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Research Article

Evaluation of Soil Physicochemical Properties Under Different Soil Conservation Techniques Across Slope Gradients in Northwestern Ethiopia

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Soil degradation, marked by erosion, nutrient depletion, and organic matter loss, is a significant challenge to agricultural productivity and environmental sustainability globally. Soil and water conservation (SWC) practices are essential in reducing soil erosion and preserving soil health. This study aimed to assess the impact of SWC structures on soil physicochemical properties in northwestern Ethiopia. Soil samples were gathered and analyzed from fields using three treatments: soil bunds alone, soil bunds stabilized with vetiver grass (*Chrysopogon zizanioides* (L.)), and nonconserved fields, across various slope gradients. A total of 27 composite soil samples were collected from the depth of 0–20 cm using X-sampling technique (four samples from the corner and one sample from the center). Results indicated notable improvements in soil properties in conserved fields, with the lowest bulk density (1.26 gm/cm^3) in grass-stabilized bunds and the highest (1.53 gm/cm^3) in nonconserved fields. Soil moisture content also improved in fields conserved by soil bund stabilized with vetiver grass. The maximum soil pH, organic carbon (OC), and total nitrogen (TN) levels 5.89, 2.84%, and 0.20%, respectively, were recorded in grass-stabilized bunds. The highest levels of available phosphorus (23.16 cmol (+) kg^{-1}), magnesium (4.94 cmol (+) kg^{-1}), calcium (16.78 cmol (+) kg^{-1}), and potassium (16.8 cmol (+) kg^{-1}) were observed in soil bunds with vetiver grass. These findings underscore the effectiveness of SWC practices, particularly those incorporating biological components, in improving soil properties.

Keywords: conservation practices; erosion control; land productivity; soil fertility; water retention

1. Introduction

Soil degradation is a critical issue that affects agricultural productivity, food security, and environmental sustainability worldwide. It encompasses various processes such as soil erosion, nutrient depletion, loss of soil organic matter (SOM), salinization, and soil compaction [1]. These processes lead to a decline in soil health and functionality, posing significant challenges to both agriculture and the environment. Soil erosion is one of the most pervasive forms of soil degradation. It involves the removal of the topsoil layer by water, wind, or tillage, which is rich in organic matter and nutrients [2]. Soil erosion affects approximately 75 billion tons of soil annually worldwide. This process not only reduces soil fertility but also leads to sedimentation in water bodies, impacting water quality and aquatic ecosystems [3]. Intensive farming practices, without adequate replenishment of nutrients, lead to nutrient depletion in soils [4]. This results in reduced soil fertility and lower crop yields. Studies highlighted that sub-Saharan Africa faces significant challenges due to nutrient-depleted soils, impacting food production and livelihoods [5]. SOM is crucial for maintaining soil structure, fertility, and water-holding capacity. Practices such as deforestation,

overgrazing, and unsustainable agricultural practices reduce SOM levels [6]. The loss of SOM is a major factor contributing to soil degradation and reduced agricultural productivity [7].

Soil degradation is a significant challenge in Ethiopia, particularly in the northwestern region, where agricultural productivity and environmental sustainability are threatened by various forms of soil degradation, including erosion, nutrient depletion, and loss of SOM [8]. Effective soil conservation strategies are crucial for mitigating these issues and enhancing soil health. Despite efforts to implement such strategies, there are ongoing challenges and gaps in understanding their effectiveness and impact on soil properties in this region [9].

Northwestern Ethiopia, characterized by its rugged terrain and heavy reliance on rain-fed agriculture, faces severe soil degradation due to intensive agricultural practices, deforestation, and overgrazing. The highland areas in northwestern Ethiopia are particularly prone to soil erosion, which significantly reduces soil fertility and agricultural productivity [10]. Soil erosion rates in some parts of Ethiopia can exceed 100 tons per hectare per year, leading to substantial loss of topsoil and nutrients [11]. Slope gradient is also one of the major challenges affecting soil properties, influencing erosion rates, water retention, and nutrient distribution. Studies in Gumara watershed, northwestern Ethiopia, indicated that the highest and the lowest values of pH, exchangeable bases, cation exchange capacity (CEC), and Av. P were recorded at gentler and steeper slopes, respectively [12]. Another study in Ayiba watershed, northern Ethiopia, also found the highest accumulation of TN and soil organic carbon (SOC) at the lowest elevation sites [13].

