

Research Article

Assessing the Impacts of Soil Water Conservation Activities and Slope Position on the Soil Properties of the Gelda Watershed, Northwest Ethiopia

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Soil erosion debilitates soil fertility and agricultural productivity in Ethiopia. Soil and water conservation (SWC) measures have been implemented to address this issue, but their effects have not been evaluated in different parts of the country. This study was therefore conducted to evaluate the effects of SWC structures and slope position on soil properties in the Gelda watershed, northwestern Ethiopia. Core and disturbed composite soil samples were collected at a depth of 0–20 cm from the upper (15–20%), middle (10–15%), and lower (4–10%) slope positions of cultivated fields treated with soil bund (SB), stone-faced soil bund (SFSB), and stone-faced soil bund stabilized by *Sesbania sesban* (SFSBS) and from untreated fields (control). The samples were analyzed by soil analytical techniques. The results revealed that the clay particles, pH, soil organic matter (SOM), total nitrogen (TN), available phosphorus (AvP), cation-exchange capacity (CEC), and exchangeable Ca^{2+} , Mg^{2+} , and K^{+} were significantly ($p < 0.05$) increased, while bulk density (BD) and the sand fractions decreased in SWC-treated plots. On the lower slope, significantly higher ($p < 0.05$) clay, silt, pH, SOM, TN, AvP, CEC, and exchangeable bases were recorded, while the upper slope had the highest sand and BD values. The interactions of slope and SWC structures affected the distribution of sand, TN, AvP, exchangeable Ca^{2+} , and Mg^{2+} . The SWC structures implemented in the watershed improved soil fertility, but the impact was stronger when stone-faced soil bunds were integrated with *Sesbania sesban* plant species. Therefore, during the implementation of SWC structures, the integration of soil physical structures with plant species aligned with slope positions should be considered, as both factors have an impact on soil fertility improvement and soil erosion in the study area and similar agroecologies. The impacts of SWC structures on crop yield, their economic implications, and environmental benefits for the studied watershed and for the region as a whole need further investigation.

1. Introduction

The economy of Ethiopia is mainly dependent on rain-fed agriculture. Agriculture plays a central role in the life and livelihood of the country, which accounts for more than 85% of the labor force, 50% of the gross domestic product (GDP), and more than 90% of foreign exchange earnings [1]. However, soil degradation and land degradation in Ethiopia's agriculture sector are overwhelming, impeding agricultural development and threatening the sustainability of the ecosystem [2]. Particularly in the highlands of Ethiopia, soil erosion and fertility depletion pose a significant threat to

agricultural productivity, food security, and the conservation of natural resources [3–5]. These were the results of converting natural forests to farmlands, cultivating steep slopes and marginal lands, and overgrazing that made agricultural lands more vulnerable to soil erosion and nutrient depletion [6]. Soil erosion is a serious environmental problem that causes topsoil removal and affects agricultural sustainability and food security in the country [7]. In particular, soil erosion driven by water is the most serious type of land degradation, threatening food security, environmental sustainability, and rural development in the highlands of Ethiopia [6, 7]. As a result of soil erosion, it is

estimated that 179 tons of soil per hectare are lost annually in the highlands of Ethiopia [8]. The severity of this problem was further demonstrated by a plot-level soil loss assessment. It was reported that the average soil loss rates on croplands are estimated to be $42 \text{ t} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$; however, in individual fields, the rates increase as high as $300 \text{ t} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ [9]. Besides, population growth and improper land resource management are the major causes for the decline of crop productivity in the highlands of Ethiopia [4]. As a result of the significant effects soil erosion has had on the nation's agricultural production, food security, water sanitation, and environmental quality, effective conservation efforts are now necessary to preserve the land and maintain community livelihoods [8, 10]. This environmental challenge demands urgent action with the implementation of effective policies to ensure the well-being of ecosystems, enhance agricultural output, and increase food security in the country [9, 10].

The practice of implementing soil and water conservation structures was generally neglected prior to the 1970s, despite the fact that soil erosion was a major problem in Ethiopia [7]. However, to address the problems of soil erosion and land degradation, the government of Ethiopia has implemented extensive soil and water conservation (SWC) programs since the 1970s and 1980s by mobilizing farmers mainly through food-for-work programs [7, 10]. These SWC measures were believed to play a key role in reducing soil erosion, rehabilitating degraded lands, increasing agricultural production, and improving community livelihoods [11, 12]. As a result, in addition to the government, nongovernmental organizations have taken the initiative and participated in the implementation of different SWC measures, mainly in the highlands of Ethiopia [13]. However, the success of these SWC practices has fallen far short of expectations, and the country has been dealing with soil fertility decline and lower agricultural productivity. The shortcomings of earlier extensive SWC practices were mainly caused by a lack of community participation, inappropriate conservation methods, land policy, illiteracy, and poor transportation and communication networks [8, 14]. Moreover, farmers refrain from SWC activities due to water logging, weed and rodent problems, and high maintenance requirements [14]. In particular, most of the previous initiatives ultimately proved ineffective because the programs and SWC techniques failed to take into account the pressing needs and benefits of impoverished smallholder farmers [15]. All these factors contributed in one way or another to the low adoption of SWC practices, soil fertility depletion, and low agricultural productivity. Nevertheless, since 2011, the government of Ethiopia has been actively involved in an annual statewide SWC construction program to protect soil erosion and enhance agricultural productivity across the country [15]. The main goal of the campaign is to actively engage and mobilize members of the community, change the attitudes of the farmers, and establish sustainable and effective SWC structures on their farmlands [16]. However, this program should also consider and be supported by an in-depth analysis of the factors influencing community participation and their adoption of SWC activities.

The Gelda watershed is located in the upper Lake Tana basin, northwestern Ethiopia. Lake Tana is among the four UNESCO World Biosphere Reserve sites in Ethiopia [17]. The watershed experiences deforestation followed by intensive cultivation, overgrazing, and poor soil management that have a significant impact on livelihoods and ecosystem health. These problems were mainly caused by population pressure, improper land use, and land cover changes in the watershed [18]. In addition, the nature of the topography, which has terrain and steep slopes, exposed the watershed to soil erosion and land degradation. In order to reduce soil erosion, rehabilitate degraded lands, and improve the soil's fertility, different SWC practices, including soil bunds (SBs), stone-faced soil bunds (SFSBs), and stone-faced soil bunds stabilized by *Sesbania sesban* (SFSBS), were put into place in the watershed. Although some studies were conducted on land use and cover dynamics [18] and climate variability patterns [19], none of these studies addressed the effects of these SWC structures and slope positions on soil fertility in the watershed. Hence, information on the effects of these SWC practices and the influence of slope position on soil fertility and productivity has remained largely unquantified in the watershed, and the adoption and implementation of SWC by many farmers in their croplands is low, as they believe that such practices do not improve soil fertility other than occupying and reducing the size of their farmlands [20]. In addition, there is limited available data regarding the effectiveness of various SWC measures in the region, making it challenging to draw site-specific conclusions on the success of different soil conservation practices. Hence, conducting comprehensive watershed-level research is essential to showcasing the effectiveness of different SWC methods and convincing farmers to adopt the best SWC practices on their farmlands. Furthermore, as the watershed is located within the upper Lake Tana basin, this study will give an insight into how to design appropriate land management practices to reduce soil erosion and protect Lake Tana against the detrimental effects of sedimentation caused by erosion. These kinds of local studies are also necessary for developing region-specific solutions and can contribute to the design of effective soil and land management strategies by policymakers. The study was, therefore, initiated to evaluate the effects of SWC practices and slope positions on selected soil properties in the Gelda watershed, Dera district, northwest Ethiopia. The findings of this study are expected to further scientific knowledge for researchers, provide new insights to policymakers into how slope position and different SWC structures affect soil properties, and implement site-specific soil conservation and land management strategies in the country.

