Hindawi
Applied and Environmental Soil Science
Volume 2020, Article ID 6161059, 16 pages
https://doi.org/10.1155/2020/6161059

Research Article

Explaining Soil Fertility Heterogeneity in Smallholder Farms of Southern Ethiopia

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Received 14 February 2020; Revised 24 March 2020; Accepted 1 May 2020; Published 13 May 2020

Academic Editor: Teodoro M. Miano

Soil is spatially heterogeneous and needs site-specific management. However, soil nutrient information at larger scale in most cases is lacking. Consequently, fertilizer advisory services become dependent upon blanket recommendation approach. Subsequently, it affects yield and profitability. This study is aimed at explaining soil fertility heterogeneity in Wolaita zone, Southern Ethiopia. About 789 soil samples were collected to evaluate soil physical (color, particle size, and bulk density) and chemical properties (pH, OC, N, P, K, Ca, Mg, B, Cu, Fe, Mn, Zn, PBS, and CEC). The laser diffraction method for soil particles and mid-infrared diffused reflectance (MIR) spectral analysis for OC, TN, and CEC determination were employed. Mehlich-III extraction and inductively coupled plasma (ICP) spectrometer measurement were used for the remaining elements. The result based on principal component analysis showed that 52% of the total variations were explained by exchangeable bases, CEC, pH, available P, Cu, B, and particle sizes. Clay texture and acidic soil reaction are dominant. Soil parameters with the following ranges were found at low status: soil OC (0.2–6.9%), total N (0.01–0.7%), available P (0.1–238 mg/kg), S (4–30 mg/kg), B (0.01–6.9 mg/kg), and Cu (0.01–5.0 mg/kg). Besides, low levels of exchangeable Ca, Mg, and K (Mg-induced K deficiency) on 22, 34, and 54% soil samples, respectively, were recorded. The soil contained sufficient Fe, Zn, and Mn. In conclusion, the study aids in developing practical decision for optimum soil management interventions and overcomes lower productivity occurring due to fertilizer use that is not tailored to the local conditions. Overall, continuous cropping, low return of crop residues, and low and/or no fertilizer application might have caused the low status of N, P, K, S, B, and Cu. Therefore, application of inorganic fertilizers specific to the site, lime in acidic soils, and organic fertilizers are recommended to restore the soil fertility and improve crop productivity.

1. Introduction

In this planet, soil is one of the important resources. Healthy soil is key component to the efficient utilization of soil nutrients in the production of food in sustainable manner. Soil properties vary within the farmland or at the landscape scale [1, 2]. The causes for spatial variation are both inherent soil-landscape and human-induced across farms differing in resources and practices [3, 4]. Information on spatial heterogeneity of soil properties within farmland/landscape scale is crucial in determining production constraints and taking appropriate management practices [3].

The livelihood of Ethiopian population is based on agriculture as it supports over 80% of the Ethiopian population [5]. The sector is still characterized by low input and low yield [5, 6]. Having healthy soil has a paramount importance to sustainable livelihood. Nevertheless, studies conducted in different parts of Ethiopia have pointed out that soil-related problems such as erosion [7] and continuous cultivation without addition of external inputs [6–9] have been the major constraints to improving farm productivity and farmer livelihoods.

The soil loss due to erosion in Ethiopian highlands was high, varying between 42 t/ha/yr and 175.5 t/ha/yr [7]. Earlier study on nutrient balance in the country indicated −122 N kg nitrogen (N), −13 kg phosphorus (P), and −82 kg/ha potassium (K) per year [10] signifying large rates of macronutrient depletion. In addition, loss of organic matter

(OM), macro- and micronutrient depletion, acidity, and deterioration of physical soil properties were also reported [8]. This indicates that interventions targeting poor soil fertility must be designed to improve the success of agriculture. In this regard, up-to-date assessments of soil properties at scales relevant for decision-making and management, including properties that are dynamic and hence change in response to management, are needed [11].

Owing to differences in farming topography, soil management practices, inherent soil properties, and biophysical and socioeconomic conditions [4], soil heterogeneity at farm level and in vast areas of agricultural lands is expected to occur. However, at local scale, the information on soil nutrient contents and nutrient availability is limited. Consequently, the soil management interventions are subjected to blanket recommendation approach. The approach is not suitable to farmers as it does not take sufficient layers of complexity into account [4]. Any advice about fertilizers, especially to resource-poor smallholder farmers, needs to consider soil conditions at farm scales in order to maximize yield and profitability. Hence, this study aims to quantify the soil nutrient status of agricultural lands and explain the relationship with soil management practices for improved efficiency of fertilizer advisory services.

2. Materials and Methods

2.1. Description of the Study Area. The study was conducted in three adjacent and potential districts of Wolaita zone, Southern Nations, Nationalities, and Peoples' Regional State (SNNPRS) of Ethiopia, namely, Damot Gale, Damot Sore, and Sodo Zuria (Figure 1). The area is located between 037°35′30″–037°58′36″E and 06°57′20″–07°04′31″N. A total of 82 *kebeles* were surveyed: 31 from Damot Gale, 18 from Damot Sore, and 33 from Sodo Zuria district. The total study area covers about 84,000 hectares (ha). The area has a bimodal rainfall pattern with mean annual precipitation of 1355 mm. The mean monthly temperature ranges from 17.7 to 21.7°C with an average of 19.7°C. The elevation varies between 1473 and 2873 meter above sea level (m.a.s.l.) with mid-highland (1500–2300 m.a.s.l.) agroecology (Figure 2). Eutric Nitisols associated with humic Nitisols are the most prevalent soils in Wolaita zone [12]. These soils are dark reddish brown with a deep profile [13]. Agriculture is predominantly small-scale mixed subsistence farming and is being rainfed. Continuous cultivation without any fallow periods coupled with complete removal of crop residues is a common practice on cultivated fields.

2.2. Soil Sampling Procedure and Laboratory Analysis. Geographical information system (GIS) was employed to randomly assign predefined sampling locations. A total number of 789 preidentified sampling points were generated and displayed over the study area. During survey work, the predefined sample locations were navigated using geographical positioning system receiver (model Garmin GPSMAP 60Cx).

Once the sampling point was navigated, sampling depth was 0–20 cm for tef *(Eragrostis tef* (Zucc.) Trotter*)*, haricot bean (*Phaseolus vulgaris* L.), wheat (*Triticum aestivum* L.), maize *(Zea mays* L.*)*, grazing spp., etc., while it extended to 50 cm for perennial crops such as *enset (Ensete ventricosum)* and *coffee (Coffea arabica* L.*)*. About 10 to 15 subsamples were taken based on the complexity of topography and heterogeneity of the soil type using soil auger, and then one kilogram (kg) composite was taken for laboratory analysis. During sample collection, hot spot areas (manure and crop threshing sites) were excluded. To reduce the potential for cross-sample contamination, the soil auger and other sampling tools were cleaned before taking the next sample at different locations. For soil bulk density determination, undisturbed soil samples using core-sampler were collected.

2.3. Sample Preparation and Soil Analysis. After soil processing (drying, grinding, and sieving), soil physicochemical properties like particle size distribution (PSD), pH, soil organic carbon (OC), macro- and micronutrient contents, and cation exchange capacity (CEC) were analyzed. Particle size distribution, pH, OC, TN, and CEC were analyzed at the National Soil Testing Center (NSTC), Addis Ababa, Ethiopia, while Ca, Mg, K, Na, B, Cu, Fe, Mn, and Zn were analyzed in Altic BV, Dronten, Netherlands.

