Hindawi
Applied and Environmental Soil Science
Volume 2023, Article ID 3946508, 18 pages
https://doi.org/10.1155/2023/3946508

Research Article

Assessment and Characterization of Agricultural Salt-Affected Soils around Abaya and Chamo Lakes, South Ethiopia Rift Valley

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Received 25 May 2023; Revised 27 August 2023; Accepted 1 September 2023; Published 12 September 2023

Academic Editor: Claudio Cocozza

Soil salinity/sodicity is becoming a challenge for crop production in Ethiopia's semi-arid and arid regions. However, more information on soil salinity/sodicity needs to be available around Abaya and Chamo Lakes, South Ethiopia Rift Valley. This study aimed to assess and characterize soil salinity/sodicity and determine salt-affected soils' morphological, physical, and chemical properties. The representative soil pits that were 60 ∗ 60 ∗ 60 cm in size were examined, and samples were taken from 0–20, 20–40, and 40–60 cm depths based on the criteria set for agricultural salt-affected soil studies. The soil properties determined include soil color, structure, consistency, bulk density, particle density, porosity, texture, pH, EC, SAR, ESP, CEC, BS, OC, TN, available P, $CaCO_3^-$, exchangeable bases, and soluble ions (Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{-2}, NO_3^-, CO_3^{-2}, and HCO_3^-. The soil-analyzed results were rated and interpreted following a guide to standardized analysis methods for soil data. The results of this study reveal that the soils had considerable heterogeneity in soil morphological, physical, and chemical properties. The soils of the study site were highly alkaline and had very high sodium content, very high CEC value, and low levels of organic carbon and exchangeable calcium. The dominant soluble cation was sodium, followed by magnesium, calcium, and potassium in all soil depths of the pits. Similarly, Cl^- was dominant among the anions throughout the soil depth, followed by HCO_3^-, SO_4^{2-}, and NO_3^-. The findings of this study imply that removing sodium and salts from the soil depth may improve the salt-affected soils' productivity in the study area. Application of organic amendments, including manures and crop residues, may also be beneficial in increasing fertility and organic matter content.

1. Introduction

Soil degradation is a major global problem in nearly all developing countries where large proportions of the population get their livelihoods directly from the soil [1]. After soil erosion, soil salinity is the second-largest factor in land degradation, and it has been linked to the downfall of agricultural communities for 10,000 years [2]. Salt-affected soils are distributed worldwide, and no continent is free from this problem under almost all climatic conditions [3, 4]. However, their distribution is relatively more extensive in the arid and semi-arid regions than in the humid regions. Especially in arid and semi-arid regions, salt-affected soils often occur on irrigated lands, where annual rainfall is insufficient to meet plants' evaporation needs and salts' leaching [4].

The sources of salts append saline parent materials, extreme weathering of rocks and primary minerals, fossil salts of retired marine and lacustrine deposits, atmospheric deposition, a troupe of saline sediments in catchment areas, irrigation waters, and fertilization [5]. Irrigation water or fertilization may also introduce salts into the arable lands [4]. A large land area is becoming unproductive yearly because of salinity and sodicity. Soil salinization is a growing issue whenever irrigation is used as a result of the reliance on rain-fed agriculture, especially in arid and semi-arid regions. Soil degradation due to salinity and sodicity is increasing at an alarming rate, endangering the environment, agricultural ecosystems, and human life [6]. About 10–20% yield loss can be caused by salinity for many crops, which may prevent cropping altogether when severe and lead to desertification [2].

Globally, a total land area of 1 billion hectares is salt-affected [7], and nearly, 2000 ha of agricultural land is lost to production every day because of salinization [2]. Different African nations are affected by salt to varying degrees, including Kenya (8.2 million hectares), Nigeria (5.6 million hectares), Sudan (4.8 million hectares), Tunisia (1.8 million hectares), Tanzania (1.7 million hectares), and Ghana (0.79 million hectares) [8]. In Ethiopia, it was reported that there are over 11 million hectares of unproductive, naturally salt-affected wastelands, ranking first in Africa [9]. With this, 44 million ha are prominently susceptible to salinity problems [10]. In the country, the natural salt-affected areas are found in the arid and semi-arid lowlands and in Rift Valley areas, which have higher evapotranspiration rates when compared to precipitation [11]. The Rift Valley, the Denakil Plains, the Wabi Shebelle River Basin, and lowland irrigated regions of Ethiopia all have these salt-affected zones [5]. The development of large-scale irrigation projects and the lack of proper drainage systems in the Rift Valley are increasing because of export crop production. Due to this, salinity has resulted in the increasing severity and rapid expansion of soil salinity and sodicity problems, consequently leading to a loss of land for crop cultivation in these areas [12].

When plants grow under saline conditions, they are subjected to three types of stress: water stress caused by the osmotic pressure, mineral toxicity stress caused by the salt, and disturbances in the balance of minerals [13]. Salinity becomes problematic when enough salts accumulate in the root zone to negatively affect plant growth. In the root zone from the surrounding soil excess salts hinder plant roots from withdrawing water. In this regard lowers the amount of water available to the plant [14]. This problem harms soil fertility, reducing soil productivity [11]. In addition, issues with water infiltration, air movement, root penetration, and seedling emergence are caused by the changing of soil physical qualities brought on by the swelling and dispersion of colloidal soil particles brought on by an excess of exchangeable Na [15].

Finding solutions to these problems requires identifying the currently geo-referenced soil fertility status [16] and irrigation water management systems [17] and the chemical and physical nature of the soil that induces the problem of salt-affected soils [18]. Due to the need for more quality irrigation water to satisfy the water requirements of all crops grown in these arid and semi-arid regions, farmers are forced to use all irrigation water sources of any quality. This practice often led to the gradual development of salt-affected soils. Hence, knowledge of the kinds and properties of soils and irrigation water quality is critical for decision-making concerning soil management and crop production [19, 20]. Land degradation due to poor land management practices continues without any reduction. Farmers' output and productivity are thus falling. This fall in production and productivity endangers the food and nutrition security of the community [21]. In some respects, addressing sodicity/salinity-induced soil degradation constantly improved soil, water, and crop management practices is essential for achieving food security and avoiding desertification [2]. Furthermore, the prevailing land use system and management interventions must be held up by information showing the potential and constraints of soil resources [21]. Generally, in Ethiopia, few studies have been carried out on assessing and characterizing agricultural salt-affected soil properties, particularly around Abaya and Chamo Lakes in the South Ethiopia Rift Valley; the study still needs to be carried out. The assessment and characterization study of agricultural salt-affected soil assesses soil condition, identifies problems, and determines the best reclamation method for a site. This information helps monitor the success of reclamation efforts and adjust the plan as needed. Reclaiming salt-affected soil can improve productivity and food security and reduce water use in Ethiopia. It also enhances soil health, increasing crop yields by 50% [17] and reducing pest and disease problems. Knowledge gaps exist in the study area to manage the potential agricultural soils. This study will investigate to fill the knowledge and give direction on managing agricultural soils since the area is prone to soil sodicity/salinity. Since the nature and characteristics of these soils vary, they also require unique approaches to reclamation and management in order to maintain production. Therefore, this study was initiated to assess and characterize the extent, nature, and distribution of agricultural salt-affected soils among the soil depths in the South Ethiopia Rift Valley.

2. Materials and Methods

2.1. Descriptions of the Study Area

2.1.1. Location and Climate of the Study Area. A sub-basin of the South Ethiopia Rift Valley that cuts through Ethiopia in a north-south orientation in the middle is the Abaya-Chamo drainage basin. The basin comprises mainly the two lower-lying lakes, Abaya and Chamo Lakes [22]. The latitude of the study area falls between $5°50'00''$N and $6010'0''$N, and the longitude of the study area falls between $37°26'0''$E and $37°40'0''$E. The total area of the four watersheds is 807 km^2: Elgo (249 km^2), Sile (227 km^2), Baso (167 km^2), and Shafe (164 km^2). Elgo and Sile catchments drain Lake Chamo, whereas Baso and Shafe drain Lake Abaya. Of all Abaya-Chamo Lake watersheds, Arba Minch University (AMU) and Institutional University Cooperation (IUC) Program (Belgium) (AMU-IUC Project 4, Vilrous) (Reducing land degradation through and for sustainable rural land use in the South Ethiopia Rift Valley) site under 2017–2022, the area around two lower-lying lakes, Abaya and Chamo Lakes, were selected for this specific study based on accessibility and the productive potential of the site for crop production and covered a 2019 sq·km area (Figure 1).