2. Materials and Methods

2.1. Description of the Study Area. The study was conducted in the Gelda watershed ($11^{\circ}41'45''$ – $11^{\circ}43'17''$ N and $37^{\circ}34'54''$ – $37^{\circ}37'43''$ E) in the northwestern highlands of Ethiopia. It is located 614 kilometers northwest of Addis Ababa, the capital city of Ethiopia. The study site covers 572 ha of land, of which 69.2% (396 ha) were treated with

SWC structures. The watershed is part of the upper Lake Tana basin, which is the source of the Blue Nile river (Figure 1). This basin plays a crucial role in the region's ecosystem and sustains various communities that rely on its resources for their livelihoods [18].

The Gelda watershed is characterized by flat to moderately steep topography with a slope range of 4–20%. Its elevation ranges from 1911 m at the outlet of the river to 2024 m above sea level at its highest point on the watershed divide. The upper part of the watershed is represented by mountainous and hilly dissected terrain with steep slopes, whereas the lower part is represented by rolling topography and gentle slopes, offering a suitable environment for different land uses. These topographical features play an important role in influencing the patterns of water flow, land utilization, and erosion dynamics within the watershed [18]. Several smaller streams drain the area, including *Gelda* (the watershed's largest stream), which flows into Lake Tana from the west [19]. The study area's weather is typically humid, characterized by a subtropical (*Woina Dega*) agroclimatic zone with an average annual rainfall of 1845.83 mm. The watershed experiences a unimodal rainy season that lasts from mid-May to October, reaching its peaks during July and August. Although this extended period of precipitation plays an important role in replenishing water sources and supporting agricultural productivity, it is also a major cause of soil erosion in the watershed. A ten-year analysis of climatic data (2011–2020) showed that the mean minimum and maximum temperatures are 10.70°C and 25°Ce, respectively [21].

In the watershed, cultivated land accounts for the majority of land use and cover (82.4%), followed by grazing land (6.6%), plantation forests (4%), and settlement areas (7%). The predominance of cultivated lands in the watershed has significant implications as it exposes the soil to erosion risks, which indicates the need to implement sustainable land management activities. The farmers' livelihood is based on traditional rain-fed subsistence farming, which involves growing both crops and livestock on an average farm size of roughly one hectare. Farmers also generate additional income from off-farm activities such as petty trade, daily labor work, and the sale of firewood, charcoal, and poles. In addition to being a source of milk, meat, and cash income, livestock supports agricultural activities mainly as draft power. The major cultivated crops are maize (*Zea mays*), *teff* (*Eragrostis tef*), finger millet (*Eleusine coracana*), *noug* (*Guizotia abyssinica*), and potato (*Solanum tuberosum*). Among the scattered indigenous tree species found in the watershed are *Juniperus procera*, *Hagenia abyssinica*, *Albizia gummifera*, *Podocarpus falcatus*, *Cordia africana*, *Dodonaea angustifolia*, *Euclea schimperi*, and *Ficus* species. These tree species are found dominantly around churches, burial grounds, and inaccessible areas of the upper slope positions and could have an impact on reducing soil erosion. Other native species, such as *Syzygium guineense* and *Ficus* sp., are also found around stream banks and on gentler slopes. The exotic trees, including *Cupressus*, *Acacia sieberiana*, and

Eucalyptus species, are also found dominantly in the middle and lower slopes and around homesteads and serve as a source of fuel wood and construction materials.

The geology of Dera district is dominated by horizontally bedded, massive, generally basaltic lava flows that form the plateau [18]. The dominant soil types in the watershed are classified as shallow Leptosols, Nitisols, and Luvisols [22]. Most of the cultivated fields in the watershed are treated with SWC practices such as soil bunds, stone-faced soil bunds, and stone-faced soil bunds stabilized by *Sesbania sesban* plant species. Twelve years have passed since these soil and water conservation measures were implemented in the watershed.

2.2. Experimental Design. The watershed was first divided into three slope classes: lower (4–10%), middle (10–15%), and upper (15–20%) slope positions [23]. In addition to physiographic conditions, soil type, land use/cover, and implemented SWC structures were taken into account to minimize variability within each slope class. During sampling, the land use types of both the treated and untreated slope classes were farmlands. The experiment considered four different treatments: fields treated with soil bund (SB), stone-faced soil bund (SFSB), stone-faced soil bund stabilized by *Sesbania sesban* (SFSBS), and fields without SWC practices (control, C) located in the three slope positions.

2.3. Soil Sampling. Soil samples were collected from farmland plots in each of the three slope positions with twelve-year-old SWC structures: SB, SFSB, and SFSBS, and from control plots. Composite soil samples were collected at a distance of 1.5 m from the upper side of each SWC structure and at a depth of 0–20 cm, with the assumption that the deposited sediment would not exceed this depth [24].

For each conservation structure and the control, three representative plots were selected in each slope position with a maximum distance of 18–20 m between each sampling plot. Before sampling, plant and grass litter, animal manure, and any other material on the soil surface were removed to avoid contamination or changes to the soil's characteristics. Then, for each SWC structure (SB, SFSB, and SFSBS), soil samples were collected at the four corners and the center of a 10 m × 10 m plot using the "X" sampling method. The soil samples collected from the four corners and the center of each plot were carefully mixed and bulked to make a single composite sample. In a similar way, soil samples were collected from the untreated fields', i.e., the control. A total of 36 disturbed composite soil samples (4 treatments × 3 slope classes × 3 replications) were collected from January 15 to January 17, 2021, for the analysis of selected soil physicochemical properties (Table 1). Similarly, 36 undisturbed core soil samples were collected for bulk density determination. The soil samples were properly bagged, labeled with the appropriate information, and kept in a separate room until they were air-dried.

