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Impacts of soil and water conservation practices on finger millet production in northwestern Ethiopia

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Abstract

Crop yield decline, primarily caused by soil erosion, is a major challenge in rain-fed agriculture. Massive soil and water conservation (SWC) practices are conducted each year in the country of Ethiopia, including the study sites, to tackle the problems, but there is not enough information about the impacts those practices on crop yields in the study area. The impacts of different soil conservation practices on finger millet yield (*Eleusine coracana* (L.) Gaertn.) were evaluated on conserved and non-conserved croplands during the 2021/2022 cropping season. The experimental fields were blocked based on slope classes to account for topographic variation. A total of 27 plots having 3.2 × 3 m size were established. The highest plant height (73.24 cm), biomass yield (2.50 t ha^{-1}), and grain yield (1.57 t ha^{-1}) were recorded from soil bunds stabilized with grass. The interaction of conservation practices and slope gradient positively influenced plant height, biomass, and grain yield. Biological soil conservation practices + foot slope yielded the highest plant height (79.71 cm), biomass (3.08 t ha^{-1}), and grain yield (1.57 t ha^{-1}). The result showed that there was a significant difference of millet yield and yield components in conserved and non-conserved fields ($p < 0.05$). This study implies that implementing suitable soil conservation techniques based on slope characteristics is the best solution to improve finger millet yield in northwestern Ethiopia. It is recommended that farmers adopt slope-specific SWC measures, such as soil and grass-stabilized bunds, to reduce erosion and improve soil fertility and finger millet yield.

Plain Language Summary

Although a large number of Ethiopian farmers depend on rain-fed agriculture, soil erosion is causing crop yields to decline. Large-scale soil and water conservation programs are conducted annually to address this. However, in many regions, the impact of these methods on crop yield is poorly understood. We examined the effects of sev-

Abbreviations: BSWCP, biological soil and water conservation practice; SWC, soil and water conservation.

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eral soil conservation techniques on the yield of finger millet, a significant food crop, in this study. Small test plots were used to compare conserved and non-conserved areas over a 2-year period. In areas with a combination of soil bunds and grass, we saw that finger millet grew taller and generated more grain and biomass. Where plants grew taller and yielded more, the lower slope locations showed the best outcomes. Thus, increasing food production in northwest Ethiopia can be achieved by using the appropriate conservation techniques based on the slope position.

1 | INTRODUCTION

Land degradation, such as soil erosion and nutrient depletion by water, influences food security and sustainability of agricultural production in sub-Saharan Africa (Erkossa et al., 2015). Land degradation is acknowledged as a problem affecting land production, and it has a greater effect in underdeveloped countries. Numerous researchers claimed that various factors that can impede ecological processes exacerbate it. For example, land degradation, including population pressure and land use/cover change, is attributed to human interaction with natural ecosystems (Molla et al., 2019; Shittu et al., 2021). In addition to affecting food production, soil erosion and nutrient depletion can worsen climate change, endanger human health, and degrade water by releasing particles and accumulating nutrients (Lal et al., 2021). Worldwide, about 0.41% of the GDP is reduced due to soil degradation (Nkonya et al., 2016). Using ecologically friendly and sustainable farming methods such as soil and water conservation (SWC), both biologically and physically, is seen as a positive step toward meeting the world's food needs in a sustainable way (Fontes, 2020). In the absence of sustainable SWC methods, land degradation costs would rise, productivity would decrease, agricultural export earnings would drop, and food insecurity would rise (Darkwah et al., 2019).

In Ethiopia, the decline of soil fertility is the greatest environmental challenge. Soil erosion is considered a major economic and environmental problem in the highlands of Ethiopia (Haregeweyn et al., 2017). Soil erosion caused by water influences national food security (Mekuriaw et al., 2018), declines in the fertility of soil and agricultural productivity (Mesene, 2017), downstream flooding and sedimentation of reservoirs (Ebabu et al., 2018), and the loss of important plant nutrients (Grum et al., 2017). In order to reduce soil erosion and low crop yield, the practice of conserving soil and water was initiated in the mid-1970s and early 1980s in Ethiopia (Kedir, 2024). Integrated SWC is commonly used to boost soil productivity and slow down the loss of soil fertility (Erkossa et al., 2018). Conservation of soil and water is an essential method to enhance crop yield and decrease soil and water degradation from agricultural fields (Sileshi et al., 2019).

