica de campo y análisis de laboratorio para caracterizar y clasificar los suelos de Kokate, Hawassa y Alage en el sur de Etiopía. Se abrió un perfil de suelo representativo (2 m x 2 m x 2 m) en cada sitio, para la descripción del perfil del suelo. Para cada perfil, se recolectaron muestras de suelo para cada uno de los horizontes genéticos identificados y se analizaron las muestras para determinar sus propiedades fisicoquímicas del suelo. **Resultados**: Según el estudio, las superficies de Kokate, Hawassa y Alage eran fuertemente ácidas, neutras y moderadamente alcalinas, respectivamente. El suelo superficial de Kokate tenía textura arcillosa, alto contenido de micronutrientes, capacidad de intercambio catiónico y saturación de bases moderada, bajo carbono orgánico del suelo y fósforo disponible. El suelo superficial de Hawassa tenía textura franca, alta saturación de bases, capacidad de intercambio catiónico y bajos niveles. del carbono orgánico del suelo, fósforo

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disponible y micronutrientes. El suelo superficial de Alage tenía una textura franco arcillosa limosa, alta saturación de bases, capacidad de intercambio catiónico, contenido de sodio y bajo contenido de carbono orgánico, fósforo disponible y micronutrientes. Con base en la WRB, los suelos de Kokate, Hawassa y Alage se clasificaron como Luvisoles Vérticos con un horizonte subsuperficial de diagnóstico árgico, Cambisoles Háplicos con horizonte subsuperficial de diagnóstico cámbico y Fluvisoles Calcáricos con material de diagnóstico flúvico, respectivamente. **Implicaciones:** Las diferencias pueden sugerir que se desea un manejo de la fertilidad del suelo específico del sitio y los resultados pueden proporcionar información básica para diseñar opciones de manejo del suelo para mejorar la productividad de la tierra. **Conclusiones:** El presente estudio mostró tres tipos de suelo y reveló su bajo contenido de nutrientes y diferente pH de suelo.
Palabras clave: Horizontes del suelo; caracterización del suelo; clasificación de suelos; perfil del suelo; propiedades del suelo; tipos de suelo.

INTRODUCTION

Soil is a nonrenewable natural capital resource, that formed by solid particles, gases, and liquid materials on land surface and capable of supporting plants (Juilleret *et al*., 2016). Formation of soils is essentially contributed by several important factors: the parent materials, climate, topography, biological components and time (Jenny, 1994). Their influence on soil types varies accordingly from one location to another and depends on accumulated individual interaction of each factor (Moustakas and Georgoulias, 2005). According to Jonsson and Daviosdottir, 2016; Santos-Frances *et al*., 2021), soil formation takes several years to form. Despite this, soil erodes quickly due to improper use or poor management. The soil is perhaps the most difficult, underrated, and little understood environment (Balestrini *et al*., 2024; Saljnikov *et al*., 2021). Soil, like other habitats and ecosystems, is facing increasing pressure from anthropogenic activities (Jonsson and Daviosdottir, 2016; Steffen *et al*., 2007). Thus, the soil resources in Ethiopia and other regions are at risk due to population growth, increased food demand, land use competition, vegetation clearing, desertification, overuse, and mismanagement which is manifested by land degradation (Chen *et al*., 2022; Saljnikov *et al*., 2021). Proper pedological characterization and classification of soils are crucial for sustainable agricultural activities (Tenga *et al*., 2018).

Soil characterization gives information about soil fertility as well as mineralogical and microbiological aspects. In addition to soil-forming components, soil characterization describes soil morphological characteristics (FAO, 2006; Saether and De Caritat, 2020). Soil characterization is a key step in understanding the nature and properties of soil (Onyekanne, 2012). It is essential for soil management practices methods and has a major impact on agricultural productivity (Dessalegn *et al*., 2014; Fekadu *et al*., 2018). Information about the physical and chemical properties of soil is critical for planning soil management, environmental services, and crop productivity (Alias, 2016). Soil fertility is the quality of soil that provides adequate amounts of nutrients for plant growth and favorable chemical, physical and biological properties as a habitat for plant growth (FAO, 2019). However, tropical soils may be challenged due to misuse, low fertilizer application, continuous cultivation, removal of crop residues and overall soil fertility degradation. With this regard, various studies revealed that the soils of sub-Saharan Africa (SSA) are largely unhealthy due to years of nutrient mining and limited organic or inorganic inputs. The average soil organic carbon balance in the highlands of Ethiopia is steadily decreasing at a rate of -3.7 t $ha^{-1}y^{-1}$ (VanBeek *et al*., 2018). Moreover, soil nitrogen, phosphorus and potassium were lost at rates 13, 3 and 10 kg $ha^{-1}y^{-1}$, respectively (Gebremeskel and Mengist, 2016).

Soil classification helps organize knowledge and facilitates the transfer of scientific knowledge and techniques from one site to another (Adhanom and Toshome, 2016). The World Reference Base (WRB) for Soil Resources is a comprehensive and widely accepted soil classification system used in many countries (IUSS Working Group WRB, 2022). Soil characterization and classification are therefore crucial for understanding and promoting sustainable soil management (Esu *et al*., 2008; Rabia *et al*., 2013). In Ethiopia, integrated soil fertility management has been recognized as a crucial strategy for addressing soil degradation and enhancing agricultural production (Hörner and Wollni, 2021). In line with this, a study addressing the implementation of integrated soil fertility management would be conducted in selected common bean growing areas in different agroecology in the southern Ethiopia. Therefore, this study aims to characterize and classify soil types at three selected agricultural sites in southern Ethiopia as a basis for site-specific soil management options. We hypothesize these study soils in different agroecology vary in soil formation and thus in soil types and properties. The outcomes of this study could improve land utilization, productivity, and soil management in similar soils and grocery stores by availing soil types and characterizing them using WRB legends (IUSS Working Group WRB, 2022).

MATERIALS AND METHODS

Description of the Study Areas

The study was conducted in Kokate, Hawassa, and Alage in southern Ethiopia (Figure 1). The sites were selected because they are found in common bean growing areas that lie in different agroecology in the southern Ethiopia. This study characterized and classified the soils as a basis for a study that would be conducted to implement appropriate integrated soil fertility management in these selected areas.

