CHARACTERIZATION OF SALT-AFFECTED SOILS AT METEHARA SUGAR ESTATE, CENTRAL RIFT VALLEY OF ETHIOPIA †

[CARACTERIZACIÓN DE SUELOS AFECTADOS POR SAL EN LA PLANTA AZUCARERA DE METEHARA, VALLE DEL RIFT CENTRAL DE ETIOPÍA]

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SUMMARY

Background: Understanding the behavior of salt-affected soils is crucial for recommending appropriate management practices that improve soil health and crop productivity. **Objective:** To characterize salt-affected soils of Metehara Sugar Estate, Central Rift Valley of Ethiopia. **Methodology:** Two representative pedons were opened. After describing the soil morphological attributes, soil samples were collected from every identified horizon for soil analysis in the laboratory. **Results:** There were variations in soil properties among the studied pedons. Soil textural class in both pedons ranges from sandy loam to silty clay loam. In MZ-50-1 pedon, bulk density values are between 1.2 and 1.3 g cm^{-3}, while in MZ-50-2 pedon, they range from 1.2 to 1.4 g cm^{-3}. At 20 cm depth, saturated hydraulic conductivity varies from a slow rate (3.74 µm s^{-1}) in pedon MZ-50-2 to moderate rate (4.86 µm s^{-1}) in pedon MZ-50-1. In the MZ-50-1 pedon soils, the pHe ranged from 8.2 to 9.1, the ECe varied between 9.5 and 13.6 dS m^{-1}, and the ESP spanned from 28.4 to 37.2%. In contrast, MZ-50-2 pedon exhibited a pHe ranged from 7.8 to 8.5, ECe from 10.4 to 14.0 dS m^{-1}, and ESP of 30.2-40.4%. The soil organic carbon content, total nitrogen, available P, CEC and CEC-clay values in the MZ-50-1 pedon and the MZ-50-2 pedon ranged from 0.5 to 1.6% and 0.6 to 2.0%; 0.04 to 0.12% and 0.05 to 0.15%; 3.9 to 6.75 mg kg^{-1} and 4.9 to 7.6 mg kg^{-1}; 12.9 to 21.9 Cmolc kg^{-1} and 11.2 to 24.4 Cmolc kg^{-1}; and 71.4 to 117.8 Cmolc kg^{-1} and 58.3 to 110.7 Cmolc kg^{-1}, respectively. **Implications:** The differences may suggest that site-specific soil fertility and reclamation are desired, and the results may provide basic information to design soil management options to improve land productivity. **Conclusions:** The salinity and sodicity levels, and the amounts of TN, available P, and micronutrients in the studied soils, were within a range that can significantly affect plant growth. Therefore, the results confirmed that the Metehara sugar estate's soils fall into a highly saline-sodic category, requiring appropriate management strategies for sustainable crop production.
Key words: Metehara; physicochemical properties; salt; soil; soil type.

RESUMEN

Antecedentes: Comprender el comportamiento de los suelos salinos es crucial para recomendar prácticas de manejo adecuadas que mejoren la salud del suelo y la productividad de los cultivos. **Objetivo:** Caracterizar los suelos salinos

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de la plantación azucarera Metehara, en el Valle del Rift Central de Etiopía. **Metodología:** Se abrieron dos pedones representativos. Tras describir los atributos morfológicos del suelo, se recolectaron muestras de cada horizonte identificado para su análisis en el laboratorio. **Resultados:** Se observaron variaciones en las propiedades del suelo entre los pedones estudiados. La clase textural del suelo en ambos pedones varía de franco arenoso a franco arcilloso limoso. En el pedón MZ-50-1, los valores de densidad aparente están entre 1.2 y 1.3 g cm^{-3}, mientras que en el pedón MZ-50-2, varían de 1.2 a 1.4 g cm^{-3}. A 20 cm de profundidad, la conductividad hidráulica saturada varía de una tasa lenta (3.74 µm s^{-1}) en el pedón MZ-50-2 a una tasa moderada (4.86 µm s^{-1}) en el pedón MZ-50-1. En los suelos del pedón MZ-50-1, el pHe varió de 8.2 a 9.1, la CEe varió de 9.5 a 13.6 dS m^{-1}, y la ESP varió de 28.4 a 37.2%. En contraste, el pedón MZ-50-2 exhibió un pHe que varió de 7.8 a 8.5, CEe de 10.4 a 14.0 dS m^{-1}, y ESP de 30.2-40.4%. El contenido de carbono orgánico del suelo, nitrógeno total, P disponible, valores de CIC y CIC-arcilla en el pedón MZ-50-1 y el pedón MZ-50-2 variaron de 0.5 a 1.6% y 0.6 a 2.0%; 0.04 a 0.12% y 0.05 a 0.15%; 3.9 a 6.75 mg kg^{-1} y 4.9 a 7.6 mg kg^{-1}; 12.9 a 21.9 Cmolc kg^{-1} y 11.2 a 24.4 Cmolc kg^{-1}; y 71.4 a 117.8 Cmolc kg^{-1} y 58.3 a 110.7 Cmolc kg^{-1}, respectivamente. **Implicaciones:** Las diferencias podrían sugerir que se busca la fertilidad y recuperación del suelo en cada sitio, y los resultados podrían proporcionar información básica para diseñar opciones de manejo del suelo que mejoren su productividad. **Conclusiones**: Los niveles de salinidad y contenido de Na, así como las cantidades de TN, P disponible y micronutrientes en los suelos estudiados, se encontraron dentro de un rango que puede afectar significativamente el crecimiento de las plantas. Por lo tanto, los resultados confirmaron que los suelos de la plantación azucarera de Metehara se clasifican en una categoría altamente salino-sódica, lo que requiere estrategias adecuadas de recuperación y manejo para una producción agrícola sostenible.
Palabras clave: Metehara; propiedades fisicoquímicas; sal; suelo; tipo de suelo.

INTRODUCTION

Soil is a precious resource that must be managed properly to ensure long-term agricultural production and ecosystem services (Pereira *et al.,* 2018; Amita-Raj *et al.,* 2019; Shah and Wu, 2019). However, soil resource degradation due to improper management is a serious problem in almost every developing country, where a significant part of the population depends on soil for their livelihoods (Sileshi *et al.,* 2020; Wassie, 2020; Rai *et al.,* 2023). Although irrigation significantly increased crop production in many lowland areas across the world, it can also be a cause of soil salinization and/or sodification, threatening agricultural land productivity (Yang *et al.,* 2023). In Sub-Saharan Africa (SSA), the effects of soil salinization and/or sodification increased from 19 million ha (Tully *et al.,* 2015) to 69 million ha (Kebede, 2023). Salinity and/or sodicity of soils are prevalent largely in the lowlands of Eastern Africa, along the coast of Western Africa, the countries of the Lake Chad Basin, and in pockets of Southern Africa (Kebede, 2023). Irrigated farmlands affecting salinity (>5 dS m^{-1}) have recently been mapped using remote sensing and soil data in four Ethiopian regions (30% Afar, 6% Oromia, 9% Amhara, and 2.71% Tigray) (Qureshi *et al.,* 2019).

In the late nighty sixteenth, a total of 134,121 ha of irrigated agriculture was started in Ethiopia's Awash basin (Awulachew, 2019), which included large-scale (79,065 ha), medium-scale (24,500 ha), and small-scale (30,556 ha) irrigation, wherein the Metehara sugar estate farm is the largest and most prominent example. This estate farm is utilized mainly for sugarcane production with poor irrigation water management, such as unmeasured irrigation water application with respect to crop needs and a poor drainage system, which is a significant cause of soil salinity and/or sodicity (Megersa *et al.,* 2009; Afework, 2018). Cane yields have declined dramatically over time as a result of this problem, with a severely salinized 6% (779.59 ha), a moderately salinized 20% (2474.03 ha), and a slightly salinized 24% (2999.31 ha) (Afework, 2018). Accordingly, one of the major bottlenecks to attaining optimum crop production is salinity and/or sodicity, particularly in irrigated soils of Ethiopia's main Rift Valley (Qureshi *et al.,* 2019; Daba and Qureshi, 2021). In general, soil salinity and/or sodicity reduce plant growth and affect soil properties by limiting water availability to plants; specific ions toxicity; imbalance plant nutrition; alteration of soil physical properties and effect composition and activity of beneficial soil microorganisms (Hopmans *et al.,* 2021). Therefore, the reclamation of soil salinity and/or sodicity is very crucial to developing different options for their optimal utilization (Daba, 2015; Zaman *et al.,* 2018; Qureshi *et al.,* 2019; Daba and Qureshi, 2021).

As a result, understanding how soil salinity and/or sodicity characterization is critical, as it provides essential information on soil properties necessary for assessing the reclamation of soil salinity and/or sodicity as well as evaluating soil fertility (Ukut *et al.,* 2014; Fekadu *et al.,* 2018). This understanding ultimately contributes to improving the productivity of affected soils. Furthermore, management and reclamation of salt-affected soils for agricultural purposes are dependent on the salt types (Gupta *et al.,* 2016; Qureshi *et al.,* 2019). Reclaiming sodic and saline-sodic soils requires a different approach than reclaiming saline soils, and the former require an additional cost in purchasing chemical amendments to remove or replace exchangeable sodium from soil colloids (Zaman *et al.,* 2018; Mishra *et al.,* 2019). In general, systematic studies on the characterization of salt-affected soils are critical for taking reclamation measures and recommending appropriate agronomic practices (Gupta *et al.,* 2016; Zaman *et al.,* 2018; Mishra *et al.,* 2019). Furthermore, salt affected soil characterization is essential for closing the gap between fertilizer types and crop nutrient demand; before applying nutrients. It is also necessary to understand the site-specific variability related to nutrient availability as well as identifying management options for marginal soils (Csikós and Tóth, 2023).

Currently, there is very little available information on soils of the Metehara area of Central rift valley of Ethiopia. Some studies conducted in the study areas, were mainly on surface soil assessment (Booker, 2009; Afework, 2018) and characterization of soil management groups for their physical and hydraulic properties (Teshome and Kibret, 2014). For these reasons, it is critical to conduct site-specific characterization of salt-affected soils to collect appropriate information for proper reclamation and management practices. As a result, there is a need to characterize salt-affected soils at Metehara Sugar Estate in Ethiopia's Central Rift Valley, which will be valuable in determining the area's total production potential and identifying the factors that likely limit production. Therefore, this study was carried out to characterize the physical, chemical, and morphological properties of salt-affected soils at Metehara Sugar Estate and examine their major constraints to crop production, and to suggest useful management options to improve their productivity.