The climate around the Abaya and Chamo Lakes basin is classified as tropical. It has a hot, semi-arid tropical climate [23]. The humid breeze from the Indian Ocean that is brought by the bimodal rainfall system is brought by the

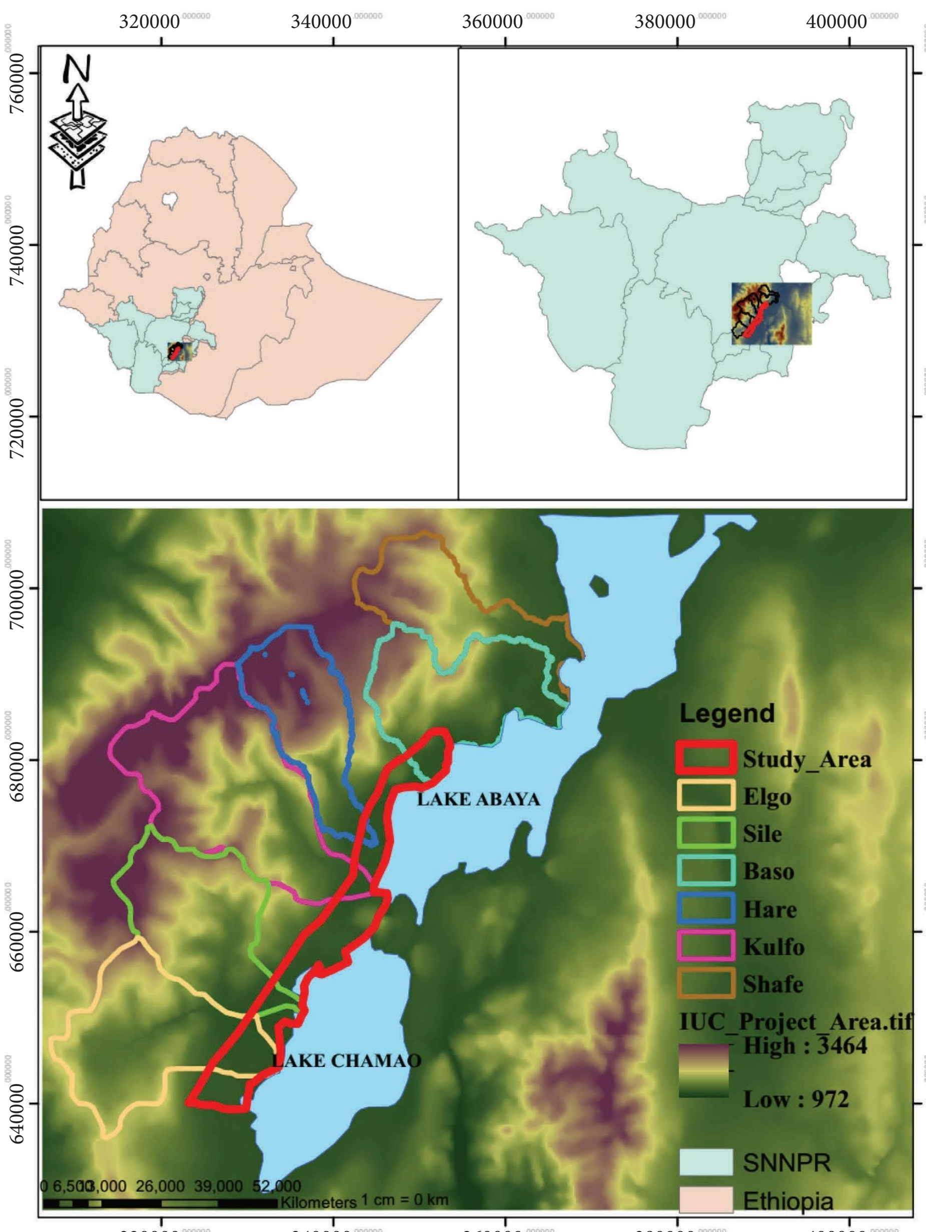

Figure 1: Location map of the project area and the study area.

intertropical convergence zone (ITCZ). Apart from the ITCZ, the rainfall distribution in the area is affected by the effects of altitude [24]. Most parts of the Abaya Chamo watersheds have a bimodal rainfall distribution, with short rains in spring (belg) and long rains in summer (kremt) [24]. In the study area, there are two months when rainfall is abundant. They are April and May, where 152 mm and 133.5 mm of rainfall are recorded, respectively, and the lowest rainfall in January and February, 9 mm and 20 mm, respectively. The mean annual rainfall is recorded as 500–1100 mm; the annual average air temperature is 17–39°C; and the mean soil temperature is 22–35°C in different depths of soil (AMU-IUC Project 4) (Figure 2). The cultivation of banana, mango, papaya, maize cotton, sweet potato, tomato, onion, and haricot beans is dominant. Soil salinity and sodicity around Abaya and Chamo Lakes are caused by natural sources, such as low rainfall and high evaporation rates, close or adjacent water tables, weathering rocks, and minerals, while anthropogenic sources include human activities such as poor irrigation, deforestation, and livestock overgrazing [17].

2.2. Soil Sampling and Laboratory Analysis. The terrain features such as elevation, slope, aspect, and curvature are similar in the study area (Table 1). Hence, based on the data obtained from the preliminary soil survey through a sodicity and salinity indicator-based approach and visual observation regarding the presence of white salt crust and the black hardened upper layers, the soils around Abaya and Chamo

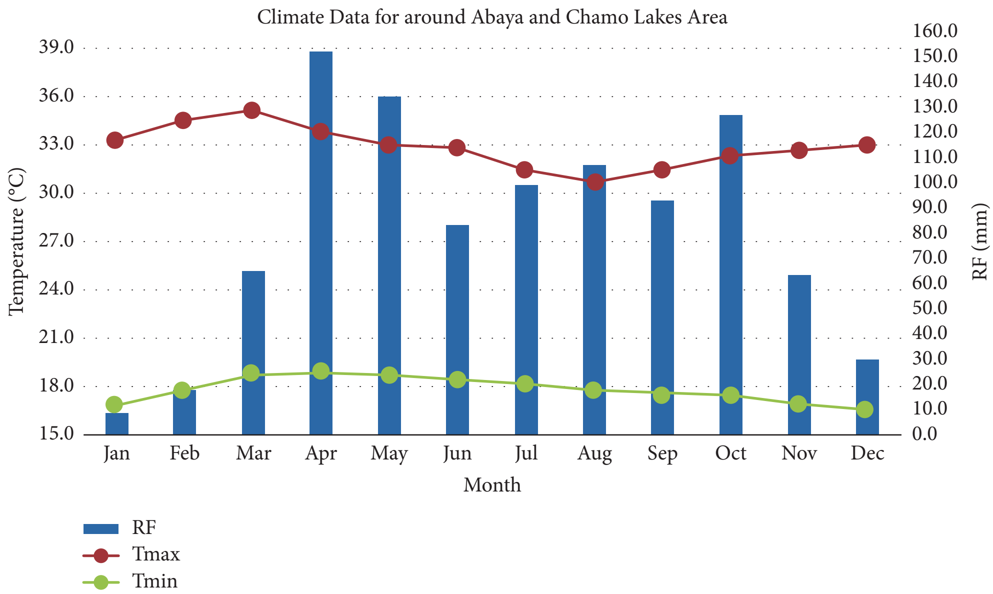

FIGURE 2: Annual climate data around Abaya and Chamo lakes (1983–2020 average) (source: AMU-IUC project 4 meteorology station).

Lakes were subsequently assessed and characterized. Accordingly, the study area was classified into different map units. In this study, the mapping unit was 5. From each map unit, one representative soil sampling pit at 60 ∗ 60 ∗ 60 cm size was opened for soil morphological examination and soil sample collection. Then, soil samples were collected from three soil depths (0–20, 20–40, and 40–60 cm) based on the criteria set for agricultural salt-affected soil studies by [25]. A total of 15 soil samples were collected. After cleaning away loose debris from the pit face, color, texture, consistency, structure, plant rooting patterns, and other soil features were then made following the Guidelines for Soil Description [26]. Soil color was measured under uniform conditions using the Munsell Soil Color Chart [27]. The pycnometer method was used to determine the particle density (PD) [28]. Particle size was determined by a hydrometer [29], and bulk density (BD) was determined by the core method [30]. The total porosity was estimated from the determined particle and bulk density.

A pH meter determined the soil pH from saturated soil paste extract. Electrical conductivity (EC) was measured from a soil saturation extract by a conductivity meter. Organic matter (OM) was determined by the modified procedure of Walkley and Black [31]. Neutral 1 N ammonium acetate extracts were used to determine the cation exchange capacity (CEC) and the exchangeable bases. Sodium (Na) and potassium (K) were measured using flame photometry. Titration was used to determine the amounts of magnesium (Mg) and calcium (Ca). Using HCl, the acid neutralization method was used to measure the amount of calcium carbonate ($CaCO_3$). Total nitrogen (TN) was determined by the micro-Kjeldahl method [32], while available phosphorus (Av. P) was extracted and determined using the sodium bicarbonate solution following the standard procedure [33]. The method outlined in Handbook No. 60 was used to determine the solubility of cations and anions [34].