The Kokate site is found at 390 km south of Addis Ababa and 5-15 km east of Wolaita Sodo in Wolaita zone, Southern Ethiopia. It is located in the Cool sub-humid mid highlands agroecology zone at 06º52’42``N and 37º48’30``E with altitude of 2143 m a.s.l (Figure 2). The Hawassa site is found in Hawassa University Main Campus at 273 km south of Addis Ababa in Sidama Region, Ethiopia. It is located in the Tepid moist mid highlands agroecology zone at 07º3'3.2``N and 38º30'23.2``E with altitude of 1694 m a.s.l (Figure 2). The Alage site is found at 217 km south of Addis Ababa and 38 km west of Bulbula town in the vicinity of Rift Valley Lakes (Abijata and Shaalla). It is located in the Tepid Semi-Arid Mid-Highlands agroecology zone at 7°35`30``N and 38°24`59``E with altitude 1585 m a.s.l (Figure 2).

Climatic Conditions

The Kokate area receives annual rainfall that ranges between 1200 and 1300 mm, and the mean minimum and maximum temperatures 16 and 29ºC, respectively. The Hawassa site has rainfall ranging from 900 to 1100 mm and the mean annual minimum and maximum temperatures of 12ºC and 33ºC, respectively. The Alage area receives annual rainfall is 693 mm, and the mean minimum and maximum temperatures 17 to 34ºC, respectively (Figure 2).

Soil Profile Description and Soil Sampling

Representative spots for profile description were selected in crop fields based on similarities of landforms and other physiographic attributes in the three sites. Surface soil samples (0-20 cm; n = 30) were collected in each site using an ‘Edelman auger’ to identify variations in soil depth and texture characteristics

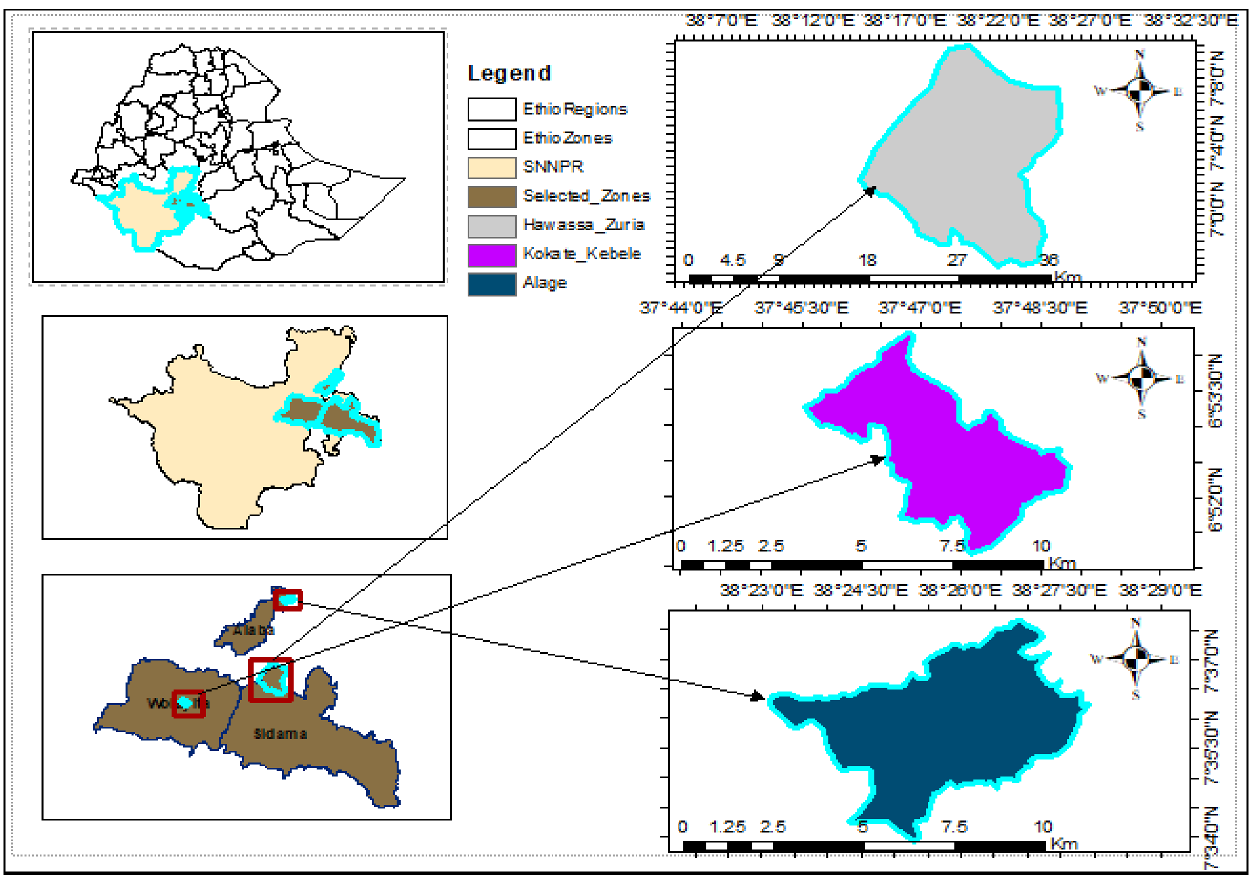

Figure 1. Map of the study areas.

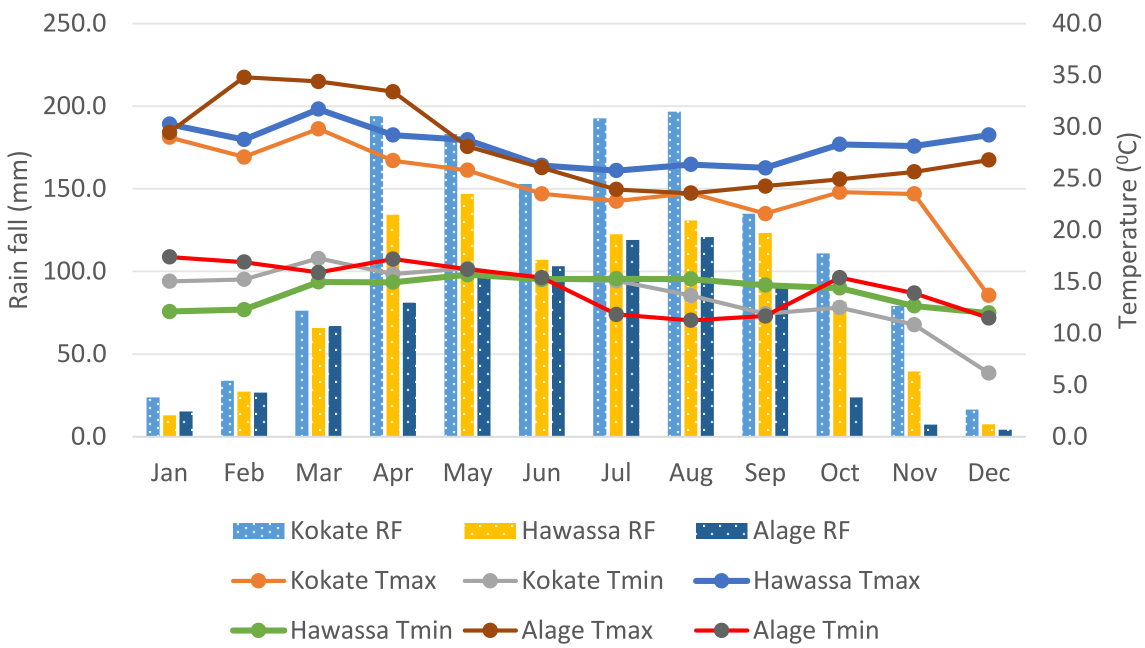

Figure 2. Mean annual rainfall and average minimum and maximum temperatures at three sites.

