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Effects of soil and water conservation practices on soil physical and chemical properties: evidence from estie district, Northwestern Ethiopia

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Abstract

Soil erosion remains one of the most widespread forms of land degradation affecting agricultural productivity and ecosystem services in the Ethiopian highlands. Soil and water conservation (SWC) practices have been widely promoted to rehabilitate degraded lands; however, their effects vary across landscapes and management conditions. This study assessed the impacts of major SWC practices on selected soil physical and chemical properties in the Estie District of northwestern Ethiopia. Soil samples were collected from conserved plots under soil bunds (SB), soil bunds stabilized with *Sesbania cannabina* (SBS), and adjacent non-conserved plots. Samples were taken at two terrace positions, low-bund and mid-bund, across three agro-ecological zones (highland, midland, and lowland). Standard laboratory procedures were applied to analyze pH, soil organic matter (SOM), total nitrogen (TN), cation exchange capacity (CEC), available phosphorus (Av. P), available potassium (Av. K), texture, bulk density, and moisture content. Data were evaluated using two-way ANOVA ($p < 0.05$). Results revealed that SWC practices significantly improved soil fertility and structural stability. Compared to non-conserved plots, both SB and SBS treatments exhibited higher SOM, TN, CEC, Av. P, and Av. K. with SBS showing the greatest improvements. Bulk density was lowest under SBS plots, indicating reduced compaction and enhanced root-zone conditions. Nutrient enrichment was most pronounced at low-bund positions, reflecting downslope deposition effects. Additionally in SOM and moisture content, there is a decreasing of values in treatments (SBS, SB and control) in each bund positions. As a result, integrated SWC measures, particularly bunds stabilized with leguminous species, substantially enhance soil physicochemical properties and contribute to sustainable land management. These findings underscore the importance of combining physical and biological conservation measures to restore degraded soils in erosion-prone farming systems.

1. Introduction

Soil degradation is a persistent environmental and agricultural challenge in many parts of sub-Saharan Africa, and Ethiopia represents one of the most severely affected regions. The severity of land degradation is closely linked to steep topography, erosive rainfall, continuous cultivation, and population-driven land-use pressure, all of which accelerate soil nutrient depletion and productivity decline (Hurni *et al* 2015, Berihun *et al* 2019). Soil erosion in these landscapes undermines key soil physicochemical properties, including soil organic matter,

nutrient availability, moisture retention, and structural stability, ultimately threatening food security and livelihoods in predominantly rain-fed agricultural systems (Belayneh *et al* 2019, FAO 2022, Ermias *et al* 2024).

In response, Ethiopia has implemented extensive Soil and Water Conservation (SWC) interventions for several decades (Belachew *et al* 2020, Dessie *et al* 2025, Estefanos *et al* 2025). Early efforts emphasized physical structures such as soil bunds, stone bunds, and terraces to reduce runoff and stabilize slopes (Adimassu *et al* 2017, Dimtsu *et al* 2018, Jiru and Wegari 2022). More recently, integrated approaches combining physical and biological measures, such as vegetative stabilization, agroforestry species, and leguminous cover crops, have been promoted to enhance soil organic matter and long-term resilience (Sultan *et al* 2018, Bayle and Muluye 2023). Evidence from Ethiopian watersheds demonstrates that well-managed SWC practices can improve soil pH, organic carbon, total nitrogen, cation exchange capacity, moisture retention, and crop productivity (Husen *et al* 2017, Alemayehu and Fisseha 2018, Debisa *et al* 2025). Yet, the effectiveness of these practices remains highly context-specific, influenced by agro-ecological conditions, slope, maintenance, and farmers' perceptions and adoption behavior (Asfaw and Neka 2017, Sileshi *et al* 2019, Desta *et al* 2025).

Despite substantial national investment, empirical evidence on SWC effectiveness remains mixed. Some studies report clear improvements in soil fertility and moisture following conservation interventions (Tanto and Laekemariam 2019, Taye *et al* 2024), while others highlight limited or inconsistent outcomes due to poor maintenance, variable implementation, and site-specific erosion dynamics (Moges and Taye 2017, Fenta *et al* 2024). These inconsistencies emphasize the need for localized, comparative studies that assess SWC performance across different landscapes and landforms.

The Estie District of northwestern Ethiopia presents a particularly relevant case for this assessment due to its diverse agro-ecological conditions, spanning highland, midland, and lowland zones with variable rainfall regimes, complex topography, and high susceptibility to soil erosion. The district's soils originate from varied parent materials, including volcanic basalt and sedimentary formations, which influence inherent fertility, texture, and drainage characteristics. Agricultural land-use is dominated by smallholder mixed farming systems, with cereal-legume rotations and intensive tillage practices, which have historically contributed to soil degradation and nutrient depletion. Over the past decade, soil bunds (SBs) and biologically stabilized bunds using *Sesbania cannabina* (SBSs) have been extensively implemented across these zones. However, comparative evaluations of physical versus biologically stabilized bunds across different terrace positions remain limited. Since soil accumulation, nutrient redistribution, and sediment deposition vary along bund catena positions, assessing these effects is critical for understanding soil rehabilitation processes, interpreting physicochemical changes accurately, and improving conservation strategies in erosion-prone landscapes.

This study, therefore, examines the effects of SBs, SBSs, and adjacent non-conserved plots on key soil physical and chemical properties, including soil pH, organic matter, total nitrogen, cation exchange capacity, available phosphorus, and soil texture, across mid-bund and low-bund positions in Estie District. By providing site-specific, position-sensitive insights, this research addresses a gap in the literature and offers practical evidence to inform targeted SWC planning, implementation, and scaling up in the Ethiopian highlands.