Some soil conservation strategies have been implemented in Ethiopia to combat soil degradation, including terracing, contour plowing, agroforestry, and the use of cover crops. Soil and water conservation (SWC) practices, both physical and biological, significantly influence soil properties. For instance, physical conservation techniques such as soil bunds, stone bunds, stone-faced soil bunds, terraces, fanya juu, cutoff drains, traditional ditches, and waterways have been employed [14]. Physical SWC practices, such as terracing and stone bunds, have been shown to decrease soil bulk density (BD) and improve soil texture by reducing soil erosion. Treated lands tend to retain finer particles, leading to higher clay content and lower sand content compared to untreated lands. This is attributed to the prevention of soil erosion, which otherwise removes fine particles and organic matter from the soil [15]. These practices also enhance soil porosity, leading to better water retention and reduced surface runoff. This improvement in soil structure increases the soil's capacity to hold water, which is crucial for maintaining soil moisture and supporting plant growth [16]. Biological SWC practices, such as agroforestry and cover cropping, contribute to the increase in SOM. The presence of organic matter also improves soil structure, water retention, and microbial activity and helps in the cycling of nutrients, making them more available to plants and reducing the need for chemical fertilizers [15]. Despite the positive effects of these SWC practices on soil fertility, their sustainability is inconsistent among smallholder farmers due to a lack of site-specific empirical evidence. For instance, research by [17] indicated that while terracing and agroforestry significantly reduce soil erosion and improve soil moisture retention, the adoption and maintenance of these practices by local farmers remain inconsistent.

In Awi Zone, most researches focused on other investigation rather than SWC impacts on soil property enhancement. For instance, study by [18] on spatiotemporal dynamics of *Acacia decurrens* plantation in the highland area of Awi Zone, physical performance of small-scale irrigation scheme on Tilku Fetam River [19], and effects of disturbance on woody species composition in Ura natural forest in Guangua district [20]. These researches indicated that there is no enough site-specific data about the impacts of SWC practices in the study area. This study aims to fill a critical research gap by providing comprehensive and site-specific empirical evidence on the effects of SWC measures on soil physicochemical properties in a northwestern Ethiopian watershed. The novelty of this investigation lies in its evaluation of the effects of physical and biological SWC practices on soil properties along a specific slope gradient, providing localized data crucial for promoting sustainable soil management in the region. Therefore, it is imperative to investigate the effects of SWC structures on soil physicochemical properties in the study area. The main objective of this research was to evaluate the effects of SWC measures on physicochemical properties of soil along a slope gradient.

2. Materials and Methods

2.1. Description of Study Area. The study was conducted at Tiru Birhan kebele in Guangua district of Awi Zone. The main farming system in Tiru Birhan kebele (the smallest administrative unit in Ethiopia) is mixed farming system [21]. The study area is located between 11°40′–11°60′ N latitude and 36°32′–36°37′ E longitude (Figure 1). The main crops cultivated in the main season in the district are finger millet, maize, teff, niger seed, wheat, and sorghum, respectively, in their order of importance.

2.2. Research Design and Soil Sample Collection Methods. The experiment was conducted in 2022/23 on 6 years old conservation sites and nonconserved croplands adjacent to conserved sites with similar slope characteristics in Tiru Birhan kebele. To reduce variability, the experimental land was blocked into three classes based on slope gradient. Accordingly, three slope classes were selected: lower (5%–10%), middle (10%–15%), and upper (> 15%) following the classification of [22]. The experiment considered three treatments: fields treated with physical SWC practices (PSWCPs (soil bund alone), biophysical SWC practices (BSWCPs (soil bund stabilized with vetiver grass (*Chrysopogon zizanioides* (L.)), and nonconserved land (control) adjacent to conserved sites having similar slope classification. Each treatment was replicated three times (R1, R2, and R3). The number of conservation lines for both the soil bund