in order to assess the uniformity of the soils. Based on this assessment, three soil profiles (2 m x 2 m x 2 m), one for each site, were excavated at a representative profile. The soil samples were described following the guidelines for soil profile description (FAO, 2006). Soil samples were also collected from the identified soil horizons of each profile for characterization and classification. The collected soil samples were properly tagged, packed in clean plastic bags, and transported for physicochemical properties analysis. Soil core samples were collected for determination of bulk density. The soil samples were air-dried at room temperature and ground to pass through a 2 mm sieve for determination of the physical and chemical properties of the soil. A 0.5 mm sieve was used for further sieving of the samples for determinations of OC and TN.

Soil Morphological Characteristics

Soil morphological characteristics were described following the Guidelines for Soil Profile Description (FAO, 2006). The color, texture, consistency, structure, plant rooting patterns and other soil features were examined. The soil color notations were described using the Munsell Color Chart (Munsell Color, 1954). The sequence, grade, size, and type (shape) of aggregates were used to characterize the soil structure, while the depth and distinctness of horizon borders were used to define the horizon boundaries. The consistency of the soil was determined in dry, moist, and wet moisture conditions.

Soil Laboratory Analysis

Physical Properties

The particle size distribution of the soil samples was determined using modified sedimentation by a hydrometer (Bouyoucos, 1962). The bulk density (BD) of the soil sample was determined using core sampling methods (Blake and Hartge, 1986). The particle density was determined by the Pycnometer method (Blake and Hartge, 1986). The total porosity was computed from the measurements of soil dry BD and soil particle density (PD) using the formula below.

Total porosity = 1- (BD/PD) x 100

Chemical Properties

Soil pH was measured using a pH meter in suspensions of a 1:2.5 soil-to-water ratio. Electrical conductivity (EC) was measured using a conductivity meter on saturated soil paste extracts (Okalebo *et al*., 2002). Soil organic carbon (SOC) was determined by the wet oxidation method (Walkley, 1934). The total nitrogen (TN) content in the soil samples was determined using the Kjeldahl procedure (Sahlemedhin and Taye, 2000). The available phosphorus (avail. P) in the soil samples was determined by the Olsen method (Olsen, 1954). Cation exchange capacity (CEC) was determined by the ammonium acetate method after extraction with 1 *M* ammonium acetate at pH 7 (Chapman, 1965). A flame photometer was used to determine exchangeable K and Na, and an atomic absorption spectrophotometer (AAS) was used for the determination of exchangeable Ca and Mg (Rowell, 1994). Then, percent base saturation (PBS) was calculated from the sum of exchangeable bases as a percent of the sum of CEC

$$PBS = \frac{\text{Sum of exchangeable bases}}{\text{CEC}} \times 100$$

The exchangeable sodium percentage (ESP) the ratio of exchangeable sodium (Exch. Na) to the cation exchange capacity of the soil (CEC) (Richards, 1954).

$$ESP = \frac{\text{Exchangeable Na}}{\text{CEC}} \times 100$$

The soil calcium carbonate equivalent (CCE) was determined using the trimetric method (FAO, 2020). Soil micronutrients (Fe, Cu, Mn and Zn) were extracted following Diethylene Triamine Penta acetic Acid triethanolamine (DTPA) method as described by Lindsay and Norvell (1978), and their concentrations in the soil digests were measured using AAS. During the analysis, lanthanum was added to prevent condensed phase interference.

Soil Classification

The soils of the studied sites were classified following the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022). The morphological properties in the field description and the physicochemical analysis results of the samples collected from every identified horizon were used for the classifications. The presence or absence of specific diagnostic horizons, properties and materials were detected and used to distinguish Reference Soil Groups (RSGs) according to the classification rules of the above mentioned classification system.

RESULTS AND DISCUSSION

Soil Morphological Properties

The morphological properties of soils; depth, horizon, color, structure, consistency and horizon boundary varied within soil depth at the studied sites. All soil profiles were very deep (>200 cm). The number of genetic horizons per profile was two in Kokate, three in Hawassa and Alage soils. The Kokate site was characterized by Ap-AB-Bt1-Bt2-Bt3 sequence of horizons. The Hawassa site was characterized by A-Bw1-Bw2-Bw3-BC-C, while the Alage site was characterized by Ap-BC-C-2B1-2B2-2C-3B sequence of horizons showing deposition of materials resulting in lithological discontinuity. The surface horizon of the Kokate site was thinner as compared to other profiles. The relatively thin topsoil of Kokate could be attributed to the influence of runoff (Abuye *et al*., 2023; Beyene, 2017; Gebrehanna *et al*., 2022). The soil horizon thickness increased with soil depth indicating the increase in the movement of small-size material in profile within the depth (Beyene, 2017; Seid *et al*., 2018; Yitbarek *et al*., 2016). However, soil depth showed inconsistent trend in the Alage site. The A horizons were formed as a consequence of incorporation of humified organic materials from agricultural crops in the Kokate and Alage sites, while Hawassa site from grass. The B horizons are the result of in situ weathering of the parent material. Variation in soil depth, particle size distribution, structure, and color could also be due to the difference in parent material (Abuye *et al*., 2023; Dengiz *et al*., 2011; Gebrehanna *et al*., 2022).

The study found that the moist colors of the soils varied within and between profiles of different locations, as shown in Table 1. The Kokate site's surface horizon's moist soil color was reddish black (2.5YR 2.5/1), while its subsurface horizons' colors dusky red (10R 3/3). The Hawassa site's surface horizons' soil was very dark brown (10YR2/2), while its subsurface horizons' colors dark brown (10YR 3/3). The Alage site's surface horizon soil was dark brown (7.5YR 3/2), while its subsurface horizons brown (7.5YR 4/4). The color variations between surface and subsurface layers are primarily due to biological processes, particularly those influenced by soil organic matter. In the Kokate, Hawassa, and Alage, the surface horizon had darker color as compared to subsurface horizons which could be due to the relatively higher organic matter contents in the surface horizons (Yacob and Nigussie, 2022; Yitbarek *et al*., 2016). Similarly, the difference in color among the profiles and within a profile can be due to variations in forms of iron oxide, the types of parent material, and OM content (Dinssa and Elias, 2021; Nahusenay, 2014).