2. Materials and methods

2.1. Description of the study area

The study was conducted in the Estie District, located in the South Gondar Zone of the Amhara Regional State in northwestern Ethiopia (figure 1). Estie is situated approximately 676 km from Addis Ababa, 106 km from the regional capital Bahir Dar, and 52 km from the zonal town of Debre Tabor. Geographically, the district lies between 11°00'–11°31' N latitude and 36°36'–37°10' E longitude. It is bordered by Lay Gaint and Simada to the east, Fogera to the west, Farta to the north, and the East Gojjam Zone to the south. The district is characterized by diverse and complex topography, with elevation ranging from 1,500 to 4,231 meters above sea level. This altitudinal variation creates three major agro-ecological zones: highland (>2,400 m a.s.l.), midland (1,800–2,400 m a.s.l.), and lowland (<1,800 m a.s.l.). Annual rainfall ranges from 1,200 to 1,600 mm, mainly occurring between June and September, while mean annual temperatures vary between 14 °C and 24 °C depending on elevation. Estie's dominant soil types include Nitisols and Cambisols in the highland areas and Vertisols in the midland and lowland zones.

Agriculture is predominantly rain-fed, and households rely on mixed crop–livestock production as their primary livelihood system. The district is highly susceptible to soil erosion due to its steep slopes, intensive cultivation, and erratic rainfall patterns. In response, extensive soil and water conservation (SWC) practices, particularly soil bunds and vegetative stabilized bunds, have been promoted and widely implemented through community participation and government-supported integrated watershed management programs (EWAO 2025).

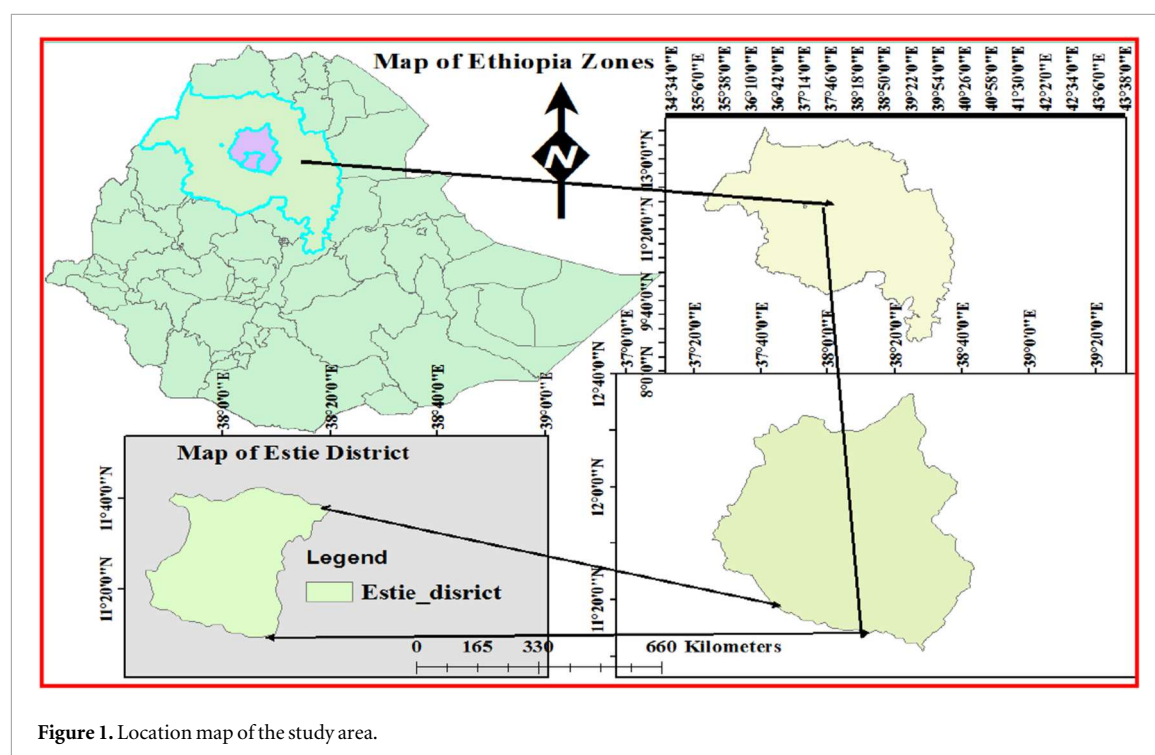


Figure 1. Location map of the study area.

2.2. Soil and water conservation practices examined

The study evaluated three land management treatments commonly applied in Estie District to mitigate soil erosion. The first treatment, Soil Bunds (SBs), consists of earthen embankments constructed along the contour to reduce runoff velocity and prevent soil loss. The second treatment, Soil Bunds Stabilized with *Sesbania cannabina* (SBSs), involves reinforcing the soil bunds with *S. cannabina*, a fast-growing, nitrogen-fixing legume that enhances root reinforcement, soil structure, and soil fertility. In the study area, both SBs and SBSs had been established and maintained for more than ten (10) years, duration sufficient to allow measurable and stable changes in soil physicochemical properties to occur (Estie Woreda Agriculture Office (EWAO 2025).