Soluble calcium and magnesium were determined by titration with ethylenediaminetetraacetate (versenate) as described by [35], while sodium and potassium were measured by flame photometer from ammonium acetate, approximately 1 N. Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) were determined by titration with acid. Chloride (Cl^-) was determined by titration with the silver nitrate method. Nitrate (NO_3^-) was determined by phenoldisulfonic acid method [34]. Sulfate (SO_4^{-2}) contents were determined by a turbidimetric procedure using a UV-visible spectrophotometer [36]. All soil samples were analyzed for critical salinity and sodicity parameters. The sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) were calculated by the procedure outlined in Hand Book No. 60 [34].

$$\begin{aligned} SAR &= \frac{Na^+}{\left(Ca^{2+} + Mg^{2+}/2\right)^{(1/2)}}, \\ ESP &= \frac{(100\,(-0.0126 + 0.01475\,(SAR))}{1 + (-0.0126 + 0.01475\,(SAR)}. \end{aligned} \tag{1}$$

According to the findings of the analyses, the soils in the research region were assessed and divided into different salt-affected soil classes (sodic and non-saline non-sodic soils) by the standards established by the USSLS, as shown in Table 2 [7]. A licensed geostatistical analyst extension tool in Arc GIS 10.81 software was used to produce maps of salt-affected soils in the study area.

2.3. Data Analysis. Following a guide to standardized analytical methodologies for soil data, the results of the soil analysis were evaluated and interpreted. The outcomes of the soil study were further subjected to PCA and clustering using the statistical analysis program R. In addition,

Table 1: Representative salt-affected soils pits site characteristics.

Parameters		Around Chamo lake		Around Abaya lake		
		Pit, CL01	Pit, CL02	Pit, AL01	Pit, AL02	Pit, AL03
Cordinate[a]	Latitude	584129	584140	606999	612708	616202
	Longitude	3745538	3745538	3757727	3763443	3766494
Altitude[b]		1107	1128	1191	1184	1183
Slope (%)		2	2	2	2	2
Slope position		Bottom (flat)	Bottom (flat)	Bottom (flat)	Bottom (flat)	Bottom (flat)
Drainage class		Imperfectly	Poorly drained	Poorly drained	Poorly drained	Poorly drained
Erosion/deposition		N[c]	N	N	N	N
Parent material		Colluvium sedimentary	Colluvium sedimentary	Colluvium sedimentary	Colluvium sedimentary	Colluvium sedimentary
Land use		Animal husbandry	Animal husbandry	Animal husbandry	Animal husbandry	Animal husbandry

[a]UTM coordinate, zone 37 N, datum WGS 1984. [b]Meter above sea level. [c]No evidence of erosion.

Table 2: Guideline for classification of salt-affected soils.

Classification	EC of saturation extracts (ECe) at 25°C (mmhos/cm)	Exchangeable Na percentage (ESP)	pH (H_2O)	Soil physical condition
Saline	>4	<15	<8.5	Normal
Sodic (alkali)	<4	>15	>8.5	Very poor
Saline sodic	>4	>15	<8.5	Normal
Non-saline non-sodic	<4	<15	≈7.0	Normal

Source: [7].

connections between soil chemical characteristics were determined by computing correlation coefficients.

3. Result and Discussion

3.1. Salt-Affected Soils: Site Characteristics of Representative Pits. According to the site characteristics of the study locations, the slope and degree of water erosion were similar (Table 1). Pits AL01, AL02, and AL03 are situated surrounding Abaya Lake, while Pits CL01 and CL02 are situated close to Chamo Lake. Around Abaya and Chamo Lakes, low-altitude areas of the South Ethiopian Rift Valley include soils. Five separate pits represented the flat area in the study site; based on their slope placements, the area is flat and known for its alkaline environment, including the Abaya and Chamo Lakes and soils. The area around the pit is grassland used for animal husbandry, and it is bare land. Better drainage is required for soils since they are made of lacustrine and sedimentary colluvium deposits. The research site had 2% gradients.

3.2. Salt-Affected Soils Morphological Properties. The soil pits are very dark grayish brown (10YR 3/2) to brown (7.5YR 4/3) in color (moist) in the surface depth (0–20 cm); black (10YR 2/1) to very dark brown (7.5YR 2.5/2) subsurface depth (20–40 cm); and very dark brown (10YR 2/2) to brown (7.5YR 4/3) subsurface depth (40–60) (Table 3). A brownish to black soil color of studied agricultural salt-affected soils could be due to the dispersion of soil organic matter and humic substances. Historically, sodic soils were often called black alkali soils, the dispersion and dissolution of humic substances resulted in a dark color [37]. The color of the soil is a crucial characteristic that can be used to determine the degree of mineral weathering, the amount of organic matter, and the soil's aeration [38]. The soil structure was angular blocky in the surface depth (0–20 cm) and subangular blocky in the rest of the soil depth. The blocky structure of soils could be due to their higher clay content. It can be divided into two categories: subangular blocky, which has more rounded corners, and angular blocky, which has sharp angles most commonly found in higher clay soils [39]. Consistency (dry) is hard in the surface depth (0–20 cm) and slightly hard in the subsurface depth (20–60 cm). Both surface and subsurface depth are sticky and plastic (wet). Although consistency is an inherent soil characteristic, high OM in the surface layer changes its consistency [40]. Root abundance ranged from none (<2 mm) to very few (1–20 mm) (Table 3). It could be due to the net effect of sodicity and salinity. Thus, when clay particles disperse within the soil, they plug macropores in the surface soil by blocking avenue roots from moving through the soil and the surface crust, restricting plant emergence. The findings of [41] supported that salt stress induces changes in soil physical properties, limiting root growth in salt-affected soils.

3.3. Salt-Affected Soils Physical Properties. Soil texture is clay loam and heavy clay for a pit, CL01 and CL02, respectively, while clay, clay, and sandy clay for a pit, AL01, AL02, and AL03, respectively. This result revealed that there is some textural variation among the studied pits. Textural variations can help explore soil genesis by providing clues about the parent material and influencing soil formation rate and nutrient availability. Sand and clayey soils have different textures, with sandy soils forming more slowly due to their smaller surface area and weathering process. Clayey soils have a higher nutrient content due to their larger surface area and complex bonding with nutrients, making them more accessible to plants. Soil texture is in surface and subsurface with different particle size distributions, with silt-to-clay ratios greater than 0.3 indicating that the soils are young (Table 4). Young parent materials usually have a silt/clay ratio above 0.15 [42]. These results indicated that the soils around Abaya and Chamo Lakes are relatively young and have a high degree of weathering potential. Similar results have been reported for other soils in similar ecological settings [43, 44]. The bulk density of the soils around Abaya and Chamo Lakes varied from 1.2 to 1.52 $g{\cdot}cm^{-3}$ on the surface depth (0–20 cm), from 1.18 to 1.55 $g{\cdot}cm^{-3}$ in the sub-surface depth (20–40 cm) and from 1.17 to 1.44 $g{\cdot}cm^{-3}$ in the sub-surface depth (40–60 cm) (Table 4). The increased trend was revealed on the sodic soils of Pits CL01, CL02, and AL03. This bulk density increase on the surface of sodic soils is due to the high accumulation of exchangeable sodium on the surface soil. This high accumulation of exchangeable sodium makes the compaction and dispersion of soil structure, in connection with this bulk density, high on the surface of sodic soils. Moreover, bulk densities in the non-saline non-sodic soils of pits AL01 and AL02 increased with depth. Lower bulk density in pits AL01 and AL02 could be due to organic matter content that was relatively higher in the surface depth (0–20 cm) as compared to the sub-surface depth (20–40, 40–60 cm), contributing to porous and well-aggregated structures and thereby lower bulk densities [45]. The mean bulk density of the soils around Abaya and Chamo Lakes was 1.35 $gm{\cdot}cm^{-3}$. Similarly, [46] reported a bulk density of 1.5 $gm{\cdot}cm^{-3}$ Sile-sego watershed around Chamo Lake. Though generally, the bulk density of 1.35 $gm{\cdot}cm^{-3}$ soils around Abaya and Chamo Lakes was rated in the excellent range according to the critical value of bulk density.

Table 3: Salt-affected soils morphological characteristics.