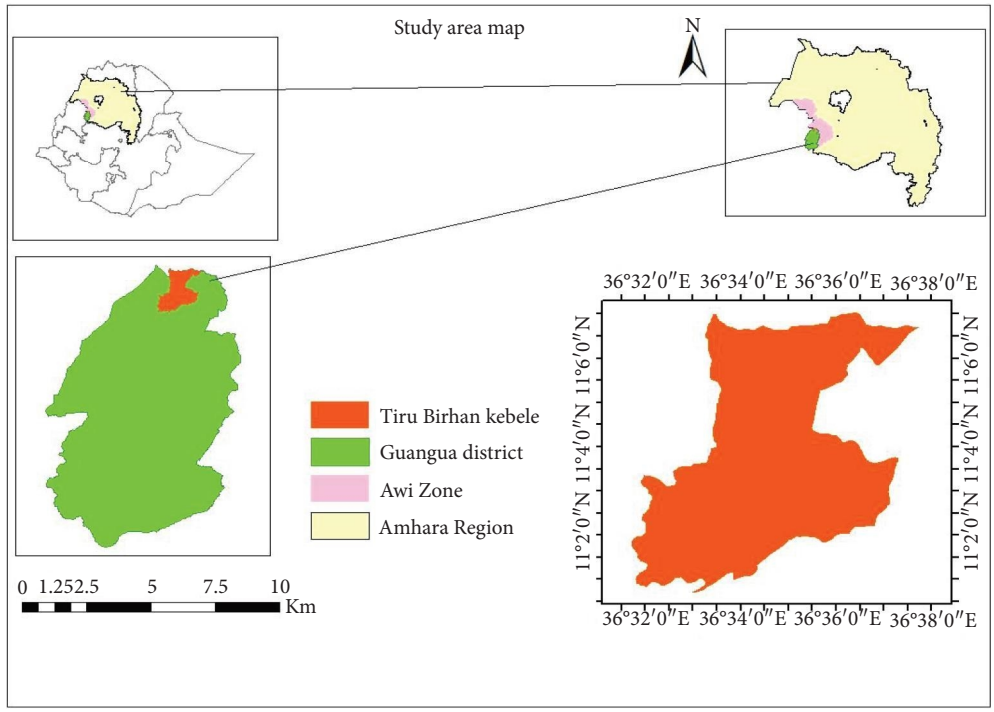


Figure 1: Map of Tiru Birhan Kebele, Guangua district of Awi Zone, northwestern Ethiopia.

alone and the biophysical soil bund stabilized with vetiver grass was two in each block (one soil bund alone and one biophysical soil bund), making a total of six lines. The spacing between two consecutive bunds were 20, 15, and 10 m for the lower, middle, and upper slope classes, respectively, following soil conservation standards [23] (Figure 2). Soil samples were collected to represent three treatments, three slope classes, and three replications (R), resulting in a total of 27 composite soil samples ($3 \times 3 \times 3 = 27$). The sampling was conducted using the X-sampling method, where five individual soil samples (four from the corners and one from the center of each plot) were collected with an auger from a depth of 0–20 cm and combined to form a single composite sample during dry season in mid-April. For the analysis of BD, undisturbed soil samples were collected using a core sampler of known volume. For the analysis of soil physicochemical properties, disturbed soil samples were collected using an auger. Approximately 1 kg of composite soil was collected from each sample plot. The collected soil samples were transported to the laboratory, where they were air-dried, mixed thoroughly, and passed through a 2 mm sieve to prepare them for subsequent analysis.

2.3. Method of Soil Analysis. A soil sample was collected and weighed and then oven-dried at 105°C for 24 h. The moisture content was calculated as the mass loss upon drying, expressed as a percentage of the dry soil mass by the gravimetric method [24]. BD was calculated by dividing the dry soil mass by the known volume following [25]. Soil pH was measured in a suspension prepared with a 1:2.5 ratio of soil to a potassium chloride (KCl) solution [26]. The OC content was analyzed using a wet oxidation method with potassium dichromate ($K_2Cr_2O_7$) in a sulfuric acid solution [27]. TN was determined by the Kjeldahl digestion, distillation, and titration method [28]. The available phosphorus (Av.P) content was determined using the Bray II method [29]. Exchangeable calcium (Ca), magnesium (Mg), and potassium (K) were measured using an atomic absorption spectrophotometer (AAS) [30]. The CEC was determined using 1M-neutral ammonium acetate (1N NH4OAc) at a pH of 7.0 [31]. This method involves saturating the soil's exchange sites with ammonium ions and then displacing them with another cation to be measured, thus quantifying the total CEC.