The third treatment, Non-Conserved Plots (Control), includes adjacent cultivated fields without any conservation structures, representing erosion-prone soils frequently exposed to runoff and topsoil depletion. Each treatment was assessed at two terrace positions: the mid-bund position, located at the middle section of the bund, and the low-bund position, situated at the lower section. These positions were selected to account for spatial variability in erosion–deposition processes within banded landscapes, which can significantly influence soil loss and accumulation patterns.

2.3. Data sources

Both primary and secondary data sources were utilized to conduct this study. Primary data were collected from the district agricultural experts and practitioners involved in soil and water conservation activities. Secondary data were obtained from published sources such as peer-reviewed journals, books, and conference proceedings, as well as from various unpublished documents and reports relevant to the study area and research topic.

2.4. Methods of data collection

2.4.1. Soil data collection methods

Soil data were collected from the field using appropriate tools and with the assistance of development agents (DAs) from the district. Sampling equipment included shovels, plastic containers for packing composite soil samples, measuring tapes to determine sample locations along bunds, core samplers, flat timbers, knives, and line levels or water-tube levels to measure slope along 10 m transects. Collected samples were transported to the laboratory for further analysis. Three villages were purposively selected from different agro-climatic zones due to their relatively well-established soil and water conservation (SWC) and land management practices. A reconnaissance survey was conducted to identify representative farmland plots for sampling. Based on this survey, three treatments were selected: soil bunds (SB), soil bunds reinforced with *Sesbania cannabina* (SBS), and adjacent non-terraced plots (control).

Soil samples were collected from the 0–20 cm depth, consistent with standard agronomic practices, as this layer encompasses a large proportion of the active root zone (Vadas *et al* 2006). As presented in figure 2,



Figure 2. Soil sampling along mid-bund and low-bund positions in the study area.



Figure 3. Soil sample collection at the field of the study area, (a) core sampler for bulk density and moisture contents determination; (b) Collection of composite soil samples from agricultural plots.

sampling was performed at two bund positions: thus, Mid-bund position: the central section between consecutive bunds, and Low-bund position: approximately 50 cm upslope from the base of the bund, minimizing the effect of water accumulation on nutrient distribution (Shiene 2012).

Sampling from SBS, SB, and control plots allowed assessment of the effects of physical and vegetatively reinforced conservation practices on soil properties. For bulk density and moisture content, a core sampler of known volume (98.125 cm^3) was used to collect undisturbed soil from each plot (figure 3(a)). Soil samples from each village were collected in 12 replicates: 2 replicate $\times$ 3 treatments $\times$ 2 bund positions = 12 samples per village. These were thoroughly mixed to form composite samples, resulting in a total of 36 composite soil samples across the three villages (figure 3(b)).

2.4.2. Soil laboratory analysis

Soil samples collected from the field were analyzed in the laboratory for moisture content, bulk density, texture, pH, cation exchange capacity, organic matter, and major nutrients using standard procedures. Soil Moisture

Content (SMC): Determined by the gravimetric method, which measures water loss from a soil sample before and after oven-drying at 105 °C for 24 h (ASTM 2005). Moisture content (%) was calculated as:

$$\text{Moisture content(\%)} = \frac{\text{weight of fresh soil} - \text{weight of oven dry soil}}{\text{weight of oven dry soil}} * 100$$

Bulk Density (ρ_b): Measured on undisturbed soil cores as the oven-dried mass per unit total volume, including pore space (Miller and Donahue 1990):

$$\rho_b = \frac{M_s}{V_t}$$

Where, ρ_b = bulk density, M_s = oven-dried mass of soil, V_t = total volume of the soil sample.

Along with, **Soil Texture**: Determined by the pipette method (Haluschak 2006), which separates soil particles into sand (0.05–2.0 mm), silt (0.002–0.05 mm), and clay (<0.002 mm) fractions based on sedimentation and sieving techniques (Gankiso 2017).

Soil pH: Measured using a potentiometer with glass electrodes (Bates 1954).

Cation Exchange Capacity (CEC): Determined by the ammonium acetate saturation method at pH 7.0 (Rhoades 1982).

Soil Organic Matter (SOM): Organic carbon content was measured using the wet digestion method of Walkley and Black (1934) and converted to organic matter by multiplying by 1.724.

Total Nitrogen (TN), Available Phosphorus (Av. P), and Available Potassium (Av. K): TN was determined using the Kjeldahl wet digestion method, Av. P by extraction, and Av. K by ammonium acetate extraction (Black *et al* 1965).

2.4.3. Methods of statistical data analysis

All soil sample analyses were conducted at the Adet Agricultural research center (Soil Research Laboratory) following standardized laboratory procedures. The quantitative data were analyzed statistically to evaluate the effects of conservation practices and terrace positions on soil properties. A two-way analysis of variance (two-way ANOVA) was employed to examine the main and interaction effects of terrace position and types of conservation practices on the measured soil parameters. Mean separation was performed using the Least Significant Difference (LSD) test at a 5% probability level to determine statistically significant differences among treatments. All statistical analyses were carried out using the General Linear Model (PROC GLM) procedure.

The absence of pre-intervention baseline soil data was addressed by deliberately selecting adjacent non-conserved plots with comparable slope, soil type, land-use history, and management practices as reference controls, thereby providing a practical and widely accepted comparative baseline in soil and water conservation impact studies where pre-implementation data are unavailable.

3. Results and discussions

This section presents the effects of soil and water conservation (SWC) practices, soil bund (SB), soil bund stabilized with *Sesbania cannabina* (SBS), and non-conserved plots, on key soil chemical and physical properties across highland, midland, and lowland agro-ecological zones. The results reflect both the main effects of conservation practices and terrace positions (low-bund versus mid-bund), as well as their interactions. Differences among means were evaluated using two-way ANOVA followed by LSD tests at $p < 0.05$.

