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Impacts of Soil and Water Conservation Measures on Selected Soil Properties in Bolo Micro-Watershed, Western Ethiopia

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Research Article

Keywords: Slope class, Soil and water conservation, Soil physicochemical properties, Bolo Micro-Watershed

Posted Date: June 8th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9940347/v1

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Additional Declarations: No competing interests reported.

Abstract

Land degradation driven by soil erosion remains a major constraint to agricultural productivity and food security in Ethiopia. Soil and water conservation (SWC) measures have been widely promoted under sustainable land management programs; however, their effectiveness on soil properties in specific local contexts remains insufficiently documented. This study evaluated the impacts of SWC measures on selected soil physicochemical properties in the Bolo Micro-Watershed, Western Ethiopia. Soil samples were collected from conserved and adjacent non-conserved fields across three slope classes (5–10%, 10–15%, and 15–30%) and two terrace positions (upper and lower). Standard laboratory procedures were used to analyze soil properties. The results revealed that soil porosity, moisture content, soil organic carbon, total nitrogen, and cation exchange capacity were significantly higher in conserved fields compared to non-conserved fields, indicating improved soil quality under SWC practices. Although soil pH and available phosphorus did not show statistically significant differences, their mean values were generally higher in conserved plots. Slope class significantly influenced available phosphorus, while its effect on other soil properties was limited. Moderate slopes (10–15%) exhibited relatively better soil quality compared to steeper slopes (15–30%), likely due to reduced erosion and nutrient loss. Terrace position showed minimal influence on most soil properties, suggesting limitations in terrace design and maintenance. Overall, the study demonstrates that SWC measures play a vital role in improving soil fertility and sustaining land productivity in the study area. Strengthening the design and management of conservation structures is recommended to enhance their effectiveness.

1. Introduction

1.1. Background and Justification

Soil erosion-induced land degradation poses a significant environmental challenge, threatening global agricultural productivity and food security (1). In sub-Saharan Africa, factors such as continuous cultivation, inadequate land management, and population pressure have accelerated the loss of fertile topsoil, resulting in nutrient depletion and reduced crop yields (2). This degradation disrupts the ecological balance and economic stability of millions of smallholder farmers who rely on natural resources for their livelihoods (3). In Ethiopia, over 80% of the population resides in rural areas and is primarily dependent on small-scale rain-fed agriculture (5). However, this sector faces severe challenges owing to soil erosion, declining soil fertility, and limited land management capacity (6). Research indicates that annual soil loss in the Ethiopian highlands ranges from 42 to 175.5 t ha^{-1} $year^{-1}$ (7, 8), leading to significant declines in soil productivity and heightened vulnerability to food insecurity. The combination of rugged terrain, intense rainfall, and unsustainable farming practices exacerbates this issue (9). To combat this challenge, Ethiopia has implemented extensive Soil and Water Conservation (SWC) programs since the 1970s, particularly following the devastating famines of that decade (10). These programs advocate both indigenous and introduced conservation measures, including soil and stone bunds, fanya juu, terraces, check dams, and biological practices such as grass strips and area enclosures (11). SWC measures aim to reduce soil erosion, enhance soil moisture, restore fertility, and improve rural livelihoods (12). However, the success of these measures often hinges on site-specific factors, such as slope, soil type, and community participation. Despite the widespread adoption of SWC practices across Ethiopia, evidence of their combined impact on soil physicochemical properties and local livelihoods remains limited, especially in western Ethiopia. Previous studies in the region have primarily focused on the effects of land use types on soil fertility (13, 14), with little emphasis on evaluating how different conservation structures influence soil quality and the well-being of farming communities at the micro-watershed

level. Consequently, this study was conducted in the Bolo Micro-Watershed of Horro District, Western Ethiopia, to assess the impacts of soil and water conservation measures on key soil physicochemical properties and the livelihoods of local communities. The findings are expected to provide scientific evidence to guide policymakers and practitioners in strengthening sustainable land-management interventions.