MATERIALS AND METHODS

Site description

The study was conducted at Metehara Sugar Estate, Central Rift Valley of Ethiopia (Figure 1), which is situated between 8˚75' to 8˚89' North latitudes and 39˚82' to 40˚00' East longitudes, with an elevation ranging from 910 to 982 meters above sea level. The climate of the study area is classified as warm semi-arid agroecological zone (MoARD, 2005). Based on meteorological station data collected from the Metehara sugar plantation between 1985 and 2022, the mean annual rainfall is 549 mm, with annual average minimum and maximum temperatures of 17 and 33 °C, respectively (Figure 2). The annual reference crop evapotranspiration (ETo) was calculated to be 2059.6 mm, with daily reference crop evapotranspiration ranging from 5 to 6.2 mm. This implies that evapotranspiration is by far greater than rainfall and the need to supplement irrigation water for the growing of different crops.

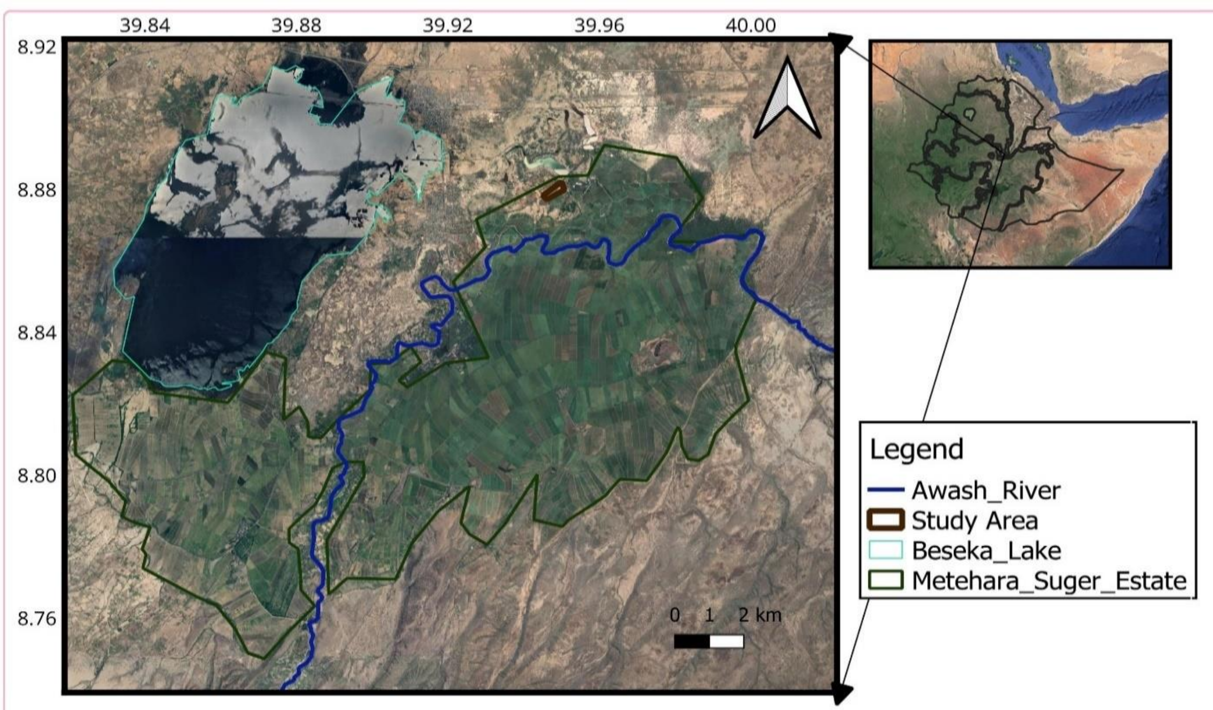

Figure 1. Locations map of Metehara sugar estate, Central Rift Valley, Ethiopia (The shape file is adapted from Afework (2018) and the image used is from Google Earth accessed on May 2, 2024).

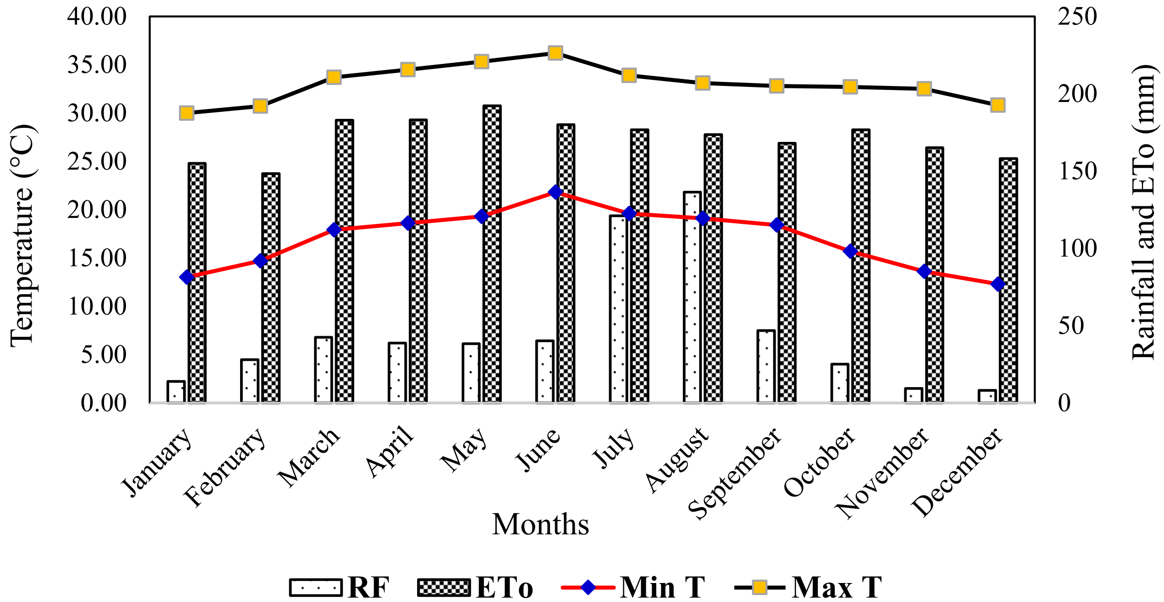

Figure 2. Thirty-five years' mean monthly rainfall, reference crop evapotranspiration (ETo), and monthly minimum (Min) and maximum (Max) temperatures at Metehara Sugar Estate.

The major geologic materials for soil formation in the Metehara sugar estate are alluvium parent materials mainly from mixture of volcanic materials (predominantly peralkaline in composition) and ancient alluvial soils laid down by river systems (MoWR, 1999), as presented in Table 1. These geological materials are responsible for the formation of Cambisols, Solonchaks, Vertisols and Solonetz soil types, which are the most common soil types in the study area (Booker, 2009).

Sugarcane is the main crop grown in this area; while fruit trees such as *Citrus sinensis (L.), Mangifera indica*, *Citrus limon*, and *Citrus paradisi* are also the widely grown horticultural crops (Table 1). This estate farm has 10,230 hectares of irrigated land with intensive cultivation year-round through full irrigation capacity (ESIG, 2023). Irrigation water is drawn from the Awash River via two diversion weirs and intake head-works located at Metehara (4 m^3/s) and Abadir (8.3 m^3/s) (Awulachew, 2019). The application of unmeasured irrigation water to farm land resulted in rising groundwater levels close to the surface, making farm areas prone to secondary salinization and to poor sugarcane plantation (Afework, 2018), as indicated in Table 1. In general, a combination of two or more of the above factors highly aggravated the distribution of salt affected soils.

Site selection, pedon description and soil sampling

The study site was selected purposively because of the prevalence of soil salinity and/or sodicity problems. Representative pedons were selected based on information obtained from the farm manager, and field and soil auger observations. Soil auger observations were implemented using 'Edelman auger' to identify variation in soil depth and texture characteristics. Points with the same soil depth and texture classes were considered as a pedon. Accordingly, two representative pedons were excavated for soil profile description following the IUSS Working Group WRB (2022) standard. Additionally, a total of 270 soil samples were collected from three soil depths (i.e., 0-20, 20-40, and 40-60 cm) from ninety (90) auger sampling points after diving the total area, 20250 m^2, by 225 m^2 (i.e., a 15 x 15 m grid cell) (Figure 3).

Table 1. Selected site characteristics of representative soil pedons.

Pedons	Coordinates (WGS 84)		Altitude (m)	Slope gradient	Parent material	Soil drainage	Land use	Human influence	Soil salinity and/or sodicity distribution	
	Northing	Easting							Cover (%)	Thickness
MZ-50-1	8.87991°	39.94957°	968	FS	QU	PD	A	FI	61 %	C
MZ-50-2	8.88110°	39.94934°	968	FS	QU	VPD	A	FI	70 %	C

FS = Flat Surface; QU = Undifferentiated Quaternary volcanic parent material; PD = poorly drained; VPD = Very poorly drained; A = agricultural (horticultural crops); FI = flood irrigation; C = thick

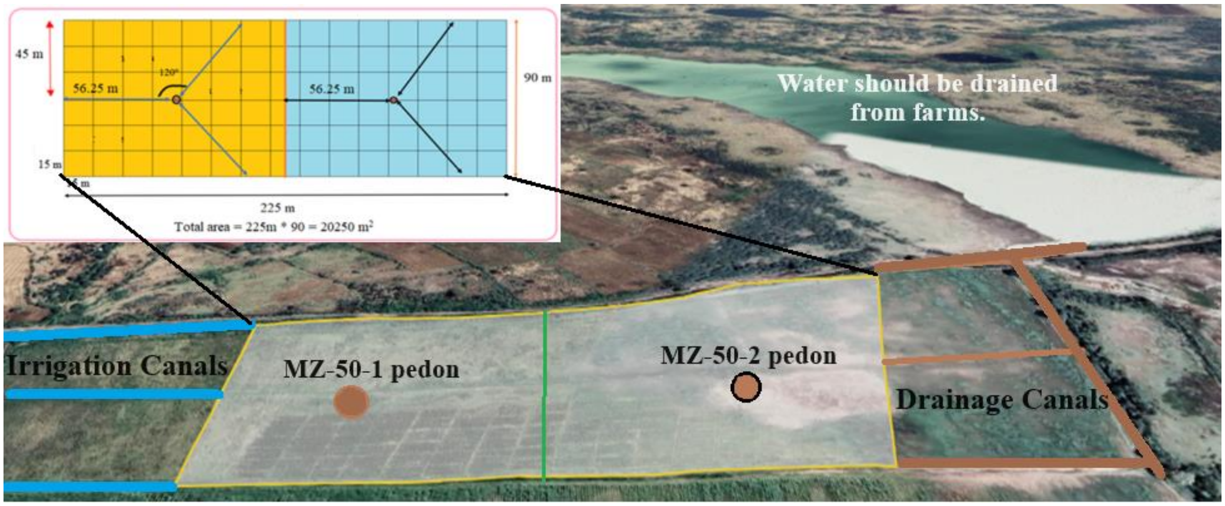

Figure 3. Pictorial representation of composite soil sample areas around the pedons (The image used is from Google Earth accessed on May 2, 2024).