3.1. Effects of soil and water conservation practices on soil chemical properties

3.1.1. Soil pH (H_2O)

The variation of soil pH under different bund positions and conservation practices is presented in table 1. In the midland village, the soil pH under the SBS (soil bund with *Sesbania cannabina*) was significantly higher than under SB (bare bund) and control plots, especially at both low- and mid-bund positions. This pattern likely reflects organic matter accumulation and deposition of soluble bases in banded zones, consistent with similar findings in conserved Ethiopian watersheds. For example, Alemayehu *et al* (2020) observed higher pH in the lower sections of stone bunds due to sediment buildup enriched in basic cations. Furthermore, empirical research shows that long-term conservation structures reduce leaching of exchangeable cations, resulting in higher pH compared to untreated fields (Gadisa and Hailu 2020).

In the highland and lowland villages, although some comparisons were not statistically significant, conserved plots (especially SBS) still tended to have a more neutral pH than control plots. This suggests a general buffering effect of conservation measures via increased organic inputs and reduced acidity, a result also supported in other Ethiopian landscapes. These results also align with findings by Megersa (2011) and Worku

Table 1. Soil pH (H₂O) under different bund positions and soil and water conservation practices.

Position on bunds	Treatments	Study villages		
		Midland	Highland	Lowland
Low-bund	SBS	7.3 ^a	6.90 ^a	6.04 ^a
	SB	6.36 ^{ab}	6.31 ^a	6.08 ^a
	Control	4.59 ^b	5.35 ^a	5.12 ^a
	P-value	0.05	0.16	0.45
	LSD	1.96	1.86	2.40
Mid-bund	SBS	6.38 ^a	6.45 ^a	6.54 ^a
	SB	5.71 ^{ab}	5.56 ^b	5.77 ^b
	Control	5.02 ^b	4.90 ^b	5.07 ^c
	P-value	0.02	0.02	0.01
	LSD	0.69	0.78	0.59

Values are means of soil pH measurements. Means within the same column followed by the same superscript letter are not significantly different at $\alpha = 0.05$, as determined by the Least Significant Difference (LSD) post-hoc test following analysis of variance (ANOVA). SBS = Soil Bund stabilized with *Sesbania cannabina*; SB = Soil Bund without vegetation; Control = Non-conserved plot; LSD = Least Significant Difference.

Table 2. Soil organic matter (SOM, %) under different bund positions and soil and water conservation practices.

Position on bunds	Treatments	Study villages		
		Midland	Highland	Lowland
Low-bund	SBS	1.89 ^a	2.27 ^a	1.77 ^a
	SB	1.39 ^a	2.01 ^a	1.94 ^a
	Control	1.01 ^a	0.89 ^b	1.04 ^b
	P-value	0.18	0.01	0.01
	LSD	1.12	0.62	0.44
Mid-bund	SBS	1.50 ^a	2.54 ^a	1.46 ^a
	SB	0.86 ^b	2.36 ^a	0.81 ^a
	Control	0.06 ^c	1.31 ^a	0.06 ^b
	P-value	0.01	0.14	0.02
	LSD	0.62	1.49	0.72

Values are means of soil organic matter content (%). Means within the same column followed by the same superscript letter are not significantly different at $\alpha = 0.05$, based on the Least Significant Difference (LSD) post-hoc test following ANOVA. SBS = Soil Bund stabilized with *Sesbania cannabina*; SB = Soil Bund without vegetation; Control = Non-conserved plot; LSD = Least Significant Difference.

(2017), who reported that conservation structures enhance soil organic matter accumulation and reduce cation leaching, resulting in higher soil pH compared to untreated fields.

3.1.2. Soil organic matter (SOM)

Soil organic matter content varied with bund position and conservation treatment (table 2). Overall, plots treated with conservation practices exhibited higher SOM than control plots. The highest SOM values were observed under SBS at low-bund positions, while mid-bund positions and SB treatments had lower values, except in the highland village. Similar findings have been reported in enclosure-based conservation systems in northern Ethiopia, where terraces supported with vegetation promote significant organic carbon accumulation (Welemariam *et al* 2018). Moreover, the decrease in SOM from low- to mid-bund positions suggests downslope transport of organic matter via runoff. Highland sites showed the highest SOM, possibly due to slower decomposition under cooler temperatures and higher moisture content, which restricts microbial activity and organic matter breakdown (Belayneh *et al* 2019).

Table 3. Cation exchange capacity (CEC, cmol kg⁻¹) under different bund positions and soil and water conservation practices.

Position on bunds	Treatments	Study sites		
		Midland	Highland	Lowland
Low-bund	SBS	41.2 ^a	31.34 ^a	36.87 ^a
	SB	31.67 ^a	28.52 ^{ab}	36.10 ^a
	Control	27.81 ^a	22.88 ^b	32.01 ^a
	P-value	0.16	0.06	0.65
	LSD	16.23	6.73	16.7
Mid-bund	SBS	40.02 ^a	33.67 ^a	33.87 ^a
	SB	37.16 ^a	28.73 ^{ab}	26.16 ^a
	Control	23.40 ^b	25.76 ^b	21.99 ^a
	P-value	0.01	0.04	0.11
	LSD	7.86	5.08	11.96

Values are means of cation exchange capacity (cmol kg⁻¹). Means within the same column followed by the same superscript letter are not significantly different at $\alpha = 0.05$, based on the Least Significant Difference (LSD) post-hoc test following one-way ANOVA. SBS = Soil Bund stabilized with *Sesbania cannabina*; SB = Soil Bund without vegetation; Control = Non-conserved plot; LSD = Least Significant Difference.