The soil of the surface horizon at the Kokate site had a weak, fine to coarse, and granular structure that changing into moderate, medium and sub-angular blocky structure within depth (Table 1). The surface horizon of the Hawassa site had a weak, fine to coarse and granular structure changing into a weak, medium, and sub-angular blocky structure in the subsurface horizon. The structure of the surface horizon at the Alage site was weak, fine, and granular structure changing into weak, very fine and sub-angular blocky within depth. Granular soil structures form with higher organic matter levels on surface horizons, while blocky structures form in subsurface horizons due to overlying layers, reduced organic matter, higher clay content, and reduced plant root abundance. Dinssa and

Table 1. Soil depth, moist soil color, soil structure, consistency and horizon boundary of soils in Kokate, Hawassa and Alage

Depth (cm)	Horizon	Moist Color	Structure Grade/Size/Type	Consistency Dry/Moist/Wet	Horizon Boundary
			Kokate profile		
0-21	Ap	2.5YR2.5/1	WE, FC, GR	HA, FR, S/P	D, S
21-45	AB	2.5YR2.5/2	MO, ME, AB	SHA, FI, S/P	G, S
45-85	Bt1	10R3/3	MO, ME, SAB	SHA, FI, VSVP	G, S
85-150	Bt2	10R3/3	WE, ME, SAB	SHA, FR, VSVP	G, S
150-200$^+$	Bt3	10R3/4	WE, F, SAB	SHA, FR, VSVP	
			Hawassa profile		
0-27	A	10YR2/2	WE, FC, GR	SHA, FR, S/P	D, S
27-50	Bw1	10YR3/3	WE, ME, SAB	HA, VFR, S/P	G, S
50-90	Bw2	10YR3/3	WE, ME, SAB	HA, FI, S/P	G, S
90-110	Bw3	10YR4/2	WE, ME, SAB	SHA, FR, S/P	C, S
110-150	BC	10YR6/2	WE, ME, SAB	HA, FI, SS/SP	G, S
150-200+	C	10YR6/2	WE, ME, SG	HA, FI, NS/NP	
			Alage profile		
0-35	Ap	7.5YR3/2	WE, F, GR	SHA, FR, S/P	C, S
35-70	BC	7.5YR3/4	WE, FC, SAB	HA, VFI, SS/PP	A, W
70-80	C	7.5YR6/3	ST, ME, SG	HA, VFI, NS/NP	A, W
80-105	2B1	7.5YR4/4	WE, F, SAB	SHA, FR, SP	C, S
105-130	2B2	7.5YR4/6	WE, F, SAB	SHA, FR, SP	A, S
130-160	2C	7.5YR6/4	ST, ME, SG	HA, VFI, NS/NP	A, S
160-200+	3B	7.5YR4/4	WE, VF, SAB	SHA,VFR, SP/SP	

* WE = Weak; MO = Moderate; ST = Strong; FC = Fine to coarse; ME = Medium; F = Fine; VF = Very fine; GR = Granular; AB = Angular blocky; SAB = Sub angular blocky; SG = single grain; SHA = Slightly hard; HA = Hard; FR = Friable; FI = Firm; VFR = Very friable; VFI = Very firm; NS/NP = non-stick, non-plastic; SS/SP = Slightly sticky and slightly plastic; S/P= Sticky and plastic; VSVP = Very sticky and very plastic; G, S = Gradual and smooth; D, S = diffuse and smooth; C, S = Clear and smooth; A, W = Abrupt and wave; A, S = Abrupt and smooth

Elias (2021) and Yitbarek *et al*. (2016) found that the granular soil structure in upper horizons changed into angular and sub-angular structures in the subsurface profile. Soil organic matter and particle size distribution have the greatest influence on aggregate dynamics (Tobiasova *et al*., 2013). A better structural development down the profiles except the ‘C’ horizon was due to the relatively higher clay content of the subsurface horizons than their respective surface horizons (Gebrehanna *et al*., 2022; Kiflu and Beyene, 2013; Yacob and Nigussie, 2022). Organic matter and microbial exudates serve to form and temporally stabilize the granular aggregates (Buol *et al.,* 2011), although physical disruption of surface horizons reduces the microbial activity and aggregate stability as the stabilizing organic compounds are decomposed.

The dry consistency of the surface horizons of Kokate, Hawassa, and Alage was slightly hard to hard. The soils in all studied sites had both moist and wet consistencies, which varied within and between profiles. The three profiles studied showed a friable, moist consistency across most surface and subsurface layers, making them suitable for soil work. Ali *et al*. (2010) and Ayalew *et al*. (2015) also reported that the friable consistency of the soils indicates workability of the soils at appropriate moisture content. The wet consistency is also in the range of non-sticky/non-plastic in the Alage soil profile to very sticky/very plastic in the Kokate soil profile (Table 1). The subsurface layers exhibit sticky, very sticky, and plastic, very plastic consistency due to decreased organic matter content, increased clay particles, and difficulty in working with soils. Beyene (2017) and Dinssa and Elias (2021) reported similar results in that the sticky and plastic consistency indicates the existence of high clay content and difficulty in working. The increase in clay content with depth may explain the change in the consistency of the soil at different moisture levels. The variations in moist and wet consistencies are most likely explained by differences in OM and clay fraction (Gebrehanna *et al*., 2022; Moradi, 2013; Yacob and Nigussie, 2022). The friable, non to slightly sticky, and non-to-slightly plastic consistencies could be attributed to the low clay contents of the soils (Beyene, 2017; Yacob and Nigussie, 2022). In contrast, the sticky, very sticky, plastic, and very plastic consistencies show the presence of high clay and low OC contents and difficulty to till (Yacob and Nigussie, 2022). The very sticky and very plastic consistency could be attributed to the presence of smectitic clays in the soils (Ali *et al*., 2010; Ayalew *et al*., 2015). The friable consistency observed in the surface horizons of the profiles (Table 1) could be attributed to the higher organic matter contents, which reduces the stickiness of clay soils (Ayalew *et al*., 2015; Demiss and Beyene, 2010; Fekadu *et al*., 2018).