The effect of irrigation water entering and exiting the field on the physicochemical characteristics of the soil can be observed through the identification of pedons MZ-50-1 (from the irrigation water entering side) and MZ-50-2 (from the irrigation water exiting side) (Figure 3). There was slightly more soil drainage from the irrigation water entering side of the MZ-50-1 pedon than from the water draining side of the MZ-50-2 pedon (Table 3). The soil pedons were geo-referenced using Global Positioning System (GPS). Soil samples were separately collected from the entire area of identified soil horizons for characterization of the salt-affected soils. Undisturbed soil samples were also collected using a core sampler to determine bulk density. Soil color (dry and moist) was determined using the Munsell color chart (Munsell, 2009). Other soil morphological features including field texture, structure, consistence as well as size and abundance of roots were determined following the guidelines for soil description (IUSS Working Group WRB, 2022). The collected soil samples were then bagged and labelled before being transported to the laboratory for further analysis.

Laboratory analysis

The soil samples were processed and analyzed using standard laboratory procedures at soil and water laboratories of Werer Agricultural Research Center and Hawassa University. Soil samples were air-dried and crushed to pass through a 2 mm sieve for soil physicochemical analysis, with the exception for the determinations of total N and OC, where the samples were further passed through a 0.5 mm sieve.

Soil physical analysis

Particle size distribution was determined by the Bouyoucos hydrometer method (Bouyoucos, 1962) and the soil textural class was determined using a textural triangle (Ditzler *et al.,* 2017). Bulk and particle densities were determined by core method (Blake and Hartge, 1986) and pycnometer (Blake, 1965) methods, respectively. The total soil porosity was calculated from the values of bulk density (ρ_b) and particle density (ρ_s) (Hillel, 2004).

$$\text{Total porosity (f) (\%)} = \left[1-\frac{\rho_b}{\rho_s}\right] \text{ x } 100$$

where; ρ_b = bulk density (g cm^{-3}) and ρ_s = particle density (g cm^{-3})

Soil-water characteristics were measured at a depth of 100 cm, which is dependent on the root depth of the main crop grown in the study area, such as the sugarcane plantation. Soil-water retention characteristics were determined using a sand box (-1 and -10 kPa) and pressure plate apparatus at different potential points (suction heads) to develop soil-water retention curve (pF curve) (Hillel, 2004). Water retention at field capacity (FC) and permanent wilting point (PWP) were measured at -1/3 and -15 bars soil water potential, using pressure plate apparatus as described by Gupta (2004); and the plant available water content (PAWC) was computed by subtracting the values of permanent wilting point percentage from the field capacity. Saturated hydraulic conductivity was determined in field using the Guelph permeameter (Model 2800 KI) apparatus (Reynolds and Elrick, 1985).

The distribution of soil aggregate sizes was determined from the dry sieving methods (Elliott, 1986). Soil samples were collected from the 0-20 cm soil layer and air-dried for two weeks before being passed through an 8 mm sieve to determine soil aggregate sizes after removing coarse plant residues, roots, and stones from the prepared soil sample (CIMMYT, 2013). Two hundred gram from the prepared air-dried soil samples were used for determination of soil aggregate size distribution at different sieve sizes of >5, 5-3, 3-2, 2-1, 1-0.5, 0.5-0.25, 0.25-0.1, 0.1-0.075, and < 0.075 mm. The whole series of sieves were mechanically sieved in a shaker for 3 minutes at 240 rpm (Børresen and Haugen, 2003). The mass of aggregates retained on each sieve was measured and summarized separately for large macro-aggregates (> 2.0 mm), macro-aggregates (size 2.0 – 1 mm), small macro-aggregates (1–0.25 mm), and micro-aggregates (< 0.25 mm) in accordance with the categories defined by Briar *et al.* (2011).

A widely used index for aggregate size distribution of salt-affected soils were expressed by the mean weight diameter (MWD), and then the mass of aggregate is expressed as percentage of the mass of the samples taking from the dry sieving (Hillel, 2004). The MWD was calculated from dry aggregate separates to get a parameter of aggregate size distribution for each sample (Hillel, 2004).

$$\mathrm{MWD} = \sum_{i=0}^{n} \mathrm{Xi}^{*}\mathrm{Wid}$$

where, Wid is the weight percentage of each aggregate size fraction collected by dry-sieving with respect to the bulk soil, and Xi (mm) is the mean diameter of each aggregate size fraction.

Soil chemical analysis

Soil reaction (pHe), electrical conductivity (ECe) and water-soluble basic cations and anions were determined from soil:water ratio used (1:1) saturated paste extract following the methods described by Allison and Richards (1954) and FAO (1999). Soil pHe was measured potentiometrically with a digital pH-meter (FAO, 1999) and ECe was measured with a digital conductivity meter using the methods described in (Allison and Richards, 1954). Organic carbon was analysed by wet oxidation method as described in (Walkley and Black, 1934). Total N was determined by the Kjeldahl wet digestion and distillation method (Blake, 1965) and available P was determined by the modified Olsen method (Olsen *et al.,* 1954). The ratio of C:N was estimated from obtained values of organic carbon and total nitrogen. The CEC and exchangeable bases were extracted by 1 M ammonium acetate (pH 7) method (van-Reewijk, 1992) and exchangeable Ca and Mg were determined by atomic absorption spectrophotometer (AAS), while exchangeable K and Na were analyzed by flame photometer. A useful way to express the CEC of soils with low organic matter, such as our studied soils, is to divide it by the concentration of clay in the soil (Landon, 2014).

$$\text{CEC clay (cmol}_c\text{/kg)} = \frac{\text{CEC soil}}{\text{\% of clay}} * 100$$

Finally, per cent base saturation (PBS) and exchangeable sodium percentage (ESP) were computed as following:

$$\text{PBS (\%)} = \frac{\text{Exchangeable bases (Ca, Mg, K and Na)}}{\text{CEC}} * 100$$

$$\text{ESP (\%)} = \frac{\text{Exchangeable sodium (Na)}}{\text{CEC}} * 100$$

Where concentrations are in Cmolc kg^{-1} of soil.

Water soluble basic cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) and anions (Cl^{-}, SO_4^{2-}, HCO_3^{-}, and CO_3^{2-}) were measured from a saturated paste extract following the methods described by the US Salinity Laboratory (Allison and Richards, 1954). Soluble Ca and Mg were determined using AAS while flame photometer was used for Na and K measurements. Chloride was determined from the soil-saturated paste extract by titration against 0.1N $AgNO_3$ solution with potassium chromate as an indicator and the concentrations of SO_4^{2-} in soils were determined by precipitation as barium sulfate ($BaSO_4$) (Allison and Richards, 1954). The CO_3^{-} and HCO_3^{2-} ions were determined by titrating with sulfuric acid (H_2SO_4) to phenolphthalein and methyl orange endpoints, respectively (Allison and Richards, 1954). The sodium adsorption ratio (SAR) of the soil solution was calculated from the concentrations of soluble Na^{+}, Ca^{2+}, and Mg^{2+}.

$$\mathrm{SA}R = \frac{\mathrm{Na}^{+}}{\sqrt{\frac{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}}{2}}}$$

Extractable micronutrients (Fe, Mn, Zn, and Cu) of the soils were extracted by the diethylene triamine pentaacetic acid (DTPA) method as described in (Lindsay and Norvell, 1978) and determined using AAS. Soil Boron (B) was extracted by hot-water method and determined by spectrophotometer (Berger and Truog, 1939). Finally, the soils of the study area were classified into the different salt-affected soil classes based on the criteria established by Allison and Richards (1954).

Soil type Identification

Based on the site characteristics and field description of the soil pedons, a preliminary soil type identification was made in the field. Furthermore, soil physical, morphological and chemical properties of the current study area were used for a precise classification of the soil in accordance with the IUSS Working Group WRB (2022).

Statistical analysis

Simple descriptive statistics were used to measure the variability of the soil properties within the horizons of the pedon and standard errors (SE) were used to measure the errors. The soil data from laboratory analyses were subjected to simple correlation analysis to distinguish functional relationships among and within selected soil physicochemical properties with the help of SAS software (Statistical Analysis System (SAS) Institute Inc., 2023). In general, the interpretations were made based on critical values for the respective parameters.

RESULTS AND DISCUSSION

Morphological properties of the soils

The morphological properties of soils; depth, horizon, color, structure, consistence and horizon boundary varied between the two pedons (Figure 3). Both pedons were greater than 1.85 m deep; though groundwater was found below 1.85 m in Pedon MZ-50-2 (Table 2). The groundwater level of MZ-50-1 pedon was deeper than that of MZ-50-02 resulting in higher soluble salt accumulation and lower sodium risks at surface horizons of the former than the latter (Tables 5 and 8), which exhibited higher clay dispersion and favored sodium-loving grasses like *Cynodon dactylon* and *Cypress grass.* In contrast, the MZ-50-2 pedon had increased sub-surface salinity due to shallow groundwater near the surface and more moisture at the surface, which promotes the leaching of soluble salts to the lower soil horizons as compared to MZ-50-1 pedon (Table 5).

The Ap-Bn-Bkn and Ap-AB-Bkn horizon sequence indicates in MZ-50-1 and MZ-50-2 pedons respectively, that factors such as irrigation water, sugarcane residuals, tillage, drainage, and time have contributed to the soil development of this area. Similar finding was reported for the same soil (Booker, 2009). The formation of A-horizons in the soil pedons resulted mainly from the deposition and accumulation of pumice gravels and humified organic matter from sugarcane residue. It was formed by dense subsurface horizons in the soil pedons, particularly the Bkn2 and Bkn3 horizons in MZ-50-1 and MZ-50-2, due to pedogenic features resulting from translocation of soil materials. All horizons in the soil pedons had distinct horizon boundaries but the transitions from A to B horizons were gradual and diffuse with smooth boundaries in the MZ-50-1 and the MZ-50-2 pedons, respectively (Table 2).