The soil color (dry) was described using Munsell soil color chart during the noon hours [14]. Soil bulk density (BD) was determined using core method as described by Anderson and Ingram [15]. PSD was analyzed by laser diffraction method using laser scattering particle size distribution analyzer (Horiba, Partica LA-950V2) [16]. A teaspoon of soil (approximately 10 g) sieved through 2 mm was introduced into the dispersion unit of the laser particle analyzer for measurement. The soil sample was run in a wet mode using deionized water and 1% sodium hexametaphosphate (Calgon) solution as dispersing agent. To maintain the random orientation of particles in suspension, automatic ultrasonication was applied. All the required operations were controlled by a personal computer. The LA-950 software version 7.01 for Windows [17] was used to run the analysis. For each sample, four consecutive readings were taken within 15-minute duration. The readings were converted to % (sand, silt, and clay), using the appropriate script on the R language and environment for statistical computing [18]. The fourth reading that was taken after continuous agitation of the particles was considered as final data for the particle size distribution.

Soil pH (1 : 2 soil : water suspension) was measured with a glass electrode (model CP-501) [19]. For soils having pH < 5.5, exchangeable acidity was measured using the method described by Sahlemedhin and Taye [20]. Available P, available S, exchangeable basic cations (Ca, K, Mg, and sodium (Na)), and extractable micronutrients (Fe, manganese (Mn), Zn, Cu, and B) were determined using Mehlich-III multinutrient extraction method [21]. The concentration of elements in the supernatant was measured using inductively coupled plasma (ICP) spectrometer. The available

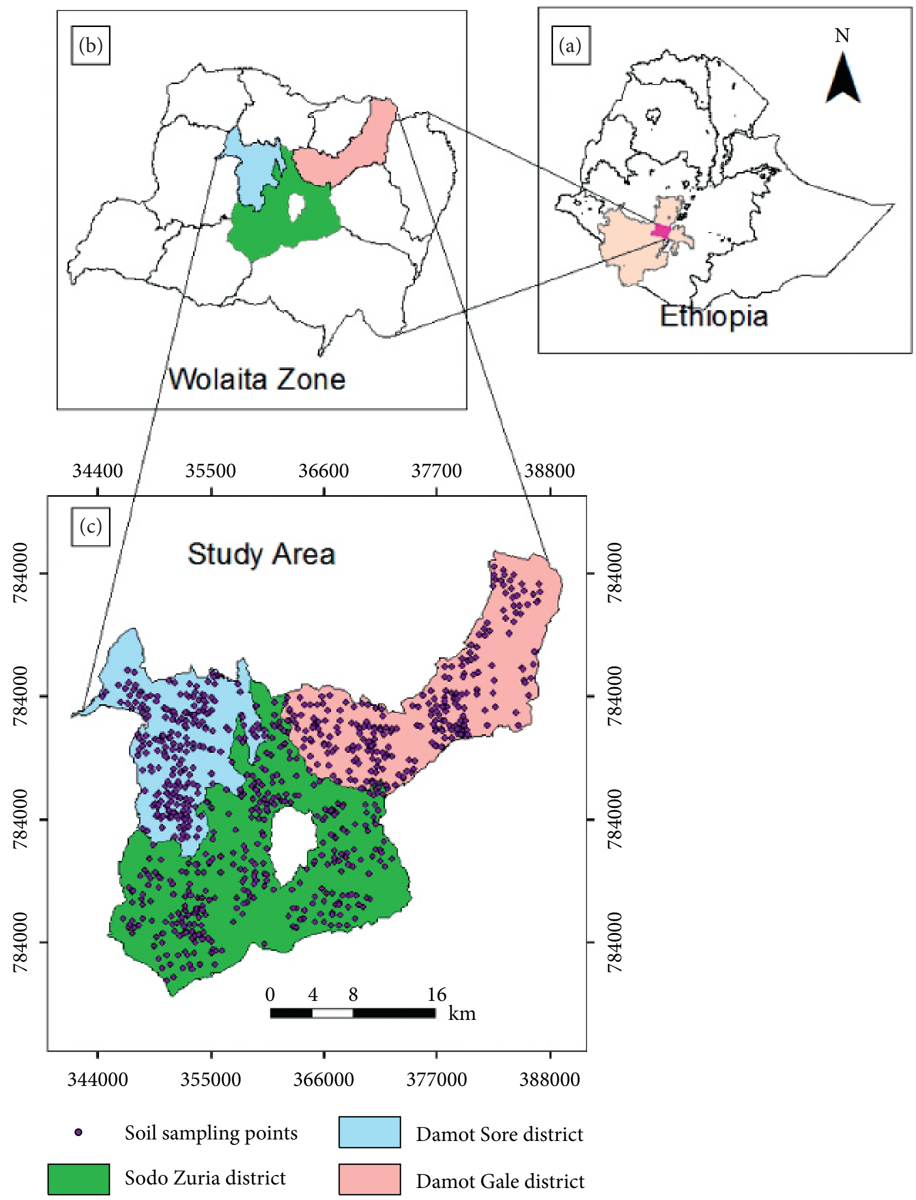

Figure 1: The location map of Wolaita zone in Ethiopia (a), study districts in Wolaita zone (b), and soil sampling points in the study areas (c).

soil Mn content was determined using manganese activity index (MnAI) as described by Karltun et al. [22]:

$$\text{MnAI} = 101.7 - (15.2 * \text{pH}) + 3.75 * \text{Mn\_soil}, \quad (1)$$

where pH is pH (H_2O) and Mn_soil the concentration of Mehlich-III extracted manganese.

The same samples used for wet chemistry were also subjected to MIR spectral analysis to determine the amount of soil OC, total N, and CEC. For MIR spectral analysis, soil samples were ground using Retsch mortar grinder RM 200 to size smaller than 0.5 mm. Soil samples weighing 0.035 g were loaded in a single well, and one sample was loaded in four consecutive wells of an aluminum microplate having 96 wells. The sample surface was gently pressed, leveled, and smoothed using a microspatula (a rounded, smooth surface glass rod). The absorbance of diffused reflectance spectra was scanned using the HTS-XT accessory of a Bruker-TENSOR 27 spectrometer. The background (i.e., soil sample-free well) was scanned using roughened surface well of the aluminum microplate. Absorbance spectra of the entire soil samples were measured using OPUS version 7.0 software [23] with 32 scans and spectral range of 7400–600 cm^{-1} (wave numbers) including part of near infrared (NIR) region. The spectrum acquisition took an hour per plate. The MIR region spectra in the wave number range of 4000–600 cm^{-1} (2500–16667 ηm) were used to predict soil properties. Quantitative analysis of the

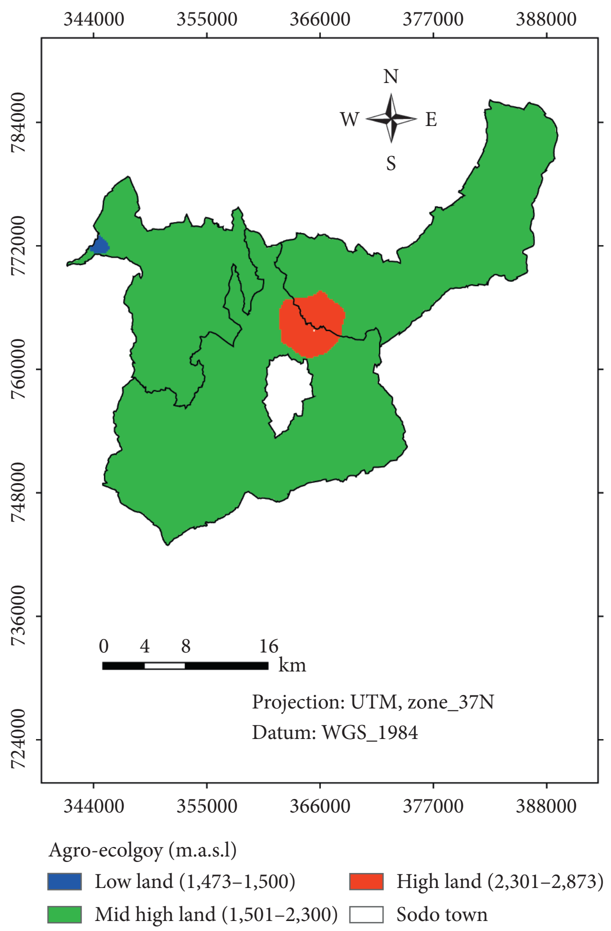

Figure 2: Agroecology of the study area.

spectra was done using Quant 2 evaluation function of OPUS (software version 7) to predict the concentration of OC, TN, and CEC. The average of four consecutive scans of each parameter was taken as predicted data for the report.