Different scholars conducted research on the effectiveness of SWC in Ethiopia, where soil degradation has been a long-term challenge that affects sustainable land use and food security (Fontes, 2020). Some studies indicated that the practices of SWC practices in watershed development could increase agricultural productivity and employment opportunities and enhance household income and food security (Siraw et al., 2018). However, there are rare empirical studies conducted on the economics of SWC practices (Addis et al., 2020). Some findings of the empirical studies on the impacts of SWC measures demonstrated that they might improve the fertility of the soil (Belayneh et al., 2019; Hishe et al., 2019) and enhance crop production (Erkossa et al., 2018) and the yield of fodder (Abiye, 2022). More precisely, according to Masha et al. (2021), soil bund and fanyajuu conservation measures had positive impacts on agricultural yields in different parts of the country.

The practice of SWC measures and the productivity of crops are enormously complementary. The reason behind this is when soil and water are conserved, the fertility and water availability of soil increase, which leads to high crop productivity. This indicated that appropriate SWC according to the biophysical attribute of the area could improve crop productivity as well as livelihood improvement (Bojago et al., 2022). According to Addis et al. (2020) investigation, integrated SWC, such as soil bunds (earthen embankments constructed along the contour to reduce runoff), fanyajuu (embankments formed by throwing soil uphill to create a bench), and trench in situ water harvesting structures at the Gumara-Maksegnit watershed, were able to decline sediment loss, total nitrogen (TN), available phosphorus, and soil organic carbon by 46.8%, 57.95%, 65.86%, and 61.3%, respectively. The results of several studies conducted on various SWC measures on crop production indicated that crop growth improved due to the accumulation of sediments on the topsoil. For instance, studies conducted by Guadie et al. (2020) in the northwest highlands of the Lole watershed indicated that maize and barley yields from stone-faced soil bunds and

soil bunds improved by 56% and 48%, respectively, compared to non-conserved fields.

Despite the fact that integrated SWC measures are rarely used in our country, some research has shown that they are highly effective in raising crop yields because they improve moisture conservation, reduce runoff and soil loss, and increase the amount of organic matter in the soil. For example, soil bund with biological measures increased crop production by 170% compared to stone bund and fanyajuu (Abera et al., 2020). A study at the Debre-Yakob watershed in northern Ethiopia also indicated that the integration of soil bund with pigeon pea increased maize crop yield by 52% compared to non-conserved land (Alemayehu & Fisseha, 2018). This is because SWC has a lot of functions in the ecosystem, such as reducing raindrop impact, increasing the infiltration rate of the soil, reducing runoff impact, trapping sediment, and enhancing crop productivity. Even though different researchers confirmed that implementation of SWC practices showed positive impacts on soil properties and crop yield, farmers frequently destroy SWC practices in their fields. This is due to those farmers claiming that the practices did not show a positive impact but rather occupied their fields. Such claims need further studies and measured data to design alternative land management strategies.

In the study area, few researchers conducted their research about the impacts of SWC practices, for example, about indigenous soil fertility and water resources management in Awi Zone (Seyoum, 2022), about determinants of farmers' perception to invest in SWC technologies (Moges & Taye, 2017), and about farmers soil management practices and their perceptions to soil acidity in Ankesha district(Tessema et al., 2012). However, there is no quantitative evidence that has been reported on the impacts of SWC on crop productivity in the study area. Therefore, empirical evidence on the impacts of SWC for crop yield improvement is required. Hence, the objective of the present study was to evaluate the impacts of SWC on finger millet yield. To this end, conserved and non-conserved sites as well as foot slope and upper slope gradient were compared on the yield and yield components of millet yield. Due to limited awareness of the benefits of SWC for crop productivity, soil health, and forage from grass-stabilized bunds, many farmers still destroy these structures, viewing them as a loss of farmland. Investigating this research in Tiru Birhan kebele is crucial because it generates practical evidence that can shift farmers' perceptions, promote wider adoption of SWC practices, and reduce the destruction of existing conservation structures. The objective of this paper was to evaluate the impacts of SWC practices on millet production in northwestern Ethiopia.