The soil color (moist) of the surface horizons was very dark gray (2.5Y 3/1) for the MZ-50-1 pedon and black (10YR 2/1) for the MZ-50-2 pedon (Table 2). Similarly, the subsurface horizons of MZ-50-1 pedon had soil colors (moist) of dark gray (5Y 4/1) to very dark grayish brown (10YR 3/2). whereas the subsurface horizons of MZ-50-2 pedon had moist soil colors of very dark greenish gray (10Y 3/1) to very dark greyish brown (2.5Y 3/2) (Table 2). A brownish to black soil color of the studied soils could be due to the dispersion of soil organic matter and humic substances. Factually, soils with increased sodium levels were called black alkali soils for the reason that a complex of Na-humic substances resulted in their dark color (Rashad *et al.,* 2022). Numerous studies confirm that drainage water promote the ability to mobilize salts and sodium hazards in the saline-sodic soil, directly influencing the soil color (Sharma *et al.,* 2016; Mohamed, 2017; Choudhury, 2021).

The surface horizons exhibited a weak, very fine granular soil structure, whereas different structures including weak to moderate grade, medium to very fine aggregates and angular and sub-angular blocky structures were observed in subsurface horizons (Table 2). Similarly, Jafarpoor *et al.* (2021) reported that the structures of surface horizons were weak to medium, very fine to coarse granular, and also medium subangular blocky in saline-sodic soils of the Urmia plain in the Northwest of Iran. Perhaps the EC to ESP ratio play an important role in regulating soil structure, particularly through their effect on cementing agents between soil particles (Odeh and Onus, 2008). The weak and small granular structure at the surface may indicate the dispersing effect of higher sodium content as compared to the subsurface, especially in the soil MZ-50-2 pedon (Table 2). In general, the EC to ESP ratio showed a stronger relationship with soil particle dispersion scores than ESP, indicating that soil dispersion can be more objectively determined by incorporating the correlation between EC and Na^+ content (Odeh and Onus, 2008; Jafarpoor *et al.,* 2021). Surface horizons in the two pedons showed two to five percent coarse fragments by volume, while coarse surface fragments showed medium size in the two soil pedons. This finding could be attributed to the destructive effect of sodium on soil aggregates through the dispersion of clay particles, resulted for the reduction coarse fragments (Liu and She, 2017).

Table 2. Selected morphological properties of the pedons.

Horizon	Depth (cm)	[1]Coarse fragment		Colour Munsell		[2]Soil structure			[3]Boundary		[4]Soil consistence		
		Abun. (%)	Size	Dry	Moist	Grade	Size	Type	Distinctness	Shape	Dry	Moist	W.
Pedon 1, MZ-50-1 (from irrigation water on the taking side)													
Ap	0-38	2	M	2.5Y 7/1	2.5Y 3/1	W	VF	GR	C	S	SO	LO	SP
Bn	38-70	0	-	7.5YR 7/1	5YR 4/1	W	VF	BS	G	S	LO	FR	NP
Bkn1	70-150	0	-	2.5Y 8/2	2.5Y 4/1	W	VF	BS	C	S	LO	VF	NP
Bkn2	150-200^{+}	5	F	7.5YR 7/8	10YR 3/2	M	ME	BA	-	-	SH	FR	SP
Pedon 2, MZ-50-2 (from irrigation water on the draining side)													
Ap	0-23	2	M	10YR 6/1	10YR 2/1	W	VF	GR	C	S	SO	LO	SP
AB	23-40	5	M	2.5Y 6/2	10Y 3/1	W	FI	BS	D	S	SO	VF	NP
Bkn1	40-75	0	-	2.5Y 7/1	2.5Y 3/1	W	ME	BS	C	S	LO	VF	NP
Bkn2	75-155	0	-	10Y 7/1	5YR 4/2	W	FI	BS	C	S	LO	FR	NP
Bkn3	155-185^{+}	2	F	10YR 5.5/4	2.5Y 3/2	M	ME	BS	-	-	SH	FR	SP

1. **Coarse fragment:** *Size:* - M = Medium; F = Fine
2. **Soil structure:** *Grade:* - W = Weak; M = moderate
   Size: - VF = Very fine; FI = Fine; ME = Medium
   Type: - GR = Granular; BA =Angular blocky; BS = Sub-angular blocky
3. **Boundary:** *Distinctness:* - C = Clear; G = Gradual; D = Diffuse
   Shape: - S = Smooth
4. **Soil consistence:** *Dry:* - LO = Loose; SO = Soft (very weakly coherent and fragile); SH = Slightly hard
   Moist: - LO = Loose; VF = Very friable; FR = Friable
   Wet plastic: - NP = Non-plastic, SP = slightly plastic

The surface soil showed a soft consistency when dry, a loose consistency when moist, and a slightly plastic consistency when wet in the two soil pedons (Table 2). Likewise, the subsurface horizons had loose to slightly hard (dry), loose to friable soil (moist) and non-plastic to slightly plastic (wet) consistence (Table 2). They have slightly harder dry soil consistency than other surface horizons due to the high clay content in the Bkn2 horizon of the MZ-50-2 pedon and the Bkn3 horizon of the MZ-50-1 pedon. An excess concentration of exchangeable calcium or sodium in soil colloids affects the degree of cohesion or adhesion of the soil mass (Taghizadehghasab *et al.,* 2021). Researchers found that friability decreased in high-sodium soils, like the studied soils, due to poor physical properties, such as increased bulk density and reduced soil aggregates, leading to loss of workability (Liu and She, 2017; Taghizadehghasab *et al.,* 2021).

Soil physical characteristics

Particle size distribution

The sand proportion was the highest in all horizons of the soil pedons (Table 3). Accordingly, the textural classes of the soils of the study site ranged from sandy loam-to-silty clay loam in the two pedons (Table 3). The sand and clay contents showed an irregular trend with soil depths (Table 3). The possible reason for the predominance of sand is due to the pumice material deposited by alluvial processes and the removal of finer particles by wind showing that these soils are shaped by both geological and climatic factors. In line with this, Mesfin (1998) and Zewdie (2004) also reported that the soils in the Rift Valley areas were highly eroded by wind during dry seasons because of their low structural stability, weak coherence, low bulk density and low moisture retaining capacity. Hailay *et al.* (2000) and Getahun (2009) observed a similar phenomenon in the soils of Abaya Estate Farm in the southern Rift Valley of Ethiopia and the Dirma Irrigation Project in Dessie Zuria and Kalu districts.

The silt-to-clay ratio in the soil pedons ranged from 1.01 to 1.50 for the MZ-50-1 pedon and from 1.10 to 2.84 for the MZ-50-2 pedon (Table 3). The soils in both pedons have a silt-to-clay ratio greater than 1.00, suggesting the parent material is not overly altered by pedogenic processes like chemical weathering (Nwaka, 1990; Yakubu and Ojanuga, 2013). This could be the case for soils derived from alluvium parent materials or soils in environments with relatively stable conditions. As van-Wambeke (1962) reported, the silt-to-clay ratio of the studied pedons is greater than 0.15, indicating a young soil with a high degree of weathering potential.

Bulk and particle densities, total porosity, and soil water retention

The bulk densities of the soils in both pedons ranged from 1.18 to 1.37 g cm^{-3}, but there was no clear trend with depth (Table 3). The highest bulk density values were recorded in the sub-surface horizons Bkn2 of the MZ-50-1 pedon and Bkn3 of the MZ-50-2 pedon (Table 3). On the other hand, the bulk density values of the surface layers (A horizons) ranged from 1.19 to 1.25 g cm^{-3} (Table 3). The bulk density values of the surface layers are within an ideal range for plant growth in mineral soils in accordance with the rating by Hazelton and Murphy (2016). The particle densities of soils varied from 2.47 to 2.60 g cm^{-3} in the two pedons (Table 3). Similar to the bulk density, the particle density data in the two pedons did not indicate a consistent pattern with soil depth. According to various literature sources (e.g. Gerrard, 2000; Brady and Weil, 2017) indicate that particle density is affected by the mineral composition, crystal structure of mineral particles, and organic matter content in soils. The particle density of most mineral soils ranges from 2.60 to 2.75 g cm^{-3} (Hazelton and Murphy, 2016); based on this, particle density values of the soil in the two pedons were below critical. In general, high pumice mineral compositions in the soils of the present study might have reduced the bulk and particle density values, due to their lightweight and porous nature (Arbelo *et al.,* 2006; Bache *et al.,* 2008; Panagos *et al.,* 2024).

The soil porosity in the studied soil pedons varied from 45.63 to 54.09% (Table 3). The variation in total porosity could be due to changes in soil bulk and particle density values. The lowest soil total porosity values were recorded in the subsurface horizons of the pedons (Table 3). It is the texture of the soil that determines the range of total porosity that is going to affect soil properties and root growth. Sands with less than 40% pore space can restrict root growth because of their excessive strength (Licida *et al.,* 2024). In contrast, clay soils can have higher limits on total porosity, with values below 50% being a rough approximation for restriction, as indicated by (Harrod, 1975). As a result of the above criteria, the studied soils have an optimal soil porosity for root growth. A similar result was reported by (Arbelo *et al.,* 2006) in pumice-derived saline-sodic soils with Anthracambids soil properties on the southeastern slopes of Tenerife (Canary Islands).

Table 3. Selected physical properties of the studied soils in Metehara Sugar Estate, Central Rift Valley of Ethiopia.