2.4. Statistical Analyses. Principal component analysis (PCA) was run to group related soil properties and explain most of the variance with a small set of variables. The Kaiser-Meyer-Olkin measure (KMO) of sampling adequacy was performed prior to PCA. Descriptive statistics such as mean, standard deviation, minimum, maximum, median, and percentage was employed. In addition, analysis of variance test, Pearson's correlation, and regression analyses were performed to evaluate relationships among the soil properties. Variation in soil properties was determined using the coefficient of variation (CV) and rated as low (<20%), moderate (20–50%), and highly variable (>50%) according to Amuyou et al. [24]. For the management purposes, interpretation of the results was given using proper ratings. Data analysis was carried out using Microsoft Excel and Statistical Package for the Social Sciences (SPSS) software version 20.

3. Results and Discussion

3.1. Principal Component Analysis of Soil Properties. The KMO values of PCA were 0.75 for Damot Gale, 0.69 for Damot Sore, 0.69 for Sodo Zuria, and 0.70 overall. The values were above 0.6 indicating that the sample size was adequate to run PCA, and the result is presented in Table 1 and Figures 3(a)–3(d). In Damot Gale district, 57% of the total variation was explained by PCA 1 and PCA 2. In Damot Sore district, PCA 1 and PCA 2 together were able to explain 53% of the total variation. In Damot Sore district, PCA 1 and PCA 2 together were able to explain 53% of the total variation. Overall, the first two components explained 52% of the variance among soil properties, of which component 1 explained 32% while the second explained 20%.

The most important variables accounting for soil variability were exchangeable bases (Ca, Mg, K), CEC, soil pH, available P, Cu, and soil particle size. These variables could be associated with both inherent soil-landscape (e.g., clay mineralogy and topography) and human-induced factors (e.g., soil management practices and land use types) [1, 2, 6, 25, 26].

Nitisols are dominant in the study area in which their clay assemblage is dominated by kaolinite [13]. These clay minerals have pH-dependent charges [27]. Thus, the association between soil pH and increase in CEC might be linked with the presence of pH-dependent charges, probably kaolinite clay mineralogy [27]. The soil pH in the present study also covaried with and influenced CEC, exchangeable bases (Ca, Mg, K), available P, and Cu. This is evidenced by the significant ($p \leq 0.001$) and positive correlation between soil pH and available P ($r = 0.44$), Ca ($r = 0.66$), Mg ($r = 0.52$), K ($r = 0.65$), Cu ($r = 0.27$), B ($r = 0.33$), and CEC ($r = 0.53$). Similarly, Maria and Yost [28] and Joao et al. [29] observed variation in the soil CEC along with soil pH.

Difference in particle size distribution and soil textural classes might be the reason for appearance as an important source of variability. Clay content was found to show a significant and inverse relationship with sand ($r = -0.8$), silt ($r = -0.98$), pH ($r = -0.3$), available P ($r = -0.3$), and Ca ($r = -0.3$). This would imply that the higher clay content might be associated with gradual accumulation of acidic cation such as exchangeable Al, H, and oxides of Al and Fe. This results in P fixation and reduces its availability [2, 30]. Besides, the negative correlation between clay and Ca, according to Tabu et al. [31], indicates the dominance of low activity clay minerals that predispose it to leaching of exchangeable bases.

3.2. Soil Physical and Chemical Properties

3.2.1. Selected Soil Physical Properties. The hue index was 2.5 YR, 5 YR, 7.5 YR, and 10 YR. The value index of most samples was between 3 and 5 whereas chroma was between 3 and 4 (Figure 4). Damot Gale district soil has dominantly brown color whereas soils in Damot Sore and Sodo Zuria districts have shown brown, dark reddish brown, and reddish brown colors. Combining the indices, brown, dark reddish brown, reddish brown, and gray soil colors were observed. Light reflection tends to increase on brown and reddish soil colors and results in increase of color value. Similarly, purity of spectral colors increases

Table 1: Eigen value and explained variances of PCA for the study districts in Ethiopia during 2013.

PCA	Damot Gale			Damot Sore			Sodo Zuria			Total		
	Eigen value	Var (%)	Cum %	Eigen value	Var (%)	Cum %	Eigen value	Var (%)	Cum %	Eigen value	Var (%)	Cum %
1	7	41	41	6	33	33	5	30	30	5	32	32
2	3	16	57	3	20	53	4	21	51	3	20	52
3	2	14	71	2	14	67	2	14	65	2	13	65
4	1	7	78	1	8	75	1	6	72	1	7	72

Var: explained variance; Cum: cumulative variance.

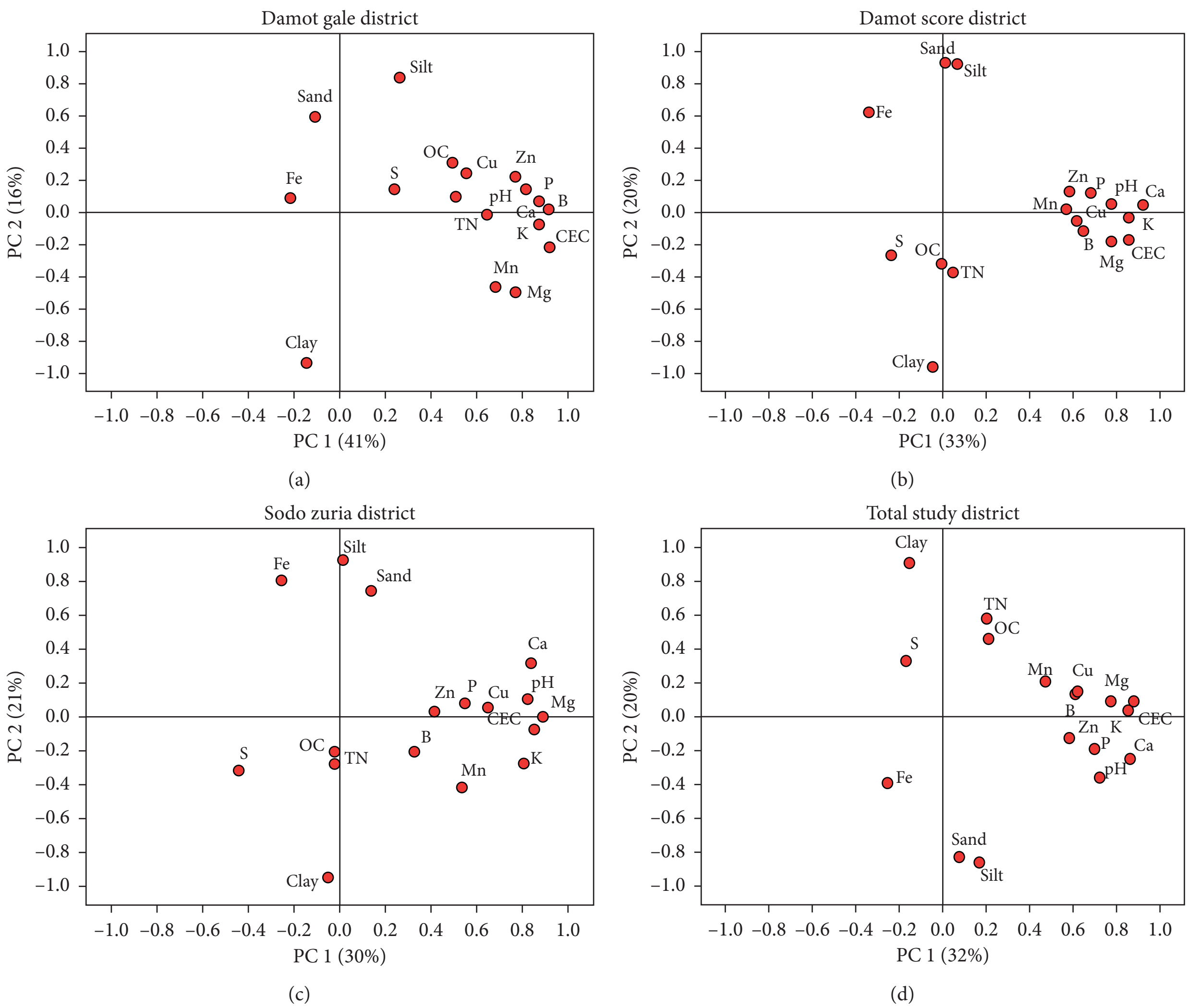

Figure 3: Component plot of soil properties of Damot Gale (a), Damot Sore (b), Sodo Zuria (c), and total study area (d).

with increase in reflection resulting in an increase of the chroma.