2. Materials and Methods

2.1. Description of the Study Area

2.1.1. Location

The study was conducted in the Horro District, situated in the Horo Guduru Wollega Zone of the Oromia Regional State in western Ethiopia. Geographically, the district is positioned between 9°28'–9°52' N latitude and 36°50'–37°20' E longitude, with elevations ranging from 1,226 to 1,388 meters above sea level (masl) (Fig. 1). The area is characterized by mixed farming systems, where crop production and livestock rearing are the primary livelihood activities for the local community. The district faces significant land degradation owing to intensive cultivation, overgrazing, and improper land-use practices. To address these issues, the government, in partnership with the Sustainable Land Management Program (SLMP) and the Resilient Landscape and Livelihood Project (RLLP), has implemented various soil and water conservation (SWC) measures. As part of this initiative, larger watersheds were divided into micro-watersheds for better management. The Bolo micro-watershed, one of the 12 protected micro-watersheds in the district, was selected for this study. It is located in the Doyyo Barriso Kebele and spans a total area of 633 hectares. The land-use distribution of the micro-watershed includes 370 ha of farmland, 139 ha of homestead areas, 32 ha of grazing land, 11 ha of water bodies, and 1 ha of gully affected land (15).

2.1.2. Socio-Economic Data

According to the 16) national census report, the Horro District had a total population of 64,158, of which 6,966 (10.86%) were urban inhabitants. A total of 11,021 rural households and 10,634 housing units were recorded (15). Most of the population practices mixed farming, with approximately 95% engaged in agriculture and the remainder in the service sector. Farming is predominantly rain-fed and subsistence-oriented, relying on traditional methods. The major crops include wheat, maize, teff, barley, beans, peas, sorghum, and oats. Livestock rearing is also a key component of household livelihood. The district's livestock population includes 113,894 cattle, 11,058 sheep, 6,029 goats, 74,787 poultry, 6,692 horses, 396 mules, and 2,742 donkeys (17).

2.1.3. Topography and Climate

The study area is characterized by a rugged landscape featuring undulating plains, hills, slopes, deep valleys, and extensively cultivated plateaus. The altitude in Horro District ranges from 1,450 to 3,228 meters above sea level (m.a.s.l.), with approximately 49.8% classified as highland, 48.96% as midland, and 1.24% as lowland (15). This elevation variation results in diverse agro-ecological conditions throughout the district that vary with elevation. The climate is predominantly subtropical, influenced by varied topography. The district encompasses three major agro-ecological zones: highland, midland, and lowland, each with distinct temperature and rainfall patterns. The area receives a mean annual rainfall of between 800 and 2,200 mm, which is considered reliable for rain-fed agriculture. The mean annual temperature ranges from 12.4°C to 24.6°C (15). Overall, the area is characterized by

a moist climate with moderately acidic soils conducive to livestock rearing and mixed farming systems, which are the primary livelihoods of the local community.

2.1.4. Land Use and Soil Type

Land use in the study area is predominantly agricultural, with rain-fed subsistence farming and livestock husbandry as the main livelihoods of local communities. However, arable land scarcity, driven largely by population pressure and the expansion of cultivation into marginal areas, has become a critical challenge (18). Continuous cultivation without adequate soil fertility management has led to nutrient depletion, soil structure deterioration and increased erosion rates. According to (15), agricultural land constitutes the largest share of total land use within the district, followed by grazing land, homesteads and forest areas. The dominant soil types in the Bolo micro-watershed are loam (approximately 65%), black (approximately 25%), and clay (approximately 10%) soils. These soils vary in fertility and texture, influencing the productivity and management practices of local farming systems in the region.

2.1.5. Vegetation

Shrublands dominate the vegetation in the area, with grasses and other plants scattered throughout. The exotic eucalyptus plant, known for its rapid growth, is widely planted as windbreaks along boundaries, in farm fields, and around homesteads, requiring little maintenance (15). Despite its economic value as fuel wood, charcoal, building materials, and timber, farmers are largely unaware of its detrimental effects on soil fertility and water resources. Field reconnaissance revealed that widespread planting of eucalyptus has led to the replacement of native tree species, resulting in deforestation. The Horro District still maintains several natural and semi-natural forest patches, including Sawa (3,742.56 ha), Jobira (1,701.17 ha), Gabar (816.56 ha), Konge (340.23 ha), Chancho (136.61 ha), Sakke (136.29 ha), and Kombe (68.05 ha), which are distributed across different localities and play an important role in maintaining ecosystem stability and watershed protection (15).