Core Ideas

- Crop yield decline due to soil erosion remains a major challenge in rain-fed agriculture in northwestern Ethiopia.
- The effects of different soil conservation practices on finger millet yield were evaluated using a randomized complete block design over 2 years.
- Soil bunds stabilized with vetiver grass recorded the highest plant height, biomass yield, and grain yield of finger millet.
- Conservation practice versus slope gradient interaction significantly affected yield components, with biological soil conservation + foot slope giving the best results.
- Improving finger millet productivity in the study area requires the implementation of soil conservation strategies according to slope features.

2 | MATERIALS AND METHODS

2.1 | Description of the study

The study was conducted at Tiru Birhan kebele in the Guangua district of the Awi Zone (Figure 1). The district is located about 52 and 513 km away from Inijibara and Addis Ababa, respectively. The total area of the district is about 106,914 ha; among this, 29% of the land is cultivated during the main season, and 12% of the land is cultivated using irrigation. The area receives an annual rainfall ranging from 1300 to 1800 mm, and the mean maximum and minimum daily temperatures are 27˚C and 15˚C, respectively. The altitude ranges from 1600 to 1710 m.a.s.l. The total population of the district is estimated to be 223,066, of which 49.8 and 50.2 percent are males and females, respectively, and the household size is 11,936 (GDAO, 2022). The district comprises 16 rural kebele administrations (RKAs), which are mainly dependent on agriculture. The main crops cultivated in the main season in the district are finger millet, maize (*Zea mays* L.), teff [*Eragrostis tef* (*Zucc*.)], and wheat (*Triticum aestivum*), in their order of importance (GDAO, 2022).

2.2 | Experimental design

The experiment was done on a farmer's field using physical, biological SWC and an unconcerned (control) plot as treatment and finger millet (*Eleusine coracana* (L) Gaertn.) as a test crop at Tiru Birhan kebele in the year 2021/2022 crop-