The soil colors in the studied soils might reflect the low status of soil OM and influence of oxidized Fe. Higher content of Fe in Nitisols would result in red or reddish brown soil colors [13]. Analogously, Desbiez et al. [32] found higher value and chroma for red and least fertile soils, and lower value and chroma for darker and fertile soils. Though caution is needed, the perception of considering reddish colors as less fertile soil by farmers than the darker soil colors has also been stated by Desbiez et al. [32], Pound and Jonfa [33], and Hailesilase et al. [34].

Results on soil particle size distribution, textural classes, and bulk density (BD) are presented in Table 2. Statistically significant differences ($p < 0.001$) among sampled soils were recorded. The mean particle size distribution was silt > clay > sand (Damot Gale) and clay > silt > sand (Damot Sore and Sodo Zuria). The dominant textural class is silty loam (Damot Gale) and clay (Damot Sore and Sodo Zuria) (Table 2 and Figure 5). The silt/clay ratio was above 0.8

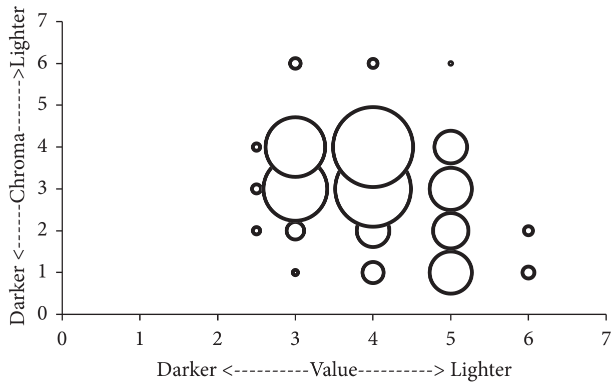

Figure 4: Soil color value and chroma indices of samples collected from Damot Gale, Damot Sore, and Sodo Zuria districts in Ethiopia. The size of each bubble is proportional to the number of samples at the corresponding value/chroma combination.

(Table 2). According to Young [35], a ratio of silt/clay greater than 0.15 indicated young soil, not highly weathered and having easily weatherable minerals. However, soil samples are from Nitisols which are known to have relatively advanced weathering [13]. This implies that the clay in the upper surface soil might have been translocated to the deeper layer or removed by erosion to cause higher silt/clay ratio. In agreement with this, the report of Alemayehu and Sheleme [36] in Sodo Zuria district revealed a high silt/clay ratio with a relative reduction with depth.

The soil bulk density (BD) varied with soil textural classes. Soils with silty loam textural classes had lower BD values than those with clay textural classes. This is evidenced by significant ($p < 0.01$) correlation of BD with silt ($r = -0.44$) and clay (0.43) particles. Soil BD also showed significantly ($p < 0.01$) inverse relation with soil OM ($r = -0.33^*$), which is in agreement with Oguike and Mbagwu [37] and Gajic et al. [38].

Bulk density influences soil physical properties, particularly soil-water movement, aeration, and root proliferation. The soil BD values of the silty loam textured soils varied from 0.76 to 1.48 g/cm^3, whereas on clay textured soils it was from 0.76 to 1.52 g/cm^3. Hazelton and Murphy [39] indicated 1.6 and 1.4 g/cm^3 as critical BD values for loam/clay loam and clay textures, respectively. Thus, soils are satisfactory for plant growth and root restriction because compaction would be less likely to occur.

3.2.2. Soil pH and Exchangeable Acidity. Soil pH ranged from 4.5 (strongly acidic) to 8.0 (moderately alkaline) with low variability among soil samples (CV < 20%) (Table 3). About 21% of total samples had pH < 5.5 (strongly acidic reaction), 53.3% [moderately acidic (5.6–6.5)], 22.7% [neutral (6.6–7.3)], and 3.06% [moderately alkaline (7.4–8.4)] based on EthioSIS [40] ratings. Most nutrients for field crops are available at pH value between 5.5 and 8.0 [41], and the optimal pH for many plant species in absence of free exchangeable Al is 5.5 to 6.8 [42]. Nevertheless, crops can differently adapt below and above optimum pH values.

Generally, the study area is categorized under acidic soil reaction of varying degree. This might be due to the leaching of basic cations, removal of bases by crop harvest, and Al hydrolysis. Various research results showed that basic cations removal through crop harvest [30, 43, 44], leaching due to excessive precipitation, steepness of the topography, application of inorganic fertilizer [44, 45], and mineralization and formation of humic substances [46] were reported as causes for soil acidity formation. Cardelli et al. [47] and Alexandra et al. [48] also indicated that H^+ ion released through nitrification of NH_4^+ sourced fertilizers on cultivated lands might also encourage the development of lower pH.

Under strongly acidic soils, hydrolysis of Al and a sharp increase in exchangeable Al are expected [49]. This process releases H^+ ions that further lower the soil pH to a level that seriously affects the availability of certain nutrient elements, such as P, and increases Al and Fe toxicity. Significant ($p \leq 0.001$) and positive correlation between pH and available P ($r = 0.4$) was also recorded (Table 4).

The exchangeable acidity (cmol (+)/kg) varied from nil to 5.1 whereas the acid saturation (%) ranged from 0 to 21 (Table 3). The exchangeable acidity and acid saturation were higher in clay textured soils than silty loam soils, and the permissible acid saturation (PAS) which is crop tolerance level for annual crops growing in Ethiopian soil is 10% [50]. This value is used for determination of lime rate. Generally, strongly acidic soils should be managed using lime, whereas on moderately acidic soil lime can be applied, but looking for acid-tolerant crop varieties is also suggested.

3.2.3. Soil OC, TN, and Available P and S. The soil OC (%) ranged from 0.2 to 6.9 (Table 5). This may reflect differences in organic matter management. About 48%, 51%, and 1% of soil samples contain very low (<2%), low (2–4%), and moderate (4–10%) OC based on the rating suggested by Landon [41]. The very low to low estimated OC might be due to complete removal of crop residues and no addition of external organic material inputs such as compost or manure. In conformity with this, complete removal of aboveground biomass, continuous tillage, insufficient application of organic inputs, and heavy grazing were reported as the major reasons for extremely low soil OC in Ethiopian soils [2, 6, 26, 51].

The lower soil OC could result in poor aggregate stability and thereby aggravate soil degradation [38] and also influence soil macro- and micronutrient reserves. Using simple aggregate stability estimation equation (% OM × 100/% clay ≤) [52], the soil OM on about 62% of the sampled fields does not contribute to soil aggregate stability. This implies that soil particles are more likely to be detached with erosion. Hence, farming practices that improve soil OC are encouraged.

Total nitrogen varied between 0.01 and 0.7% (Table 5), but most soils contain very low (<0.1) to low (0.1–0.15) TN based on the ratings suggested by EthioSIS [40]. TN followed the trend of soil OC. Pearson correlation matrix shows that OC was positively and significantly correlated with TN ($r = 0.95$) (Table 4). The C to N ratio of soil samples varied

Table 2: Descriptive statistics of particle size distribution, silt : clay ratio, and bulk density for surface soils.