Parameters		Around Chamo lake						Around Abaya lake								
		Pit, CL01			Pit, CL02			Pit, AL01			Pit, AL02			Pit, AL03		
		Depth (cm)			Depth (cm)			Depth (cm)			Depth (cm)			Depth (cm)		
		0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60
Color	Moist	7.5YR 4/3	7.5YR 2.5/2	7.5YR 4/3	10YR 2/2	10YR3/3	10YR3/2	10YR 3/1	10YR 2/1	10YR 4/3	10YR 3/2	10YR 2/2	10YR 4/2	10YR 3/2	10YR 3/2	10YR 2/2
Structure units[a]	Grade, Size, and type	ST, VF, AB	MO, FI, SB	MO, FI, AB	ST, ME, AB	MO, ME, SB	MO, ME, SB	MO, FI, GR	ST, ME, AB	WE, FI, GR	MO, ME, SB	MO,ME, SB	MO,ME, SB	ST, ME, AB	MO, FI, SB	MO, FI, SB
Consistency[b]	Dry	HA	SO	SHA	HA	SHA	SHA	HA	SHA	SHA	SHA	SHA	SHA	HA	SHA	SHA
	Moist	VFI	LO	FR	FR	FR	FR	VFR	FR	FR	FR	FR	FR	FI	FR	FR
	Wet	ST, VPL	NST, NPL	VST, VP	ST, PL	VST, PL	VST, VPL	ST, VPL	VST, VPL	VST, VPL	ST, PL	ST, PL	ST, PL	ST, PL	VST, VPL	ST, PL
Texture[c]	Feel	SCL	SL	SL	C	C	C	C	CL	C	C	CL	CL	CL	C	C
Roots[d]	Size and abundance	VF, V	VF, V	VF, N	VF, N	VF, N	VF, N	VF, V	N, N	N, N	M, C	F, V	F, V	VF, V	N, N	N, N

[a]AB, angular blocky; FI, fine/thin, GR: granular, ME: medium, MO: moderate; SB, subangular blocky; and ST: strong. [b]FI, firm; FR, friable; HA, hard; LO, loose; NPL, nonplastic; NST, nonsticky; PL, plastic; SHA: slightly hard; SO, soft; VFI, weak; and VFR, very friable. [c]C, clay; CL, clay loam; and SCL, silty clay loam; [d]F, fine; N, none; V, very few; and VF, very few.

Table 4: Salt-affected soils physical and chemical properties.

Parameters		Around Chamo lake									Around Abaya lake					
		Pit, CL01			Pit, CL02			Pit, AL01			Pit, AL02			Pit, AL03		
		Depth (cm)			Depth (cm)			Depth (cm)			Depth (cm)			Depth (cm)		
		0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60
Particle size analysis (%)	Sand	14.00	56.00	60.00	18.00	2.00	8.00	28.00	24.00	38.00	62.00	8.00	20.00	56.00	52.00	54.00
	Silt	52.00	16.00	16.00	20.00	32.00	26.00	26.00	28.00	26.00	10.00	32.00	48.00	10.00	10.00	4.00
	Clay	34.00	28.00	24.00	62.00	66.00	66.00	46.00	48.00	36.00	28.00	60.00	32.00	34.00	38.00	42.00
Textural class		Silty clay loam	Sandy clay loam	Sandy clay loam	Heavy clay	Heavy clay	Heavy clay	Clay	Clay	Clay loam	Sandy clay loam	Clay	Silt clay loam	Sandy clay loam	Sandy clay	Sandy clay
Silt/clay		1.50	0.60	0.70	0.30	0.50	0.40	0.60	0.60	0.70	0.40	0.50	1.50	0.30	0.30	0.10
BD (gcm^{-3})		1.52	1.22	1.17	1.40	1.18	1.41	1.34	1.39	1.29	1.20	1.37	1.33	1.52	1.55	1.44
PD (gcm^{-3})		2.50	1.70	2.00	2.50	2.50	2.50	2.40	2.50	2.50	3.10	3.30	2.50	3.30	3.10	2.40
Porosity (%)		39.00	27.00	41.00	44.00	41.00	29.00	44.00	45.00	49.00	61.00	59.00	47.00	54.00	50.00	40.00
CEC (cmolc kg^{-1})		44.80	46.30	43.30	64.90	52.20	55.90	48.90	44.30	40.90	47.40	46.60	41.10	48.20	46.10	49.40
BS (%)		151.00	131.00	135.00	153.00	131.00	106.00	101.00	85.00	71.00	74.00	91.00	145.00	82.00	113.00	88.00
Av.P (ppm)		42.05	13.78	8.56	77.29	78.98	23.39	29.52	31.43	8.28	5.64	2.38	21.37	44.58	24.07	19.4
OC (%)		0.78	0.28	0.21	1.88	0.91	0.97	1.43	0.53	0.36	0.81	0.51	0.61	0.68	0.42	0.46
TN (%)		0.06	0.06	0.04	0.03	0.05	0.04	0.06	0.05	0.07	0.06	0.06	0.09	0.04	0.06	0.06
$CaCO_3$ (%)		3.80	2.20	1.50	2.30	2.00	1.20	2.80	2.20	0.10	1.10	2.40	2.40	2.80	2.70	2.40

The optimum bulk density value for plant growth at limited root penetration is 1.4 g·cm^{-3} for clay soils [47]. The particle density of most depths of pits CL01, CL02, and AL01 was almost similar to the average values for mineral soils, as indicated by [3], while that of pits AL02 and AL03 was somewhat above the average values for mineral soils worldwide which are 2.65 (Table 4). In the study area, the total porosity decreased in the depth of all soil pits. Total porosity ranged from 39% in pit 1 to 61% in pit AL02 of the surface soil depth (0–20 cm). On the other hand, it varied from 27% in pit CL01 to 59% in pit AL02 of the subsurface soil depth (20–40, 40–60 cm).

3.4. Salt-Affected Soils Chemical Properties. The CEC of soils ranged from 41.1 to 64.9 cmolc·kg^{-1} (Table 4). This result revealed that the soil can store more cations, and soils with a high CEC are more fertile. The relatively high CEC of the soils in the study area suggests that they are fertile and capable of supporting an extensive variety of plant growth [48]. The type of soil, the amount of clay and organic matter in the soil, and the pH of the soil all have an impact on the CEC of the soil [49]. Because clay particles have a larger surface area and can bind more cations, they have a higher CEC than sand-based soils. Because organic matter has a high CEC, soils with high levels of organic matter will also have high levels of CEC [50]. The CEC is additionally affected by the pH of the soil. The CEC is higher in alkaline than acidic soils [51]. In acidic soils, the hydrogen ions (H^+) compete with the cations for binding sites on the clay minerals and organic matter. This reduces the CEC of the soil. There are fewer H^+ ions in alkaline soils, so the clay minerals and organic matter can hold more cations and have a higher CEC [52].

According to [25], this higher CEC is above the very high value (>40 cmolc kg^{-1}) for both surface depth (0–20 cm) and subsurface depth (20–40 and 40–60 cm), which indicates that the soils could be made productive by reclamation. This very high rating of CEC in the study area soils could be due to the presence of more weatherable primary minerals as a plant nutrient reserve. Thus, such soils are considered capable of good production if other factors are favorable [53]. Similarly, soil's total nutrient fixing capacity is well expressed by its cation exchange capacity, and values over 10 cmol·kg^{-1} are considered satisfactory for most crops [54]. These soils have a well-buffering capacity for changes in chemical properties [55].

The available phosphorus content on the surface soil depth (0–20 cm) of all pits (sites) was found to be very high except pit AL02 (Lante site), which was rated low (Table 4) by [25] while in the subsurface depth (20–40, and 40–60 cm) found to be irregular. It could be soil alkaline phosphatase activity due to an increase in the proportion of active inorganic phosphorus and medium-active inorganic phosphorus in the soil phosphorus pool, which explains the effect of soil alkaline phosphatase activity on soil available phosphorus [56].

The organic carbon (OC) concentration in this soil is rated low to very low, according to [25]. It could be because the arid areas have a relatively lower amount of OM because of lower vegetation, indicating the absence of healthy soil biological conditions in the study area [57]. Similarly, low organic carbon could be due to the rapid decomposition of organic matter in semi-arid climatic conditions [58].

Total surface and subsurface depth nitrogen were rated as medium [25]. The trend in total nitrogen distribution within the pits was not similar to that of OC, implying that the organic matter was not the primary source of total nitrogen in the study soils. Though maybe even within specific environments, there seems to be no general agreement on ratings of *N* values measured by the same method [59], and ratings of total nitrogen are given as a very general reference to total N content for Ethiopian soils [25]. In contrast, [53] reported a strong correlation between total *N* and organic carbon, stating that the variation in total nitrogen content is related to the variation in organic carbon in salt-affected soils of the North-Eastern Rift Valley of Ethiopia. Most pits had 2–3.8% $CaCO_3$ content throughout the soil depth, rated low $CaCO_3$ content (Table 4), and physically less visible effervescences of calcaric soil material. At the same time, surface soil depth (0–20 cm) for Pit AL02 and subsurface soil depth (40–60 cm) for Pits CL01, CL02, and AL01 were <2% $CaCO_3$ which was rated none to very low by [54]. This low content of $CaCO_3$ could be due to precipitation combined with bicarbonate ions. The $CaCO_3$ variation may be ascribed to the parent material's nature and the irrigation water quality [60]. A smaller amount of calcium carbonate enhances soil structure and is essential to the productivity of soils. However, higher concentrations may create iron deficiency and, when cemented, reduce the water storage capacity of soils [54].