Horizons	Depth	PSD (%)			ST	Silt/clay	SD (g cm^{-3})		TP	SMC (vol. %)		AW
	(cm)	Sand	Silt	Clay			BD	PD	(%)	FC	PWP	(mm/m)
Pedon 1, MZ-50-1 (from irrigation water on the taking side)												
Ap	0-38	52.93	23.66	23.41	SCL	1.01	1.22	2.60	53.07	28.49	13.55	149.4
Bn	38-70	59.41	24.06	16.53	SCL	1.45	1.19	2.54	53.15	23.71	10.87	128.4
Bkn1	70-150	63.26	19.15	17.59	SL	1.09	1.25	2.59	51.74	-	-	-
Bkn2	150-200^{+}	49.98	29.99	20.03	L	1.50	1.34	2.54	47.24	-	-	-
Mean		56.40	24.22	19.39	-	1.26	1.25	2.57	51.30	26.10	12.21	138.90
SE		3.02	2.22	1.53	-	0.12	0.03	0.02	1.39	2.39	1.34	10.50
Pedon 2, MZ-50-2 (from irrigation water on the draining side)												
Ap	0-23	45.93	32.04	22.03	L	1.45	1.21	2.47	51.01	28.64	13.42	152.2
AB	23-40	46.63	27.90	25.42	SCL	1.10	1.25	2.51	50.20	26.71	12.85	138.6
Bkn1	40-75	51.78	28.84	19.38	L	1.47	1.18	2.57	54.09	24.65	11.99	126.6
Bkn2	75-155	53.62	32.00	14.38	SL	2.84	1.31	2.54	48.43	-	-	-
Bkn3	155-185^{+}	44.08	32.18	23.74	L	1.35	1.37	2.52	45.63	-	-	-
Mean		48.41	30.59	20.99	-	1.64	1.26	2.52	49.87	26.67	12.75	139.13
SE		1.82	0.92	1.93	-	0.31	0.03	0.02	1.40	1.15	0.42	7.39

SE = Standard error; PSD = Particle size distribution; ST = soil texture; SD = soil density; BD = bulk density; PD = particle density; TP = total porosity; SMC = soil moisture content; FC = field capacity; PWP = permanent waiting point; AW = available water; SCT = silty clay loam; SL= sandy loam; L = loam

At field capacity (-33 kPa), the volumetric soil water content of the effective root zone for sugarcane ranged from 22.71 to 28.64%, whereas it ranged from 10.87 to 13.55% at permanent wilting point (-1500 kPa) (Table 3). According to the correlation analysis (Table 7), bulk density was significantly correlated with water content at field capacity (r=-0.69*) and permanent wilting point (r=-0.62*). As bulk density decreases and vice versa, this negative correlation implies that water retention at these two points increases. From the correlation matrix, it is evident that bulk density had a less significant effect on water content at permanent wilting point. Furthermore, OC (r = 0.82** and r = 0.71**) were strongly associated with field capacity and permanent wilting point soil water content, respectively, but ESP (r = -0.73* and r = -0.62*) had a negative correlation with field capacity and permanent wilting point soil water content respectively (Table 7). Soil organic carbon and ESP influenced soil water retention, especially high affect water on content at field capacity due to their hydrophilic and hydrophobic properties, as well as their respective positive and negative effects on soil structure (Singh *et al.,* 2023).

The available water holding capacity, between FC and PWP, of the surface layers were 149.4 mm m^{-1} for the MZ-50-1 pedon and 152.2 mm m^{-1} for the MZ-50-2 pedon (Table 3). Thus, as soil textures become finer, the amount of potentially plant-available water increases, particularly in soils containing silt plus clay. The available water of the subsurface layers 128.4 mm m^{-1} for the MZ-50-1 pedon and 126.6 to 138.6 mm m^{-1} for the MZ-50-2 pedon (Table 3). The soils of the two pedons were categorized as medium (120 - 180 mm m^{-1}) according to Landon (2014) established irrigation suitability ratings.

The soil water retention characteristic curves for the two soil pedons, the volumetric water contents at different heads were plotted against the specific matric potential values as indicated in the Figure 4. The dehydration process showed that the soil water contents decreased as the matric suction increased in the two pedons. In the lower suction range (pF <1), the soil water retention capacity was non-significantly changed between soil horizons of the two pedons, whereas in the higher suction range (pF = 1.7–2.5), the soil water retention capacities were changed among soil horizons of the two pedons (Figure 4). Overall, the soil water retention capacities of the MZ-50-1 pedon were relatively higher than those of the MZ-50-2 pedon in most of soil horizons under a given matric suction in the lower matric suction range. In contrast, the higher matric suction region of soil water retention capacities in the MZ-50-1 pedon sharply declined than in the MZ-50-2 pedon in most soil horizons. In general, at high matric potentials, soil water retention increased with increasing ESP because sodium disperses soil particles, resulting in increased interlayer and adsorptive surfaces (Chaganti and Crohn, 2015). This result could be associated with sodium's deteriorating effect on soil structure, which causes clay particles to disperse and reduce structural stability.

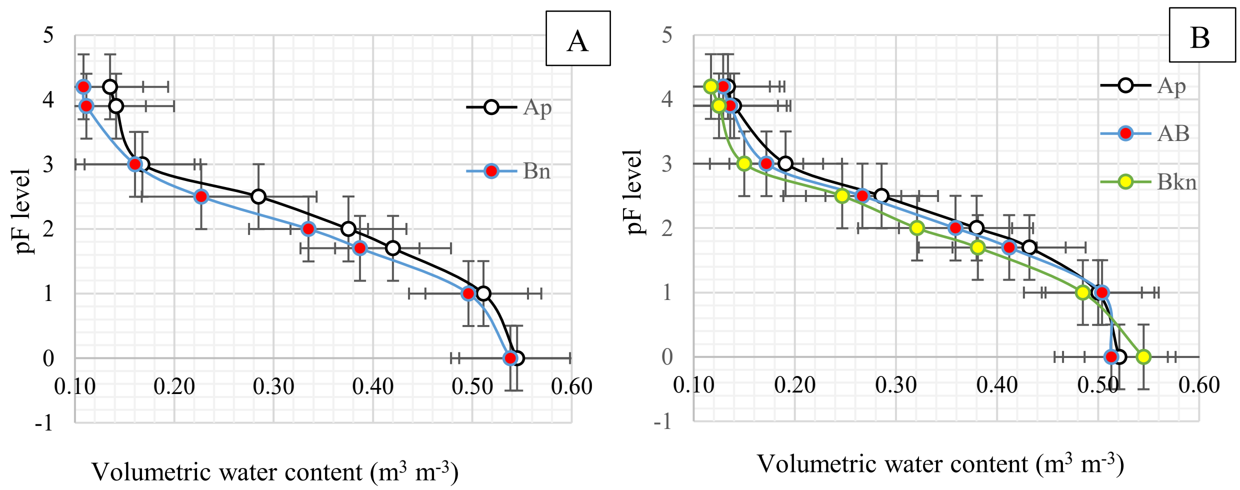

Figure 4. Soil-water retention characteristic curves of the MZ-50-1 (A) and the MZ-50-2 (B) soil pedons.

Soil aggregate and hydraulic conductivity

Soil grain sizes less than 2 mm dominated the aggregate size distribution in the topsoil (0 – 20cm) of the two pedons (Figure 5). Based on aggregate size categories defined by (Briar *et al.,* 2011), the large macro-aggregates (size > 2.0 mm) ranged from 14.80 to 16.03% and the macro-aggregates (size 2.0 – 1 mm) varied from 18.18 to 21.90% (Figure 5). Similarly, the small macro-aggregate (1 – 0.25 mm) ranged from 37.12 to 41.80%, while the micro-aggregate, silt, and clay fractions (<0.25 mm) ranged from 24.95 to 25.19% (Figure 5). The small aggregate size (< 1 mm) in the surface soils accounted for 62.07 to 67.00%, which was greater than the large aggregate size (> 1 mm) that accounted for 33.00% to 37.93%. This could be due to the higher ESP value (Table 8) which was large enough to cause pronounced dispersion in the topsoils of the two pedons. In addition, the studied soils have low clay and organic matter contents, which resulted in weakly cemented soil particles and formation of soil aggregates. Several works studying the distribution of organic matter at different soil aggregate size fractions confirmed these conclusions (Okolo *et al.,* 2020; Cao *et al.,* 2021; Du *et al.,* 2022) as well as the clay content affecting aggregate size (Biesgen *et al.,* 2020; Zhai *et al.,* 2021).

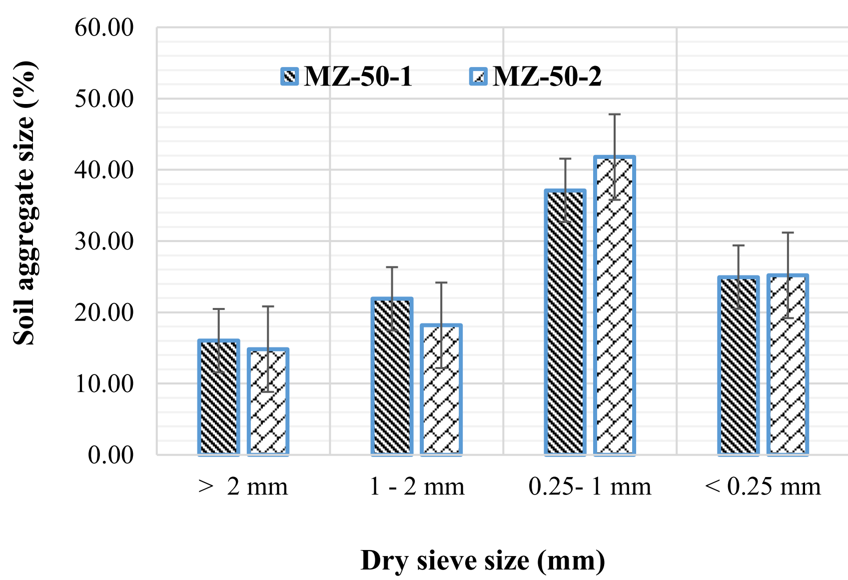

Figure 5. The dry sieve fractions of soil aggregate size of two surfaces (0–20 cm) soils from Metehara sugar estate farm.

The mean weight diameters (MWD) of soil aggregate size of the two top soils (0-20 cm) ranged from 1.46 mm for Pedon MZ-50-2 to 1.55 mm for Pedon MZ-50-1 (Table 4). Results showed that MWD decreased with increasing ESP due to negative effects of sodium on soil structure in agreement with (Emdad *et al.,* 2004); while increasing of EC diminished the effect of the ESP and increased soil structural stability. Studies conducted by Emdad *et al.* (2004), Gorakhki (2015) and Taghizadehghasab *et al.* (2021) showed that an increase in ESP to EC ratio results in the reduction of macroaggregates. For example, the lowest values of MWD (0.210 mm and 0.293 mm in sandy loam and clay loam soils, respectively) were observed in the soils treated with EC 0.2 dS m^{-1} and SAR 12 due to higher presence of sodium (Taghizadehghasab *et al.,* 2021). In general, MWD in dry-sieved aggregate indicates the soil's relative stability to external factors such as high sodium hazards and low organic carbon and clay content.