District	Descriptive statistics	Sand	Silt	Clay	Silt : clay ratio	*BD (g/cm^3)	Soil textural classes
Damot Gale ($N = 243$)	Mean	18.4	56.2	25.4	3.2	1.14	Silt loam
	Std. dev	6.6	10.6	13.7	2.1	0.12	
	Median	17.3	58.0	21.7	2.8	1.13	
	Minimum	0.5	17.0	6.1	0.2	0.76	
	Maximum	39.5	78.6	79.9	10.7	1.48	
	CV (%)	36	19	54	66	11	
Damot Sore ($N = 216$)	Mean	12.0	24.7	63.3	0.4	1.23	Clay
	Std. dev	4.1	7.8	11.4	0.2	0.13	
	Median	13.2	24.7	62.1	0.4	1.22	
	Minimum	2.8	7.3	32.5	0.1	1.04	
	Maximum	23.3	47.9	89.7	1.5	1.52	
	CV (%)	34	32	18	50	11	
Sodo Zuria ($N = 331$)	Mean	11.4	21.6	67.0	0.4	1.20	Clay
	Std. dev	4.3	10.0	13.0	0.3	0.13	
	Median	11.5	19.6	69.2	0.3	1.19	
	Minimum	1.3	3.0	28.6	0.03	0.76	
	Maximum	30.8	51.5	95.6	1.8	1.50	
	CV (%)	38	46	19	75	11	
Total ($N = 789$)	Mean	13.7	33.1	53.2	1.3	1.18	Clay
	Std. dev	5.9	18.2	22.6	1.8	0.13	
	Median	13.1	27.5	58.8	0.5	1.17	
	Minimum	0.5	3.0	6.1	0.03	0.76	
	Maximum	39.5	78.6	95.6	10.7	1.52	
	CV (%)	43	55	42	138	11	
	F_{value}	150	1015	827	503.5	18.4	
	p value	0.000	0.000	0.000	0.000	0.000	

*Sample size for BD (bulk density) of Damot Gale = 197, Damot Sore = 42, Sodo Zuria = 193, and total = 432.

from 7 to 41 (Table 5) in which mean ratio was 15 implying that soil OM decomposition proceeded at the maximum rate (if C/N < 25) [39].

The lower TN may be ascribed to complete removal of crop residues, less organic input application, and more intensive cultivation. Frequent cultivation would accelerate the higher oxidation rate of soil OM. In general, the existing input use practices could not compensate for the observed mineralization of OM and N losses. In line with this finding, Abreha et al. [30], Girma and Endalkachew [53], and Tsehaye and Mohammed [54] reported lower soil TN due to intensive cultivation, less input application, and higher mineralization rate in Ethiopian soils.

Organic matter is the main supplier of soil N, S, and P in low input farming systems. Tiejun et al. [55] and Alexandra et al. [48] reported that changes in soil OM could lead to changes in total N. Long-term cultivation without organic fertilizers leads to a decrease in soil OC and total N contents because organic matter accounts for more than 95% of soil N [48, 55]. Hence, gradual build-up of soil OM for ensuring sustainable productivity is recommended.

The available P (AvP) content of soils varied from 0.1 to 238.1 mg/kg (Table 5). Variation in AvP content among samples could be due to differences in acidity, organic matter content, and P fertilizer application differences in the soils. However, 83.9% and 7.3% of soil samples contained very low (<15 mg/kg) and low (15–30 mg/kg) levels of P, respectively, on the basis of EthioSIS [40] ratings. This might be attributed to P fixation in strongly acid soils [30, 56]. Pearson correlation matrix also shows significant ($p \le 0.001$) and positive correlation ($r = 0.44$) between available P and soil pH (Table 4). Decline of P in most cultivated soils of Ethiopia resulted from the impacts of low P fertilizer application rate, massive nutrient depletion through complete crop harvest, low return of crop residues, and soil erosion [6, 30, 51, 53, 57].

In this study, though small, significant ($p \le 0.001$) and positive correlation ($r = 0.14$) is observed between available P and OC (Table 4). Organic materials can be used as soil conditioners due to chelation of Fe and Al (hydr) oxides and corresponding release of OH^-. Apart from this, organic matter is also one of the pools in the soil. Its mineralization can contribute to available P [56]. Low soil OM may therefore imply low available P if other sources are not there. In addition, the available P was found to significantly correlate with Ca ($r = 0.5$), Mg ($r = 0.4$), K ($r = 0.6$), B ($r = 0.4$), Cu ($r = 0.4$), Mn ($r = 0.2$), and Zn ($r = 0.5$) (Table 4). This implies that they have no antagonistic effect on this nutrient. The low P status in this finding indicates the need for application of P fertilizer for soils of the study areas.

Soils of the study area contain low available S (<30 mg/kg) (Table 5) based on the ratings suggested by EthioSIS [40]. The correlation analysis also indicated significantly ($p < 0.001$) negative ($r = -0.35$) and positive ($r = 0.25$) relationship of available S with pH and OC, respectively (Table 4). Different authors associated the lower S content with lower OM, as it is the major source of total S in surface soils [58–61]. In addition, SO_4^{2-} adsorption to Al and Fe oxides at lower pH, increasing cropping intensity

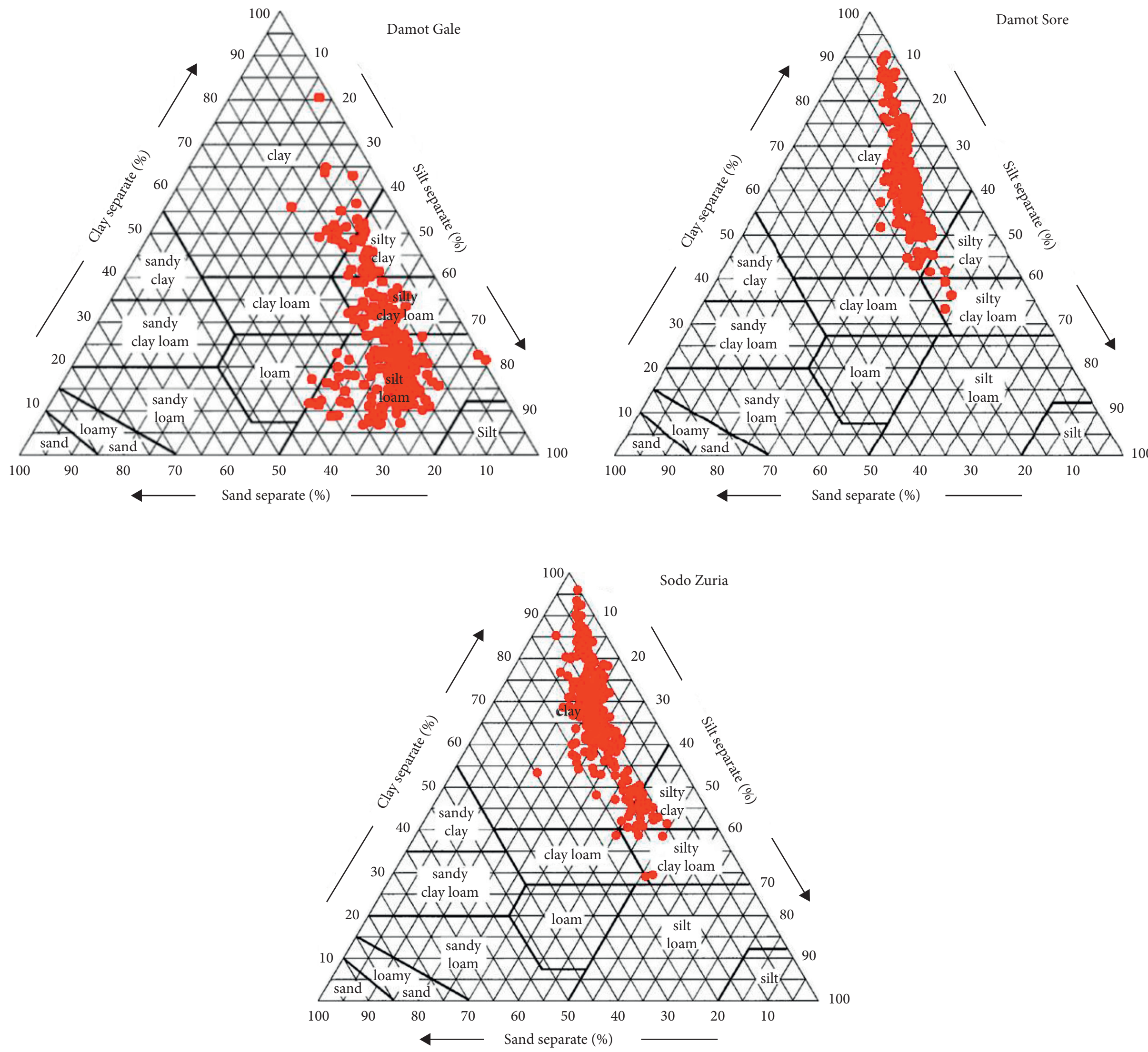

Figure 5: Soil textural classes of the study districts in Ethiopia.