The distinctness of horizon boundary between surface and subsurface horizons was diffuse smooth boundary (D, S) in Kokate, and in Hawassa and clear smooth boundary (C, S) in Alage profiles, while gradual smooth boundary (G, S) in Kokate, and in Hawassa and abrupt smooth boundary (A, S) in Alage were observed subsurface profiles (Table 1). Variation of the boundaries might be due to anthropogenic interferences in addition to the natural phenomena. A biological activity was relatively higher in the surface horizons and decreased with increasing soil depth might be due to the abundance of roots and having favorable soil conditions (Abuye *et al*., 2023).

Physical Properties of the Soil Profiles

The study revealed that the distribution of soil particle size in the soil horizons of the profile varied with soil depth (Table 2). At the Kokate site, the surface soil particle size fractions of clay, silt, and sand were 46, 28, and 26%, respectively. The surface soil was clayey in texture, and it was similar throughout the profile. The clay, silt, and sand fractions of the surface soil at Hawassa site were 24, 33, and 43%, respectively, and the surface soil texture was loam, but it changed with depth to clay loam. Whereas the surface soil particle fractions at the Alage site were 36% clay, 46% silt, and 18% sand, and the surface soil texture was silt clay loam, but the profile showed textural variation with depth (Hazelton and Murphy, 2016). In the Kokate site, the clay content of the soil increases with depth. It revealed most subsoil horizons are argic (Bt), which were formed by the illuviation of clay minerals from the upper horizons. Thus, the accumulation of clay in the subsoil horizons of the profiles could have been due to the main in situ synthesis of clay from the weathering of primary minerals in B-horizons. This finding was in line with Abuye *et al*. (2023) and Ghonamey *et al*. (2020), who state that clay minerals might be present as a result of inheritance from the parent material through weathering, degradation of primary minerals, and addition. Other studies have also shown that the clay content of their study soils increased with depth (Dinssa and Elias, 2021; Yacob and Nigussie, 2021).

The silt/clay ratio of the profiles' surface and subsurface soils varied within depths of 0.61 to 0.26 (Kokate), 1.38 to 1.14 (Hawassa) and 1.28 to 3.00 (Alage) (Table 2). There was no clear pattern of decreasing or increasing the silt/clay ratio in all soil profiles within depth. Ahukaemere *et al*. (2017) found that soils with a silt/clay ratio < 0.15 are weathered, but soils with a silt/clay ratio > 0.15 are younger and have a higher weathering potential of all studied soils. In the soil horizons of Kokate, Hawassa, and Alage sites, the BD values ranged from 1.23 to 1.33, 1.10 to 1.44, and 1.20 to 1.70 gcm^{-3}, respectively (Table 2). The BD values of the surface horizon are 1.23 in Kokate, 1.10 in Hawassa and 1.20 gcm^{-3} in the Alage sites, respectively. The study found that cultivated land in Kokate and Alage sites had higher surface horizon bulk density, possibly due to compaction, while in fallow land in Hawassa site low bulk density was recorded; it increased with soil depth, which is in agreement with other studies (Adhanom and Toshome, 2016; Mohamed *et al*., 2021). Surface horizons have low BD due to higher SOC content and abundant root systems, while subsurface horizons have high BD due to decreasing SOC content, few roots, and soil depth (Adhanom and Toshome, 2016; Yacob and Nigussie, 2021). The total porosity in Kokate ranged from 54 to 50%; in Hawassa, it ranged from 59 to 46%; and in Alage, it ranged from 55 to 36% (Table 2**)**. The total pore space in the surface layer ranged from 54 to 59. The values were within the range (36 to 59%) and showed a decreasing trend with soil depth, except Alage soils showed an inconsistence trend. This could be related to the distribution of organic matter content and natural compaction of the subsurface soils by the load of surface soils (Gebrehanna *et al*., 2022). As the soil OM contents decreased, the soils would be less aggregated, and the bulk density would be increased.

Chemical Properties of the Soil Profiles

The soil pH in Kokate, Hawassa, and Alage ranged from 4.6 to 5.0, 6.8 to 7.1, and 7.9 to 9.4, respectively. For Kokate, Hawassa, and Alage profiles, the surface soil pH values were 4.6, 6.8, and 7.9, respectively. Following Hazelton and Murphy (2016), the surface soil was very strongly acidic in Kokate, neutral in Hawassa, and moderately alkaline in Alage (Table 3). The soil pH (H_2O) revealed a slightly increasing trend within depth. Significant amounts of fertile topsoil are lost due to water erosion. The low pH of the surface and subsurface soil of Kokate could be attributed to the removal of base cations because of the high rainfall and humid climate of the study area (Abuye *et al*., 2023; Mohammed *et al*., 2017; Mohamed *et al*., 2021). According to Beyene *et al.* (2023), soil acidity, which is either severely or moderately acidic, affects broad

Table 2. Soil particle size, textural class, Si/C, BD and TP of soils in Kokate, Hawassa and Alage.

Depth (cm)	Horizon	Particle size (%)			Textural class	Si/C	BD (g cm^{-3})	TP(%)
		Clay	Silt	Sand				
				Kokate profile				
0-21	Ap	46	28	26	C	0.61	1.23	54
21-45	AB	48	32	20	C	0.67	1.25	53
45-85	Bt1	68	18	14	C	0.26	1.27	52
85-150	Bt2	78	16	6	C	0.21	1.30	51
$150\text{-}200^{+}$	Bt3	78	15	7	C	0.19	1.33	50
				Hawassa profile				
0-27	A	24	33	43	L	1.38	1.10	59
27-50	Bw1	28	32	40	CL	1.14	1.25	53
50-90	Bw2	29	36	35	CL	1.24	1.27	52
90-110	Bw3	36	30	34	CL	0.83	1.34	49
110-150	BC	27	37	36	CL	1.37	1.36	49
$150\text{-}200^{+}$	C	26	32	42	L	1.23	1.44	46
				Alage profile				
0-35	Ap	36	46	18	SiCL	1.28	1.20	55
35-70	BC	22	62	16	SiL	2.82	1.35	49
70-80	C	6	16	78	LS	2.67	1.48	44
80-105	2B1	16	48	36	L	3.00	1.22	54
105-130	2B2	20	64	16	SiL	3.20	1.22	54
130-160	2C	12	22	66	SL	1.83	1.70	36
$160\text{-}200^{+}$	3B	26	64	10	SiL	2.46	1.27	52

Where: C = clay; L= loam; CL= clay loam; SiCL = silt clay loam; SiL= silt loam; LS = loam sand; SL= sandy loam; Si/C = silt clay ratio; BD = bulk density; TP = total porosity

regions of the highlands, and salinity and/or sodicity affects around 10% of the total land area. EC determination is often sufficient for diagnosing, surveying, and monitoring soil salinity and for assessing the adequacy of leaching and drainage (FAO, 2021). The electrical conductivity in the study area was very low in Kokate, low in Hawassa, and high in Alage soils; its surface value varied between 0.08 (Kokate) and 1.20 dS/m (Alage), which means that the soils are not affected by salinity (FAO, 1988). The very low electrical conductivity could be due to higher rainfall levels in the Kokate site and allowable drainage situations favoring leaching of drained bases with infiltrating water.