The saturated hydraulic conductivity (SHC) of the upper 20 cm soil depth ranged from 3.74 µm s^{-1} for Pedon MZ-50-2 to 4.86 µm s^{-1} for Pedon MZ-50-1 (Table 4). Based on USDA-NRCS (2020) soil health classification system, the topsoil (0-20 cm) of the two pedons had moderately slow flow. This might have been due to slaking of the detached heavy texture particles and the breakdown resulting in the clogging of pores to some extent during flow (Hillel, 2004), increasing the resistance to water flow into the soil pore spaces. Additionally, the studied soil had a high ESP/ECe ratio that ensures soil dispersion, which resulted in markedly decreased saturated hydraulic conductivity values (Bache *et al.,* 2008). In general, several researchers (Hillel, 2004; Bache *et al.,* 2008) found the similar results with the current finding.

Table 4. Mean weight diameter (MWD) and saturated hydraulic conductivity (SHC) of two surfaces soils from Metehara sugar estate farm.

Pedon	Soil depth (cm)	Mean weight diameter (mm)	HC (µm s^{-1})
MZ-50-1	0-20	1.55	4.86
MZ-50-2	0-20	1.46	3.74
Mean		1.51	4.30
SE		0.05	0.56

SE = Standard error

Soil chemical properties

Soil reaction (pHe) and electrical conductivity (ECe)

The pHe values (1: 1) soil to water ratio of saturated soil paste extracts differed across soil horizons of the two soil pedons (Table 5). Based on the rating by Jones (2003), the pHe of the surface soil of the MZ-50-1 (8.22) and MZ-50-2 pedons (8.18) were moderately alkaline. In similar rating, the pHe of the sub-surface soils ranged from moderately alkaline to strongly alkaline in the MZ-50-1 soil pedon while the range was from slightly alkaline to moderately alkaline in the MZ-50-2 pedon (Table 5).

Table 5. Soil reaction (pHe), electrical conductivity (ECe), water-soluble cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) and anions (CO_3^{2-}, HCO_3^-, SO_4^{2-} and Cl^-) and sodium adsorption ratio (SAR) of the soils of Metehara sugar estate.

Horizon	Depth (cm)	pHe	ECe (dS m^{-1})	Soluble cations (meq/l)				Soluble anions (meq/l)				SAR
				Ca^{2+}	Mg^{2+}	Na^+	K^+	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	
Pedon 1, MZ-50-1												
Ap	0-38	8.22	13.64	5.99	0.66	28.77	1.00	0.88	20.67	73.22	39.02	22.30
Bn	38-70	8.54	9.51	3.25	0.77	34.17	0.82	0.91	8.82	67.50	37.50	34.08
Bkn1	70-150	9.05	10.47	2.78	0.25	27.96	0.54	1.00	9.53	54.50	29.83	32.12
Bkn2	150-200+	8.33	12.60	3.67	0.15	32.01	0.79	0.64	10.84	84.73	44.49	31.76
Mean		8.54	11.56	3.92	0.46	30.73	0.79	0.86	12.47	69.99	37.71	30.07
SE		0.18	0.95	0.71	0.15	1.44	0.09	0.08	2.77	6.28	3.03	2.64
Pedon 2, MZ-50-2												
Ap	0-23	8.18	10.43	4.65	0.41	34.51	1.33	0.85	16.96	82.64	61.67	30.68
AB	23-40	8.45	11.80	4.82	0.67	42.37	0.84	0.84	9.57	72.40	46.93	36.17
Bkn1	40-75	8.09	13.58	6.07	0.25	36.30	0.63	0.46	4.09	51.90	31.58	28.88
Bkn2	75-155	8.08	13.06	1.80	0.17	21.15	0.94	0.52	5.53	68.25	44.50	30.13
Bkn3	155-185+	7.81	14.05	2.17	0.12	17.43	0.56	0.78	6.12	79.10	74.73	23.04
Mean		8.12	12.58	3.90	0.32	30.35	0.86	0.69	8.45	70.86	51.88	29.78
SE		0.10	0.66	0.82	0.10	4.74	0.14	0.08	2.31	5.36	7.45	2.10

SE = Standard error

A slightly lower alkaline pHe was recorded in the sub-surface of MZ-50-2 pedon, the irrigation water exiting/draining side, compared to MZ-50-1 pedon, the irrigation water entrance side. The main reason for the lower pHe value could be due to high moisture throughout the whole soil horizons of MZ-50-2 pedon and shallow ground water as compared to MZ-50-1 pedon. This promotes leaching of soluble salt in the bottom soil depth and leached soluble salt accumulation in the groundwater (Gebrekidan, 1985), lowering the pHe of MZ-50-2 pedon soil, as compared to the MZ-50-1 pedon.

This might also be attributed to the relatively high amount of sodium compared to the other basic cations such as Ca^{2+} and Mg^{2+}, which was expressed as an increase in ESP or SAR value with an increase in soil pHe, especially in the subsurface of MZ-50-1 pedon. Pearson's correlation matrix also showed soil reaction (pHe) was significantly and positively correlated with ESP (r = 0.62*) (Table 7), whereas it was negatively correlated with ECe (r = -0.63*). The results of this study were in agreement with those reported by different authors (Ghafoor *et al.,* 2004; Mukungurutse *et al.,* 2018).

The electrical conductivity (ECe) of the soils determined in 1 to 1 (soil water ratio of saturated paste extract) is the most commonly used method for determining salt in soils. The ECe of the soils ranged from 9.51 to 14.05 dS m^{-1} (Table 5). According to the rate developed by (FAO, 1988), the soil ECe values obtained from the two studied pedons were classified as high to very high soil salinity class for most crops. The ECe values decreased irregularly with depth in the soil of MZ-50-1 pedon but increased with depth in the soil of MZ-50-2 pedon.

This high ECe is exacerbated by poor irrigation practices, unmeasured and excess application of irrigation water, and a lack of an appropriate drainage system, which resulted in rising groundwater levels close to the surface, making farm areas vulnerable to secondary salinization. Furthermore, the expansion and intrusion of Lake Beseka, which is sodic (Na 1758 to 1196.3 mg/l) and saline (EC 4934.2 to 6745.0 µs/cm) at different flow rate (Shishaye and Asfaw, 2020), into the Metehara estate farm might have resulted in the formation and expansion of salt-affected soils, primarily in the Abadir and northern sections of the estate farm (Booker, 2009; Afework, 2018).

Organic Carbon, Total Nitrogen, Carbon to Nitrogen Ratio and Available Phosphorus

The soil organic carbon (OC) content in the 0 to 75 cm depth of the two pedons ranged from 0.98 to 2.04% (Table 6). Based on classifications by Tadese (1991), the soil organic carbon contents in the pedons could be classified as low to medium. In the topsoil, the MZ-50-2 pedon had higher soil organic carbon content when compared to the MZ-50-1 pedon. This is due to the substantially increased sodicity of the MZ-50-2 pedon in the topsoil layer, which might have induced soil particle dispersion and anaerobic conditions, lowering oxidation of organic matter and increased soil organic carbon.

Table 6. Organic carbon (OC), total nitrogen (TN), carbon to nitrogen ratio (C:N), and available phosphorus (Av. P) contents of the soils of Metehara sugar estate.

Horizon	Depth (cm)	OC (%)	TN (%)	C:N	Av. P (mg kg^{-1})
Pedon 1, MZ-50-1					
Ap	0-38	1.62	0.123	13.11	6.75
Bn	38-70	0.98	0.078	12.56	5.24
Bkn1	70-150	0.47	0.037	12.70	4.37
Bkn2	$150\text{-}200^{+}$	0.52	0.048	10.83	3.92
Mean		0.90	0.07	12.30	5.07
SE		0.27	0.02	0.50	0.62
Pedon 2, MZ-50-2					
Ap	0-23	2.04	0.150	13.60	7.58
AB	23-40	1.53	0.131	12.75	6.92
Bkn1	40-75	0.98	0.089	11.01	5.84
Bkn2	75-155	0.79	0.078	10.13	5.98
Bkn3	$155\text{-}185^{+}$	0.58	0.053	10.94	4.85
Mean		1.18	0.10	11.69	6.23
SE		0.27	0.02	0.64	0.47

SE = Standard error

Table 7. Pearson's correlation matrix for various soil physicochemical parameters.

	BD	FC	PWP	pHe	ECe	Ex. Ca	Ex. Mg	Ex. K	ESP	OC	TN	Av. P	CEC	Fe	Cu	Zn	Mn
BD	1																
FC	-0.69*	1															
PWP	-0.62*	0.78**	1														
pHe	-0.31^{NS}	-0.52^{NS}	-0.44^{NS}	1													
ECe	0.47^{NS}	0.63*	0.45^{NS}	-0.63*	1												
Ex. Ca	-0.63*	0.84**	0.63*	-0.51^{NS}	0.69*	1											
Ex. Mg	-0.51^{NS}	0.42^{NS}	0.50^{NS}	0.02^{NS}	-0.34^{NS}	0.67*	1										
Ex. K	-0.35^{NS}	0.57*	0.64*	-0.17^{NS}	0.56^{NS}	0.64*	0.67*	1									
ESP	0.65*	-0.73*	-0.62*	0.62*	-0.40^{NS}	-0.61^{NS}	-0.19^{NS}	-0.55^{NS}	1								
OC	-0.59^{NS}	0.82**	0.71*	-0.15^{NS}	-0.61^{NS}	0.65*	0.61^{NS}	0.69*	-0.69*	1							
TN	-0.57^{NS}	0.67**	0.60^{NS}	-0.21^{NS}	-0.63*	0.62*	0.59^{NS}	0.73*	-0.66*	0.96**	1						
Av. P	-0.54^{NS}	0.59^{NS}	0.66*	0.77*	-0.50^{NS}	0.55^{NS}	0.67*	0.60^{NS}	0.64*	0.74*	0.67*	1					
CEC	-0.71*	0.80**	0.74*	-0.06^{NS}	-0.46^{NS}	0.86**	0.59^{NS}	0.64*	-0.05^{NS}	0.68*	0.61^{NS}	0.76*	1				
Fe	-0.71*	0.68*	0.58^{NS}	-0.36^{NS}	-0.35^{NS}	0.70*	0.49^{NS}	0.60^{NS}	-0.26^{NS}	0.73*	0.72*	0.65*	0.67*	1			
Cu	-0.64*	0.71*	0.65*	-0.47^{NS}	-0.29^{NS}	0.61^{NS}	0.54^{NS}	0.65*	-0.54^{NS}	0.68*	0.63*	0.59^{NS}	0.62*	0.74*	1		
Zn	-0.46^{NS}	0.77*	0.80**	-0.32^{NS}	-0.09^{NS}	0.69*	0.38^{NS}	0.61^{NS}	-0.11^{NS}	0.78**	0.66*	0.53^{NS}	0.67*	0.71*	0.67*	1	
Mn	-0.57^{NS}	0.48^{NS}	0.37^{NS}	-0.63*	-0.25^{NS}	0.46^{NS}	0.54*	0.55^{NS}	-0.14^{NS}	0.65*	0.59^{NS}	0.48^{NS}	0.63*	0.46^{NS}	0.71*	0.79**	1

* = significant at $P < 0.05$; ** = significant at $P < 0.01$; NS = non-significant; BD = bulk density; FC = field capacity; PWP = premiant waiting point; ECe = Electrical conductivity; Ex. Ca = exchangeable calcium; Ex. Mg = exchangeable magnesium; Ex. K = exchangeable potassium; ESP = Exchangeable sodium percentage; OC = organic carbon; TN = total nitrogen Av. P = Available phosphorus; CEC = Cation exchange capacity; Fe = Iron; Mn = manganese; Zn = Zinc and Cu = Cupper.