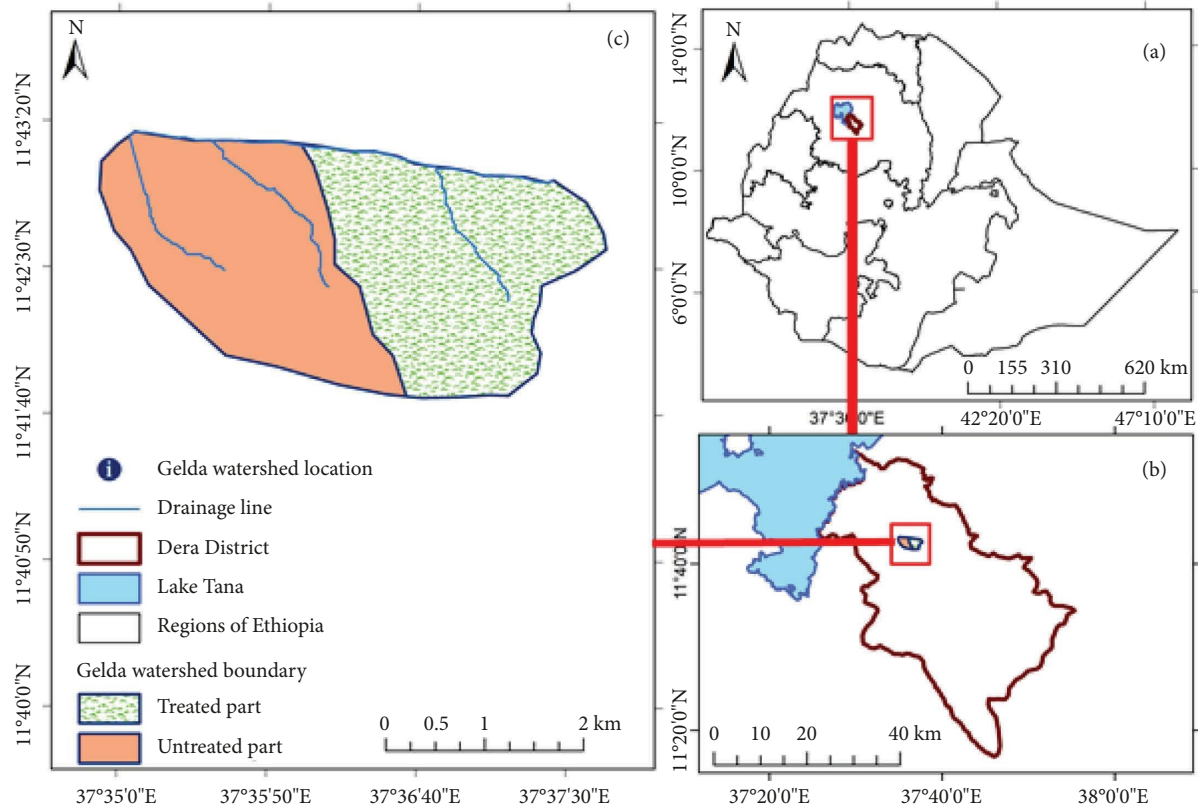


FIGURE 1: Location map of the study area. (a) Regions of Ethiopia, (b) Dera district, and (c) Gelda watershed.

2.4. Laboratory Analysis of Soil Samples. After being air dried, the disturbed composite soil samples were mixed well and passed through a 2 mm sieve for the determination of all soil parameters, except for total nitrogen and organic carbon, which passed through a 0.5 mm sieve. The analysis was carried out in the soil testing laboratory of Amhara Design and Supervision Works Enterprise, Bahir Dar, Ethiopia. The important soil properties were analyzed using standard methods, as given in Table 2.

2.5. Data Analysis. The statistical differences in soil characteristics among SWC practices and slope positions were tested using a two-way analysis of variance (ANOVA) following the general linear model (GLM) procedure of the Statistical Analysis System, SAS 9.0 version. When significant differences were found, Tukey's honest least significant difference (LSD) at a 5% probability level was used to compare the means. The Pearson correlation analyses were carried out to determine the relationships between soil parameters.

3. Results and Discussion

3.1. Effects of Soil Water Conservation (SWC) Practices and Slope Position on Soil Properties

3.1.1. Soil Texture. In the studied watershed, two different kinds of soil textures were identified: clay texture in the conserved farmlands and clay loam in the nonconserved

farmlands. The ANOVA result showed that the sand ($p < 0.01$) and clay ($p < 0.05$) fractions were affected by SWC structures. The clay, sand, and silt fractions were also highly significantly ($p < 0.01$) affected by slope positions. The interaction effects of SWC structures and slope position, on the other hand, had a significant ($p < 0.01$) effect on the sand fractions (Table 3). The total mean percentage of clay content was significantly higher ($p < 0.05$), while the sand fraction was significantly lower ($p < 0.01$) in the treated fields than in the untreated fields. Nevertheless, the silt fraction did not show a significant difference ($p > 0.05$) between the treated and untreated fields; however, numerically higher silt contents were observed in the treated fields (Table 4). This was associated with water erosion that selectively removes and deposits the fine-textured clay and silt fractions from the back of the implemented SWC structures. This redistribution of soil particles will have an impact on the soil nutrient composition, water retention, and overall productivity of the agricultural system. The result was in line with the reports of Guadie et al. [24] and Hishe et al. [32], who reported significantly higher clay fractions in farmlands treated with SWC than in the untreated fields in the Lole watershed, northwestern highlands of Ethiopia, and middle Silluh Valley, Northern Ethiopia, respectively. Similarly, Alene et al. [33] reported numerically higher silt and significantly lower sand contents from stone-faced soil bund SWC structures stabilized with grass-treated fields due to the reduced runoff and improvement of soil organic matter in the Dawnt watershed, northwestern Ethiopia. In a related

TABLE 1: Number of composite soil samples in the study watershed.

SN	Types of SWC practices	Lower (4–10%)		Middle (10–15%)		Upper (15–20%)		Total composite sample
		Treated	Untreated	Treated	Untreated	Treated	Untreated	
1	SB	3		3		3		
2	SFSB	3	3	3	3	3	3	
3	SFSBS	3		3		3		
	Total	9	3	9	3	9	3	36

SB: soil bund; SFSB: stone-faced soil bund; SFSBS: stone-faced soil bund stabilized by *Sesbania sesban*.

study, Bojago et al. [34] also reported a higher concentration of clay and a lower concentration of sand in *Fanya Juu* and stone bund-treated plots, but lowest clay and sand contents in nonconserved plots in the Anuwa watershed, southern Ethiopia. Our findings, however, go contrary with those of Masha et al. [35], who showed a lower percentage of clay in soils with soil bunds, *Fanya Juu*, and stone bunds than the nonconserved plots in contrasting landscapes of southern Ethiopia. This discrepancy might stem from variances in soil composition and environmental conditions between the two study locations.

The overall mean of the sand fraction was higher ($38.00 \pm 3.46\%$) in the upper and lower ($18.33 \pm 1.03\%$) slope positions. However, the clay and silt fractions were higher in the lower slope and lower in the upper slope positions (Table 4). This could be due to the removal and transport of fine soil particles such as clay and silt to the lower slope by water erosion, leaving coarser materials (sand and gravel) onsite in the upper slope positions. The removal of clay and silt fractions in the upper slope area by erosion creates shallow soil depth and might negatively affect the productivity of cultivated crops. It is therefore important for the local farmers to implement SWC to mitigate these effects and sustain crop yields in their cropland. This result was comparable to that reported by Guadie et al. [24] and Teressa [36], who found increased sand and decreased clay and silt fractions with an increase in slope gradient in the Lole watershed, northwestern highlands of Ethiopia, and Weday watershed of eastern Ethiopia, respectively. Their findings suggest that soil erosion on steep slopes can significantly impact soil fertility, ultimately affecting agricultural productivity. Furthermore, this finding agreed with those of Masha et al. [37], who reported a higher clay content and silt in the lower slope position of the Wamancho watershed, southern Ethiopia. However, it differed from their results regarding sand concentration, where they reported higher values in the lower slope positions. This study also contradicts with the study of Masha et al. [35], who reported higher silt concentrations in the upper slope position than in the lower and middle slope positions in contrasting landscapes of southern Ethiopia. This highlights the significant impact that landform attributes can have on the distribution patterns of soil texture components across distinct slope categories [37].

3.1.2. Bulk Density (BD). The BD showed a significant difference ($p < 0.01$) between the SWC-treated and untreated fields and slope positions, indicating that the treated

plots had a lower mean value of bulk density than the nontreated plots (Table 3). The total mean BD was lower (1.09 g cm^{-3}) in the fields treated with SFSBS and higher (1.27 g cm^{-3}) in the untreated fields (Table 4). Specifically, the conservation structures had BD values in the order of $\text{SFSBS} < \text{SFSB} < \text{SB}$, with the lowest in SFSBS indicating the positive impact of the integration of biological and physical structures in lowering the soil BD. Thus, relative to the control, BD in SWC-treated fields declined by 6.29, 10.23, and 14.17% in SB, SFSB, and SFSBS-treated fields, respectively. The higher BD in the untreated fields may be linked to the lack of SWC structures that caused the washing out of silt and clay particles with the reduction of organic matter, leaving behind the sand particles onsite. Hence, an increase in BD signifies reduced pore space, poor water infiltration and root penetration, and compaction of the soil, which impedes agricultural productivity. The result was in line with Guadie et al. [24], Demelash and Karl [38], and Challa et al. [39], who showed a considerably lower BD in SWC-treated watersheds in the central and northwestern highlands of Ethiopia. This finding was also consistent with Bojago et al. [34] and Masha et al. [35], who reported lower BD in conserved plots than in nonconserved ones in different watersheds of southern Ethiopia.