2.4. Data Analysis. Data obtained from the laboratory analyses were subjected to one-way analysis of variance (ANOVA) using SAS software version 9.4 [32]. When results showed significant, mean separation was made using the least significant difference (LSD) at the $p < 0.05$ level.

3. Results and Discussion

3.1. Soil BD. The impacts of biophysical (stabilized soil bund with vetiver grass) and physical (soil bund alone) conservation structures significantly ($p < 0.05$) influenced soil BD. Significant differences were observed between conserved and nonconserved sites (Table 1). The highest BD (1.53 gm/cm^3) was found on sites that were not treated, while the lowest (1.26 gm/cm^3) was found in sites that were treated with biophysical SWC practices. Relative to nonconserved sites, sites treated with physical and biophysical conservation reduced by 7.18% and 17.64%, respectively. The reason is

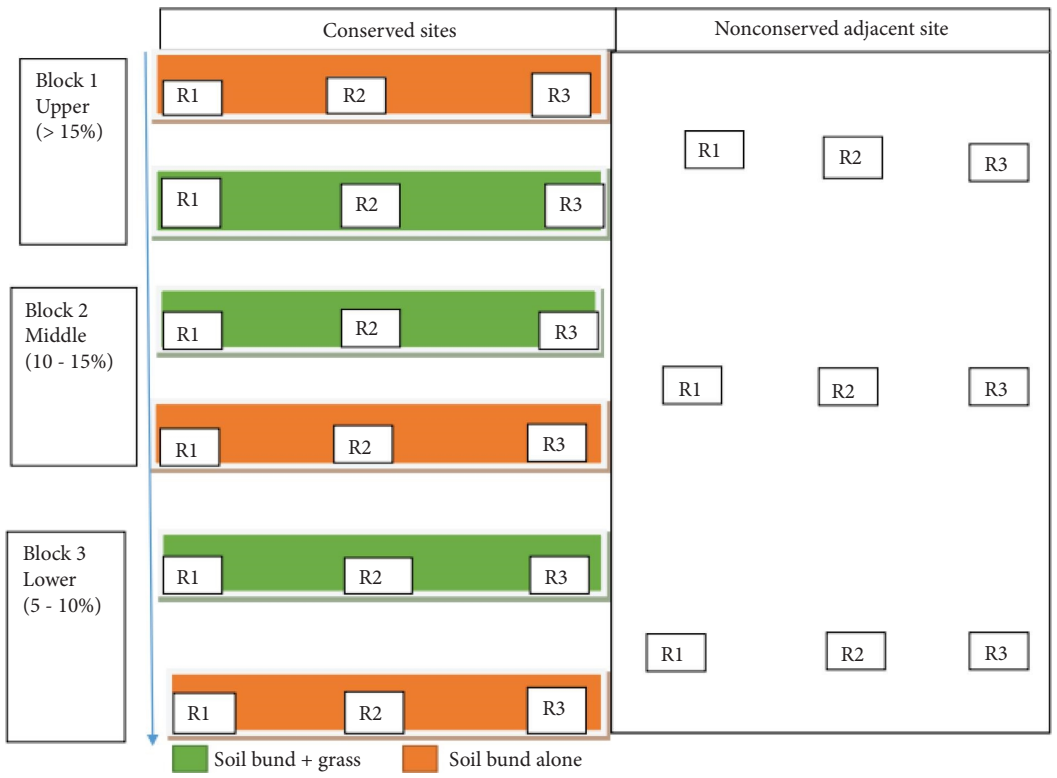


Figure 2: Graphical representation of treatments and replications in conserved and nonconserved sites.

Table 1: Effects conservation and slope factor on soil chemical properties (pH, OC, total N, and Av. P).

Treatments	Soil parameters					
Conservation factors	**BD (gm/cm^3)**	**SMC (%)**	**pH**	**SOC (%)**	**TN (%)**	**Av. P (mg Kg^{-1})**
Nonconserved	1.53^c	8.92^c	4.75^b	0.79^c	0.08^c	6.35^c
PSWC	1.42^b	15.91^b	5.07^b	2.09^b	0.14^b	14.46^b
BSWC	1.26^a	23.97^a	5.89^a	2.84^a	0.20^a	23.16^a
p value	0.001	0.001	0.001	0.001	0.001	0.001
Slope factor						
Upper slope	1.42^a	8.92^c	5.08^b	1.60^a	0.11^b	12.24^b
Middle slope	1.40^a	15.89^b	5.16^{ab}	1.92^a	0.13^b	14.24^b
Foot slope	1.37^a	23.92^a	5.45^a	2.19^a	0.17^a	17.49^a
p value	0.371	0.0001	0.049	0.082	0.0014	0.0001
CV	4.72	19.40	6.66	20.92	17.67	19.98