[62], and large S uptake by crops [58] were indicated. Furthermore, nonuse of S fertilizers (until recently), removal of crop residues, leaching losses, and lower application of organic fertilizers [58] were also reported to be causes for low level of S for Ethiopian agricultural lands. Hence, maintaining adequate levels of soil OM and external S application is required for sustainable crop production in the study areas.

3.2.4. Exchangeable Bases, CEC, and PBS. The soil exchangeable bases, CEC, and PBS values of the study areas are presented in Table 6. The distribution on exchangeable bases in the exchange complex has been characterized to be in the order of Ca > Mg > K > Na. This could be related to the charge density as divalent cations (Ca and Mg) have higher affinity towards colloidal sites than monovalent cations (K and Na). Similar arrangement of cations was also reported by Tsehaye and Mohammed [54], Teshome et al. [51], and Okubay et al. [26].

Exchangeable Ca (cmol (+)/kg) across the study area varied from 1 to 31, and exchangeable Mg ranged between 0.2 and 9.5 cmol (+)/kg, whereas exchangeable K and Na varied from 0.1 to 6.2 and 0.1 to 3.1 cmol (+)/kg, respectively (Table 6). Using the ratings suggested by Landon [41], about 1, 21, 54, 23, and 1% of the total samples exhibited very low (<2), low (2–5), medium (5–10), high (10–20), and very high (>20) exchangeable Ca (cmol (+)/kg), respectively. Data regarding exchangeable Mg (cmol (+)/kg) indicated that 0.5, 33.6, 60.8, 4.8, and 0.3% of samples across the study areas qualified to be very low (<0.3), low (0.3–1.0), medium (1.0–3.0), high (3.0–8.0), and very high (>8.0) in exchangeable Mg, respectively, as per the ratings of Landon [41]. Based on the suggestion made to Ethiopian soil [40], the proportion of soil exchangeable K across districts categorized as very low (<0.2), low (0.2–0.5), optimum (0.51–1.5), high (1.51–2.3), and very high (>2.31) was 0.1, 14.7, 57.7, 14.8, and 12.7%, respectively. Additionally, exchangeable sodium percentage values across districts were found below the critical level (15%).

Table 3: Descriptive statistics of soil pH, exchangeable acidity, and acid saturation for surface soils.

Districts	Descriptive statistics	pH (H_2O)	Exc. acidity (cmol (+)/kg)	Acid saturation (%)
Damot Gale ($N = 243$)	Mean	6.4	0.00	0.10
	Std. dev	0.5	0.10	0.60
	Median	6.3	0.00	0.00
	Minimum	5.2	0.00	0.00
	Maximum	8.0	1.30	7.10
	CV (%)	8.0	—	—
Damot Sore ($N = 216$)	Mean	6.0	0.50	2.30
	Std. dev	0.7	1.00	4.70
	Median	5.9	0.00	0.00
	Minimum	4.5	0.00	0.00
	Maximum	7.8	5.10	20.80
	CV (%)	12.0	—	—
Sodo Zuria ($N = 330$)	Mean	5.9	0.40	2.20
	Std. dev	0.6	0.90	4.40
	Median	5.9	0.00	0.00
	Minimum	4.7	0.00	0.00
	Maximum	7.4	4.10	19.50
	CV (%)	10.0	—	—
Total ($N = 789$)	Mean	6.1	0.30	1.60
	Std. dev	0.6	0.80	3.90
	Median	6.1	0.00	0.00
	Minimum	4.5	0.00	0.00
	Maximum	8.0	5.10	20.80
	CV (%)	10.0	—	—
	F_{value}	49.0	26.0	27.0
	p	0.000	0.000	0.000

Numbers in brackets refer to sample size.

Antagonistic effects could exist when disproportionate quantities of exchangeable cations are present in the soil [63]. The Ca/Mg ratio across studied districts using the rating of Eckert [64] has shown low level of Ca (1–4) on 35%, balanced ratio (4–6) on 60%, and low Mg (6–10) on 5% of the samples. The K/Mg ratio has been evaluated with consideration of soil textures, in which it is 1 : 1 for loamy soils and 0.7 : 1 for clay soils [65]. In silty loam textured soils of Damot Gale, the K/Mg ratio varied from 0.2 to 1.6, while the ratio ranged between 0.1 and 1.5 in clay textured soils of Damot Sore and Sodo Zuria district. Accordingly, 47, 57, and 54% of the silty loam soils, clay soils, and total soil samples, respectively, have shown the potential of Mg-induced K deficiency. The observed cation order in the exchange complex (Ca > Mg > K > Na) could also support the existence of Mg-induced K deficiency [63]. Hence, fertilizer containing K is suggested.

In the present study, exchangeable bases showed non-significant and very weak correlation with OC, implying that the contribution of soil OM is low for these elements. Hence, the medium to high contents of exchangeable bases could be associated with the variation of parent material mineralogy [25, 66, 67]. Kibet [25] stated that the variation in Ca and K concentrations is largely related to the variation in mineralogy of parent rock with high source from K-feldspars followed by kaolinite/1 : 1 clays, then quartz, and plagioclase. In addition, Ca and K are presumed to be originating primarily from parent material, i.e., feldspar as reported by USEPA [67] and Kabata- Pendias and Murkhejee [66].

On the other hand, low soil OM, soil erosion, acidic nature of the soil, continuous removal with crop harvest, and lack of K containing fertilizer could explain the low level of exchangeable Ca, Mg, and K in some of the soil samples. In addition, the presence of moderate to high leaching on sampled soil [39] would also result in low exchangeable cation. In line with this finding, Adesodun et al. [68] reported that continuous cultivation led to reduction, uptake, and leaching of exchangeable cations, especially in acidic tropical soils. Furthermore, breakdown of primary minerals, particularly K-feldspars and plagioclase [69], or depletion in well-drained soils over long periods of pedogenic weathering [72] could cause lower Ca and K.

Owing to the differences in soil environment, clay, and soil organic matter contents, variation in cation exchange capacity (CEC) within and among districts was recorded (Table 6). However, the mean values across districts were found to be almost similar. The CEC of soils ranged from 3.3 cmol (+) kg^{-1} in the silty loam soils of Damot Gale to 50.5 cmol (+) kg^{-1} in clay soils of Damot Sore. According to Landon [41], the proportions of soil samples (%) which fall in the very low (<5), low (5–15), moderate (15–25), and high (25–40) CEC content categories were 2, 75, 19, and 4, respectively. Overall, the majority (83%) of the soil samples across districts showed medium CEC values.

Cation exchange capacity is highly influenced by soil pH, OM, and clay particles. The CEC of soil could vary with soil pH, if soil has pH-dependent charge edges [27]. Different scholars also reported an increase in the CEC of soils due to high OM

Table 4: Pearson correlation matrix of soil properties in the studied districts in Ethiopia.