Similarly, the overall mean value of BD varied significantly ($p < 0.01$) across slope positions. It was found to be lower (1.12 g cm^{-3}) in the lower than in the upper (1.22 g cm^{-3}) slope positions (Table 4). Hence, as the slope gradient increases, BD increases, and as the slope gradient decreases, BD decreases. This could be the effect of the slope gradient, which caused differences in the amount of organic matter in the soil due to erosion and deposition, making its content lower in the upper and higher in the lower slope positions. As the concentration of organic matter increases, BD tends to decrease, showcasing the intricate relationship between soil organic matter and BD and highlighting the impact of topographical features on soil compaction. This result was comparable to that reported by Hailu et al. [40], Challa et al. [39], and Guadie et al. [24], who noted higher BD in cultivated fields in the upper slope positions than in the lower slope positions in the Goromti watershed, western Ethiopia, Adda Berga district, Western Shewa, Ethiopia, and the Lole watershed, northwestern highlands of Ethiopia, respectively. These results, however, were in contrast with those of Masha et al. [35], who found a higher mean BD (1.32 g cm^{-3}) in the lower slope position and a lower mean BD value (1.12 g cm^{-3}) in the upper slope resulted from uncontrolled grazing on the lower slope as opposed to the

TABLE 2: Methods of analysis of different soil parameters.

No.	Measured soil parameters	Method of analysis	Instrument applied/extractant	Reference
1	Soil texture	Bouyoucos hydrometer	Hydrometer	[25]
2	Bulk density (BD)	Core method, the undisturbed soil samples were weighed after being dried to a constant temperature (105°C) and the dry soil quality was calculated in units of volume	Metal core sampler Oven dry (DK610 Yamato)	[26]
3	pH	Potentiometrically in a 1 : 2.5 soil-to-water suspension and measured with a digital pH meter	pH meter (Hanna HI-98107, USA)	[27]
4	Organic carbon (OC)	Walkley and Black wet digestion method	Titration method	[28]
5	Total nitrogen (TN)	Micro-Kjeldahl digestion, distillation, and titration method	Kjeldahl digestion and distillation apparatus (UDK 129, VELP Scientifica, Italy)	[29]
6	Available phosphorus (AvP)	Olsen method	Spectrophotometer Hitachi-120, Japan	[30]
7	Exchangeable Ca and Mg	Ammonium acetate (1 N NH ₄ OAc) at pH 7.0 method	Measured by atomic absorption spectrophotometer	[25]
8	Exchangeable K	Ammonium acetate (1 N NH ₄ OAc) at pH 7.0, method	410 flame photometer (GAMBICA, UK)	[25]
9	Cation-exchange capacity (CEC)	Ammonium acetate saturation method at pH 7.0	Titration method	[31]

TABLE 3: Mean square estimate of two-way analysis of variance of soil properties under SWC practices and slope position in the Gelda watershed.

Soil parameter	Mean square of sources of variation [†]				CV (%)
	SWCPs (3)	Slope position (2)	SWCPs x slope position (6)	Error (22)	
Clay (%)	104.96*	285.44**	0.74 ^{ns}	27.01	13.03
Sand (%)	184.96**	1219.11**	18.29**	4.90	8.20
Silt (%)	11.33 ^{ns}	324.77**	20.33 ^{ns}	11.75	10.32
BD (gcm ⁻³)	0.05**	0.03**	0.0003 ^{ns}	0.002	4.06
pH (H ₂ O)	0.12**	0.60**	0.011 ^{ns}	0.01	2.13
SOM (%)	0.73**	4.70**	0.076 ^{ns}	0.03	6.16
TN (%)	0.002**	0.011**	0.0006**	0.00009	6.16
AvP(mgkg ⁻¹)	14.51**	60.06**	2.99**	0.75	8.54
CEC (coml _c kg ⁻¹)	1023.03**	1170.84**	14.36 ^{ns}	31.23	14.44
Ca (coml _c kg ⁻¹)	33.71**	111.00**	4.35*	1.39	14.22
Mg (coml _c kg ⁻¹)	1.05**	11.93**	0.35 ^{ns}	0.14	12.47
K (coml _c kg ⁻¹)	6.42**	21.73**	2.32**	0.35	29.44
Na (coml _c kg ⁻¹)	0.10**	0.68**	0.02 ^{ns}	0.009	24.05

Figures in parenthesis: degrees of freedom. *Significant at $p = 0.05$. **Significant at $p = 0.01$. ns: nonsignificant; C: N=carbon nitrogen ratio; CEC: cation-exchange capacity.

TABLE 4: Effects of SWC structures and slope position on soil physical properties (mean $\pm$ SE).

Treatments/SWC structures	Particle size distribution (%)			BD (gcm ⁻³)
	Clay	Sand	Silt	
Control	34.77 $\pm$ 2.01 ^b	33.67 $\pm$ 1.33 ^a	31.56 $\pm$ 1.38	1.27 $\pm$ 0.06 ^a
SB	41.55 $\pm$ 6.75 ^a	24.56 $\pm$ 2.50 ^b	33.89 $\pm$ 5.17	1.19 $\pm$ 0.08 ^b
SFSB	41.33 $\pm$ 3.37 ^a	25.11 $\pm$ 1.86 ^b	33.56 $\pm$ 1.72	1.14 $\pm$ 0.05 ^c
SFSBS	41.89 $\pm$ 2.24 ^a	24.22 $\pm$ 1.05 ^b	33.89 $\pm$ 1.38	1.09 $\pm$ 0.03 ^d
LSD (0.05)	5.07	2.15	3.34	0.047
P	*	**	NS	**
SEM ($\pm$)	3.60	1.68	2.41	0.055
<i>Slope class</i>				
Lower (4–10%)	44.00 $\pm$ 1.65 ^a	18.33 $\pm$ 1.03 ^c	37.67 $\pm$ 0.94 ^a	1.12 $\pm$ 0.06 ^b
Middle (10–15%)	41.17 $\pm$ 2.43 ^a	24.33 $\pm$ 1.35 ^b	34.50 $\pm$ 1.94 ^b	1.18 $\pm$ 0.04 ^a
Upper (15–20%)	34.50 $\pm$ 8.37 ^b	38.00 $\pm$ 3.46 ^a	27.50 $\pm$ 5.48 ^c	1.22 $\pm$ 0.09 ^a
LSD (0.05)	4.39	1.86	2.89	0.04
P	**	**	**	**
SEM ($\pm$)	4.15	1.95	2.79	0.06
CV (%)	13.03	8.20	10.32	4.06

Mean values followed by different letters along the same column are significantly different at ** $p < 0.01$ and * $p < 0.05$. LSD: least significant difference; NS: not significant; CV: coefficient of variance; BD: bulk density; SB: soil bund; SFSB: stone-faced soil bund; SFSBS: stone-faced soil bund stabilized by *Sesbania sesban*.

upper slope positions in contrasting landscapes of southern Ethiopia. Masha et al. [37] also reported an insignificant difference in BD between the slope positions in the Wamancho watershed, southern Ethiopia. The discrepancies in these results could be the influence of factors such as soil composition, topography, and land management practices, indicating the need for a comprehensive understanding of the underlying causes. The correlation analysis showed that BD was significantly and negatively correlated with the clay fraction ($r = -0.51^{**}$), organic matter ($r = -0.43^{**}$), and silt fraction ($r = -0.39^{*}$), while it was positively and significantly correlated ($r = 0.58^{**}$) with the sand fraction (Table 5). These relationships highlight how changes in one soil component can affect or be affected by changes in another, indicating the interactions between soil properties.