Note: Different letters (a,b,c) indicate significant differences among treatment.
Abbreviation: CV, coefficient of variation.

likely due to nonconserved sites being more vulnerable to surface runoff and erosion, which can cause soil particles to become compacted. This result is similar to another study that has found higher BD on untreated land than treated [33]. Similarly, the BD in the foot slope was significantly less than the upper slope. A lower BD was recorded in conserved lands and at lower foot slopes in the Agemi watershed in northwestern Ethiopia, as reported by studies [16].-

3.2. Soil Moisture Content (SMC %). SMC was significantly higher ($p < 0.05$) in site conserved with SWC structures compared to nonconserved fields. The highest SMC (23.97%) was recorded in fields treated with soil bund stabilized with vetiver grass while the lowest (8.92%) recorded in nonconserved fields (Table 1). Compared to nonconserved sites, sites treated with physical and biophysical SWC practices, the SMC was increased by 6.99 and 15.05 units, respectively. The highest SMC found in conserved fields is likely due to the reduction of runoff and increasing infiltration. Along the slope gradient, the highest SMC was observed under foot slopes and the lowest was found in the upper slope classes. This result similar with [34] who reported that fields treated with biological SWC practices showed the highest SMC compared to nonconserved fields. Another study also confirmed by [35] who reported that the higher SMC was

recorded in fields treated with conserved fields compared to nonconserved fields at foot slope position.

3.3. Soil Reaction (pH). Soil pH between soil bund and stabilized soil bund was insignificant at ($p < 0.05$). The soil in the study area had pH values of 5.08–5.45 (Table 1). The highest pH (5.89) was recorded from sites treated with soil bund stabilized with grass, whereas the lowest value (4.75) was obtained from nonconserved lands. Soil reaction (pH) was increased by 6.73% and 24% in fields treated with soil bund alone and soil bund stabilized with vetiver grass, respectively, compared to the control. This difference is most likely due to soil bunds stabilized with grass effectively reducing soil erosion. These structures can help maintain soil structure and composition, as well as stabilizing soil reactions by reducing the loss of topsoil. The result is agreed with another study at Lole watershed, northwestern Ethiopia [33]. Another study at Jibgedel watershed confirmed that nonconserved sites had the lowest soil pH [15]. Considering the slope gradient, a significant difference was observed between foot slope and upper slope at ($p < 0.05$). The pH value of soil in the study area ranged from 5.08 to 5.45 (Table 1). The foot slope (gentle slope) had the highest pH (5.45), while the upper slope (steeper slopes) had the lowest pH (5.08). Soil pH at the foot slope was higher by 0.37 units compared to the upper slope position. The reason for this difference is likely due to the removal of topsoil, which is frequently richer in organic matter and nutrients that help buffer soil pH from increased runoff and erosion on steeper slopes. Different scholars conducting research in different parts of Ethiopia have agreed on this result [16, 36].

3.4. SOC. The effects of soil bunds, soil bunds stabilized with grass, and nonconserved lands on soil properties, as well as the impact of different slope positions (foot slope, middle slope, and upper slope), can be significant. Differences in soil SOC content were observed among fields treated with soil bund, fields stabilized with grass, and nonconserved fields ($p < 0.05$). Fields that were treated with soil bund stabilized with grass achieved the highest SOC (2.84%), followed by those that were treated with soil bund only (2.09%). In contrast, nonconserved fields had the lowest SOC (0.79%) recorded (Table 1). The result showed that there was a significant difference between fields that were conserved and those that were not. The reason is most likely because soil bunds act as physical barriers that slow down surface runoff, resulting in a significant decrease in soil erosion. On the other hand, grass on buds adds organic matter (leaves, roots, and biomass) to the soil and increases SOC levels. This result agreed with other studies which reported that higher SOC was found in fields treated with SWC than nonconserved fields [37, 38]. Another study in northern Ethiopia also found that a higher SOC was recorded from croplands treated with SWC integrated with fodder trees than SWC alone and nonconserved croplands [39].