3.5. Salt-Affected Soils' Soil Reaction, Electric Conductivity, Exchangeable Bases, and Exchangeable Sodium Percentage. According to [25], the soil reaction was highly alkaline throughout pits CL01, CL02, and AL03, ranging from a value of 9.4 at the subsurface depth (40–60 cm) of pit AL03 to 10.3 in pits CL01 and AL03 surface depth (0–20 cm) (Table 5). At the same time, pits AL01 and AL02 were mildly alkaline to highly alkaline and ranged from a value of 7.7 at the surface depth (0–20 cm) to 9.8 subsurface depth (20–40) of pit 4 (Table 5). This can be attributed to the low leaching of bases in clay soils [59, 61], typical in pits CL01, CL02, and AL03. Soil reaction generally revealed decreasing trend throughout the soil depth in the pits. The soil was rated none strong an electrical conductivity ranging from 0.67 dS m^{-1} at the subsurface depth (40–60 cm) of pit AL02 to 8.21 dS m^{-1} for the surface depth (0–20 cm) of pit 2 based on the rating of [7]. ECe is rated slightly for pits AL01 and AL02, so it is suitable for crop production compared to pits CL01, CL02, and AL03. Since 1954 to date, the ECe has been considered the best indicator of crop response to salinity compared with the EC from other soil-to-water ratio suspension methods [62–64]. The pH and EC values indicate that the soils of the study area are non-saline non-sodic for pits AL01 and AL02 and for pits CL01, CL02, and AL03 sodic by the rating of [7]. There were regular patterns in EC and pH with depth. The exchange complex of the soils was dominated by Na,

Table 5: Salt-affected soils soil reaction, electric conductivity, exchangeable bases, exchangeable sodium percentages, and soluble chemical properties.

Parameters	Around Chamo lake						Around Abaya lake								
	Pit, CL01 Depth (cm)			Pit, CL02 Depth (cm)			Pit, AL01 Depth (cm)			Pit, AL02 Depth (cm)			Pit, AL03 Depth (cm)		
	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60	0–20	20–40	40–60
pH	10.30	9.90	9.60	10.30	9.70	9.40	9.20	8.60	8.30	7.70	9.80	9.50	10.30	9.70	9.40
EC (ds/m)	3.27	1.38	1.32	3.21	2.34	1.64	1.93	0.92	0.67	1.02	1.19	1.86	3.15	1.58	1.31
Ex. Na	57.84	54.92	53.92	93.68	61.42	53.48	28.26	17.18	6.68	4.16	26.77	48.18	33.27	44.63	34.4
Ex. K	1.35	0.80	0.50	1.37	1.27	1.22	2.32	1.20	0.91	0.76	0.68	1.00	1.25	1.19	1.17
Ex. Ca	6.05	2.13	0.59	2.86	2.20	0.78	7.94	6.08	7.74	25.28	10.52	6.44	3.66	2.81	2.34
Ex. Mg	2.57	2.62	3.41	1.32	3.33	3.95	10.79	13.29	13.90	5.10	4.62	3.92	1.56	3.47	5.33
SAR (%)	27.86	35.64	38.13	64.8	36.94	34.78	9.23	5.52	2.03	1.07	9.73	21.17	20.59	25.19	17.57
ESP (%)	40.23	51.82	55.53	95.26	53.75	50.53	12.48	6.95	1.75	0.32	13.22	30.26	29.41	36.25	24.90
S-a-s-c[a]	Sodic	Sodic	Sodic	Sodic	Sodic	Sodic	Non	Non	Non	Non	Non	Non	Sodic	Sodic	Sodic
Na^+	565.36	481.50	445.07	947.83	547.51	496.19	318.52	160.20	166.97	72.01	249.60	509.60	715.65	383.22	432.90
K^+	42.65	26.27	23.58	44.72	33.51	30.11	36.43	23.73	22.87	14.47	15.10	29.65	25.64	18.00	23.12
Ca^{2+}	126.00	109.00	121.00	163.50	130.00	103.00	177.60	200.00	100.00	80.00	130.00	160.00	230.00	180.00	100.00
Mg^{2+}	189.00	109.00	121.00	43.60	80.00	154.50	122.10	120.00	230.00	250.00	170.00	90.00	120.00	180.00	175.00
Cl^-	302.02	276.64	272.98	184.43	279.18	159.75	156.51	276.08	205.3	179.63	259.44	290.18	141	131.98	179.63
SO_4^{-2}	5.10	6.87	4.31	67.60	5.40	5.05	9.87	6.53	2.84	6.77	3.87	6.53	11.39	4.31	3.82
NO_3^-	0.31	0.03	0.01	6.37	1.46	0.17	0.00	0.02	0.07	0.03	0.00	0.06	2.09	0.41	0.39
CO_3^{2-}	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
HCO_3^-	33.93	11.43	14.00	30.00	18.52	3.33	12.50	17.50	12.00	9.00	18.18	30.00	65.00	12.50	3.03

[a]S-a-s-c, salt-affected soil class; sodic, sodic soil; and non, non-saline-non-sodic soil.

followed by Mg, K, and Ca. Exchangeable Na ranged from 33.27 to 93.68 $cmol_{(+)}\ kg^{-1}$ and was categorized as very high according to [25] (Table 5). Consequently, most of the pit's ESP values were higher than 15%, and the highest value was recorded in pit CL02 (around Chamo Lake) (Table 5), which is usually taken as the critical limit for classification as a sodic soil [3]. The increase in sodium content and decrease in calcium and magnesium content due to precipitation—such a reaction is enhanced under the semiarid climatic conditions with the low partial pressure of CO_2 and low content of organic matter in the soil might be the reason for high ESP values, as reported by [58]. The soils' relatively medium and heavier texture, soil erosion, and low-lying area with poor drainage could be attributed as probable reasons for the higher ESP [65]. Thus, reclamation measures to remove excess Na through the application of gypsum followed by leaching should be employed for successful crop production at site/pit CL01, CL02, and AL03; the rest of pits AL01 and AL02 require leaching with good irrigation water and recommended integrated soil management practice [66, 67]. Exchangeable Mg and K were found to be in the medium to high amount [25]. The calcium content was in the very low to low range (<2 to 2–5 $cmol_{(+)}\ kg^{-1}$) for pits CL01, CL02, and AL03, while in the medium to very high range (5–10 to >20 $cmol_{(+)}\ kg^{-1}$) for pits AL01 and AL02.

3.6. Salt-Affected Soil Class of Studied Salt-Affected Soils. Based on agricultural arable land soil depth of 0–20 cm and 20–40 cm, Pit CL01 (around Abaya Lake), pit CL02 (around Abaya Lake), and Pit AL03 (around Abaya Lake) were categorized as sodic soil according to [7] salt-affected soil class since pH value > 8.5; EC < 4, SAR > 13, and ESP > 15. In contrast, pits AL01 and AL02 (around Abaya Lake) were categorized as non-saline non-sodic soil with EC < 4, SAR < 13, and ESP < 15. Based on this pit-based detail study, the studied soil properties revealed clues and directions to apply soil reclamation practices in the study area. However, it needs further study on agricultural salt-affected soil mapping regarding salt type and intensity of salt problems. Thus, for sample sites, pits CL01, CL02, and AL03 need calcium-rich amendment material plus leaching from good irrigation water. The ideal material for reclamation of sodic soils should provide calcium and promote the formation of gypsum ($CaSO_4$) and carbonates ($CaCO_3$) in the soil. Sodic soil reclamation involves replacing sodium with calcium and leaching excess sodium with water. Gypsum, a cost-effective, widely available amendment, is effective in supplying calcium and promoting the formation of gypsum and carbonates. It lowers pH and improves soil structure. Pits AL01 and AL02 need leaching through good irrigation water and amendments (Figure 3). Reclamation methods for saline and nonsaline soils depend on texture, salt composition, drainage, leaching, amendments, and crop selection. Leaching removes salts, while amendments improve soil structure and reduce salt concentration.