3.1.3. Soil Reaction (pH). The soil pH (H₂O) value was significantly ($p < 0.01$) affected by the individual effects of SWC structures and slope position (Table 3). The highest (5.65) and the lowest (5.37) soil pH values were recorded in the fields treated with SFSBS and in the untreated fields (control), respectively (Table 6). Thus, relative to the control, the soil pH in SB, SFSB, and SFSBS-treated farmlands increased (acidity level decreased) by 0.15, 0.19, and 0.28 units, or by 2.79, 3.24, and 5.21%, respectively. This could be associated with the effects of the leaching of essential soil nutrients, such as organic matter and basic cations, and the removal of other vital soil nutrients through water erosion from untreated fields during rainy seasons, thereby contributing to the overall degradation of nonconserved farmlands. The decline in soil pH, i.e., an increase in soil

TABLE 5: Pearson's correlation matrix for soil physicochemical parameters.

	Clay	Sand	Silt	BD	pH	SOM	TN	AvP	Ca	Mg	K	CEC
Clay	1.00											
Sand	-0.82**	1.00										
Silt	0.22	-0.74**	1.00									
BD	-0.51**	0.58**	-0.39*	1.00								
pH	0.54**	-0.80**	0.73**	-0.46**	1.00							
SOM	0.57**	-0.79**	0.68**	-0.43**	0.89**	1.00						
TN	0.55**	-0.68**	0.52**	-0.48**	0.79**	0.92**	1.00					
AvP	0.55**	-0.79**	0.70**	-0.43**	0.84**	0.89**	0.85**	1.00				
Ca	0.55**	-0.72**	0.58**	-0.53**	0.77**	0.90**	0.92**	0.87**	1.00			
Mg	0.56**	-0.73**	0.59**	-0.53**	0.76**	0.82**	0.85**	0.79**	0.86**	1.00		
K	0.54**	-0.65**	0.48**	-0.60**	0.67**	0.79**	0.82**	0.67**	0.72**	0.71**	1.00	
CEC	0.55**	-0.75**	0.64**	-0.73**	0.76**	0.77**	0.73**	0.78**	0.76**	0.75**	0.7*	1.00

**Correlation is significant at $p < 0.01$ level. *Correlation is significant at $p < 0.05$ level. BD: bulk density; SOM: organic matter; TN: total nitrogen; AvP: available phosphorus; Ca: calcium; Mg: magnesium; K: potassium; CEC: cation-exchange capacity.

TABLE 6: Effects of SWC structures and slope position on soil chemical properties (mean $\pm$ SE).

Treatments/SWC structures	pH (H ₂ O)	SOM (%)	TN (%)	AvP (mgkg ⁻¹)
Control	5.37 $\pm$ 0.09 ^c	2.64 $\pm$ 0.32 ^c	0.135 $\pm$ 0.013 ^c	8.44 $\pm$ 1.18 ^c
SB	5.50 $\pm$ 0.14 ^b	3.01 $\pm$ 0.35 ^b	0.146 $\pm$ 0.011 ^b	9.91 $\pm$ 1.33 ^b
SFSB	5.56 $\pm$ 0.16 ^{ab}	3.16 $\pm$ 0.32 ^{ab}	0.168 $\pm$ 0.016 ^a	11.08 $\pm$ 1.47 ^a
SFSBS	5.65 $\pm$ 0.10 ^a	3.30 $\pm$ 0.23 ^a	0.169 $\pm$ 0.018 ^a	11.14 $\pm$ 1.08 ^a
LSD (0.05)	0.115	0.18	0.009	0.846
P	**	**	**	**
SEM ($\pm$)	0.123	0.30	0.014	1.26
<i>Slope class</i>				
Lower (4–10%)	5.76 $\pm$ 0.10 ^a	3.67 $\pm$ 0.27 ^a	0.188 $\pm$ 0.016 ^a	12.30 $\pm$ 1.15 ^a
Middle (10–15%)	5.49 $\pm$ 0.14 ^b	2.99 $\pm$ 0.33 ^b	0.146 $\pm$ 0.019 ^b	10.30 $\pm$ 1.94 ^b
Upper (15–20%)	5.31 $\pm$ 0.18 ^c	2.42 $\pm$ 0.46 ^c	0.129 $\pm$ 0.016 ^c	7.83 $\pm$ 1.28 ^c
LSD (0.05)	0.099	0.158	0.008	0.73
P	**	**	**	**
SEM ($\pm$)	0.14	0.35	0.02	1.46
CV (%)	2.13	6.16	6.16	8.54

Mean values followed by different letters along the same column are significantly different at ** $p < 0.01$ and * $p < 0.05$. LSD: least significant difference; NS: not significant; CV: coefficient of variance; SOM: soil organic matter; TN: total nitrogen; C: N = carbon nitrogen ratio; AvP: available phosphorus.

acidity levels, affects not only crop growth but also disrupts the ecosystem, highlighting the urgent need for SWC practices to safeguard the agricultural lands. This result agrees with the work of Guadie et al. [24], Teresa [36], Bojago et al. [34], and Masha et al. [35], who reported higher soil pH values in conserved than nonconserved farmlands or plots due to water erosion that caused higher removal of soluble bases and organic matter in the nonconserved farmlands or plots. As per the ratings of Landon [41], the soil pH in the control was rated as strongly acidic but moderately acidic in SWC-treated farmlands.

The pH of the soil varied significantly ($p < 0.01$) across slope positions. On the higher slope, the total mean soil pH was low (5.31) and high (5.76) in the lower slope positions (Table 6). As the slope gradient increased, the soil pH decreased, and when the slope gradient decreased, the soil pH increased. This is due to the effect of the slope gradient, which speeds up soil erosion and the leaching of soluble basic cations. This raises the concentration of H⁺ ions in the soil solution at the upper slope positions, lowering the pH and making the soil more acidic. This result concurs with the

studies of Hailu et al. [40], who reported lower (5.55) soil pH on the upper and higher (5.77) soil pH in the lower slope positions due to high water erosion in the upper slope position in the Goromti watershed, western Ethiopia. In a similar vein, Masha et al. [35] reported a higher pH value in the lower than in the middle and upper topographic positions in contrasting landscapes in southern Ethiopia. This variation in pH value across the slope gradient could also be related to differences in the distribution of SOM and CEC because pH was significantly and positively correlated with SOM ($r = 0.89^{**}$) and CEC ($r = 0.76^{**}$) (Table 5). However, Masha et al. [37] got a higher pH value in the middle slope, followed by the upper slope, but a low pH value in the lower slope position in the Wamancho watershed, southern Ethiopia.

3.1.4. Soil Organic Matter (SOM). The SOM was significantly ($p < 0.01$) affected by SWC structures and slope position, but the interaction effect of both factors showed insignificant ($p > 0.05$) variation (Table 3). A higher content of SOM (3.30%) was found in the fields treated with SWC

structures and a lower content (2.64%) in the untreated fields. Similarly, among the conservation structures, SFSBS had the highest SOM, followed by SFSB and SB-treated fields (Table 6). More organic residues from the *Sesbania sesban* plant species might have contributed to the highest SOM in fields treated with SFSBS. This demonstrates the positive effect of the integration of physical and biological SWC structures on increasing SOM content. The lowest organic matter in the untreated fields may be attributed to the loss of fine-textured soil fractions and crop residues from the topsoil layer due to the absence of SWC structures, as opposed to the deposition of sediment and decomposing crop residues resulting from the construction of SWC structures. This signifies how the implementation of SWC structures can result in notable improvements in SOM content, indicating the need for proper soil management practices to enhance agricultural productivity and sustainability. This finding was consistent with that of Alemayehu and Fisseha [42], who reported that the SOM was much lower in untreated fields and higher in SWC structures implemented in the Debre-Yakob Micro-Watershed, northwestern Ethiopia. Similarly, Demelash and Karl [38] reported higher SOM in the Tsegur Kidanemihret microwatershed in northwest Ethiopia, where there was the implementation of SWC structures. The result also corresponds with the findings of Bojago et al. [34] and Masha et al. [35], who discovered higher soil organic carbon in the SWC-treated lands than in the nonSWC-treated ones in different watersheds of southern Ethiopia. This consistency in results indicates the relevance of soil water conservation methods to improving soil nutrient distribution and land productivity.