The SOC ranges from 1.60% to 2.19% based on slope position. The foot slope fields had the highest SOC (2.19%), whereas the upper-slope fields had the lowest (1.60%). Compared to the upper-slope position, SOC at the foot slope portion was increased by 36.87%. Slope gradients did not differ significantly (Table 1). The fact that the same agricultural practices (such as plowing, planting, fertilization, and harvesting) are used consistently throughout the study area's slope positions may be the main cause of the insignificant changes in SOC. Statistically, however, the SOC content at the foot slope fields of the study site was significantly different from that of the upper and middle slope fields. This result is consistent with other studies that have reported higher SOC levels at lower foot slope positions [16, 40, 41].

3.5. TN Content. At $p < 0.05$, there was a notable variation in the TN concentration among soil bunds alone, soil bunds protected with grass, and nonconserved fields. The soil's overall N concentration varies from 0.08% to 0.20% (Table 1). Fields treated with soil bund stabilized with grass had the highest TN concentration (0.20%), followed by 0.14% from soil bund alone, and the lowest (0.08%) from nonconserved fields (Table 1). Sites treated by soil bund and biophysical soil bund showed 75% and 150% increment, respectively, compared to nonconserved sites. The findings demonstrated that conserved lands have more total N content in the soil than nonconserved lands. This variation is most likely brought about by conservation practices that introduce a lot of organic matter to the soil, such as the use of grass-stabilized soil bunds. The TN levels are increased by the addition of organic material from grassroots, leaf litter, and degraded plant leftovers. Another study that discovered a greater concentration of TN on locations treated with soil bund stabilized with chomo grass (*Brachiaria humidicola*) than on nonconserved lands supports this conclusion [42]. Another study in the Hobicheka Sub-watershed of southern Ethiopia also found that higher TN in fields treated by soil bund stabilized with desho grass than soil bund alone [43].

The TN concentration ranges from 0.11% to 0.17%, according to the gradient of the slope (Table 1). The foot slope fields had the highest N level (0.17%), while the upper-slope regions had the lowest (0.11%) (Table 1). The findings, therefore, showed that the study site's foot slope fields had the greatest N concentration. The TN content at the foot slope position was increased by 54.54% compared to the upper-slope position. This could be caused by increased water infiltration, higher soil moisture, the accumulation of organic matter and eroded soil, and improved nutrient cycling and microbial activity. Other research has confirmed that agricultural land at lower altitudes and foot slopes have higher TN content supporting this finding [44, 45]. Another study also confirmed that higher TN concentrations are found in foot slope fields due to the accumulation of organic matter [46].

3.6. Soil Av. P. The P content of soils treated with only soil bunds, soil bunds that were stabilized with grass, and nonconserved fields varied significantly ($p < 0.05$) (Table 1). Nonconserved fields and fields treated in soil bund stabilized with grass had values ranging from 6.35–23.16 mg kg^{-1}, respectively. Fields that were treated with soil bunds that were stabilized with grass had the highest P content (23.19 mg kg^{-1}), followed by fields that were exclusively protected by soil bunds, with 14.46 mg kg^{-1}. Nonconserved fields had the lowest P content, at 6.35 mg kg^{-1} (Table 1). According to the results, the lowest amount of Av. P was found in fields that were not conserved, while the highest amount was recorded in fields that had soil bunds stabilized with grass. Due to increased erosion and nutrient depletion, the amount of Av. P is typically lowest in fields that are not protected. Due to less erosion and enhanced water retention, fields treated with soil bunds alone and biophysical soil bund increased by 8.11 and 16.81 units compared to nonconserved sites. The highest levels of Av. P were found in fields treated with soil bunds that were stabilized with grass because of the combined effects of improved erosion control, organic matter addition, better soil structure, and increased microbial activity. According to a research in the southern regions of Ethiopia, fields treated with SWC have the greatest amount of P, not fields that are not conserved [47]. This study is also supported by another study which found that a higher percentage of Av. P is found in croplands conserved by SWC practices than in nonconserved lands [12, 37, 48].