The results of this research were consistent with the review paper by (Datta *et al.,* 2019) in the major salt-affected soils of irrigated areas around the world. Soil organic carbon decreased with increasing depth in the studied pedons, with the exception of the top layer of the soil MZ-50-1 pedon (Table 6). In general, the study soils are severely affected by salinity and/or sodicity, which reduces plant growth and root biomass. Additionally, complete removal of sugarcane residue result in a decrease of soil organic carbon (Datta *et al.,* 2019). The findings of this study are in agreement with the results reported by van-Noordwijk *et al.* (1997) and Datta *et al.* (2019).

The total nitrogen in the soils of the two pedons ranged from 0.037 to 0.15%, indicating that the soils have low total nitrogen contents (EthioSIS, 2014). It was also observed that the total nitrogen content of both soil pedons decreased with depth, as was the case with soil organic carbon (Table 6). As indicated in Table 7, TN is positively correlated with OC (r = 0.96, $p < 0.001$) and clay content (r = 0.65, $p < 0.05$) but negatively correlated with ECe (r = -0.63, $p < 0.05$) and ESP (r = -0.66, $p < 0.05$). The main reasons for the low N status of the soils of the study areas could be due to i) volatilization loss of N in the form of ammonia which is likely to occur in alkaline soils (Wu *et al.,* 2023); ii) low input of organic matter in salt-affected soils (Rao and Batra, 1983); iii) high leaching losses of N in the form of NO_3 under saline soil (Nacide *et al.,* 2013); iv) induced biological stress on microbial assemblages that resulted in smaller and less efficient microbial communities for nitrogen mineralization (Zhang *et al.,* 2023).

The present finding is supported by different reports (Rao and Batra, 1983; Nacide *et al.,* 2013; Zhang *et al.,* 2023). Soils with high salt content like the studied soils can indeed lead to a nitrogen deficiency for crops. Soils with less than 0.07% total N tend to have limited potential for nitrogen mineralization, while significant amount of nitrogen mineralization for the next crop cycle would likely occur in those exceeding 0.15% TN (Hartz, 2007). Based on this, it seems that the studied soils fall within the low nitrogen mineralization potential range. Thus, devising an appropriate strategy to supply nitrogen fertilizer is crucial for supporting and enhancing crop productivity in such challenging soil conditions.

The carbon to nitrogen ratio (C:N) showed narrow variation among the soils of the two pedons (Table 6). In general, the C:N values were between 10.13 and 13.60 showing an optimal range of mineralization accordance with the ratings of (Brust, 2019). However, there is an irregular variation in the carbon-to-nitrogen ratio (C:N) with increasing soil depth, indicating that the recognized horizons are subjected to different conditions of mineralization (Table 6). This is similar to the findings by Gebrekidan and Negassa (2006) where the C:N ratio varied markedly with increasing soil depth. High concentrations of salts in soils results in decreased microbial respiration which alters microbial nitrogen (N) and carbon (C) mineralization (Pathak and Rao, 1998; Yousif and Mubarak, 2009).

The available phosphorus content of the soils in the pedons ranged from 3.92 to 7.58 mg kg^{-1} (Table 6), indicating a low available P content the soils across horizons (Cottenie, 1980). Available P content showed non-systematic patterns of distribution with depth and did not show any clear pattern of variability among soils of studied pedons. This low phosphorous content in the soils could be due to lack of phosphorus fertiliser application and complete removal of sugarcane residues from the fields for more than 55 years. In addition, the studied soils were derived from extrusive volcanic materials like pumice that can have very high phosphate-fixation properties (Rechberger *et al.,* 2021). The findings of this study are in line with the reports by Havlin *et al.* (1999) and Booker (2009). The low P content of the soils could be one of the major soil fertility limiting factors in the area. Therefore, any economical agricultural production would require raising the available P content of the soils through various P management methods, such as fertilization and/or organic material applications.

Cation exchange capacity, exchangeable bases, and base saturation

The cation exchange capacity (CEC) of the soils in the two pedons ranged from 11.23 to 24.39 Cmolc kg^{-1} (Table 8). The CEC of the soils generally showed decreasing trend with soil depth in both pedons. Similar results were reported by Gao and Chang (1996) from the same site. The soils in the pedons have higher proportions of sand than clay particles, resulting in lower negatively charged sites that facilitate the adsorption and retention of cations. The low organic matter content observed in the studied soils (Table 6) also leads to a decrease in negatively charged sites. Based on the rating by Hazelton and Murphy (2016), the CEC values of the studied soils could be classified as low to medium, which result in poor to medium nutrient retention and buffering ability of the soils. On the other hand, the CEC of the clay varied from 58.34 to 117.79 cmolc kg^{-1}, indicating a higher proportion of 2:1 clay minerals, most likely sodium and calcium montmorillonite, as suggested by Ismadji *et al.* (2015). Generally, CEC clay is a very important soil property influencing soil structure stability, nutrient availability, soil pH, and the soil's reaction to fertilizers and other ameliorants (Hazelton and Murphy, 2016).

Table 8. Cation exchange capacity (CEC), exchangeable bases (Ca, Mg, K and Na), Ca:Mg, K:Mg, ESP and base saturation of soils in the pedons of Metehara sugar estate.

Horizon	Depth (cm)	CEC ($cmol_c \cdot kg^{-1}$) Soil	Clay	Ex. basic cations ($cmol_c \cdot kg^{-1}$) Ca	Mg	Na	K	Ca:Mg	K:Mg	ESP (%)	PBS (%)
Pedon 1, MZ-50-1											
Ap	0-38	21.85	93.77	11.45	1.92	6.19	1.77	6.00	0.91	28.41	97.61
Bn	38-70	19.47	117.79	9.01	1.88	7.25	0.87	4.79	0.46	37.24	97.64
Bkn1	70-150	12.89	73.28	5.98	1.02	4.46	0.76	5.86	0.75	34.60	94.80
Bkn2	$150\text{-}200^{+}$	14.31	71.44	6.30	1.15	5.24	0.95	5.48	0.83	36.62	95.32
Mean		17.13	89.07	8.19	1.49	5.79	1.09	5.53	0.74	34.22	96.34
SE		2.12	10.83	1.28	0.24	0.60	0.23	0.27	0.10	2.02	0.75
Pedon 2, MZ-50-2											
Ap	0-23	24.39	110.71	12.51	1.97	7.98	1.44	6.35	0.73	32.72	97.99
AB	23-40	22.34	87.88	10.27	1.47	9.03	1.16	6.99	0.79	40.42	98.16
Bkn1	40-75	19.81	102.22	8.66	1.63	6.13	0.95	5.31	0.58	30.94	87.68
Bkn2	75-155	11.23	78.09	4.97	1.00	3.39	0.83	4.97	0.83	30.19	90.74
Bkn3	$155\text{-}185^{+}$	13.85	58.34	7.18	0.84	4.10	0.73	8.55	0.87	29.60	92.78
Mean		18.32	87.45	8.72	1.38	6.13	1.02	6.43	0.76	32.77	93.47
SE		2.50	9.20	1.29	0.21	1.08	0.13	0.64	0.05	1.98	2.05

SE = Standard error

The results revealed that the contents of exchangeable Ca and Mg varied from 4.97 to 12.51 and 0.84 to 1.97 $cmol_c\ kg^{-1}$, respectively, whereas exchangeable K varied from 0.73 to 1.77 $cmol_c\ kg^{-1}$ (Table 8). According to the ratings established by FAO (2006), the exchangeable Ca and Mg contents of the soils in the pedons could be classified as medium to high and low to medium, respectively, whereas that of K could be categorised as high to very high. The variation in exchangeable basic cations in the soils might have been due to the differences in clay minerals and soil organic carbon contents (Brady and Weil, 2017). Also, the combination of volcanic materials (per-alkaline in composition plus ancient alluvial soils) for soil formation and the aridity (high evapotranspiration exceeding rainfall) of weather conditions could be responsible for net accumulation rather than leaching of cations.

The exchangeable basic cations on the soil matrix were in the order Ca > Na > Mg > K, and the amount of exchangeable sodium is greater than 15% of the cation exchangeable sites, resulting in poor soil structure (Yang *et al.,* 2023). The Ca:Mg ratio ranged from 6.00 to 6.35 in the surface soils (Table 8). In general, Ca:Mg ratio above 5:1 may induce Mg deficiency while values lower than 3:1 may result in Ca deficiency while both inhibit P availability (Hazelton and Murphy, 2016; Kibret *et al.,* 2023). On the other hand, K:Mg ratio of the soil ranged from 0.46 to 0.91 (Table 8). According to (Loide, 2004), a K:Mg ratio greater than 0.70 threshold indicates the presence of an adequate amount of potassium in the soil to meet its requirement for plant growth.

The exchangeable sodium constituted more than 28% of the cation exchangeable capacity across the studied soil pedons (Table 8) surpassing the critical threshold of 15%. According to (Hazelton and Murphy, 2016) classification system, there exists a serious sodicity problem in the studied soils. The percent base saturation (PBS) in the soil pedons ranged between 87.67 to 98.16 % (Table 8). This high base saturation is likely due to less precipitation compared to evapotranspiration at the site, causing an accumulation of basic cations in the upper soil layers. Based on (Brady and Weil, 2017) ratings, the PBS of the soils is very high indicating low level of basic cations leaching owing to lack of quality irrigation water.