2.1.6. Soil Water Conservation

A range of soil and water conservation (SWC) measures have been implemented in the study area, tailored to specific land-use systems and topographic conditions (19). These interventions play a critical role in reducing soil erosion, enhancing moisture retention, and improving land productivity, particularly in the mountainous and sloping terrain of the watershed. The major SWC structures observed include contour farming, soil bunds, stone bunds, fanya juu and bench terraces, check dams, and other moisture-retaining structures (20). These practices have been widely adopted through community-based watershed management programs supported by both government and non-governmental initiatives (22). Despite their broad implementation, limited empirical evidence exists on how these conservation measures influence soil physicochemical properties, soil fertility, and water resource availability in the Bolo micro-watershed. Therefore, understanding their effectiveness is essential for guiding sustainable land management and improving local livelihoods.

2.2 methods

2.2.1. Reconnaissance Survey and Research Design

A preliminary reconnaissance survey was conducted to identify representative micro-watersheds and suitable sampling sites in both conserved (SWC-treated) and non-conserved farmland. This survey ensured the selection of sites capturing variability in slope, terrace positions, and land use, providing adequate representation of both treatment conditions. Representative plots were selected using judgment sampling, targeting key landscape

positions relevant for evaluating SWC impacts. To standardize data collection and facilitate a systematic comparison of soil physicochemical properties, a randomized complete block design (RCBD) was applied across slope classes and terrace positions, enhancing the reliability and comparability of the results between conserved and non-conserved plots.

2.2.2. Sample Site Selection and Soil Sampling

Soil sampling in the Bolo micro-watershed was conducted using a purposive-random approach. The watershed and district were purposively selected because of the presence of soil and water conservation (SWC) practices, whereas sampling locations within the watershed were randomly chosen. Soil samples were collected from both conserved and non-conserved lands to assess the effects of SWC measures on soil physicochemical properties, considering slope gradients, terrace positions, and conservation structures. The watershed was classified into three slope categories: sloping (5–10%), strongly sloping (10–15%), and moderately steep (15–30%) (23).

Soil samples (0–20 cm) were collected from conserved plots treated with soil bunds, stone bunds, table terraces, half-moon terraces, and cut-off drains, and from non-conserved plots for comparison. Within each slope class, samples were taken from the upper and lower terrace positions at slightly sloping (5–10%), strongly sloping (10–15%), and moderately steep (15–30%) sites, with three replicates per position, using a crisscross pattern to ensure representative coverage. A total of 27 samples were collected between June and August 2023. Laboratory analyses included texture, bulk density, porosity, pH, organic carbon, total nitrogen, available phosphorus, and cation exchange capacity (Table 1) measurements. This design allowed for a comparative assessment of soil properties across slopes, terrace positions, and conservation treatments, providing insights into the effectiveness of SWC measures.

2.2.3. Soil Laboratory Analysis

Soil samples from three slope positions in both conserved and non-conserved plots were combined according to plot number and sampling replicates for each treatment. The composite samples were air-dried, gently ground, and passed through a 2 mm sieve prior to laboratory analysis. Physical properties, including bulk density, soil moisture content, and total porosity, were determined at the Wollega University, Shambu Campus Soil Laboratory, while chemical properties were analyzed at the Nekemte Soil Laboratory. Bulk density was measured using the core method, calculated as the oven-dried soil mass divided by the core volume after drying at 105°C for 24 h (23). Standard laboratory procedures, as summarized in Table 1, were followed for all other analyses to ensure accuracy and comparability.