3.1.3. Cation exchange capacity (CEC)

CEC was significantly influenced by the interaction between bund position and conservation practice, particularly at mid-bund positions in the midland and highland villages (table 3). Overall, the highest CEC values occurred under the soil bund with stabilization (SBS) treatment at low-bund positions, whereas the control plots consistently exhibited the lowest values. The elevated CEC at low-bund positions is likely associated with greater soil organic matter (SOM) accumulation and the deposition of fine sediments transported downslope. These depositional environments tend to enhance the soil's capacity to retain exchangeable cations, reflecting well-established relationships between SOM and CEC reported in earlier studies (Olarieta *et al* 2008, Rashid *et al* 2016). Across the study landscape, variation in CEC was also shaped by broader environmental factors such as parent material, local microclimatic conditions, and village-level differences in rainfall regimes. Such spatial variability aligns with findings from erosion-prone agroecosystems, where both geomorphic position and conservation practice co-determine nutrient-retention characteristics.

In both midland and lowland villages, the strong performance of SBS at low-bund positions is consistent with the higher SOM content observed in these areas, reinforcing the well-documented positive correlation between organic carbon and CEC in depositional zones of degraded landscapes (Alemayehu *et al* 2020). However, unlike these zones, highland locations did not always exhibit significant treatment-based differences in CEC at low-bund positions. This may be attributed to the effects of high rainfall intensity and associated leaching losses, which can diminish the accumulation of nutrient-rich organic residues despite the presence of conservation structures, a pattern also reported in similar Ethiopian highland environments (Alemayehu *et al* 2020).

3.1.4. Total nitrogen (TN)

As table 4 shows, Total nitrogen (TN) content was significantly influenced by bund position and treatment. The highest TN was recorded under SBS at low-bund positions in midland village (0.295%) and mid-bund positions in highland village (0.24%). The accumulation of nitrogen at lower slope positions is likely due to nutrient transport via runoff from upper slope areas, consistent with findings of Tugizimana (2015). These results also match long-term observations: older conservation structures show increased nitrogen accumulation in downslope zones, possibly due to continual organic matter input and reduced leaching (Arunrat *et al* 2022).

3.1.5. Available phosphorus (Av. P)

Available phosphorus content varied with bund position and treatment (table 5). The highest Av. P was observed under SBS at low-bund positions (15.31 ppm), whereas the lowest values occurred in control plots. The accumulation of Av. P in lower slope positions may result from sediment deposition, as phosphorus binds strongly to soil particles, facilitating its movement and concentration in terrace bottom zones (Lemma *et al* 2017, Bufebo *et al* 2021). Similar nutrient gradients have been documented in other Ethiopian terraces. For example, Alemayehu *et al* (2020) found higher Av. P in depositional zones of stone bunds. Additionally, long-term conservation in terraced rice paddies showed that older bunds (>10 years) had significantly greater

Table 4. Total Nitrogen (TN, %) under different bund positions and conservation practices.

Position on bunds	Treatments	Study sites		
		Midland	Highland	Lowland
Low-bund	SBS	0.295 ^a	0.23 ^a	0.20 ^a
	SB	0.071 ^b	0.17 ^{ab}	0.09 ^{ab}
	Control	0.06 ^b	0.03 ^b	0.05 ^b
	P-value	0.0001	0.07	0.1
	LSD	0.02	0.17	0.15
Mid-bind	SBS	0.23 ^a	0.24 ^a	0.23 ^a
	SB	0.06 ^b	0.144 ^{ab}	0.06 ^b
	Control	0.03 ^b	0.08 ^b	0.03 ^b
	P-value	0.02	0.05	0.03
	LSD	0.11	0.11	0.13

Values followed by the same letter within a column are not significantly different at $\alpha = 0.05$, based on the Least Significant Difference (LSD) test. SBS = Soil Bund stabilized with *Sesbania cannabina*; SB = Soil Bund without vegetation; Control = Non-conserved plot; LSD = Least Significant Difference.

Table 5. Available Phosphorus (Av. P, ppm) under different bund positions and conservation practices.

Bund Position	Treatments	Study sites		
		Midland	Highland	Lowland
Low-bund	SBS	15.31 ^a	7.01 ^a	14.24 ^a
	SB	11.27 ^a	8.01 ^a	12.68 ^a
	Control	5.25 ^a	1.95 ^a	9.09 ^a
	P-value	0.15	0.27	0.55
	LSD	11.66	10.02	13.94
Mid-bund	SBS	12.46 ^a	7.92 ^a	11.85 ^a
	SB	7.11 ^{ab}	7.68 ^a	7.11 ^{ab}
	Control	5.13 ^b	3.53 ^a	5.12 ^b
	P-value	0.07	0.31	0.05
	LSD	6.17	8.37	5.23

Means followed by the same letter within each column are not significantly different at $\alpha = 0.05$, based on the Least Significant Difference (LSD) test. SBS = Soil Bund stabilized with *Sesbania cannabina*; SB = Soil Bund without vegetation; Control = Non-conserved plot; LSD = Least Significant Difference.

available phosphorus than non-bund fields, highlighting the cumulative effect of erosion and deposition over time (Arunrat, *et al* 2022, Eshetu *et al* 2024).