Water-soluble cations, anions and sodium adsorption ratio (SAR)

Sodium was the dominant water-soluble cation followed by calcium, potassium and magnesium in decreasing order in all horizons of the pedons (Table 5). Similarly, Cl^- was the dominant anion throughout the pedons followed by SO_4^{2-}, HCO_3^- and CO_3^{2-} (Table 5). The consistent increments of Cl^-, SO_4^{2-} and HCO_3^- anions matched with ECe and soluble Na in the MZ-50-1 and MZ-50-2 soil pedons (Table 5). Chloride, sulphate and bicarbonate anions as well as sodium and calcium cations were the major contributor ions for the development of salinity and/or sodicity in the studied soils of Metehara sugar estate.

The sodium adsorption ratio (SAR) is a useful index of the soil sodicity in terms of the relative concentration of water soluble sodium to the proportions of water soluble calcium and magnesium concentrations in soil solution (Gregorich and Carter, 2007). The amount of SAR in soil-saturated paste extract ranged from 22.30 to 36.17 (Table 5). The SAR values across the studied pedons were greater than the critical threshold (Brady and Weil, 2017). This results in dispersion of soil particles and preventing the formation of soil aggregates (Hazelton and Murphy, 2016).

Micronutrients

The available micronutrient contents (Fe, Mn, Zn, Cu, and B) of the soil decreased irregularly with soil depth in the pedons (Table 9). In accordance with the ratings of Jones (2003), the concentrations of available micronutrients were: Fe low to medium; Mn low to very low; Zn low to very low; Cu low to medium and B medium to high (Table 9). The deficiencies of Fe, Mn, Cu, and Zn are commonly associated with high soil alkalinity and low soil organic matter, as well as excessive irrigation, prolonged wet soil conditions, poor drainage, and soil salinity (Daba, 2015). Mohiuddin *et al.* (2022) reported similar results and showed the significant influence of soil texture, alkalinity, organic matter, exchangeable sodium percentage and salinity on the available and mobility of micronutrients in salt affected soils within the arid and semiarid agricultural regions of Pakistan.

The deficiency of the micronutrients might have also resulted from the absence of micronutrient in the fertilizers used, alongside their continuous removal by sugarcane biomass for more 55 years. Sugarcane plantations have specific micronutrient requirements, such as 6 to 10 kg ha^{-1} Fe, 2.5 to 6 kg ha^{-1} Cu, 3 to 6 kg ha^{-1} Mn, and 5 to 8 kg ha^{-1} Zn to achieve optimal production (Spironello *et al.,* 1997; Calheiros *et al.,* 2007; Penatti, 2013). On the other hand, the amount of B in the studied soil pedons was sufficient for supporting plant growth. High B concentrations occur in salt affected soils of arid and semiarid regions with limited rainfall that restricts leaching as was also reported by different authors (Vijayakumar *et al.,* 2011; Mohiuddin *et al.,* 2022) in different salt-affected soils of arid and semiarid agricultural areas.

Available micronutrient concentrations (Fe, Cu, Mn, Zn, and B) declined with increasing soil depths of the studied pedons (Table 9) corroborating previous findings (Macedo *et al.,* 2017; Dhaliwal *et al.,* 2022). This could be attributed to the declining OC with soil depth (Table 6). A positive significant correlation was also observed between all micronutrients with soil OC and CEC (Table 7).

Salinity and Sodicity Characteristics of Soils

Salt-affected soils have high levels of soluble salts, exchangeable sodium, or both, necessitating special remedial measures and management practices (Ghafoor *et al.,* 2004). Salt-affected soils are in general classified as; saline, sodic or saline-sodic, based on their respective electrical conductivity (ECe) and sodium adsorption ratio (SAR) of the saturated paste extracts or the sodium on the exchange sites (exchangeable sodium percentage, ESP) (Allison and Richards, 1954; FAO, 1988). Accordingly, the soils in the study area are saline-sodic, with ECe and ESP values greater than 4 dS m^{-1} and 15%, respectively, in all horizons of the two pedons (Table 10).

Table 9. Available micronutrients (Fe, Mn, Zn Cu, and B) contents of soils of Metehara sugar estate.

Horizon	Depth (cm)	Available soil micronutrients (mg kg^{-1})				
		Fe	Mn	Zn	Cu	B
Pedon 1, MZ-50-1						
Ap	0-38	10.67	7.94	0.98	3.05	2.33
Bn	38-70	7.80	6.80	0.74	1.86	1.43
Bkn1	70-150	5.92	5.34	0.52	2.10	2.08
Bkn2	150-200^{+}	6.13	4.12	0.63	0.94	1.17
Mean		7.63	6.05	0.72	1.99	1.75
SE		1.10	0.83	0.10	0.43	0.27
Pedon 2, MZ-50-2						
Ap	0-23	13.11	5.52	0.96	2.67	2.36
AB	23-40	10.57	6.10	0.88	1.93	2.89
Bkn1	40-75	11.09	3.08	0.53	1.98	1.71
Bkn2	75-155	7.22	3.72	0.47	1.32	0.98
Bkn3	155-185^{+}	5.35	2.35	0.56	1.67	1.34
Mean		9.47	4.15	0.68	1.91	1.86
SE		1.40	0.72	0.10	0.22	0.34

SE = Standard error

Table 10. Characterization of salt affected soils of Metehara sugar estate.

Horizon	Depth (cm)	pHe	ECe	ESP	SAR	Salt affected soils classes
Pedon 1, MZ-50-1						
Ap	0-38	8.22	13.64	28.41	22.30	Saline-sodic soils
Bn	38-70	8.54	9.51	37.24	34.08	
Bkn1	70-150	9.05	10.47	34.60	32.14	
Bkn2	150-200^{+}	8.33	14.60	36.62	31.77	
Mean		8.54	11.56	34.22	30.07	
SE		0.18	0.95	2.02	2.64	
Pedon 2, MZ-50-2						
Ap	0-23	8.18	10.43	32.72	30.68	Saline-sodic soils
AB	23-40	8.45	11.80	40.42	36.17	
Bkn1	40-75	8.09	13.58	30.94	28.88	
Bkn2	75-155	8.08	12.06	32.29	30.13	
Bkn3	155-185^{+}	7.81	14.05	29.60	23.04	
Mean		8.12	12.58	32.77	29.78	
SE		0.10	0.66	1.98	2.10	

SE = Standard error

Identification of the Soil Types of Metehara sugar estate

The soil types of the study area were identified according to 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 grouping. The surface soil of the two pedons exhibited a very fine aggregate size with a granular structure. The surface soil texture of the two pedons varied from silty clay loam to loam, with clay content greater than 10% and 3% above that of the layer directly buried by the layers. The topsoil of the two pedons had a soil organic carbon content of ≥ 0.3% with a weighted average of ≥ 0.5% soil organic carbon with the land surface being raised and a thickness of 20 cm. The surface layers of the MZ-50-2 and MZ-50-1 soil pedons meet the criteria for the Irragric diagnostic horizon and no diagnostic horizon, respectively.

Subsurface horizons of both pedons on the irrigation water entering side (MZ-50-1 pedon) and the water draining side (MZ-50-2 pedon) were greater than 15 cm in thickness, with sandy loam-to-silty-clay-loam soil texture and having in 50% of the layer soil aggregate structure. The subsurface horizon of the MZ-50-1 soil pedon has a saturation extract pHe ≥ 8.5 and ECe ≥ 8 dS m^{-1}, measured at 25 °C. The subsurface layers of the MZ-50-1 soil pedon meet the criteria for the Salic diagnostic horizon, identifying it as a Solonchak soil type (IUSS Working Group WRB, 2022). While the subsurface soil layers of the MZ-50-2 pedon also exhibited more than 1 unit value and chroma of Munsell color (moist) over 90% of their exposed moisture surface area than that of the overlying layer. As a result of the subsurface layers of MZ-50-2 soil pedon fulfilling the criteria for the Cambic diagnostic horizon, it is classified as a Cambisol (IUSS Working Group WRB, 2022).

The soil texture in the two pedons ranged from sandy loam to silty clay loam, with a thickness of ≥ 30 cm found within 100 cm of the mineral soil surface. The soil in both pedons contained more than 15% Na plus Mg and more than 6% Na in the exchange complex, with a thickness of the mineral soil surface greater than 20 cm. Additionally, the ECe of the soils is greater than 4 dS m^{-1} within 100 cm of the soil surface, and the soil has a thickness is greater than 10 cm, beginning at the surface and homogenized through ploughing. The soil's characteristics qualify it for the Loamic and Puffic suffixes identified in the MZ-50-1 pedon, as well as the Loamic, Sodic, Protosalic, and Aric suffixes identified in the MZ-50-2 pedon. Therefore, the soils represented by the MZ-50-1 and MZ-50-2 pedons were identified as Fluvic Sodic Solonchak (Loamic, Puffic) and Fluvic Irragric Cambisols (Loamic, Sodic, Protosalic, Aric), respectively (IUSS Working Group WRB, 2022).

Table 11. Diagnostic horizons, quantifiers, and soil types of Metehara sugar estate according to WRB.

Pedon	Diagnostic horizon		Diagnostic properties	Soil types
	Surface	Sub-surface		
MZ-50-1	-	Salic	-	Fluvic Sodic Solonchak (Loamic, Puffic)
MZ-50-2	Irragric	Cambic	-	Fluvic Irragric Cambisols (Loamic, Aric, Protosalic, Sodic)

CONCLUSION

A field study was carried out to characterize salt affected soils of the Metehara sugar estate, central rift valley, Ethiopia. The results revealed variations in morphological, physical, and chemical properties of the soils across the two pedons, which indicate their variation in productive potential and management requirements for specific agricultural use. Sodium and calcium, as basic cations, along with Cl^{-}, SO_4^{2-}, and HCO_3^{-} anions were the primary ions contributing to salinity and/or sodicity issues affecting plant growth in the studied soil pedons. Soil in the two studied pedons significant limitations on soil aggregate size, saturated hydraulic conductivity, and soil water retention. In the study area, organic carbon, cation exchange capacity, Cu, and Fe levels are low to medium, whereas total nitrogen, available P, Mn, and Zn levels are low to very low. Thus, the soils represented by the MZ-50-1 and MZ-50-2 pedons were identified as Fluvic Sodic Solonchak (Loamic, Puffic) and Fluvic Irragric Cambisols (Loamic, Aric, Protosalic, Sodic), respectively. Moreover, the soils in the study area were classified as saline-sodic soils with high sodium hazards and soluble salts. The extent and nature of the problem differ from plot to plot within the study area; thus, plot-specific soil characterization is crucial for recommending suitable amendments.

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