The surface SOC contents were 1.65, 2.58, and 2.15% for Kokate, Hawassa, and Alage, respectively, and were rated as medium by Tadesse *et al*. (1991). Similarly, the TN contents of the surface layer at Kokate, Hawassa, and Alage were 0.14, 0.23, and 0.20%, respectively. In our study, SOC and TN were higher in surface soils and decreased with depth. The higher SOC content in the surface soil layer than in the subsurface layer was attributed to organic matter input from plants in the surface layer (Ayalew *et al*., 2015; Dinssa and Elias, 2021; Mohammed *et al*., 2017). In addition, the high turnover of fine roots and biological activities in the surface layers could contribute to the relatively high SOC in the surface layers (Ayalew *et al*., 2015; Yacob and Nigussie, 2021). Hawassa site's higher surface SOC and TN may be due to insufficient organic material application and total biomass removal from Kokate and Alage cultivated soils (Beyene *et al*., 2023). The TN in the soils of Kokate and Alage was rated as low, whereas the TN in the soils of Hawassa was rated as medium (Landon, 2014). Of the three study sites, the highest TN was recorded on the surface horizon of the Hawassa soil. The amounts of SOC and TN decreased consistently with depth at all sites, which is in line with the results of many previous studies (Ayalew *et al*., 2015; Demiss and Beyene, 2010; Kiflu *et al*., 2016). Therefore, organic matter input integrated with mineral fertilizers could improve the SOC and TN status of soils. The C: N ratio shows the quality of organic matter in relation to nitrogen content (Hazelton and Murphy, 2016; Landon, 2014; Msanya *et al*., 2001). Soil OC is an important parameter that shows the effect of the mineralization of applied crop residues on soil nitrogen levels (Hazelton and Murphy, 2016). Consistent with assessments recommended by Abuye *et al.* (2021), soil organic carbon is below low levels. The C: N ratio of surface soil ranged from 10.8 in Alage to 11.8 in Kokate, reflecting good-quality organic matter (C: N ratio 8–13) (Msanya *et al*., 2001). According to some workers (Zhang *et al*., 2020), the

C: N ratio might not be a good parameter to evaluate soil fertility, and therefore it is suggested in this regard to use the N and C values separately for more useful interpretation. Generally, most of the values were found between 8.9: 1 and 12.3: 1, showing an optimal range of mineralization.

The avail P contents of Kokate, Hawassa, and Alage ranged from 1.3 to 3.4, 1.4 to 6.5, and 1.3 to 6.0 mg kg^{-1}, respectively (Table 3). For Kokate, Hawassa, and Alage, the surface avail P levels were 3.4, 6.5, and 6.0 mg kg^{-1}, respectively. The avail P content of the soils in all the sites (Table 3) was very low, despite the difference in soil properties (Olsen, 1954). Kokate soil with high clay content and low pH promotes P fixation (Mohammed *et al*., 2017), with high avail P compared to other sites in neutral soil pH, where P fixation is low (Ayalew *et al*., 2015; Yitbarek et al., 2016). In addition, P availability is limited because of $CaCO_3$ and the high pH of the Alage soil, which favors phosphate precipitation (Brindhavani *et al*., 2022). Low P applications as organic and inorganic fertilizers may also contribute to the low avail P content in all three sites. Moreover, the avail P showed a decreasing trend with increasing depth in all profiles because of the decreasing SOC level and fixation by clay minerals. This observation is in agreement with other studies (Ayalew *et al*., 2015; Kiflu *et al*., 2016; Yacob and Nigussie, 2021). The low level of avail P observed in the soils indicated that P availability limits crop productivity. This study is comparable with the findings of Adhanom and Toshome (2016); Melese *et al*. (2015), and Mesfin *et al*. (2017) that state P is deficient in Ethiopian soils. Therefore, external P supply, as integrated soil fertility management, is required to restore the P status of soils. According to FAO (2006), the $CaCO_3$ contents of soils in Kokate and Hawassa were low (<2%), while in Alage soil, it ranges from medium to high (Table 3).

The CEC in the three profiles varied from 25.7 to 33.6 in Kokate, 17.2 to 31.6 in Hawassa, and 15.5 to 29.5 cmol (+) kg^{-1} in Alage (Table 4). The soils' cation exchange capacity (CEC) was found to be medium to high, ranging between 15.5 and 33.6 cmol kg^{-1} (Landon, 2014). The surface CEC of the soils at the three sites was 25.7 in Kokate, 28.0 in Hawassa, and 27.0 cmol (+) kg^{-1} in Alage, which could be categorized as high (Landon, 2014). The high amount of CEC in the soils of the study area may be due to the presence of active clay mineralogy. The content of exchangeable cations and CEC increased with increasing soil depth, which could be attributed to their leaching from the surface horizon down to the sub-surface, and the high clay content increased downward, respectively (Debele *et al*., 2018; Dessalegn *et al*., 2014; Yacob and Nigussie, 2021) (Table 4).

Table 3. Soil pH, EC, SOC, TN, Avail. P and $CaCo_3$ of soils in Kokate, Hawassa and Alage.

Depth (cm)	Horizon	pH (H_2O)	EC (dSm^{-1})	SOC (%)	TN (%)	C: N ratio	Avail. P ($mg\ kg^{-1}$)	$CaCO_3$ (%)
Kokate profile								
0-21	Ap	4.6	0.08	1.65	0.14	11.8	3.4	0.35
21-45	AB	4.8	0.09	1.20	0.13	9.2	2.9	0.49
45-85	Bt1	5.0	0.09	1.30	0.11	11.8	1.9	0.61
85-150	Bt2	4.9	0.08	1.20	0.12	10.0	1.6	0.86
150-200$^+$	Bt3	4.9	0.07	0.80	0.09	8.9	1.3	1.20
Hawassa profile								
0-27	A	6.8	0.21	2.58	0.23	11.2	6.5	0.51
27-50	Bw1	6.8	0.24	2.00	0.19	10.5	4.2	0.67
50-90	Bw2	6.9	0.24	1.60	0.13	12.3	2.9	0.83
90-110	Bw3	7.1	0.28	1.20	0.11	10.9	3.0	0.95
110-150	BC	6.7	0.24	1.20	0.10	12.0	1.6	1.30
150-200$^+$	C	6.4	0.20	1.10	0.09	12.2	1.4	1.99
Alage profile								
0-35	Ap	7.9	1.2	2.15	0.20	10.8	6.0	9.5
35-70	BC	8.2	1.2	1.40	0.12	11.7	3.0	15.5
70-80	C	8.5	1.1	0.60	0.05	12.0	1.5	21.5
80-105	2B1	9.4	1.7	1.20	0.11	10.9	2.7	17.4
105-130	2B2	9.4	1.7	1.20	0.10	12.0	3.6	8.9
130-160	2C	9.4	1.2	0.98	0.08	12.3	2.9	23.6
160-200$^+$	3B	9.4	1.7	0.98	0.09	10.9	1.3	12.5

Where: EC = electrical conductivity; SOC= soil organic carbon; TN= total nitrogen; C: N = carbon nitrogen ratio; Avail. P = available phosphorus; $CaCO_3$ = calcium carbonate.