3.7. Salt-Affected Soils Soluble Chemical Properties. Soluble Na^+ in the five pits revealed dominance between different depths, in which depths 0–20 cm gave higher values over 20–40 cm and 40–60 cm depth, but no significant difference was found between 20–40 cm and 40–60 cm depths. The soluble Na^+ content of the soils decreases consistently with an increase in depth (Table 5). It could be due to the movement of soluble Ca and exchangeable Ca to

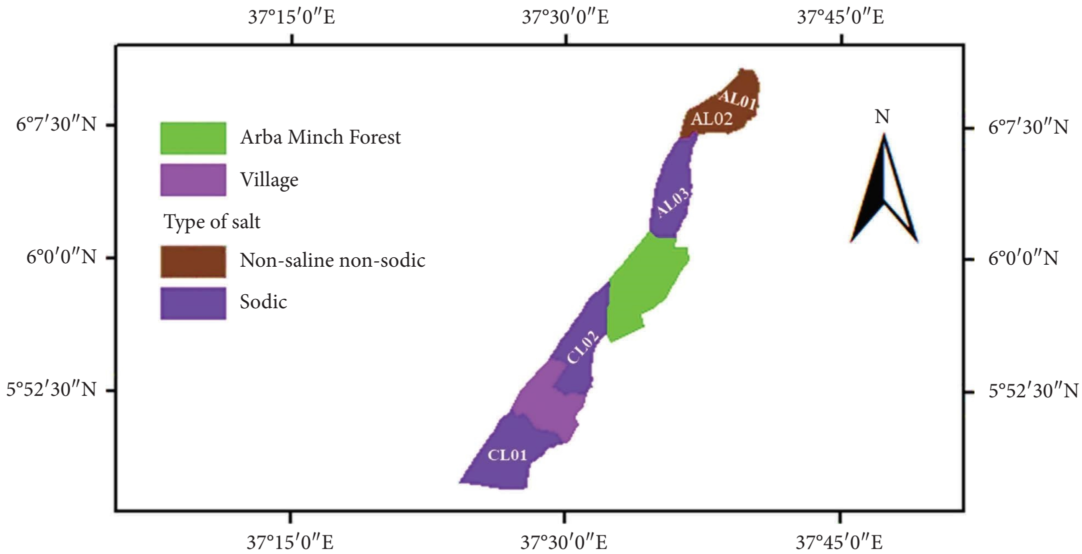

Figure 3: Salt-affected soil class for pits with depth (cm) wise (where CL01 and CL02 are pits around Chamo lake and AL01, AL02, and AL03 are pits around Abaya lake, respectively).

soil depth by leaching, displacing the exchangeable and soluble sodium. This aligned with the findings that soluble Na^+ increases from bottom to top soil depth [68]. This result indicated a similarity to that soluble Na^+ leached from the upper layer to the lower ones, as mentioned by [69]. Also, this pattern was attributed to the decreasing Ca^{2+}: Na^+ ratio in the soil solution as it moved down the soil depth displacing exchangeable Na^+, as mentioned by [70]. Sodium was the dominant soluble cation, followed by magnesium, calcium, and potassium in all soil depths of the pits. Similarly, among the anions, Cl^- was dominant throughout the soil depth, followed by HCO_3^- and SO_4^{2-}(Table 5). These anions increased with depth consistently in line with soluble Na^+. Most researchers revealed that the solution's common soluble cations associated with soil salinity are Na^+, Ca^{2+}, and Mg^{2+}, while the common anions are Cl^-, SO_4^{2-}, and HCO_3^- [7, 71]. In all the soil depths in the pits, CO_3^{2-} was absent. Among the cations and anions, Na^+, Mg^{2+}, Ca^{2+}, Cl^-, and HCO_3^- were in higher concentrations throughout the pit depth-wise. Hence, chloride and sulfate salts of sodium and calcium were the major salts contributing to the sodicity and salinity development around Abaya and Chamo Lakes soils in the south Ethiopia rift valley.

3.8. Salt-Affected Soils Multivariate Analysis between Chemical Properties

3.8.1. Salt-Affected Soils Correlation between Selected Chemical Properties. In correlation, Table 6, Pearson correlation matrix indicating the relationships between selected soil chemical properties. The soil salinity indices have also been correlated with each significant correlation with soil pH, exchangeable Na, soluble Na^+, and ESP while negatively correlated with Cl^-, Mg^{2+}, TN, Ex. Mg, and Ex. Ca (Table 6). The Ex. Na showed a significant positive correlation with pH, EC, CEC, BS, Av. P, OC, ESP, and Na^+ while negatively correlated with Ex. Ca, Ex. Mg, Mg^{2+}, and TN. The soil HCO_3^- indicated a significant positive correlation with soluble Na^+, and K^+. Exchangeable Ca showed negative significant correlations with Cl^-, NO_3^-, and HCO_3^- (Table 6). Generally, the correlation coefficient results between the selected soil chemical properties were similar to the reported correlations between similar soil properties in literature [72–74]. Correlation results, and a close view of other soil chemical parameters in this study, indicated that the possible main soil salt anions in Abaya and Chamo Lakes were $Cl^-$and HCO_3^-. On the other hand, the main salt cations in the area were Na^+ and Mg^+ in relatively higher amounts than K^+ and Ca^+ (Table 6). NaCl, $MgCl_2$, $NaHCO_3$, and $KHCO_3$ may therefore be the principal soil salt chemical components in this region, with considerably larger quantities than $CaCl_2$ and $CaHCO_3$. These findings were supported by the findings [75]. However, a study on chemical salt speciation is required to fully understand salt compounds in the area for more specific salinity management options.

3.8.2. Salt-Affected Soils Principal Components Analysis (PCA) of Selected Chemical Properties. The principal components analysis (PCA) biplot of selected soil chemical property data shows the loading of each variable (arrows) and the rate of each selected soil chemical properties and salinity, indicating soil parameters (points). 90% bivariate characteristics of the rate of each soil parameter are given for each site. The arrows' length indicates the variables' variance, whereas the angles between them (cosine) approximate their correlations. Close-together points correspond to observations with similar rates on the PCA components. The value of that observation on the variable that the arrow signifies is generally approximated by the cut-point of a perpendicular from a point to an arrow. According to the biplot, soil salinity indicators including pH, EC, ESP, and exchangeable Na have high positive correlations with one another, while CEC, OC, Ex. K, and BS have less correlations with one another and have strong negative correlations with Ex. Ca

Table 6: Pearson's correlation between selected chemical properties.

	pH	EC	Ex. Na	Ex. K	Ex. Ca	Ex. Mg	CEC	BS	Av. P	OC	TN	ESP	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	NO_3^-	HCO_3^-
pH	1.00																		
EC	0.553*	1.00																	
Ex. Na	0.757**	0.661**	1.00																
Ex. K	0.15	0.31	0.12	1.00															
Ex. Ca	−0.690**	−0.24	−0.629*	−0.14	1.00														
Ex. Mg	−0.694**	−0.50	−0.684**	0.22	0.23	1.00													
CEC	0.31	0.706**	0.618*	0.34	−0.21	−0.40	1.00												
BS	0.638*	0.44	0.880**	0.05	−0.46	−0.581*	0.26	1.00											
Av. P	0.47	0.742**	0.648**	0.48	−0.37	−0.31	0.647**	0.47	1.00										
OC	0.15	0.705**	0.44	0.668**	0.06	−0.12	0.797**	0.00	0.658**	1.00									
TN	−0.30	−0.544*	−0.42	−0.08	0.33	0.29	−0.688**	−0.07	−0.46	−0.39	1.00								
ESP	0.676**	0.674**	0.970**	0.01	−0.616*	−0.681**	0.670**	0.791**	0.614*	0.41	−0.556*	1.00							
Na^+	0.809**	0.859**	0.875**	0.22	−0.600*	−0.695**	0.623*	0.669**	0.713**	0.48	−0.46	0.860**	1.00						
K^+	0.50	0.654**	0.700**	0.600*	−0.40	−0.20	0.50	0.678**	0.732**	0.694**	−0.25	0.612*	0.699**	1.00					
Ca^{2+}	0.36	0.43	0.10	0.45	−0.27	0.02	0.04	0.03	0.40	0.22	−0.19	0.04	0.32	0.19	1.00				
Mg^{2+}	−0.576*	−0.555*	−0.716**	−0.26	0.590*	0.32	−0.45	−0.615*	−0.646**	−0.42	0.33	−0.683**	−0.699**	−0.567*	−0.49	1.00			
Cl^-	0.13	−0.22	0.17	−0.38	−0.08	−0.02	−0.39	0.47	0.00	−0.32	0.29	0.08	−0.05	0.15	−0.20	−0.23	1.00		
NO_3^-	0.39	0.937**	0.643**	0.21	−0.22	−0.39	0.794**	0.37	0.747**	0.704**	−0.576*	0.694**	0.769**	0.548*	0.30	−0.560*	−0.23	1.00	
HCO_3^-	0.51	0.641*	0.20	0.12	−0.10	−0.36	0.02	0.16	0.43	0.16	−0.17	0.16	0.551*	0.30	0.671**	−0.34	0.02	0.42	1.00