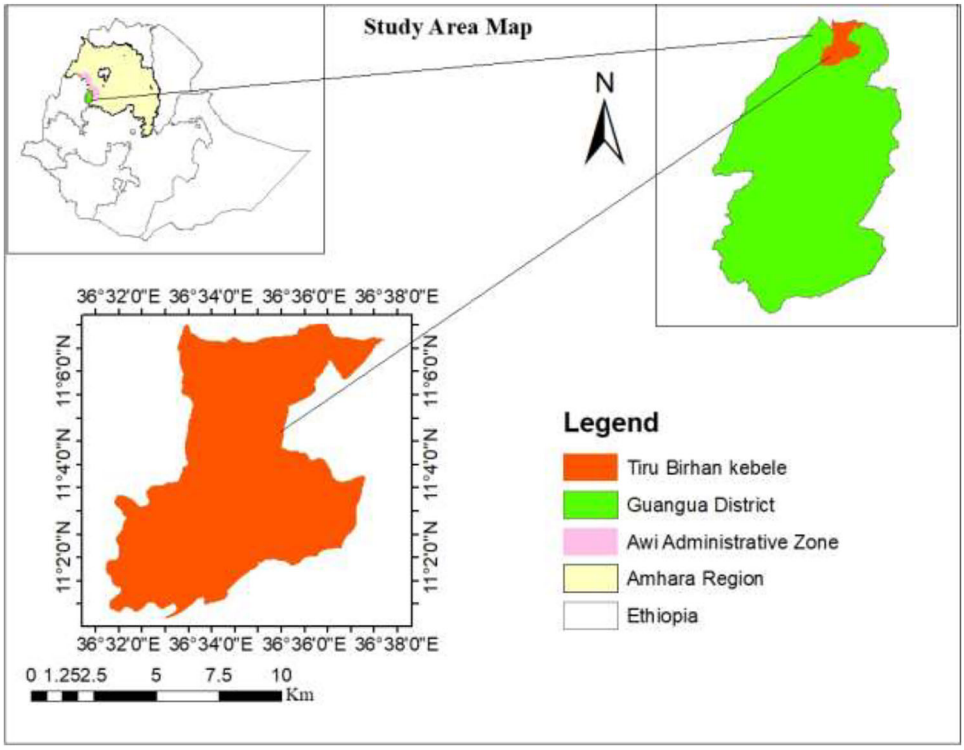


FIGURE 1 Location map of Tiru Birhan kebele.

ping season. Commonly used local finger millet varieties were obtained directly from farmers in the study area to ensure representativeness and local relevance. 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 (FAO, 2006). The experiment was laid out in three treatments: (i) fields treated with physical soil and water conservation practices (only soil bund), (ii) fields treated with biological soil and water conservation practices (BSWCPs) (soil bund + vetiver grass [*Chrysopogon zizanioides* (L.)] and (iii) fields without SWC practices (control). The experiment considered three (3) treatment (soil bund, soil bund + vetiver grass, and non-conserved control adjacent to conserved sites having similar slope class) and three slope classes (lower, middle, and upper). Each treatment was replicated three times. Plots was laid out to represent three treatments (soil bund alone, soil bund + vetiver grass, control) and three slope classes (lower, middle and upper slope class) with three replications, resulting in 27 experimental plots (3 treatment × 3 slope class × 3 replication) (Figure 2). Total plot area was 9.6 m^2 (3.2 m × 3 m) and the spacing between the blocks and plots was 1.5m and 0.5 m respectively. The two outer rows (one row from both sides of the plot) were left as border rows. Thus, the central six rows (7.2 m^2) were used for data collection and as net plot size. This experimental design is selected since it considers the natural farmers' fields as experimental plots. Moreover, it is cost-effective and better at representing the watershed scale environmental variables than the plot experiment that most researchers used for the last decades (Mekonnen et al., 2017).

2.3 | Data collection methods

Ten plants were randomly selected and tagged from the net plots area of each experimental unit to measure plant height. Then the height was measured from the selected plant from the ground to the tips of the spike (excluding awns) using of ruler and the mean value was determined respective to each plot. Biomass was measured from the plant parts (stems, leaves, and grain seeds) harvested from the net plot area for each treatment after sun drying for about 3–4 days and it is expressed in tons per hectare (t ha^{-1}). Grain yield was determined for each treatment by harvesting and threshing of crops separately from the net plot area and then weighted by electronic balance. Then the grain yield was expressed by adjusting it to 12.5% moisture content.

2.4 | Data analysis

The crop yield data collected from different SWC treatments over two consecutive years were analyzed using SPSS version 25. Analysis of variance (ANOVA) was performed to evaluate the effect of treatments and slope classes on finger millet

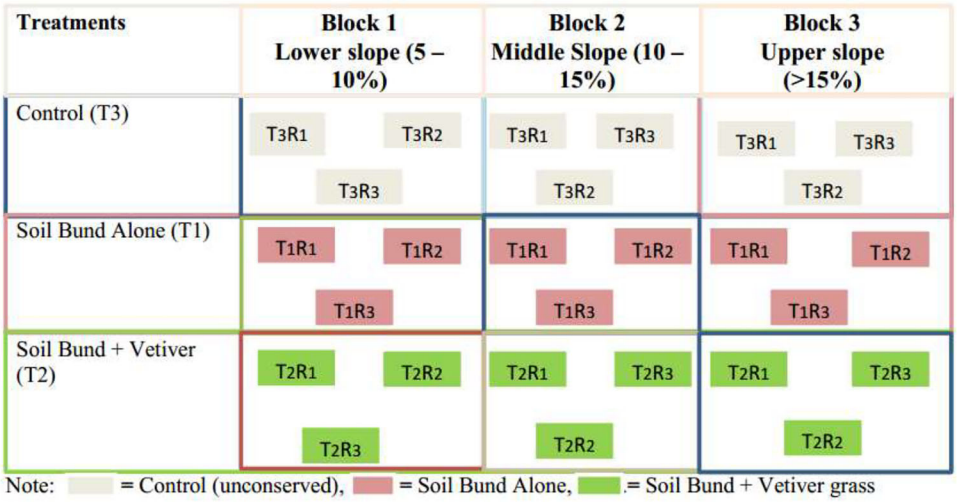


FIGURE 2 Graphical representation of treatments and plot distribution along slope gradient.