Table 4. Cation exchange capacity, exchangeable cations, Ca: Mg, PBS, ESP and available micronutrients of soils in Kokate, Hawassa and Alage.

Depth (cm)	Horizon	CEC	Ca	Mg	Na	K	Sum	Ca: Mg	PBS	ESP	Fe	Mn	Zn	Cu
				(cmol(+)kg^{-1} of soils				ratio	%			mg kg^{-1}		
						Kokate profile								
0-21	Ap	25.7	6.5	3.0	0.38	0.4	10.3	2.2	40	1.5	22.3	16.9	2.30	0.29
21-45	AB	25.9	6.7	3.3	0.39	0.4	10.8	2.0	42	1.5	18.6	15.0	1.20	0.31
45-85	Bt1	31.9	8.9	5.1	0.54	1.5	16.0	1.7	51	1.7	13.1	11.7	1.70	0.15
85-150	Bt2	32.5	10.1	5.0	0.62	1.1	16.8	2.0	52	1.9	12.2	11.3	1.40	0.12
150-200$^+$	Bt3	33.6	11.5	5.3	0.63	2.1	19.5	2.2	58	1.9	12.1	11.3	1.20	0.17
						Hawassa profile								
0-27	A	28.0	8.5	3.8	0.70	1.5	14.5	2.2	52	2.5	2.5	2.3	0.39	0.49
27-50	Bw1	26.8	8.7	3.9	0.90	1.3	14.8	2.2	55	3.4	3.1	0.5	0.19	0.35
50-90	Bw2	31.6	10.3	5.4	1.20	3.5	20.4	1.9	65	3.8	2.4	0.8	0.10	0.13
90-110	Bw3	30.6	12.7	5.7	1.50	2.3	22.2	2.2	73	4.9	2.3	1.2	0.11	0.40
110-150	BC	25.6	9.2	4.4	1.10	1.9	16.6	2.1	65	4.3	1.1	1.3	0.05	0.41
150-200$^+$	C	17.2	4.3	2.8	1.10	1.3	9.5	1.5	55	6.4	1.9	1.1	0.06	0.42
						Alage profile								
0-35	Ap	27.0	12.9	5.3	0.90	1.9	21.0	2.4	78	3.3	1.2	1.0	0.21	0.15
35-70	BC	25.6	11.0	4.7	2.60	1.8	20.1	2.3	79	10.2	0.7	0.8	0.13	0.12
70-80	C	15.6	4.7	2.2	5.70	1.1	13.7	2.1	88	36.5	0.9	0.9	0.13	0.12
80-105	2B1	28.6	11.7	3.9	5.90	1.8	23.3	3.0	81	20.6	0.4	0.4	0.10	0.22
105-130	2B2	29.5	9.2	2.4	5.40	2.5	19.5	3.8	66	18.2	2.4	1.3	0.21	0.10
130-160	2C	15.5	5.4	1.2	3.70	1.6	11.9	4.5	77	23.9	0.7	0.9	0.11	0.06
160-200$^+$	3B	20.6	3.5	1.9	3.70	1.7	10.8	1.8	52	18.0	1.3	1.1	0.23	0.20

Where: CEC = Cation exchange capacity; Ca = Calcium; Mg = Magnesium; Na = sodium; K = potassium; Ca: Mg = Calcium magnesium ratio; PBS = Percent base saturation; ESP = Exchangeable sodium percentage; Fe = Iron; Mn = manganese; Zn = Zinc and Cu = Cupper

The exchangeable bases values in Kokate, Hawassa, and Alage are listed in Table 4. The study found that exchangeable Ca, Mg, Na, and K contents varied from 3.5 to 12.9, 1.2 to 5.7, 0.38 to 5.90, and 0.4 to 3.5 cmol kg^{-1}, respectively. The highest Ca^{2+} content (12.9 cmol (+) kg^{-1}) was found in the surface horizon of Alage soil, while the lowest (6.5 cmol (+) kg^{-1}) was found in Kokate soil. This highest concentration of Ca^{2+} indicates the degree of weathering (less intensive), and the pH (H2O) value of 5–9 was the more optimum pH range for the availability of Ca^{2+} (Hazelton and Murphy, 2016). Exchangeable Mg in the topsoil ranged from 3.0 in Kokate to 5.3 cmol (+) kg^{-1} in Alage. According to the FAO (2006) assessment, both exchangeable Ca^{2+} and Mg^{2+} were found in medium to high ranges. The surface soil of exchangeable Na is between 0.38 in Kokate and 0.90 cmol (+) kg^{-1} in Alage, and K is between 0.4 in Kokate and 1.9 cmol (+) kg^{-1} in Alage. According to the FAO (2006) assessment, both exchangeable K^+ and Na^+ were rated as medium to very high. With the exception of the Alage profile, the exchangeable bases of the soils in the studied profiles were dominated by Ca, followed by Mg, K, and Na, making them ideal for plant growth, and deviations from this order can create ion-imbalance problems for plants (Bohn, 1986) (Table 4). The high presence of calcium at all study sites compared to other cations could be due to the nature of the starting material. The Na content in all profiles, except for the Alage profile, was found to be low, indicating no sodicity problem.