In addition, there was statistically significant variation ($p < 0.01$) in SOM at different slope positions (Table 6). The lower slope positions had the highest SOM (3.67%), while the upper slope positions had the lowest (2.42%). This showed that SOM increases as the slope position decreases and becomes lower as the slope position increases. This was brought on by soil erosion, primarily influenced by differences in topography that caused the removal of topsoil and organic materials from the higher slope position to the lower slope position. The result was in line with Challa et al. [39], who found the highest SOM at the lower slope positions in the Adda Berga district, Western Shewa, Ethiopia. Furthermore, Masha et al. [35, 37] discovered a higher mean organic carbon content in the lower slope and a lower organic carbon content in the upper slope position in their study in watersheds of southern Ethiopia due to the removal and subsequent deposition of topsoil on the lower slope and the presence of more vegetation compared to the upper slope positions. The SOM was positively and significantly correlated with TN ($r = 0.92^{**}$), CEC ($r = 0.77^{**}$), pH ($r = 0.89^{**}$), clay ($r = 0.57^{**}$), and silt ($r = 0.68^{**}$), while it was negatively and significantly correlated with BD ($r = -0.43^{**}$) and sand ($r = -0.79^{**}$) (Table 5). These correlations indicate the relationship between SOM and different soil properties, indicating the importance of SOM in determining soil health and productivity. As per the EthioSIS [43] ratings, the soil organic matter level of the Gelda watershed was poor in the untreated fields and optimal in the fields treated with SWC structures.

3.1.5. Total Nitrogen (TN). The SWC structures, slope position, and the interaction effect of both factors all had a significant ($p < 0.01$) effect on TN (Tables 3 and 6). A higher TN (0.169%) was recorded in SFSBS-treated fields, while a lower TN (0.135%) was found in the untreated fields (Table 6). This could be related to the implementation of SWC structures that uphold soil nutrients and reduce soil erosion's loss of SOM and TN. The highest total nitrogen in SFSBS-treated fields may be the result of the integration of physical and biological conservation that adds more nitrogen to the soil. The lowest TN in the untreated fields might be related to the nonexistence of SWC structures that protect against water erosion and the removal of crop residues and stocks. The lack of SWC structures, which prevent water erosion and the removal of agricultural residues and stocks, may be responsible for the lowest TN in the untreated fields. This indicates the significant effect of the integrated use of physical structures and plant species on enhancing overall soil fertility and productivity. The results were consistent with the reports of Hailu et al. [40] and Teressa [36], who discovered significantly lower TN content in SWC-untreated fields than in treated fields in the Goromti watershed in Western Ethiopia and in the Weday watershed in eastern Ethiopia, respectively. The result is also in line with the findings of Demelash and Karl [38], who found higher TN concentrations in areas treated with physical SWC structures than in nonconserved lands. Additional reports by Bojago et al. [34] in the Anuwa watershed, southern Ethiopia, and Masha et al. [35] in contrasting landscapes of southern Ethiopia revealed that plots treated with SWC structures had better mean TN values than the nonconserved lands.

Besides, the TN value was higher (0.188%) in the lower slope positions compared to the upper slope (0.129%) positions (Table 6). This could be connected to the leaching of nitrogen from the higher to the lower positions. Since nitrogen is a mobile nutrient, it may easily leach from the upper to the lower slope positions during water erosive runoff. This phenomenon explains the role of water erosion in the distribution of essential nutrients such as nitrogen along the slope gradient, which will have an impact on soil fertility, plant growth, and overall ecosystem health in different parts of the watershed. This result was consistent with Aytenew [44], Challa et al. [39], and Guadie et al. [24], who obtained a significantly higher TN in the lower than in the upper slope positions in the Dawja watershed, northwest Ethiopia, Adda Berga district, Western Shewa, Ethiopia, and Lole watershed, northwestern highlands of Ethiopia, respectively. Similarly, Masha et al. [35] found a considerable difference in TN content in different slope positions in contrasting slope landscapes of southern Ethiopia. However, contrary to this result, Masha et al. [37] reported insignificant variation in TN content across different slope positions in the Womanco watershed in southern Ethiopia, which may be linked to differences in climate and topography settings.

The Pearson correlation result showed that TN and SOM were significantly and positively correlated ($r = 0.92^{**}$) (Table 5). This indicates that SOM is the main source of total nitrogen. This demonstrates that applying organic matter-

containing materials improves the content of nitrogen and organic carbon in the soil, promoting soil fertility and sustainability through nutrient enrichment. According to the ratings of EthioSIS [43], the total nitrogen level in the study area ranged from low in the untreated fields to optimum levels in SWC-treated fields.

3.1.6. Available Phosphorus (AvP). The SWC practices, slope location, and the combined effect of the two parameters significantly ($p < 0.01$) affected AvP (Table 3). This shows that SWC structures had a significant impact on the amount of available phosphorus concentration. The highest AvP ($11.14 \text{ mg} \cdot \text{kg}^{-1}$) was found in the SFSBS-treated fields and the lowest ($8.44 \text{ mg} \cdot \text{kg}^{-1}$) in the untreated ones. However, there was no substantial difference between the SFSBS and SFSB-treated farmlands (Table 6). The lower AvP in the untreated fields was due to soil erosion, intensive cultivation, a lack of SWC practices, and crop residue harvesting that reduced the organic matter content and lowered the soil pH. At a lower pH, soil acidity increases, and this triggers the release of aluminum (Al) and iron (Fe) cations that fix the soluble forms of phosphorus into unavailable forms. As the fixed forms of phosphorus increase, it will ultimately impact the overall availability of phosphorus for plant uptake and the overall agricultural productivity. The correlation analysis also showed a strong and positive correlation of AvP with SOM ($r = 0.89^{**}$), with TN ($r = 0.85^{**}$), and with pH ($r = 0.84^{**}$) (Table 5). This result was in agreement with the work of Teressa [36], who reported a higher AvP in the treated farm fields in the Weday watershed, eastern Ethiopia. Similar results were also reported by Ademe et al. [2], Bojago et al. [34], and Masha et al. [35], who demonstrated higher AvP from SWC-treated structures in their different study watersheds in southern Ethiopia.

The AvP was also higher ($12.30 \text{ mg} \cdot \text{kg}^{-1}$) in the lower slope than in the upper slope positions (Table 6). This could be caused by water erosion moving the topsoil, rich in nutrients and organic matter, from higher to lower slope positions. The distribution of topsoil by water erosion could influence the AvP levels observed at the different slope positions and have an impact on soil fertility. This finding was supported by Dagnachew et al. [45], who showed higher concentrations of AvP in the lower slope positions of the Geshy subcatchment, southern Ethiopia. According to the reports of Guadie et al. [24], the higher mean AvP was recorded in the lower slope positions than in the upper ones, which was associated with the washing out of topsoil and organic matter from the higher slope positions and their subsequent accumulation at the lower gradient/deposition zone in the Lole watershed, northwestern highlands of Ethiopia. Masha et al. [35] also recorded the highest value of phosphorus content on the lower slope and the lowest value on the upper slope in contrasting slope landscapes in southern Ethiopia. As per the ratings in EthioSIS [43], the available phosphorus level in the study area was very low due to the acidic nature of the soil.