**Correlation is significant at the 0.01 level. *Correlation is significant at the 0.05 level.

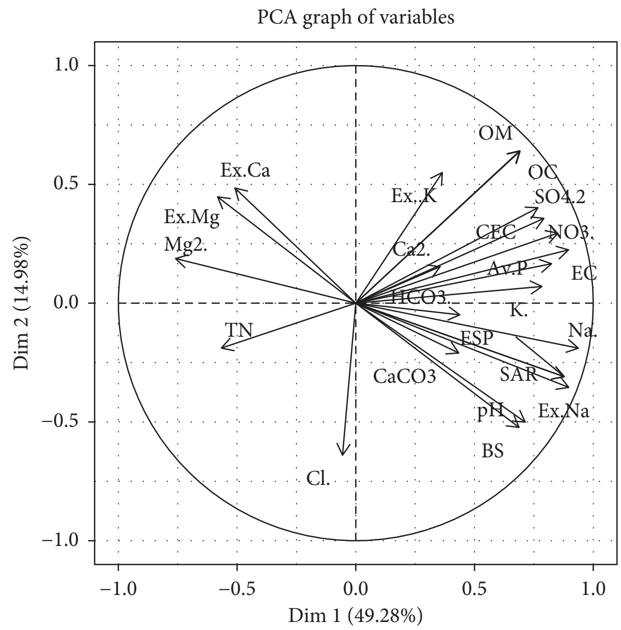

Figure 4: Salt-affected soils principal component analysis (PCA) plot of soil chemical properties. Where pH = soil reaction, EC = electroconductivity, Ex. Ca = exchangeable calcium, Ex. Mg = exchangeable magnesium, Ex. Na = exchangeable sodium, Ex. K = exchangeable potassium, Ca^{2+} = soluble calcium, Mg^{2+} = soluble magnesium, Na^{+} = soluble sodium, K^{+} = soluble potassium, OM = organic matter, OC = organic carbon, TN = total nitrogen, CEC = cation exchange capacity, BS% = percentage of base saturation, Av. P = available phosphorous, $CaCO_3$ = calcium carbonate, SAR = sodium adsorption ratio, ESP = exchangeable sodium percentage, CO_3^{2-} = carbonate, HCO_3^{-} = bicarbonate, Cl^{-} = chloride, NO_3^{-} = nitrate, and SO_4^{-2} = sulfate.

and Ex. Mg. In terms of depth, the majority of the research pits and sites are affected by soil salinity and sodicity, necessitating the use of calcium-rich soil amendment materials for reclamation (Figure 4 and Table 7).

The results showed four principal components (PCs) with eigenvalues greater than 1, so they were considered, and the others were neglected. The four PCs explained 82.01% of the studied chemical soil properties' variability: 49.28%, 14.97%, 10.49%, and 7.25% for PC1, PC2, PC3, and PC4, respectively. According to factor loadings, it was clear that soil pH, EC, SAR, ESP, CEC, BS, and Av. P was correlated with PC1. On the other hand, Ex. K, Ex. Mg, OC, and OM were correlated with PC2, while PC3 was correlated with $CaCO_3$, and PC4 correlated with Ex. Ca (Figure 4 and Table 7).

3.8.3. Salt-Affected Soils Hierarchical Cluster Analysis of Selected Chemical Properties. The selected soil chemical properties analysis on the five pits/sites depth-wise around Abaya and Chamo Lakes was processed using multivariate numerical techniques using the R software. Based on that, agglomerative hierarchical cluster analysis was applied to this study. These are the most ubiquitous clustering algorithms. This algorithm shows the relationship between individual data and cluster relationships. The algorithm is addressed by effectively connecting small clusters by following the intercluster distance. Eventually, a dendrogram revealed the relationship between the individual data and clusters. The height of the dendrogram refers to the distance between clusters. The hierarchical cluster analysis on the distance from selected soil chemical properties (especially salinity indicating soil parameters) revealed three clusters. Cluster in the black color pit, CL02 (around Chamo Lake) surface soil depth (0–20 cm) categorized as one cluster since it has the highest value of pH (10.3), Ex. Na (93.68 cmol kg^{-1}), and ESP (95.26%). Cluster green color was clustered as second, including surface soil depth (0–20 cm) from the pit, AL02, and subsurface depth (20–40 cm) from the pit, AL01 around Abaya Lake. The cluster in red color represented the third cluster, including all depths in pits CL01 and CL02 except soil depth 0–20 cm of Pit CL02 around Chamo Lake, which were categorized as sodic soils. The cluster in blue color was clustered as the fourth cluster and represented only pit AL03 surface depth 0–20 cm. The rest of the others clustered in black color were clustered in the fifth group, including most of the pits, around Abaya Lake: pit, AL01 (0–20 and 20–40 cm), pit, AL02 (20–40 cm), and pit, AL03 (20–40 and 40–60 cm) (Figure 5).

3.8.4. Salt-Affected Soils K-Means Clustering of Selected Chemical Properties. We also used K-means clustering for sampling pits (sites) with a depth-wise study for the type of salt regarding the reclamation purpose of the study area. This K-means clustering is another standard algorithm method that divides or partitions the data points into a predetermined "*K*" number of clusters. Based on that, K-means clustered the study site depth-wise and grouped it into five clusters. Cluster 1, in red color, was the pit depth 40–60 cm and depth 0–20 cm for pits AL01 and AL02, respectively, and

Table 7: Salt-affected soils principal component analysis (PCA) of soil properties.

	Loading matrix					Formatted loading matrix			
PCA	Dim. 1	Dim. 2	Dim. 3	Dim. 4	PCA	Dim. 1	Dim. 2	Dim. 3	Dim. 4
Eigenvalue	11.33	3.44	2.41	1.66	Eig. V	11.33	3.44	2.41	1.66
Variance (%)	49.28	14.97	10.49	7.25	V (%)	49.28	14.97	10.49	7.25
Cumulative variance (%)	49.28	64.26	74.75	82.01	C. V (%)	49.28	64.26	74.75	82.01
pH	0.71	−0.50	**0.29**	**−0.14**	Na^+	0.94	**−0.19**	**0.04**	**−0.15**
EC	0.90	**0.22**	**0.07**	**−0.25**	Ex. Na	0.90	−0.35	**−0.19**	**0.14**
Ex. Na	0.90	**−0.35**	**−0.19**	**0.14**	EC	0.90	**0.22**	**0.07**	**−0.25**
Ex. K	**0.36**	0.55	0.49	0.41	SAR	0.88	−0.31	−0.34	**0.00**
Ex. Ca	−0.51	0.48	**−0.08**	**−0.01**	ESP	0.88	−0.31	−0.34	**0.00**
Ex. Mg	−0.58	0.45	**0.16**	**0.33**	NO_3^-	0.85	**0.29**	**−0.16**	**−0.23**
CEC	0.77	0.40	**−0.39**	**−0.06**	Av. P	0.82	**0.17**	**0.15**	**0.11**
BS	0.69	−0.52	**−0.05**	**0.39**	SO_4^{-2}	0.79	0.36	**−0.23**	**−0.07**
Av. P	0.82	**0.17**	**0.15**	**0.11**	K^+	0.78	**0.07**	**0.15**	0.49
OC	0.69	0.64	**−0.04**	**0.26**	CEC	0.77	0.40	−0.39	**−0.06**
OM	0.69	0.64	**−0.04**	**0.26**	pH	0.71	−0.50	**0.29**	**−0.14**
TN	−0.57	**−0.19**	**0.29**	0.40	OC	0.69	0.64	**−0.04**	**0.26**
$CaCO_3$	0.43	**−0.21**	0.67	**0.08**	OM	0.69	0.64	**−0.04**	**0.26**
SAR	0.88	**−0.31**	**−0.34**	**0.00**	BS	0.69	−0.52	**−0.05**	0.39
ESP	0.88	**−0.31**	**−0.34**	**0.00**	Ex. K	0.36	0.55	0.49	0.41
Na^+	0.94	**−0.19**	**0.04**	**−0.15**	Ex. Mg	−0.58	0.45	**0.16**	0.33
K^+	0.78	**0.07**	**0.15**	0.49	Ca^{2+}	0.36	**0.15**	0.76	**−0.29**
Ca^{2+}	**0.36**	**0.15**	0.76	**−0.29**	$CaCO_3$	0.43	**−0.21**	0.67	**0.08**
Mg^{2+}	−0.76	**0.19**	**−0.15**	**−0.13**	HCO_3^-	0.44	**−0.05**	0.61	−0.45
Cl^-	**−0.06**	−0.64	**0.05**	0.45	Cl^-	**−0.06**	−0.64	**0.05**	0.45
SO_4^{-2}	0.79	**0.36**	**−0.23**	**−0.07**	Ex. Ca	−0.51	0.48	**−0.08**	**−0.01**
NO_3^-	0.85	**0.29**	**−0.16**	**−0.23**	TN	−0.57	**−0.19**	**0.29**	0.40
HCO_3^-	0.44	**−0.05**	0.61	−0.45	Mg^{2+}	−0.76	**0.19**	**−0.15**	**−0.13**

NB. The values in nonbold represent essential contributions that are above the expected value if the contributions were uniform.