The highest Av. P (17.49 mg kg^{-1}) was found in foot slope fields along the slope gradient, while the lowest (12.24 mg kg^{-1}) was found in the top slope gradient (Table 1). According to the findings, the study region's foot slope fields had a greater concentration of accessible P than the middle and top slope fields. At the foot slope position, Av. P was increased by 42.89% compared to upper-slope position. The greater P availability at the foot slopes is mostly attributed to increased microbial activity and nutrient cycling, higher soil moisture, better water infiltration, and the buildup of organic material and eroded soil. Other researchers who discovered greater Av. P in the gentler slopes (lower slope positions) than in the upper and middle slope areas support this conclusion [12, 46].

3.7. Exchangeable Bases (Mg^{2+}, Ca^{2+}, and K^{+}). As shown in Table 2, exchangeable bases like magnesium (Mg^{2+}), calcium (Ca^{2+}), and potassium (K^{+}) exhibited notable differences between fields that had been treated with soil bunds stabilized with grass, soil bunds alone, and nonconserved fields. The maximum values for Mg^{2+}, Ca^{2+}, and K^{+} were 4.94, 16.76, and 1.68 cmol kg^{-1}, respectively. The lowest values for Mg^{2+}, Ca^{2+}, and K^{+} were 1.93, 6.78, and 0.28 cmol (+) kg^{-1}, respectively (Table 2). According to the results, soil bunds alone and fields protected with grass-stabilized soil bunds had higher amounts of exchangeable bases than fields that were not conserved. Exchangeable bases such as Mg^{2+} and Ca^{2+} were improved by 155.95% and 147.19%, respectively, for fields treated with biophysical SWC practices compared to nonconserved fields. Soil conservation methods like soil bunds and grass-stabilized soil bunds may improve the retention of exchangeable bases (Mg^{2+}, Ca^{2+}, and K^{+}) by reducing erosion, enhancing water infiltration and retention, boosting organic matter accumulation, improving soil structure, and promoting microbial activity. The findings of this study are consistent with those of other studies that have found that fields protected by SWC techniques have higher exchangeable bases than fields that are not conserved [49]. Another study in the Dawnt watershed, northwestern Ethiopia, reported that higher exchangeable found in fields conserved by stone-faced soil bund stabilized with kidan grass [50].

Exchangeable bases like Mg^{2+}, Ca^{2+}, and K^{+} fluctuated among foot slope, middle slope, and upper-slope areas depending on slope location. The maximum Mg^{2+}, Ca^{2+}, and K^{+} concentrations were 3.99, 13.53, and 1.07 cmol (+) Kg^{-1}, respectively, while the lowest concentrations were 3.02, 10.37, and 0.70 cmol (+) Kg^{-1}, respectively (Table 2). The lowest amounts of exchangeable bases were seen in the higher slope fields, while the highest amounts were observed at the lower foot slope. At the foot slope position, the concentrations of Mg^{2+}, Ca^{2+}, and K^{+} improved by 32.11%, 30.74%, and 52.85%, respectively, compared to upper-slope positions. The greater concentrations of exchangeable bases (Mg^{2+}, Ca^{2+}, and K^{+}) at foot slopes as compared to upper and middle slopes are caused by the accumulation of eroded soil and organic matter, increased water infiltration, higher soil moisture, and enhanced microbial activity and nutrient cycling. Other research conducted in various areas of the region corroborates this conclusion [44, 50].

3.8. CEC. SWC techniques improved the CEC of the soil. The CEC content of the soil in the research region varied between 7.13 and 18.46 cmol (+) kg^{-1} (Table 2). Nonconserved fields had the lowest CEC content (7.13 cmol (+) kg^{-1}), while soil bund fields stabilized with grass had the highest CEC (18.46 cmol (+) kg^{-1}), followed by soil bund alone fields with 12.13 cmol (+) kg^{-1} (Table 2). Compared to nonconserved sites, the CEC increased by 70.12% and 158.90% in fields treated with soil bund and soil bund stabilized with vetiver grass, respectively. The higher CEC content of conserved lands as compared to nonconserved lands was observed in this study. In contrast to soil bunds alone and nonconserved fields, soil bundles kept in place with grass had considerably higher CEC levels (Table 2). This difference might be explained by grass providing a positive habitat for soil microorganisms. Due to the low organic matter content and bad soil conditions in unpreserved fields, microbial activity is restricted, which in turn lowers the production of humus and CEC. In contrast, these microorganisms are essential for breaking down organic matter and cycling nutrients, which causes the creation of humus and increases CEC. The lowest CEC concentration was discovered in untreated fields. A separate study at the Michel Debré watershed in northern Ethiopia supported this conclusion, showing that soil from agricultural areas protected by SWC had a higher CEC than soil from unprotected regions [51]. Other researchers also found similar results to this study [36, 49, 52].