3.1.7. Cation-Exchange Capacity (CEC). The SWC structures and slope position had a significant ($p < 0.01$) impact on the soil's CEC (Table 3). The mean CEC value recorded in the watershed under different conservation structures ranged from 39.86 to $49.04 \text{ cmol (+) kg}^{-1}$. The fields treated with SFSBS and the untreated fields had the highest ($49.04 \text{ cmol (+) kg}^{-1}$) and the lowest ($23.81 \text{ cmol (+) kg}^{-1}$) CEC values, respectively (Table 7). The higher CEC values in SWC-treated fields could result from the deposition of fine-textured fractions and SOM at the back of the SWC structures. The capacity of organic matter and clay in soil to absorb and hold positively charged ions is a well-established phenomenon that has been extensively documented in scientific literature. This illustrates the significant effect of SWC structures on CEC, with a corresponding increase in nutrient retention and availability within agricultural systems. A high cation-exchange capacity could therefore be a characteristic of soils with a high clay and organic matter concentration [35].

The correlation analysis of this study also showed a significant and positive correlation of CEC with clay ($r = 0.55^{**}$), SOM content ($r = 0.77^{**}$), and pH ($r = 0.76^{**}$) (Table 5). Therefore, soil CEC is expected to increase through the development of SOM. The SOM selectively plays an important role in soil exchangeable complexes because it provides a more negative charge surface than clay particles do [46]. This finding was in line with Guadie et al. [24], who reported a significantly higher CEC in SWC-treated fields in the Lole watershed, northwestern highlands of Ethiopia. According to Teressa [36], soils under terraced farm fields showed a higher CEC than the nonterraced farm fields, which was the result of the presence of a higher SOM due to the implemented stone bund in the terraced farm fields of the Weday watershed, eastern Ethiopia. In a similar study, both Bojago et al. [34] and Masha et al. [35] reported higher CEC values in fields treated with SWC structures in the Anuwa watershed and in contrasting landscapes of southern Ethiopia, respectively. They also associated such discrepancies with better soil organic matter and clay content in the treated fields than in the control ones, which agrees with the results of our findings. It is generally argued that improved soil fertility and higher cation retention are indicated by greater CEC values. Greater CEC values indicate the soil's ability to retain vital nutrients, which is a sign of whether or not a piece of land is suitable for a certain type of agriculture.

On the other hand, the higher overall mean CEC value ($49.41 \text{ cmol (+) kg}^{-1}$) was identified in the lower (4–9%) slope positions and the lower overall mean CEC value ($29.97 \text{ cmol (+) kg}^{-1}$) in the upper slope positions (Table 7). The CEC value decreased as the slope gradient increased and increased as the slope gradient decreased. The variation in CEC values with changing slope gradients indicates the dynamic relationship between land morphology and soil fertility patterns. This might be due to the movement of basic cations and fine-textured fractions such as clay from the upper to the lower slope positions. It is also possible that a higher soil organic matter content might be the

TABLE 7: Effects of SWC structures and slope position on soil exchangeable bases and CEC (mean $\pm$ SE).

Treatments/SWC structures	Exchangeable bases (Cmol (+) kg ⁻¹)			CEC (Cmol (+) kg ⁻¹)
	Ca	Mg	K	
Control	5.91 $\pm$ 1.65 ^c	2.60 $\pm$ 0.24 ^c	1.16 $\pm$ 0.50 ^b	23.81 $\pm$ 5.01 ^c
SB	7.68 $\pm$ 1.13 ^b	2.97 $\pm$ 0.05 ^b	1.43 $\pm$ 0.36 ^b	39.86 $\pm$ 4.47 ^b
SFSB	9.25 $\pm$ 1.66 ^a	3.04 $\pm$ 0.08 ^b	2.51 $\pm$ 0.20 ^a	42.01 $\pm$ 5.58 ^b
SFSBS	10.36 $\pm$ 2.17 ^a	3.43 $\pm$ 0.46 ^a	2.92 $\pm$ 0.70 ^a	49.04 $\pm$ 1.54 ^a
LSD (0.05)	1.15	0.37	0.58	5.45
P	**	**	**	**
SEM ($\pm$)	1.65	0.20	0.44	4.15
<i>Slope class</i>				
Lower (4–10%)	11.55 $\pm$ 3.00 ^a	4.13 $\pm$ 0.26 ^a	3.48 $\pm$ 0.65 ^a	49.41 $\pm$ 2.67 ^a
Middle (10–15%)	7.81 $\pm$ 1.92 ^b	2.66 $\pm$ 0.37 ^b	1.68 $\pm$ 0.50 ^b	36.65 $\pm$ 7.48 ^b
Upper (15–20%)	5.53 $\pm$ 0.80 ^c	2.23 $\pm$ 0.09 ^c	0.85 $\pm$ 0.38 ^c	29.97 $\pm$ 4.22 ^c
LSD (0.05)	0.10	0.32	0.50	4.72
P	**	**	**	**
SEM ($\pm$)	1.90	0.24	0.51	4.79
CV (%)	14.22	12.47	29.44	14.44

Mean values followed by different letters along the same column are significantly different at ** $p < 0.01$. LSD: least significant difference; CV: coefficient of variance; Ca: calcium; Mg: magnesium; K: potassium; Na: sodium; CEC: cation-exchange capacity.

contributing factor to the higher CEC values at lower elevations. This result was in agreement with the work of Aytenew [44], who reported the lowest CEC values (28.20 cmol (+) kg⁻¹) in the upper and the highest CEC values (41.87 cmol (+) kg⁻¹) in the lower slope positions in the Dawja watershed, northwestern Ethiopia. Similarly, Guadie et al. [24] reported a CEC value that was low in the upper and high in the lower slope positions in the Lole watershed, northwestern highlands of Ethiopia. As per the ratings of Landon [41], the soils of the studied watershed treated with SWC structures had very high CEC values, and the untreated ones had low CEC values. However, as per the ratings of Landon [41], the CEC value in this study contradicts Bojago et al.'s [34] result that reported higher CEC values both in the control and SWC-treated plots in the Anuwa watershed in southern Ethiopia. These differences between the two sites could potentially be attributed to variations in soil composition, landform pattern, rainfall dispersion, and the intensity of soil erosion.

3.2. Exchangeable Bases (Ca²⁺, Mg²⁺, and K⁺). The contents of exchangeable calcium (Ca²⁺) and magnesium (Mg²⁺) were significantly ($p < 0.05$) affected by SWC treatments and slope position. Exchangeable Ca²⁺ was also significantly ($p < 0.05$) influenced by the interaction effect of both factors, whereas exchangeable Mg²⁺ was unaffected (Tables 3 and 7). The SWC-treated fields had higher exchangeable Ca²⁺ and Mg²⁺ (10.36 cmol (+) kg⁻¹ and 3.43 cmol (+) kg⁻¹), respectively, whereas they were lower in untreated fields (5.91 cmol (+) kg⁻¹ and 2.60 cmol (+) kg⁻¹), respectively (Table 7). This was linked to the reduced impact of water erosion in the treated fields, which retains and deposits organic matter and fine-textured soil particles behind the SWC structures. Since SWC structures significantly reduce water erosion, it is noteworthy that their adoption could be beneficial in an agricultural and environmental context. The Pearson

correlation analysis also demonstrated a significant and positive correlation between these exchangeable cations (Ca²⁺ and Mg²⁺) and SOM ($r = 0.90^{**}$ and 0.82^{**}), clay ($r = 0.55^{**}$ and 0.56^{**}), and pH ($r = 0.77^{**}$ and 0.76^{**}), respectively (Table 5). These relationships underscore the fact that the distribution of exchangeable cations is also influenced by other soil properties. The result was consistent with Shafi et al. [47], who stated the beneficial impacts of SWC structures on the contents of exchangeable Ca²⁺ and Mg²⁺ in the Ezha district, southern Ethiopia. This finding was also consistent with the findings of Bojago et al. [34] and Masha et al. [35], who indicated the role of implementing SWC structures in increasing the concentration of exchangeable cations in their studied watersheds in southern Ethiopia.