Table 1
Standard Methods of Soil Parameter Analysis

No	Soil Parameter	Standard Method of Analysis
1	Bulk Density (g cm^{-3})	Determined using the core method; soil samples were oven-dried at 105°C for 24 h to obtain dry weight (24).
2	Soil Moisture Content (SMC, %)	Calculated from mass measurements during bulk density determination: SMC (%) = (Mass of water / Mass of oven-dry soil) × 100 (25).
3	Porosity (φ, %)	Computed from bulk and particle densities: φ = [1 − (BD/PD)] × 100 (26).
4	Soil Texture	Determined by the hydrometer method: %Clay = corrected hydrometer reading at 2 h × 100; %Silt = (%Silt + %Clay) − %Clay; %Sand = 100 − (%Silt + %Clay) (27).
5	Soil pH	Measured in a 1:2.5 soil-to-water suspension using a calibrated pH meter (28).
6	Soil Organic Carbon (SOC, %)	Determined by the Walkley–Black wet oxidation method using 1N $K_2Cr_2O_7$ and H_2SO_4 digestion (29).
7	Total Nitrogen (TN, %)	Measured using the Kjeldahl digestion, distillation, and titration method (30).
8	Available Phosphorus (Ava. P, mg kg^{-1})	Determined using the Bray I extraction method followed by colorimetric analysis (31).
9	Cation Exchange Capacity (CEC, meq 100 g^{-1})	Measured from 10 g of soil using 1N ammonium acetate (NH_4OAc) at pH 7.0 (32).

Note: Bd = bulk density; SMC = soil moisture content; SOC = soil organic carbon; TN = total nitrogen; Ava. P = available phosphorus; CEC = cation exchange capacity

Statistical Analysis

Data analysis was conducted us ing SPSS (Statistical Product and Service Solutions) version 28.0. Te efect of SWC practices, as well as the slope gradient, on the physico chemical properties of the soil, was assessed using one-way analysis of variance (ANOVA). A signifcance level of $p \leq 0.05$ was used for all statistical tests

3. Result and Discussion

3.1. Effect of Soil and Water Conservation on Soil Physical Properties

3.1.1. Effect on Soil Bulk Density

Soil bulk density (BD) was significantly influenced by soil and water conservation (SWC) practices. Conserved plots exhibited lower bulk density (1.611–1.75 g/cm^3) than non-conserved plots, indicating that SWC measures reduce soil compaction (Table 5). The higher bulk density in untreated plots may result from erosion-induced loss of organic matter-rich topsoil (33). This finding is consistent with (34), who reported lower bulk density in conserved lands. Slope position affected bulk density: in conserved plots, the 5–10%, 10–15%, and 15–30% slopes recorded 1.67, 1.505, and 1.65 g/cm^3, respectively. In non-conserved plots, bulk densities were 1.59–1.79 g/cm^3 across all slope classes. Bulk density tended to decrease on gentler slopes because of the accumulation of

fine soil particles, whereas steeper slopes exhibited higher compaction because of runoff and erosion. Terrace position also influenced bulk density: lower terraces had slightly lower BD (1.42 g/cm³) than upper terraces (1.44 g/cm³), reflecting the deposition of finer, fertile soil in lower positions, although the differences were not statistically significant. Overall, the interactions among SWC practices, slope, and terrace position significantly affected the bulk density, whereas the interactions between slope and terrace position were not significant. According to (36), the BD values observed in this study fall within the high category (1.6–1.9 g/cm³), likely because of anthropogenic and livestock-induced compaction.

3.1.2. Effect on Soil Moisture Content

The soil moisture content (SMC) was significantly higher in the conserved plots (35.7%) than in the non-conserved plots (30.47%), reflecting the role of SWC measures in reducing runoff, evaporation, and soil exposure (Table 5). This agrees with the findings of (37), who reported higher moisture retention in conserved lands. Slope positions influenced moisture retention, with the highest SMC observed in the medium slope class (10–15%) at 38%, whereas upper slopes (15–30%) retained less moisture (34.48%) because of higher runoff and reduced conservation effectiveness. Terrace position also affected SMC, with lower terraces having slightly higher moisture (36.22%) than upper terraces (35.17%) on conserved land, likely due to the deposition of water and fine soil particles in lower positions. Interactions among conservation practices, slope, and terrace positions were significant for SMC, whereas slope and terrace interactions alone were non-significant.