3.1.6. Available potassium (Av. K)

Available potassium was also influenced by bund position and conservation practice (table 6). The highest Av. K (85.29 ppm) was recorded under SBS at mid-bund positions, while the lowest values were observed in control plots. The accumulation of potassium at lower slope positions may be attributed to slower runoff and longer residence time of water, allowing soluble nutrients to settle (Olarieta *et al* 2008). Differences in crop type and organic matter inputs also influence potassium availability, with low organic matter and complete biomass removal reducing nutrient content. Similar processes were reported in other Ethiopian watersheds: physical conservation structures that reduce runoff velocity can enhance nutrient retention and raise soil fertility in lower slope zones (Mathewos and Lukas 2025).

3.2. Effects of SWC practices on soil physical properties

3.2.1. Soil textural class

Table 7 shows the impact of different bund positions and soil and water conservation (SWC) practices on clay content. Statistical analysis using one-way ANOVA and LSD test indicated that the interaction of bund position

Table 6. Available potassium (Av. K, ppm) under different bund positions and conservation practices.

Bund Position	Treatments	Study sites		
		Midland	Highland	Lowland
Low-bund	SBS	53.79 ^a	72.30 ^a	82.53 ^a
	SB	45.17 ^a	50.92 ^a	79.66 ^a
	Control	33.66 ^a	44.38 ^a	47.68 ^b
	P-value	0.35	0.22	0.01
	LSD	38.92	40.67	17.47
Mid-bund	SBS	48.42 ^a	85.29 ^a	47.47 ^a
	SB	35.92 ^b	48.05 ^b	36.42 ^{ab}
	Control	30.86 ^b	37.98 ^b	25.90 ^b
	P-value	0.02	0.04	0.04
	LSD	9.28	34.28	14.77

Means followed by the same letter within each column are not significantly different at $\alpha = 0.05$, based on the Least Significant Difference (LSD) test. SBS = Soil Bund stabilized with *Sesbania cannabina*; SB = Soil Bund without vegetation; Control = Non-conserved plot; LSD = Least Significant Difference.

Table 7. Clay content (%) under different bund positions and SWC practices.

Positions on bund	Treatments	Study sites		
		Midland	Highland	Lowland
Low-bund	SBS	57.5 ^a	47.0 ^a	21.0 ^a
	SB	50.50 ^a	40.0 ^{ab}	17.0 ^a
	Control	44.5 ^a	36.5 ^b	14.5 ^a
	P-value	0.33	0.1	0.41
	LSD	23.1	10.15	13.31
Mid-bund	SBS	52.5 ^a	46 ^a	54 ^a
	SB	41.0 ^a	38 ^a	39 ^a
	Control	29.25 ^a	36 ^a	28.25 ^a
	P-value	0.21	0.28	0.17
	LSD	31.22	16.64	31.72

Means followed by the same letter within each column are not significantly different at $\alpha = 0.05$, based on the Least Significant Difference (LSD) test. SBS = Soil Bund stabilized with *Sesbania cannabina*; SB = Soil Bund without vegetation; Control = Non-conserved plot; LSD = Least Significant Difference.

and conservation practices did not significantly affect clay content in the midland, highland, and lowland sites ($P > 0.05$). Nevertheless, notable differences were observed. The highest clay content (57.5%) occurred at the low-bund position under SBS treatment in the midland site, while the lowest clay values (14.5% and 17.0%) were recorded in the control and low-bund SB plots, respectively. Elevated clay content under SBS may be associated with the accumulation of organic matter from *Sesbania cannabina* litter, which indirectly improves particle aggregation and soil structure, though adding organic matter does not directly change soil texture (Moorberg and Crouse 2017).

Furthermore, SWC structures reduce runoff velocity, promoting the deposition of fine suspended particles such as clay and silt behind the bunds. Similar sediment-trapping effects have been widely reported in Ethiopian highlands, where physical and biological conservation measures enrich fine particle content upslope of bunds (Adimassu *et al* 2017, Guadie *et al* 2020, Jiru and Wegari 2022).

Table 8 presents silt content. The interaction of bund position and conservation type did not significantly influence silt content at the low-bund position ($P > 0.05$). However, significant differences were observed at the mid-bund position in the midland and lowland sites ($P < 0.05$). The highest silt content (32%) was recorded at mid-bund under SB, whereas the lowest (20%) occurred at mid-bund control plots. These differences may be partly due to poor maintenance of conservation structures, as broken or collapsed bunds can redistribute sediments downslope, reducing their effectiveness (Dabi *et al* 2017).

Table 8. Variation of silt under different bund positions and SWC practices.

Position on bunds	Treatments	Study sites		
		Midland	Highland	Lowland
Low-bund	SBS	26 ^a	27 ^a	28 ^a
	SB	27 ^a	28 ^a	25 ^a
	Control	23.5 ^a	22.5 ^a	23.5 ^a
	P-value	0.62	0.63	0.75
	LSD	10.8	17.86	18.24
Mid-bund	SBS	27 ^b	30 ^a	27 ^b
	SB	32 ^a	30 ^a	32 ^a
	Control	20 ^c	27 ^a	20 ^c
	P-value	0.004	0.54	0.004
	LSD	3.67	9.00	3.67

Means followed by the same letter within each column are not significantly different at $\alpha = 0.05$, based on the Least Significant Difference (LSD) test. SBS = Soil Bund stabilized with *Sesbania cannabina*; SB = Soil Bund without vegetation; Control = Non-conserved plot; LSD = Least Significant Difference.

Table 9. Impact of bund positions and SWC practices on sand content.