The exchangeable Ca²⁺ and Mg²⁺ was also low (5.53 cmol (+) kg⁻¹ and 4.13 cmol (+) kg⁻¹, respectively) in the upper slope locations (Table 7). This demonstrates the visible effects of the slope gradient that caused the washing out of basic cations through runoff and erosion on the higher slope and their deposition on the lower slope positions. Furthermore, the result indicates the role that topography plays in influencing soil fertility and ecosystem dynamics. This result was in agreement with the work of Aytenew [44], who reported the lowest and highest values of exchangeable Ca²⁺ and Mg²⁺ in moderately steep and gentle sloping areas, respectively, in the Dawja watershed, northwest Ethiopia. In a similar study, Masha et al. [35, 37] reported the significant effects of slope position on the distribution of exchangeable Ca²⁺ and Mg²⁺, where it was higher in the lower and middle slope positions but low in the upper slope position due to leaching and water erosion.

As per the ratings of FAO [48], the soil of untreated fields is categorized as medium, while the soil of treated fields is categorized as medium to high in exchangeable calcium content. However, exchangeable magnesium from untreated fields is categorized as medium, whereas treated fields are categorized as high.

Exchangeable potassium (K^+) was highly significantly ($p < 0.01$) affected by SWC structures, slope position, and the interaction effect of both factors (Table 3). Lower exchangeable potassium ($1.16 \text{ cmol (+) kg}^{-1}$) was found in the untreated fields with SWC, and higher exchangeable K^+ ($2.92 \text{ cmol (+) kg}^{-1}$) was obtained in SWC-treated fields (Table 7). The result of this study showed a significant and positive correlation of exchangeable K^+ with clay ($r = 0.54^{**}$), SOM content ($r = 0.79^{**}$), pH ($r = 0.67^{**}$), and OC ($r = 0.79^{**}$) (Table 5). The outcome was consistent with Shafi et al.'s [47] finding, who showed a significant ($p < 0.01$) variation in exchangeable K^+ between treated and untreated fields in the Ezha district, southern Ethiopia. Similarly, Ademe et al. [2] reported that the SWC-treated watersheds showed higher exchangeable K^+ than the untreated ones, in Wonago district, southern Ethiopia. The result was also consistent with the findings of Bojago et al. [34] and Masha et al. [35], who reported a better distribution of exchangeable K^+ in SWC-treated lands than the untreated ones (control). Similar to our findings, both studies indicate that exchangeable potassium (K^+) distribution was improved in SWC-treated lands than in the untreated control group.

The lowest ($0.85 \text{ cmol (+) kg}^{-1}$) and highest ($3.48 \text{ cmol (+) kg}^{-1}$) values of exchangeable K^+ were recorded in the upper and lower slope positions, respectively (Table 7). This was due to the higher influence of erosion in the upper slope positions. The result was consistent with the findings of Teresa [36], who found lower exchangeable K^+ in the upper slope than in the lower and middle slope positions in the Weday watershed, eastern Ethiopia. This result was comparable to the work of Aytenew [44], who reported the highest and lowest values of exchangeable K^+ in the gently sloping and moderately steep areas, respectively, in the Dawja watershed, northwest Ethiopia. Furthermore, Masha et al. [35, 37] reported the maximum availability of exchangeable K^+ in the lower slope positions in their study areas in southern Ethiopia. However, according to FAO [48], the contents of exchangeable potassium in both untreated and treated fields were not deficient in potassium.

The medium-to-high level of basic cation in both the conserved and nonconserved farmlands of the watershed might be associated with the inherent properties of the soils. Most of the Ethiopian highland soils are developed from recent Trappean lava flows, for which they have a high base status [49]. This inherent feature of the soils probably has a significant impact on the amount of basic cations that are present in the farmlands inside the watershed. The overall mean concentration of exchangeable basic cations in the exchange complex of soil samples under all the soil water conservation practices and slope positions in the study area was in the order of $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$ (Table 7). Generally, the presence of Ca^{2+} , followed by Mg^{2+} and K^+ , in the soil exchange site is important in boosting agricultural productivity [50]. This result concurs with the report of Hailu et al. [40] that, under all SWC practices and slope gradients, the overall mean concentration of exchangeable cations is in the order of $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$ in the Goromti watershed, western Ethiopia.

4. Conclusion

The study confirmed that both SWC structures and slope location have an impact on soil physicochemical properties in the Gelda watershed. This was due to the effect of both SWC structures and slope position, which in turn affected the rate of soil erosion, organic matter distribution, nutrient availability, and water-holding capacity of the soil. Most of the soil's physicochemical properties (clay, silt, BD, pH, TN, SOM, AvP, CEC, and exchangeable bases) were kept in a reasonably good condition in the SWC-treated farm fields. Besides, the untreated farm fields showed the poorest soil physicochemical properties. Similar to SWC structures, all selected soil physicochemical properties showed significant differences with slope position. The negative influences of slope position on the soil properties of untreated farm fields were higher than those of treated farm fields with SWC. These findings indicate that the SWC methods implemented in the watershed improved the majority of soil qualities. For most of the soil parameters evaluated, positive impacts were found in the farmlands treated with conservation structures, mainly stone-faced soil bund integrated with *Sesbania sesban*, followed by stone-faced soil bund and soil bund, as compared to the fields without SWC structures. Although all the SWC structures contributed to enhancing soil fertility, the positive impact was significantly increased by the integration of stone-faced soil bunds with *Sesbania sesban* plant species. This integrated approach proved to be effective, as the successful combination of plant species and physical soil structures led to an improvement in soil fertility. Therefore, the variation among SWC structures could be the result of differences in their impact on protecting the transport of soil particles and nutrients by runoff. Hence, the result demonstrates that different conservation measures have different implications for improving soil fertility in the Gelda watershed. The study will have implications for policymakers, local governments, stakeholders, and planners in the selection, proper design, and implementation of SWC structures to improve soil fertility and ensure food security for the farming community. Moreover, the findings will also provide useful information to the farmers of the watershed for choosing, implementing, and adopting the best soil conservation practices on their farmlands. Therefore, the integration of physical soil conservation structures with selected multipurpose plant species, such as *Sesbania sesban*, could have a positive effect on improving soil fertility and reducing soil erosion in the watershed and similar agroecologies. Further studies are required to investigate the effects of commonly used SWC structures on crop yield in the studied watershed and different agroecologies. In addition, for effective implementation of SWC practices, a thorough investigation of the factors influencing community participation and adoption of SWC initiatives, such as social, cultural, and economic constraints, are required in the watershed and across the country.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Disclosure

This research was formerly presented as Mr. Kefyalew Muchie's MSc thesis titled "Evaluation of the effect of SWCP and slope gradient on selected soil properties and farmers' perceptions on SWCP: The case of Gelda watershed, Dera district, northwest Ethiopia" under the supervision of Dr. Eyayu Molla, and it has been archived at the Bahir Dar University Institutional Repository System.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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