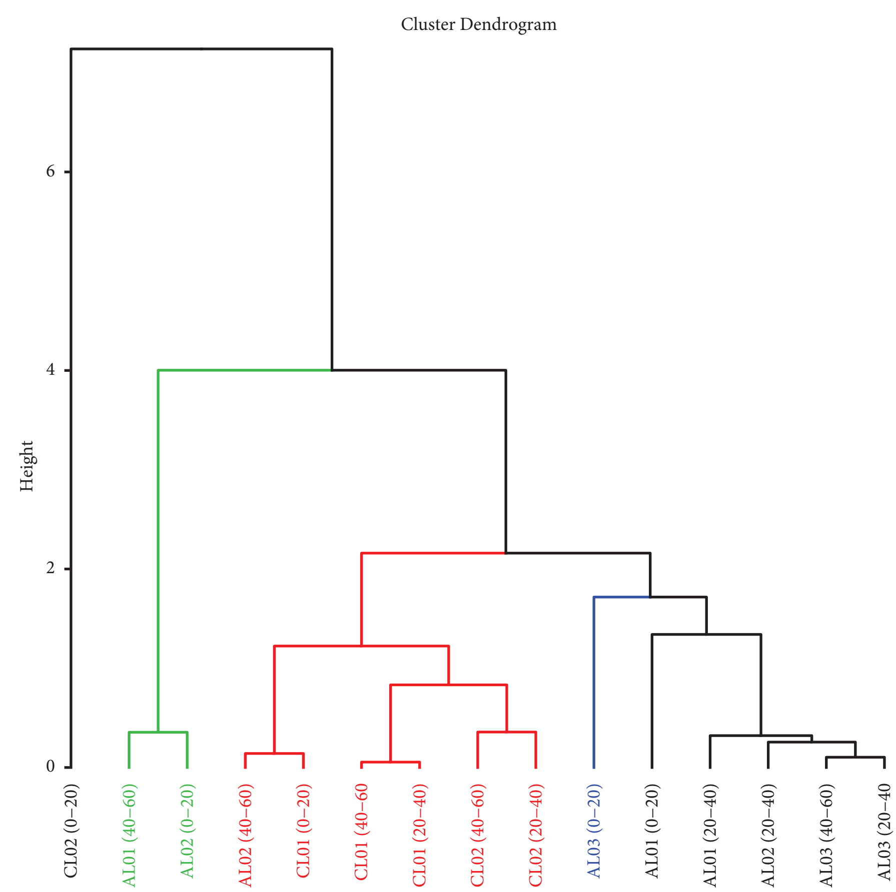

Figure 5: Salt-affected soils cluster dendrogram of chemical properties with respect to soil pits with depths (cm) wise. Where CL01 and CL02 are pits around Chamo lake and AL01, AL02, and AL03 are pits around Abaya lake, respectively.

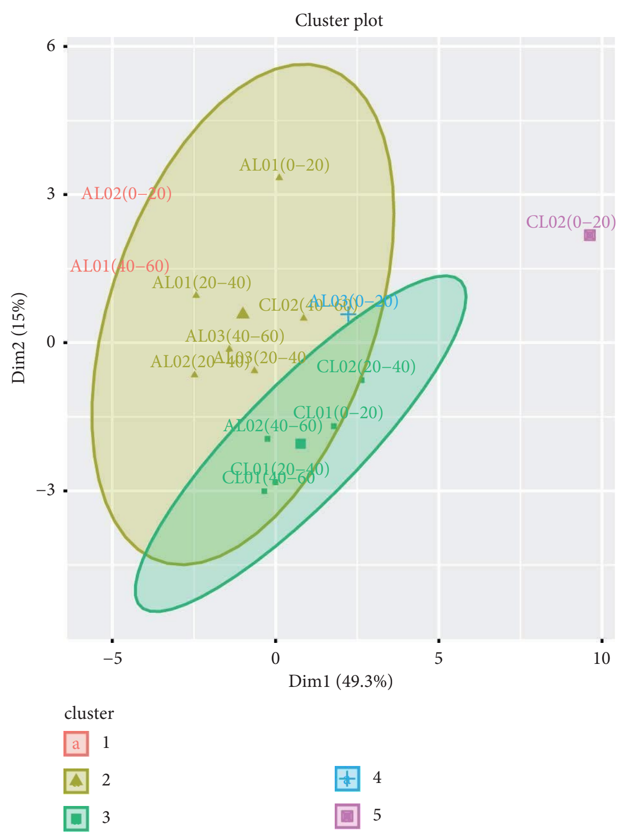

Figure 6: Salt-affected soils K-means clustering of chemical properties with respect to soil pits with depths (cm) wise. Where: CL01 and CL02 are pits around Chamo lake and AL01, AL02, and AL03 are pits around Abaya lake, respectively.

was classified in salt-affected soil classification into non-saline non-sodic soils [7], which were recommended reclamation through leaching the soluble salts by good irrigation water and practicing integrated soil management techniques (Figure 6). Cluster 2 in orange color was the pits with depth-wise for pits AL01, CL02, and AL03 were classified in salt-affected soil classification into none-saline nonsodic and sodic soils, respectively, according to [7], and recommended reclamation is the application of gypsum (chemically, organic amendment (FYM, Cow dung, husks, etc.), biological amendments (phytoremediation) (Figure 5). Cluster 3, in green color, was clustered for all depth levels except depth 0–20 cm of pit CL02 around Chamo Lake were classified as sodic soils and recommended reclamation techniques the same as cluster 2 but with the application of sand as physical reclamation required in this case since the soil was textural heavy clay soil (Figure 6).

4. Conclusions

Soil pits were used to assess and characterize the extent, nature, and distribution of salinity and sodicity in five pits among different soil depths (0–20 cm, 20–40 cm, and 40–60 cm) in agricultural salt-affected soils around Abaya and Chamo Lakes of southern Ethiopia Rift Valley. Soils are developed from colluvium sedimentary and lacustrine deposits and need a better drained. A brownish to black soil color in studied agricultural salt-affected soils could be due to the dispersion of soil organic matter and humic substances. The blocky structure of soils could be due to their higher clay content. Soil texture is in surface and subsurface with different particle size distributions, with silt-to-clay ratios greater than 0.3, indicating that the soils are young. The soils of the study site were highly alkaline and had a very high sodium content, a very high CEC value, and low levels of organic carbon and exchangeable calcium. Sodium was the dominant soluble cation, followed by magnesium, calcium, and potassium in all soil depths of the pits. The soluble Na^+ content of the soils decreases consistently with an increase in depth. This could be due to the movement of soluble Ca and exchangeable Ca to soil depth by leaching, displacing the exchangeable and soluble sodium. Among the anions, Cl^- was dominant throughout the soil depth, followed by HCO_3^-, SO_4^{2-}, and NO_3^-. According to the same criteria, pits CL01, CL02, and AL03, except pits AL01 and AL02 (non-saline non-sodic) of the agricultural salt-affected soils of the study area met the criteria to be classified as a sodic soil because the pH was greater than 8.5, EC was less than 4 dS m^{-1}, and the ESP was greater than 15%. The soil properties revealed enabled the productivity and fertility status of the soils to be assessed. The findings of this study imply that removal of the salts from the soil depth through drainage and leaching would be needed to improve the productivity of these soils, as the salt content will restrict the growth of many crops. In addition, sand mixing with clay soils is also needed to improve the soil's physical properties and drainage system. However, the feasibility of drainage could be improved due to the unavailability of fresh water for leaching and its cost. Hence, selecting salt-tolerant crops and timber plants may be more appropriate. Moreover, adding organic matter is also recommended, as the soils have little organic matter. The study underscores the need for a scientific reclamation program of salt-affected soils and irrigation water sources and a site-specific soil characterization to increase the production and productivity of the study area.

Data Availability

The study's supporting data are all included in this manuscript, and additional data can be made available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors acknowledge Samson Tsegaye (MSc) for his contribution to field and laboratory work. The authors thank the Water Supply and Environmental Engineering, Civil Engineering Laboratory, and the staff of the lab at Arba Minch University for all the facilities and support they provided. The authors also acknowledge the Engineering Corporation of Oromia and Ethiopia Design and Water

Works Soil Laboratory and the staff of the lab at Addis Ababa. Finally, the authors are also grateful to Arba Minch University for its logistic support throughout the study period. VLIR-UOS Belgium supported this work under the "Reducing land degradation through and for sustainable rural land use research" project of the Interuniversity Cooperation program with Arba Minch University of Ethiopia (AMUET2017IUC035A101). The Ethiopian Ministry of Education and Arba Minch University Research Directorate financially supported the research work in the frame of Ph.D. subsidiary funds.

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