Position on bunds	Treatments	Study sites		
		Midland	Highland	Lowland
Low-bund	SBS	16.5 ^a	26 ^b	51 ^a
	SB	22.5 ^a	32 ^{ab}	58 ^a
	Control	32 ^a	41 ^a	62 ^a
	P-value	0.16	0.1	0.57
	LSD	18.83	12.99	30.41
Mid-bund	SBS	20.5 ^b	37 ^a	19 ^b
	SB	27 ^{ab}	32 ^{ab}	29 ^{ab}
	Control	50.75 ^a	24 ^b	51.75 ^a
	P-value	0.1	0.1	0.1
	LSD	30.10	10.71	30.48

Means followed by the same letter within each column are not significantly different at $\alpha = 0.05$, based on the Least Significant Difference (LSD) test. SBS = Soil Bund stabilized with *Sesbania cannabina*; SB = Soil Bund without vegetation; Control = Non-conserved plot; LSD = Least Significant Difference.

Table 9 summarizes sand content. The highest sand percentages (62% in control, 58% in SB low-bund) were found in non-conserved plots, while the lowest sand content (16.5%) was observed under SBS at the low-bund position. High sand content in untreated plots likely reflects accelerated erosion due to the absence of structural barriers and intensive tillage, which disrupts aggregates and exposes fine particles to removal (Tesfahunegn and Gebru 2020). Overall, the results indicate that conserved plots, particularly those with SBS, generally exhibit higher clay and silt fractions and lower sand content compared to control plots, although not all differences were statistically significant. These textural patterns confirm that SWC measures, especially vegetative stabilized bunds, play a key role in controlling erosion, enhancing sediment retention, and improving soil physical conditions (Adimassu *et al* 2017, Guadie *et al* 2020, Jiru and Wegari 2022, Wolka *et al* 2022). In the lowland site, exceptions likely reflect clay-rich parent material and variable bund maintenance, where poor structural integrity can lead to patchy sediment redistribution (Dabi *et al* 2017, Belayneh *et al* 2020).

3.2.2. Soil moisture content

Table 10 shows that differences in soil moisture content across treatments and bund positions were not statistically significant. While the highest mean moisture values were observed at the low-bund position under SBS and the lowest in non-conserved plots, these differences cannot be considered statistically distinguishable. Therefore, the results should be interpreted cautiously as indicative trends rather than confirmed effects, and no claims of moisture enhancement are made.

Table 10. Impact of bund positions and SWC practices on soil moisture content.

Bund position	Treatments	Study sites		
		Midland	Highland	Lowland
Low-bund	SBS	16.19 ^a	15.62 ^a	13.95 ^a
	SB	14.81 ^a	15.03 ^a	10.52 ^a
	Control	11.98 ^a	13.83 ^a	10.03 ^a
	P-value	0.21	0.74	0.22
	LSD	5.81	7.1	6.01
Mid-bund	SBS	15.32 ^a	15.73 ^a	15.32 ^a
	SB	14.05 ^a	14.90 ^a	14.05 ^a
	Control	10.36 ^a	13.98 ^a	10.4 ^a
	P-value	0.14	0.85	0.14
	LSD	5.80	9.68	5.80

Means with the same letter in each column are not significantly different at $\alpha = 0.05$.

Table 11. Impact of bund positions and SWC practices on soil bulk density (ρ_b).

Position on bunds	Treatments	Study sites		
		Midland	Highland	Lowland
Low-bund	SBS	1.04 ^b	1.57 ^a	1.14 ^b
	SB	1.32 ^b	1.50 ^a	1.25 ^b
	Control	1.68 ^a	1.19 ^a	1.60 ^a
	P-value	0.02	0.57	0.02
	LSD	0.30	1.1	0.23
Mid-bund	SBS	1.06 ^b	1.13 ^a	1.07 ^b
	SB	1.51 ^a	1.39 ^a	1.53 ^a
	Control	1.57 ^a	1.60 ^a	1.60 ^a
	P-value	0.05	0.14	0.03
	LSD	0.40	0.51	0.34

Means with the same letter in each column are not significantly different at $\alpha = 0.05$.

The enhanced moisture content under SBS can be attributed to two reinforcing mechanisms. First, *Sesbania cannabina* provides partial shading and creates a favorable microclimate that reduces surface evaporation. Second, the combined structural and vegetative measure slows runoff and allows greater infiltration time, particularly at downslope positions where water naturally accumulates. Similar findings have been reported in micro-watershed studies, where conserved fields retained substantially higher soil moisture due to increased infiltration and reduced overland flow (Bezu and Tezera *et al* 2019, Tolesa *et al* 2021). Terracing and vegetative stabilization are also known to increase the residence time of rainwater on the soil surface, thereby improving soil water storage (Nyssen *et al* 2010).

The lower moisture values recorded in control plots reflect the rapid runoff and limited infiltration associated with non-conserved land. In such areas, rainfall energy directly impacts the soil surface, promoting sealing and crust formation that further restrict infiltration. This tendency is well-documented in degraded Ethiopian highland soils, where the absence of conservation measures leads to faster drying and poor soil moisture conditions (Wolka *et al* 2022, Teku *et al* 2025). In general, the results indicate that the integration of vegetative stabilization with physical conservation structures provides an advantage for moisture conservation.