	Sand	Silt	Clay	pH	TN	OC	P	S	B	Cu	Fe	Mn	Zn	Ca	K	Mg	CEC
		%		—	%	%				mg/kg					cmol (+)/kg		
Sand	1.0	0.66***	−0.80***	0.28***	−0.35***	−0.24***	0.19***	−0.14***	−0.05	−0.08	0.19***	−0.13***	0.11***	0.20***	0.04	−0.10***	−0.05
Silt		1.00	−0.98***	0.31***	−0.20***	−0.07*	0.29***	−0.15***	0.04	0.01	0.37***	−0.21***	0.26***	0.28***	0.06*	−0.07*	0.02
Clay			1.00	−0.32***	0.25***	0.12***	−0.28***	0.16***	−0.02	0.01	−0.35***	0.20***	−0.24***	−0.28***	−0.06*	0.08***	0.00
pH				1.00	−0.16***	−0.14***	0.44***	−0.35***	0.33***	0.27***	−0.20***	0.37***	0.38***	0.66***	0.65***	0.52***	0.53***
TN					1.00	0.95***	0.13***	0.28***	0.24***	0.30***	−0.04	−0.03	0.20***	−0.03	0.18***	0.06	0.19***
OC						1.00	0.14***	0.25***	0.24***	0.34***	0.01	−0.11***	0.27***	0.00	0.18***	0.01	0.18***
P							1.00	0.04	0.42***	0.43***	−0.03	0.23***	0.48***	0.55***	0.58***	0.36***	0.52***
S								1.00	0.05	−0.07*	−0.05	−0.09***	−0.08***	−0.27***	−0.05	−0.22***	−0.08***
B									1.00	0.35***	−0.14***	0.34***	0.32***	0.39***	0.52***	0.35***	0.43***
Cu										1.00	−0.04	0.19***	0.40***	0.47***	0.39***	0.43***	0.50***
Fe											1.00	−0.42***	−0.02***	−0.09***	−0.30***	−0.22***	−0.27***
Mn												1.00	0.25***	0.28***	0.47***	0.28***	0.32***
Zn													1.00	0.39***	0.48***	0.21***	0.35***
Ca														1.00	0.63***	0.77***	0.89***
K															1.00	0.62***	0.69***
Mg																1.00	0.86***
CEC																	1.00

*, **, *** significant at $p < 0.05, 0.01, 0.001$, respectively.

Table 5: Descriptive statistics of soil OC, TN, AvP, and SO_4^{2-}-S for surface soil.

Districts	Descriptive statistics	OC %	TN %	C : N ratio —	AvP mg/kg	SO_4^{2-}-S mg/kg
Damot Gale ($N = 243$)	Mean	1.89	0.12	17.2	18.3	10.2
	Std. dev	0.69	0.06	5.6	34.8	2.9
	Median	1.80	0.12	15.5	6.3	9.7
	Minimum	0.2	0.01	8.6	0.1	4.2
	Maximum	4.2	0.35	40.6	215.0	20.3
	CV (%)	37.0	50.0	33.0	190.0	28.0
Damot Sore ($N = 216$)	Mean	2.52	0.18	14.4	9.4	11.0
	Std. dev	0.68	0.06	2.4	25.2	3.9
	Median	2.5	0.18	14.0	3.1	10.2
	Minimum	1.0	0.04	10.1	0.1	3.7
	Maximum	4.4	0.35	30.9	238.1	28.2
	CV (%)	27.0	33.0	17.0	268.0	35.0
Sodo Zuria ($N = 330$)	Mean	1.9	0.14	14.2	5.6	11.3
	Std. dev	0.69	0.07	3.3	10.0	3.7
	Median	1.9	0.14	13.4	2.9	10.9
	Minimum	0.3	0.02	7.4	0.1	4.2
	Maximum	0.69	0.68	35.0	99.4	30.3
	CV (%)	36.0	50.0	23.0	179.0	33.0
Total ($N = 789$)	Mean	2.08	0.15	15.1	10.5	10.9
	Std. dev	0.74	0.07	4.1	24.8	3.6
	Median	2.0	0.15	14.0	3.4	10.4
	Minimum	0.2	0.01	7.4	0.1	3.7
	Maximum	6.9	0.68	40.6	238.1	30.3
	CV (%)	36.0	47.0	27.0	236	33.0
	F_{value}	60.4***	42.6***	42.9***	19.0***	6.4**

Numbers in brackets refer to sample size; **, *** significant at $p < 0.01, 0.001$, respectively.

Table 6: Descriptive statistics of soil exchangeable bases, CEC, and PBS for surface soil.

District	Descriptive Statistics	Ca	Mg	K cmol (+)/kg	Na	CEC	PBS %
Damot Gale ($N = 243$)	Mean	9.1	1.9	1.4	0.8	21.1	61.3
	Std. dev	3.1	0.6	0.8	0.3	4.0	8.4
	Median	8.4	1.9	1.1	0.7	20.3	61.4
	Minimum	1.5	0.2	0.1	0.1	3.3	30.5
	Maximum	19.6	4.2	3.9	2.1	34.3	80.1
	CV (%)	34	32	57	38	19	14
Damot Sore ($N = 216$)	Mean	8.3	2.3	1.4	0.8	22.6	53.8
	Std. dev	4.9	1.4	1.0	0.3	6.1	14.9
	Median	7.1	2.0	1.0	0.7	20.9	54.4
	Minimum	2.0	0.5	0.2	0.4	13.8	19.5
	Maximum	31.2	9.5	6.2	3.1	50.5	87.8
	CV (%)	59	61	71	38	27	28
Sodo Zuria ($N = 330$)	Mean	7.0	1.8	1.1	0.7	20.0	51.8
	Std. dev	3.6	0.7	0.7	0.3	3.7	13.8
	Median	6.4	1.8	0.9	0.6	19.4	53.2
	Minimum	1.1	0.2	0.2	0.2	12.4	8.8
	Maximum	31.3	4.6	4.5	2.3	43.8	86.5
	CV (%)	51	39	64	43	19	27
Total ($N = 789$)	Mean	8.0	2.0	1.3	0.7	21.0	55.3
	Std. dev	4.0	0.9	0.9	0.3	4.7	13.4
	Median	7.4	1.9	1.0	0.6	20.0	56.9
	Minimum	1.1	0.2	0.1	0.1	3.3	8.8
	Maximum	31.3	9.5	6.2	3.1	50.5	87.8
	CV (%)	50	45	69	43	22	24
	F_{value}	20.4***	15.2***	8.5***	13.4***	20.7***	40.5***

Numbers in brackets refer to sample size; *** significant at $p < 0.001$.

Table 7: Descriptive statistics of soil micronutrients (B Cu, Fe, Mn, and Zn) for surface soils.

District	Descriptive statistics	B	Cu	Fe mg/kg	Mn	Zn
Damot Gale ($N = 243$)	Mean	0.56	0.47	133.0	521.0	10.59
	Std. dev	0.30	0.41	29.0	162.0	7.13
	Median	0.48	0.40	133.0	523.0	8.80
	Minimum	0.01	0.01	22.0	84.0	1.10
	Maximum	1.82	5.00	259.0	950.0	51.00
	CV (%)	54.0	87.0	22.0	31.0	67.0
Damot Sore ($N = 216$)	Mean	0.60	0.78	131.0	510.0	9.03
	Std. dev	0.41	0.44	42.0	160.0	5.73
	Median	0.51	0.68	124.0	490.0	7.60
	Minimum	0.20	0.01	61.0	61.0	0.30
	Maximum	4.97	2.66	392.0	912.0	36.80
	CV (%)	68	56	32	33	63
Sodo Zuria ($N = 330$)	Mean	0.50	0.46	120.0	599.0	7.29
	Std. dev	0.41	0.27	55.0	223.0	8.13
	Median	0.42	0.41	104.0	616.0	5.40
	Minimum	0.18	0.01	45.0	50.0	0.70
	Maximum	6.90	1.42	384.0	1138	117.40
	CV (%)	82	59	46	37	112
Total ($N = 789$)	Mean	0.55	0.55	127.0	551.0	8.78
	Std. dev	0.38	0.39	45.0	193.0	7.36
	Median	0.46	0.47	119.0	545.0	7.20
	Minimum	0.01	0.01	22.0	50.0	0.30
	Maximum	6.90	5.00	392.0	1138.0	117.40
	CV (%)	69	71	35	35	84
	F_{value}	4.7^{**}	56.1^{***}	7.3^{**}	18.8^{***}	14.8^{***}