3.1.3. Effect on Total Soil Porosity

The total porosity (TP) was higher in the conserved plots (39.27%) than in the non-conserved plots (33.66%), reflecting improved soil structure due to reduced compaction and higher organic matter content (Table 2). This agrees with (38), who observed enhanced porosity in conserved lands. Slope position influenced TP, with the middle slope (10–15%) recording the highest porosity (43.3%) owing to integrated physical and biological conservation measures, whereas the upper slopes (15–30%) exhibited lower TP (36–37.5%) owing to erosion and compaction (Table 2). Lower terrace positions had slightly higher TP than upper terraces, reflecting the accumulation of finer particles in the depositional areas. Soil porosity was strongly and negatively correlated with bulk density, consistent with (40), which reported lower porosity in steeper slopes due to higher compaction and reduced organic matter. The interaction effects of conservation, slope, and terrace positions were significant, whereas slope and terrace interactions alone were not.

Table 2
Effects of soil and water conservation (SWC) measures on soil moisture content (SMC) and total porosity (TP) across slope classes in the Bolo micro-watershed.

With SWC					Without SWC		
Slope Class (%)	**Terrace Position**	**BD (g cm^{-3})**	**SMC (%)**	**TP (%)**	**BD (g cm^{-3})**	**SMC (%)**	**TP (%)**
5–10	Lower	1.70	34.4	39.0	1.68	33.8	31.0
	Upper	1.74	33.8	36.0	1.69	31.3	32.2
10–15	Lower	1.57	36.0	41.0	1.66	32.2	35.0
	Upper	1.61	35.0	39.0	1.68	31.2	37.0
15–30	Lower	1.68	33.4	37.0	1.79	28.7	38.9
	Upper	1.70	33.8	36.0	1.82	30.2	41.0

Note: SWC = Soil and Water Conservation; Bd = Bulk Density; SMC = Soil Moisture Content; TP = Total Porosity; Ter Pos = Terrace Position.

3.1.4. Effect of Soil and Water Conservation on Soil Texture

The soil texture in the Bolo micro-watershed was predominantly clay and clay loam in both conserved and non-conserved lands (Table 3). The mean clay content was higher in the conserved plots (42.97%) than in the non-conserved plots (40.87%), whereas the silt content was 22.37% and 19.86%, respectively. ANOVA results indicated that clay and silt fractions were significantly influenced by SWC practices at the 1% and 5% levels (Table 3); likely due to the conservation measures reducing the loss of fine particles through erosion. The sand content was higher in the non-conserved plots (36.54%) than in the conserved plots (32.83%), reflecting the preferential removal of fine particles from the non-conserved areas. This observation is consistent with that of a previous study (40)).

Slope Effects: Slope position had no statistically significant effect on soil texture, but some variations were observed in the results. In conserved land, clay content was highest on the medium slope (10–15%, 52.92%) due to biophysical rehabilitation and organic matter accumulation, followed by lower slopes (5–10%, 48.55%), and lowest on upper slopes (15–30%, 27.45%) (Table 3). Silt content followed a similar pattern, with higher silt content on medium slopes (26.88%) and lower silt content on upper slopes (21.61%). The sand content was higher on the upper slopes (49.83%) owing to erosion and the removal of fine particles. Non-conserved plots exhibited a similar trend but with generally lower silt and higher sand contents (40, 41).

Table 3
Soil texture variation at upper and lower terrace positions under with and without soil and water conservation (SWC) conditions in the Bolo micro-watershed.

Slope Class (%)	With SWC					Without SWC			
	Terrace Position	%Clay	%Silt	%Sand	Texture Class	%Clay	%Silt	%Sand	Texture Class
5–10	Lower	52	22	26	Clay	51	22	28	Clay Loam
	Upper	48	17	28	Clay	50	21.2	27	Clay
10–15	Lower	56	26	18	Clay	53	16	28	Clay
	Upper	54	27	19	Silty Clay	48.4	18.6	31.2	Clay
15–30	Lower	26	22	52	Clay Loam	26	16	52	Clay
	Upper	29	24	54	Clay Loam	24.5	22	51.7	Clay

Note: SWC = Soil and Water Conservation; Ter Pos = Terrace Position.