The Ca: Mg ratio of surface to subsurface horizons varies from 2.2:1 to 1.7:1 in Kokate; it varies from 2.2:1 to 1.9:1 in Hawassa and 2.4:1 to 3.0:1 in Alage profiles. The surface Ca: Mg ratio of horizon is 2.2:1 in Kokate, 2.2:1 in Hawassa, and 2.4:1 in Alage soil profiles, which is below the 4:1 Ca: Mg value for most crop production. As rated by Hazelton and Murphy (2016), the Ca: Mg ratio below 4:1 resulted in low availability of Ca, which shows the probable shortage of Ca uptake because of a surplus amount of Mg or leaching out of basic cations by the high amount of rainfall. The approximate optimum range of Ca: Mg ratio for most crops is between 3:1 and 4:1 (Landon, 2014). If it is less than 3:1, P uptake may be inhibited. Across the soil depth, the Ca: Mg ratio was irregularly distributed for all three profiles. The study found inconsistent percent base saturation across soil depths, with surface soil horizons of 40% in Kokate, 52% in Hawassa, and 78% in Alage (Table 4). As rated by Hazelton and Murphy (2016), PBS in surface horizons ranged from moderate (40, 52% in Kokate and Hawassa) to high (78% in Alage), indicating Alage soils poor leaching, while Kokate and Hawassa soils moderately leaching and potential for leaching due to high rainfall. Consequently, soils in the Alage area could be categorized as fertile soil in line with the assessment of Landon (2014), who suggested soils with more than 60% base saturation as fertile. The variation observed in PBS indicates the degree of leaching, which was used as a diagnostic character for classifying soils (Meena, 2014).

Soil sodicity measures the amount of exchangeable sodium in the soil, which can cause problems like low infiltration, dense subsoils, and clay dispersion (Hazelton and Murphy, 2016; Msanya *et al*., 2001). Kokate and Hawassa profiles have non-sodic soil suitable for crop production, while the Alage profile has a range of 3.3 to 36.5, indicating it can be used without reducing crop yield, especially in the upper 35 cm of the profile (Table 4).

The levels of micronutrients varied across all studied profiles in surface soil samples. The site and depth of the soil influenced the amount of avail micronutrients (Table 4). In the surface layer, micronutrients were categorized as low or insufficient at Hawassa and Alage, while they were categorized as high or sufficient at Kokate (Jones, 2003). This could be because of the effect of soil pH on micronutrient availability (Ayalew, 2016). The micronutrient content in all studied profiles varied with soil depth (Mohamed *et al*., 2021). Fertilizer response is unlikely for values greater than 10.0, 3.0, 1.5, and 1.0 for Fe, Mn, Zn, and Cu, respectively (Hartz, 2007). The study found that, with the exception of Cu, soils in the Kokate site are not deficient in Fe, Mn, and Zn, whereas lower values in the Hawassa and Alage sites indicate the need for micronutrient-containing fertilizer (Ali *et al*., 2010).

Classification of the Soils

The studied soils were classified according to World Reference Base Legend (IUSS Working Group, 2022). The morphological, physical, and chemical characteristics of the soils were used for classification purposes. The Kokate surface soil profile had 21 cm thick, having color values and chroma of less than 3 when moist, dark moist coloured, moderate, fine, and granular structure, friable consistency, low base saturation, and containing more than 0.6 percent organic carbon, fulfilling all the requirements of an umbric epipedon in the surface horizon. The loam sand, or finer and greater than 8% clay, is an indication of clay illuviation but doesn’t form part of the natric horizon. Furthermore, the subsurface horizon of this profile contained more clay compared to the overlying soil horizon, which started at less than 100 cm soil depth fulfilling the criteria of the argic horizon. The soils in the argic horizon had CEC greater than 24 cmol (+) kg^{-1}, BS of greater than 50% at certain depth, and high-activity clay throughout the argic horizon and hence could be classified as Luvisols. The soils also exhibited vertic properties, qualifying vertic prefix qualifiers. The soils contained more than 1 percent organic carbon in the fine earth fraction to a depth of 50 cm from the mineral soil surface and hence considered as humic suffix qualifiers. Moreover, the soils had a clay textural class that was dominant throughout the profile and thus qualified as clayic supplemental qualifier. Accordingly, the soils of the Kokate site were classified as Vertic Luvisols (Pantoclayic, Aric, Cutanic, Differentic and Humic).

The surface soil of the Hawassa soil profile had 27 cm thick, well- structured, very dark moist colored, high base saturation, high biological activity, and moderate organic matter content, indicating mollic diagnostic surface horizon. The granular and sub-angular blocky structures were dominant at the surface and subsurface horizons, respectively. The subsurface horizon was greater than 15 cm in thickness with clay loam texture. The soils in the subsurface horizon showed evidence of pedogenetic alteration in the overlying horizon, then fulfilling the criteria of the cambic horizon, and hence could be classified as Cambisols. Moreover, the soils did not have principal qualifiers, contained more than 1 percent OC throughout the soil profile, a textural class of clay loam in a layer ≥ 30 cm thick within ≤ 100 cm of the mineral soil surface, and humic and loamic supplementary qualifiers. Therefore, the soils in the Hawassa area were classified as Haplic Cambisols (Pantoloamic and Humic).

The surface soil of the Alage soil profile had 35 cm thick, dark-coloured, high base saturation, and moderate content of organic matter. The soils in the surface horizons of the Alage profile fulfill all the requirements of the mollic epipedon, whereas the subsurface diagnostic horizon is formed from fluvic material. The fluvic material of the river deposit and the horizon was with obvious stratification and weak sub-angular blocky structure and contained more than 1 percent OC throughout the soil profile. The soils of Alage area contained substantial accumulations of lime at certain depths. Therefore, the profile had Calcaric and Panofluvic principal qualifier and had different textural class and aric supplementary qualifiers. Consequently, the soil of Alage was classified as Calcaric Panofluvic Fluvisols (Endoarenic, Katoloamic, Katosiltic, Aric, Humic).

CONCLUSIONS

Field work and laboratory analysis were carried out to characterize and classify soils in the Kokate, Hawassa, and Alage areas of southern Ethiopia. Three representative profiles from the three sites were opened and described the study area. The soil horizons in the profiles showed differences in soil properties due to differences in soil formation. The Kokate soil had a very strongly acidic pH, low levels of available P, SOC, and high micronutrients. The Hawassa soil had neutral soil pH, low SOC, available P, and micronutrient contents. Whereas the Alage soil had alkaline soil pH, high Na content, low SOC, available P, and micronutrient contents in the soil profile. Based on the WRB soil classification system, the surface horizons of the Kokate, Hawassa, and Alage profiles qualify for umbric, mollic, and mollic epipedon, respectively. The subsurface diagnostic horizons of the Kokate, Hawassa, and Alage profiles were identified as argic and cambic horizons and fluvic material, respectively. Consequently, the soils of Kokate, Hawassa, and Alage were classified as Luvisols, Cambisols, and Fluvisols, respectively. The results of the study revealed variation in morphological, physical, and chemical properties of the soils within and across the study area, which indicate their variation in productive potential and management requirements for specific agricultural use. Thus, the varying properties, fertility status, and types of soils identified in the study areas constitute basic information useful to design site- specific integrated soil fertility management.

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