Numbers in brackets refer to sample size; **, *** significant at $p < 0.01, 0.001$, respectively.

and clay contents [71, 44]. Pearson correlation matrix shows that CEC was positively and significantly correlated with pH ($r = 0.5$) and OC ($r = 0.2$). The CEC also significantly ($p \leq 0.001$) correlated with Ca ($r = 0.9$), Mg ($r = 0.9$), and K ($r = 0.7$) (Table 4). However, the relation with the amount of clay was negligible. Hence, the type of clay mineralogy and soil OM might have been the factors that contributed to the CEC values of the studied soils. In accord with this finding, Maria and Yost [28] and Joao et al. [29] reported a reduction in soil CEC as soil pH became lower. Generally, moderate CEC values imply that the soil has moderate buffering capacity against the induced changes.

The percentage base saturation (PBS) in the present study followed the trend of exchangeable bases. It varied from 9% in Sodo Zuria soils to 88% in soils of Damot Sore district (Table 6). However, as per the ratings proposed by [28], 15, 45, 39, and 1% had very low (<20), low (20–40), medium (40–60), high (60–80), and very high PBS (80–100%), respectively. The values recorded indicated that soils in the study area are moderately to strongly leached [39].

3.2.5. Micronutrient Contents. The range of micronutrient content (mg/kg) was as follows: B (0.01 to 6.9), Cu (0.01 to 5), Fe (22 to 392), Mn (50 to 1138), and Zn (0.3 to 117) (Table 7). Considering the ratings proposed for Ethiopian soils by EthioSIS [40], about 57, 30, and 13% samples across districts had very low (<0.5), low (0.5–0.8), and optimum (0.8–2.0 mg/kg) B content, respectively. The result regarding Cu content also revealed that about 53, 37, and 10% of the entire soil samples qualified to be very low (<0.5), low (0.5–0.9), and optimum (1–20 mg/kg), respectively. The content of Fe was optimum except some localized deficiencies. Overall, about 7, 91, and 2% of the soil samples had low (60–80), optimum (80–300), and high Fe (300–400 mg/kg), respectively. Soil Mn (mg/kg) in all samples was above 25, which is optimum according to the EthioSIS ratings criteria [40]. Furthermore, the present finding indicated the sufficiency of Zn. In terms of proportion, 3, 65, 26, and 6% of the soil samples across districts have low (1–1.5), optimum (1.5–10), high (10–20), and very high (>20 mg/kg) Zn levels, respectively.

The variation in soil micronutrients could be linked with soil pH, OM, and soil management differences. Soil pH has an influence on the solubility and availability of soil micronutrients. This was evident in the significant ($p \leq 0.01$) correlation between soil pH and B ($r = 0.3$), Cu ($r = 0.3$), Fe ($r = -0.2$), Mn ($r = 0.4$), and Zn ($r = 0.2$). Soil OC content also indicated a significant ($p \leq 0.01$) correlation with B ($r = 0.2$), Cu ($r = 0.3$), Mn ($r = 0.1$), and Zn ($r = 0.3$) (Table 4).

Overall, B and Cu contents in all sampled soils were found to yield limiting nutrients whereas Fe, Mn, and Zn levels were sufficient for crop production. Acidic pH, loss through leaching, low B absorbing capacity of soil, and parent material containing low B might cause low B [72]. In soils, soluble B is mainly present in the form of boric acid B $(OH)_3$. In highly weathered soils like the study area, this anion is adsorbed by Al/Fe oxides and clay minerals. Hence, soils would often show low B content, and crops grown on these soils may suffer from B deficiency [73]. Furthermore, intensive cultivation of soils, lower application rate of manure, and nonuse of B containing fertilizer could also aggravate the B deficiency [57, 74].

The Cu deficiency could be linked with low soil OM, practice of intensive cropping systems, acidic nature of the soil, and nonuse of Cu containing fertilizer. Chesworth [73] and Bitondo et al. [74] reported that organic matter complexes can retain substantial proportion of micronutrients. This is significantly ($p < 0.001$) supported by the positive correlation of OC with B ($r = 0.24$) and Cu ($r = 0.34$) (Table 4). Hence, the low level of soil OM would contribute to the low level of these elements. Correspondingly, the research under intensive cropping systems of Venezuela by Rodríguez and Ramírez [75] reported Cu deficiency on acid soils (pH < 6.5), and it accounted for low level of soil OM. Reports also indicated Cu deficiency in some Nitisols of Ethiopia [36, 57, 76]: [53].

The sufficient levels of Fe and Mn could be linked with acidic nature of the soils. In agreement with the current findings, Oyinlola and Chude [72] indicated higher solubility and availability of micronutrients like Fe, Mn, and Zn under acidic conditions (pH of 5.0 to 6.5). Furthermore, the higher Fe content might also be explained by the higher content of raw mineralogy [25]. In addition, higher Mn levels are often found in soils rich in Fe [25]. Zinc is reported to be generally associated with Al- and Fe-containing minerals such as feldspars, micas, pyroxenes, and amphiboles [69].

3.3. Variability among Soil Parameters. The measured soil parameters of agricultural soils within and across districts showed considerable variability ranging between 10% and 235% (Tables 2, 3, 5–7). Soil pH was relatively less variable while available P was found to be highly variable. Similar trend was reported by Iticha and Takele [2]. According to Amuyou et al. [24] soil parameters having CV < 20% showed low variability, whereas those with $20 < CV \leq 50\%$ showed moderate variability. Similarly, soil properties having CV > 50% showed high variability compared to their mean. Variability among parameters was ascribed to (1) random pick-up of large number of data and (2) remarkably high variation of topography, management, land use types, and inherent properties like texture and pH. Similarly, in soil fertility survey researches, CV values ranging from 13 (bulk density and pH) to 585% (mineral N) [77], 0.3 (exchangeable K) to 118.64% (Zn) [78], and 5.37 (pH) to 100% (exchangeable K) [79] were reported.

4. Conclusion

Low soil OC; total N; available P, K, S; and micronutrients (B and Cu) were identified as a major limiting factors in the study areas. In addition, in some places there was also strong acidity. Both inherent soil-landscape (e.g., clay mineralogy and topography) and human-induced factors (e.g., unwise soil management practices including residue removal, continues tillage, excessive grazing, and inadequate fertilizer) might be causes of farmland constraints. The soil parameters are highly variable and also location specific. The turning point to solve the problem should be restoring, maintaining, and increasing the fertility status of the soils. Location-specific study like this offers detailed information about soils of a particular field and can be used to make informed decision for precision fertilization and liming. Thus, it overcomes blanket recommendation approaches. Therefore, soil management interventions such as soil conservation, application of sufficient organic and inorganic fertilizers, and lime in acidic soils are recommended to restore soil fertility and improve crop productivity.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

FL collected, analyzed, and interpreted the data, which was part of his Doctoral thesis on soil science at Haramaya University, Ethiopia. KK helped to draft the manuscript. Both authors read and approved the final manuscript.

Acknowledgments

The authors would like to thank Ministry of Education (MOE) for the scholarship and Ethiopian Soil Information System (EthioSIS) at the Agricultural Transformation Agency (ATA) for financial support. Acknowledgments also go to the late Prof. Tekalign Mamo for his appreciated contribution, and the authors wish that his soul rests peacefully. The authors thank Ermiyas Elka, Simon Yohannes, and the late Daninel Milkyas for their support during sample collection. The authors are very grateful for all the assistance, knowledge, and experience they have received from the farmers in Damot Gale, Damot Sore, and Sodo Zuria districts.

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