3.2. Effect of Soil and Water Conservation on Soil Chemical Properties

3.2.1. Soil pH

The mean soil pH in conserved and non-conserved plots was 5.18 and 5.08, respectively, with no significant difference (Table 4). Slightly higher pH in conserved plots may be due to reduced loss of organic matter and basic cations (Ca^{2+}, Mg^{2+}, and Na^{+}) through erosion. Slope positions showed minor variation, with the highest pH (5.34) in medium slopes (10–15%) where integrated physical and biological conservation measures increased organic matter (Table 4). Terrace positions had negligible effects on pH, with lower terraces at 5.28 and upper terraces at 5.07. Overall, soils were classified as strongly acidic (< 5.5), reflecting high rainfall conditions (42).

3.2.2. Soil Organic Carbon (SOC)

Conserved plots had significantly higher SOC (2.75%) than non-conserved plots (1.26%), likely due to reduced erosion and improved water retention enhancing organic matter accumulation. SOC decreased with increasing slope, with lower slopes (5–10%) recording 2.71% and upper slopes (15–30%) 2.57%. Medium slopes (10–15%) in conserved land showed the highest SOC (2.98%) due to the integration of physical structures with biological measures (Table 4). Lower terrace positions consistently had higher SOC than upper terraces. Interactions between conservation, slope, and terrace positions significantly influenced SOC ($p < 0.05$). SOC levels ranged from low in non-conserved to moderate in conserved plots (43).

3.2.3. Total Nitrogen (TN)

Average TN in conserved plots (0.226%) was higher than in non-conserved plots (0.153%), with significant differences ($p < 0.05$, Table 4). Higher TN in conserved land is attributed to enhanced soil organic matter from integrated physical and biological conservation measures. TN varied slightly across slope classes in conserved land (0.22–0.25%) and showed no significant difference across terrace positions. Interaction effects of

conservation, slope, and terrace were significant, indicating that integrated measures enhance nitrogen retention (44). TN levels were rated medium (0.15–0.25%) according to (45).

3.2.4. Available Phosphorus (Av. P)

Mean Av. P was higher in conserved plots (5.31 mg/kg) than non-conserved plots (2.63 mg/kg), but the difference was not statistically significant ($p = 0.07$) (Table 5). Slope affected Av. P, with higher values in lower slopes (5–10%) due to accumulation of fertile particles and lower slopes facilitating organic matter decomposition. The highest Av. P (10.98 mg/kg) occurred in medium slopes (10–15%) with integrated physical and biological conservation (Table 4). Terrace positions had minimal influence, and interactions between conservation and slope were significant ($p < 0.05$). Av. P ranged from very low in non-conserved plots to low in biophysically conserved plots (46).

3.3.5. Cation Exchange Capacity (CEC)

CEC was significantly higher in conserved plots (22.38 Cmol (+)/kg) than non-conserved plots (19.37 Cmol (+)/kg), reflecting greater clay and organic matter content. CEC decreased with slope gradient, from 24.07 Cmol (+)/kg in lower slopes to 21.08 Cmol (+)/kg in upper slopes, due to leaching and sediment movement. Terrace positions showed no significant effect (Table 5). The study area's CEC was rated as moderate (12–25 Cmol (+)/kg), consistent with high clay and organic matter content (47).

Table 4
Variation of selected soil chemical properties at upper and lower terrace positions across slope classes in the Bolo micro-watershed.