Table 2: Effects of soil and water conservation and slope factor on exchangeable bases and cation exchange capacity (CEC).

Treatments	Soil parameters			
Conservation factors	Exc. magnesium (Cmol (+) kg^{-1})	Exc. calcium (Cmol (+) kg^{-1})	Exc. potassium (Cmol (+) kg^{-1})	CEC (Cmol (+) kg^{-1})
Nonconserved	1.93[a]	6.78[a]	0.28[a]	7.13[a]
PSWC	3.32[b]	11.98[b]	0.69[b]	12.13[b]
BSWC	4.94[c]	16.76[c]	1.68[c]	18.46[c]
p value	0.0001	0.0001	0.0001	0.0001
Slope factor				
Upper slope	3.02[b]	10.37[a]	0.70[b]	10.52[a]
Middle slope	3.17[b]	11.62[b]	0.89[ac]	12.45[b]
Foot slope	3.99[c]	13.53[c]	1.07[c]	14.75[c]
p value	0.0001	0.0001	0.0003	0.0001
CV	15.73	13.41	12.75	17.75

Note: Different letters (a,b,c) indicate significant differences among treatment.
Abbreviation: CV, coefficient of variation.

There was a lot of variation in the soil's CEC across the research site's slope gradients. The soil's CEC content varied between 10.52 and 14.75 cmol (+) kg^{-1} along the slope gradient (Table 2). Foot slope fields had the highest CEC (14.75 cmol (+) kg^{-1}), followed by middle slope fields at 12.45 cmol (+) kg^{-1}, and nonconserved fields at 10.52 cmol (+) kg^{-1}. The CEC at the foot slope increased by 40.21% compared to the upper-slope position. Because organic matter accumulates there, foot slope fields were shown to have a higher CEC level, according to the data. The soil's CEC rises as a result of the buildup of these substances, notably organic matter and fine particles. Conversely, higher slope regions are more vulnerable to erosion caused by runoff and gravity, which removes the topsoil that is high in organic material and fine particles (like clay) that contribute to CEC. This study's conclusion is supported by various academics in various geographic areas [16, 46, 49].

4. Conclusion

Conservation practices significantly impacted soil physical and chemical properties, notably reducing BD and enhancing nutrient content. Fields treated with biophysical SWC measures (BSWC) showed the lowest BD (1.260 g cm^{-3}), demonstrating reduced soil compaction compared to nonconserved fields (1.53 g cm^{-3}). Conservation measures were effective in stabilizing soil pH, with BSWC fields maintaining the highest pH levels (5.89), indicating improved soil composition and structure. Vegetative components in conservation practices significantly increased SOC levels, as seen with the highest SOC (2.84%) in BSWC-treated fields. The N retention capacity of conserved soils was evident, with TN reaching 0.20% in BSWC fields, supporting enhanced fertility for crop productivity. The highest Av. P content (23.16 mg kg^{-1}) was also recorded in BSWC fields, highlighting improved nutrient retention and reduced erosion effects. The study further emphasizes that exchangeable bases, essential for soil fertility, were significantly higher in conserved fields, particularly those treated with BSWC, demonstrating the benefit of these practices. Finally, the influence of slope on soil properties was clear, with foot slope fields showing higher SOC, TN, and Av. P compared to upper slopes, reinforcing the role of topography in soil properties. These findings support the effectiveness of soil conservation practices, particularly those integrating vegetative elements, in enhancing soil quality and agricultural sustainability in northwestern Ethiopia.

Data Availability Statement

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

Disclosure

All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

The conception and design of the study were done by Fekadu Debebe, Wondwosson Kibrie and Habtamu Admas. Material preparation, data collection, and analysis were conducted by Fekadu Debebe, Dessalegn Birhanu, Wondwosson Kibrie, Beletech Kindu and Habtamu Admas. Laboratory analysis was done by Wondwosson Kibrie. The literature search and the first draft of the manuscript were written by Fekadu Debebe, and all authors commented on previous versions of the manuscript.

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