3.2.3. Soil bulk density

Table 11 shows that significant differences in bulk density were observed across treatments and bund positions in the midland and lowland sites, while differences in the highland site were not statistically significant. In the midland and lowland sites, the highest bulk density values were observed in untreated plots, whereas the lowest values were recorded under SBS treatments, particularly at low- and mid-bund positions. This pattern is consistent with the potential of soil and water conservation (SWC) practices to reduce soil compaction by

improving soil structure and facilitating organic matter accumulation. In the highland site, however, the control plots exhibited lower bulk density than some conserved plots, indicating variability that may be influenced by local soil characteristics and historical management. Earlier research has shown that terracing and vegetative stabilization significantly reduces bulk density by decreasing erosion intensity and enhancing soil aggregation (Demelash and Stahr 2010, Moges and Wondimagegn 2025). Studies of SWC-treated watersheds in Ethiopia highlands similarly reported reduced bulk density associated with higher organic matter levels and improved biological activity (Busa *et al* 2025).

Conversely, the elevated bulk density observed in untreated plots arises from the direct effects of erosion, organic matter depletion, and raindrop-induced compaction. The loss of surface organic matter limits aggregate stability, making soils more susceptible to compaction under natural processes such as trampling, rainfall impact, and repeated tillage. This aligns with previous findings that non-conserved agricultural lands in Ethiopia generally exhibit higher bulk density and poorer physical quality (Wolka *et al* 2022).

In the highland site, relatively higher bulk density recorded under SBS compared with the midland may be attributed to the steeper topography and more intense rainfall, which naturally enhance compaction despite the presence of conservation structures. High-elevation areas in Ethiopia are known to experience greater erosive forces, which can affect soil structural conditions even under SWC interventions (Dagnew *et al* 2017). Overall, the results demonstrate that vegetatively stabilized bunds offer substantial improvements in soil physical conditions, particularly in reducing bulk density and enhancing soil structure.

3.2.3.1. Limitation of the Study

This study is subject to some limitations that should be considered when interpreting the findings. The relatively small sample size, with few replicates per treatment and landscape position, may limit statistical robustness and raises the possibility of pseudo-replication. In addition, the purposive selection of three villages to represent different agro-ecological zones (highland, midland, and lowland) may constrain the generalizability of the results beyond the study areas. Future research is encouraged to employ larger sample sizes, more representative sampling strategies, and broader spatial coverage to enhance the reliability and wider applicability of the results.

4. Conclusion and recommendations

4.1. Conclusion

The findings of this study demonstrate that integrated soil and water conservation (SWC) practices exert a significant influence on a wide range of soil physical and chemical properties. Soil pH, soil organic matter (SOM), cation exchange capacity (CEC), total nitrogen (TN), available phosphorus (Av. P), soil moisture content, and clay proportion all increased from the mid-bund to the low-bund positions across the implemented conservation measures. In contrast, bulk density and sand content decreased along the same gradient, indicating improved soil structure and reduced erosion risk in the lower bund areas. Among the conservation measures, soil bunds stabilized with *Sesbania cannabina* (SBS) and conventional soil bunds (SB) showed markedly higher SOM, pH, and CEC compared to the untreated control plots. SBS, in particular, exhibited the highest TN content, likely attributable to the nitrogen-fixing capacity of the leguminous species used for stabilization. These results underscore the added value of integrating biological components with physical conservation structures.

Untreated farmland exhibited substantially higher bulk density and sand content, reflecting greater soil degradation and weaker structural stability compared to conserved plots. Variation in soil properties across landscape positions and villages further confirmed that environmental factors, including topography, rainfall, and erosion intensity, shape the degree of soil improvement under different SWC practices. Although the overall SOM level remained relatively low (1.89%), it was significantly higher in the highland village. Even though, there is no statistical significance in soil moisture content, but there is decrement of values in treatments in each bund positions. Conversely, sand content was highest in the lowland village (45.13%), indicating coarser soil texture and higher susceptibility to erosion. Overall, the results confirm that soil bunds and soil bunds stabilized with *Sesbania cannabina*, both widely used in the study area, are effective in improving key soil physical and chemical properties compared to untreated land. Their positive effects on soil fertility, moisture retention, and structural attributes highlight their importance for sustainable land management in erosion-prone agricultural landscapes.

4.2. Recommendations

Based on the outcomes of this study, soil bunds stabilized with *Sesbania* (*Sesbania sesban*) are highly recommended as an effective SWC option for improving soil physical and chemical properties while reducing

soil loss. The integration of leguminous species with physical conservation structures enhances nutrient availability, improves soil structure, and provides additional ecological benefits. Therefore, farmers and land management programs should be encouraged to adopt integrated SWC measures that combine soil bunds with leguminous shrubs, grass strips, or other suitable biological components tailored to local land-use objectives.

Although this study provides important insights, it focused solely on agricultural land and evaluated only two conservation techniques, SB and SBS. Future research should expand to include a wider range of SWC practices such as stone bunds, stone bunds stabilized with diverse vegetative species, bench terraces, and other context-appropriate interventions. Additionally, assessing the impact of these SWC options across multiple land-use types (e.g., grazing land, degraded hillslopes, and mixed farming systems) will provide a more comprehensive understanding of their effectiveness. Such studies will generate deeper evidence to guide policy-makers, development practitioners, and farmers in implementing scalable and landscape-level soil restoration strategies. Moreover, future research should include long-term, multi-season monitoring of soil and water conservation practices, coupled with economic assessments and evaluations of farmer adoption and acceptance, to provide comprehensive, site-specific evidence for sustainable land management and policy development in the Estie District.

Declaration of competing interest

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The data cannot be made publicly available upon publication due to legal restrictions preventing unrestricted public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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