Slope Class (%)	With SWC (Conserved)						Without SWC (Un-conserved)				
	Terrace Position	pH	OC (%)	TN (%)	Av. P (mg kg^{-1},	CEC (cmol(+) kg^{-1},	pH	OC (%)	TN (%)	Av. P (mg/kg^{-1},	CEC (cmol(+) kg^{-1}
3–8	Lower	5.06	2.46	0.21	2.65	26.47	5.04	1.28	0.14	2.52	22.83
	Upper	4.97	2.45	0.20	2.57	25.72	5.01	1.26	0.22	2.52	22.65
8–15	Lower	5.12	3.01	0.20	13.06	24.22	5.20	1.23	0.21	10.89	22.00
	Upper	5.03	3.15	0.26	12.95	23.06	5.15	1.24	0.21	10.49	20.21
15–30	Lower	5.06	3.06	0.24	2.33	21.68	5.00	1.11	0.09	2.45	21.53
	Upper	4.87	2.74	0.22	2.26	21.24	4.93	1.28	0.12	2.39	18.70

Note: SWCM = Soil and Water Conservation Measures; OC = Organic Carbon; TN = Total Nitrogen; Av. P = Available Phosphorus; CEC = Cation Exchange Capacity; SD = Standard Deviation.

Notes: *ANOVA = Analysis of variance; MS = Mean square; P = p-value; Bd = Bulk density, SMC = Soil moisture content, TP = Total porosity, SOC = Soil organic carbon, TN = Total nitrogen, Av.P = Available phosphorus, CEC = Cation exchange capacity; C = Conservation practices, TePo = Terrace positions, S = Slope class; CS = Interaction between conservation and slope, CTePo = Conservation × terrace, STePo = Slope × terrace, CS*TePo = Conservation × slope × terrace; = significant at 5% level, ** = significant at 1% level; SWCM = Soil and Water Conservation Measures.*

4. Conclusion and Recommendations

Soil degradation and declining agricultural productivity remain major challenges in Ethiopia, largely driven by water erosion, steep terrain, unsustainable land management practices, and declining vegetation cover. The findings of this study demonstrate that the implementation of soil and water conservation (SWC) measures significantly enhances soil physicochemical properties and contributes to improved livelihood outcomes in the Bolo micro-watershed.

Both traditional practices (such as crop rotation, contour plowing, and organic manure application) and introduced SWC measures, including soil bunds, terraces, micro-basins, cutoff drains, and biological interventions, were widely practiced in the study area. The results indicate that integrated approaches combining physical and biological conservation measures are more effective than single interventions. Conserved fields exhibited improved soil quality, including higher soil moisture content, soil organic carbon, total nitrogen, cation exchange capacity, and clay content, while bulk density and sand content were reduced compared to adjacent non-conserved lands. In addition, soil fertility tended to be higher on gentle to moderate slopes and at lower terrace positions, likely due to reduced erosion and enhanced sediment deposition.

Overall, SWC practices contributed to improved soil health, enhanced agricultural productivity, reduced dependence on chemical fertilizers, and increased socio-economic benefits for local communities. These findings underscore the critical role of integrated conservation strategies in promoting sustainable land management and resilience in smallholder farming systems.

Based on the findings, the study recommends strengthening collaboration among local government institutions, communities, non-governmental organizations, and other stakeholders to ensure effective planning, implementation, and maintenance of SWC measures. Integrated conservation approaches that combine physical and biological techniques should be widely promoted due to their superior effectiveness in restoring degraded lands. Enhancing community participation through incentive mechanisms and awareness programs is essential to improve adoption, ownership, and long-term sustainability of conservation structures. Furthermore, continuous cultivation practices should be addressed through targeted extension services focusing on soil fertility management and sustainable land use planning. Finally, further research is recommended on soil acidity management, particularly the role of lime application in improving soil pH and crop productivity, to complement existing conservation efforts.

Declarations

Data Availability Statement

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

Author Contributions

Mastewal Almayhu Mesfin: Conceptualization, data collection, data screening, formal analysis, and writing – original draft preparation.

Kinati Chemdessa Ejeta: Methodology design, supervision, project administration, validation, and writing – review and editing.

Lilo Gamechu: Data collection and analysis, data screening, quality assessment, interpretation, and writing – review and editing.

Asamnew Banite Mihretu: Conceptualization, supervision, project administration, and writing – review and editing. All authors agree to be accountable for the research presented.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing Interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Clinical Trial Registration: Not applicable.

Consent to Publish: Not applicable.

Ethics Approval and Consent to Participate: Not applicable. The study did not involve human participants or animals.

Ethics Approval and Consent to Participate

Freely given, informed consent was obtained from all participants prior to data collection. The objectives, procedures, and potential benefits of the study were clearly explained to all respondents. Participation was voluntary, and participants were informed of their right to withdraw at any stage without any consequences. Confidentiality and anonymity of the information provided were strictly maintained.

The study protocol was reviewed and approved by the **Institutional Review Board (IRB) of Wollega University, Ethiopia**.

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Figures

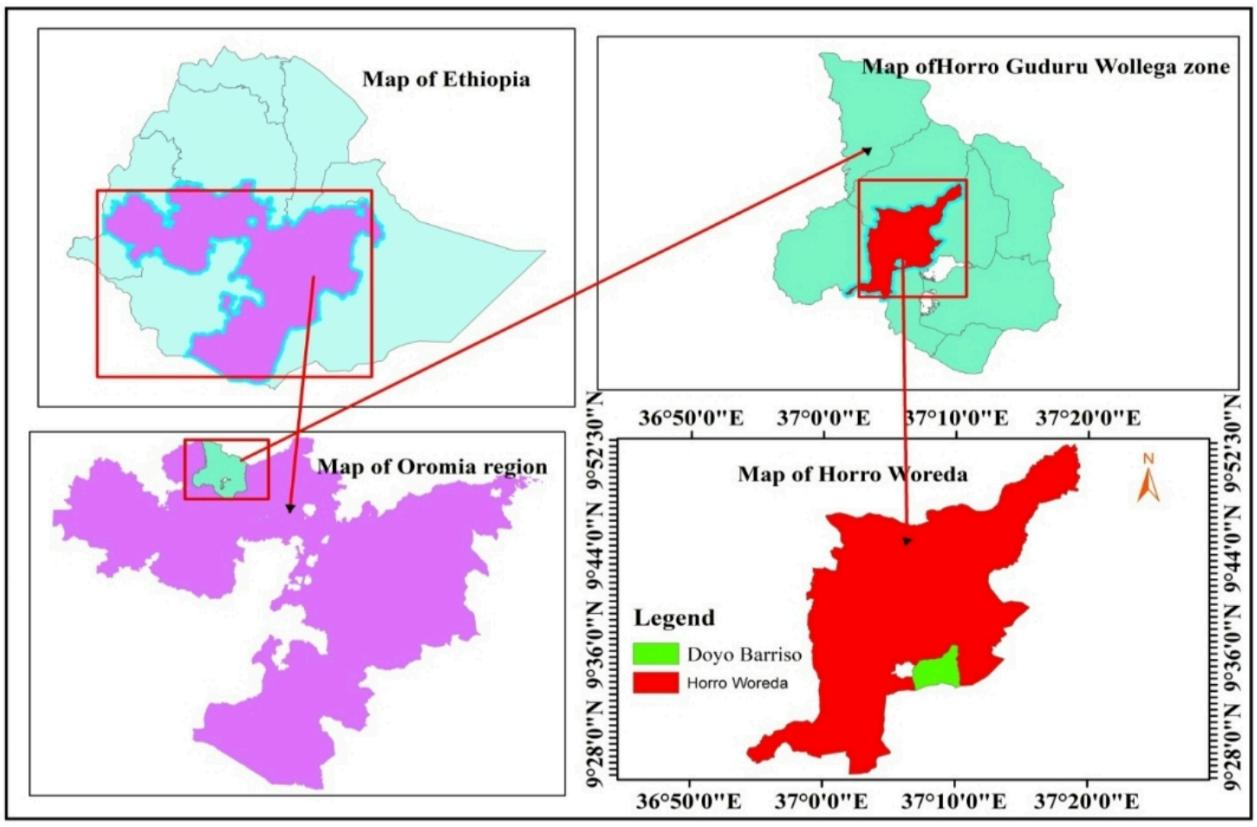


Figure 1

Map of study area