yield. Statistical significance was determined at the 5% probability level, and where significant differences were observed, mean separation was carried out using the Tukey Honestly Significant Difference test.

3 | RESULTS AND DISCUSSION

3.1 | Effects of conservation practices on finger millet yield and yield components

Improving crop yield by improving the productive capacity of the land is the foundation of SWC practices. The ANOVA indicated that biological and physical SWC and foot slope had positive impacts on plant height, biomass, and grain yield of finger millet (Table 1). The longest plant height, highest biomass, and grain yield were obtained as 73.24 cm, 2.50 t ha^{-1}, and 1.31 t ha^{-1} from plots treated with BSWCPs, and the shortest plant height (57.34 cm) was observed from plots and unconserved plots, respectively. Also, the lowest biomass and grain yield were obtained from unconserved sites (Table 1). The slope gradient can also significantly impact plant height, biomass yield, and grain yield in the study area. The longest plant height (68.92 cm), highest biomass yield (2.28 t ha^{-1}), and grain yield (1.19 t ha^{-1}) were obtained from foot slopes. The longest plant height (68.92 cm), highest biomass yield (2.28 t ha^{-1}), and grain yield (1.19 t ha^{-1}) were obtained from foot slopes. The shortest plant height, lowest biomass, and grain yield were recorded as 60.92 cm, 1.69 t ha^{-1}, and 0.86 t ha^{-1} from upper slopes, respectively (Table 1).

The result showed that there was a highly significant difference ($p < 0.05$) between plots treated with biological SWC and physical SWC over the untreated, as well as between the foot slope and middle slope over the upper slope. A significant difference between biological and physical measures might be due to biological conservation practices that can improve soil health and fertility by enhancing organic matter content, nutrient cycling, and microbial activity. These practices promote long-term soil health, leading to improved crop growth and yield (Abiye, 2022; Erkossa et al., 2018). On the other hand, physical conservation practices mainly focus on preventing soil erosion and managing water runoff. While they can help retain topsoil and prevent nutrient loss, they may not directly contribute to improving soil fertility or nutrient availability. The other reason is likely biological conservation practices often emphasize water conservation by improving soil water-holding capacity, reducing runoff, and enhancing infiltration rates. These practices can help maintain optimal soil moisture levels for crop growth and yield (Bayle & Muluye, 2023). Physical conservation practices primarily aim to control water runoff and prevent soil erosion. Although they indirectly contribute to water conservation by reducing runoff, they may not directly address soil moisture management or enhance water availability for crop plants.

Both physical and biological SWC measures had a significant difference compared to untreated sites (Table 1). This difference might be the reason that conserved sites typically have healthier soils due to reduced soil erosion, better water infiltration, and increased organic matter content. Healthy soils provide necessary nutrients and support root growth, leading to improved crop yield. While unconserved sites may experience soil degradation, such as erosion and nutrient depletion, which can negatively impact crop productivity. The result agreed with the previous studies at Lole Watershed, northwestern Ethiopia (Guadie et al., 2020). The other possible reason for the yield decrease on the control plot likely due to the lesser amount of organic matter and nitrogen nutrients, which is decreased and washed away because of water erosion in non-conserved croplands (Misebo et al., 2025).

TABLE 1 Main effects of soil and water conservation practices type and slope gradient on growth and yield parameters of finger millet.

Treatments	Parameters		
Conservation factor	**Mean plant height (cm) ± SE**	**Mean biomass yield (t ha^{-1}) ± SE**	**Mean grain yield (t ha^{-1}) ± SE**
BSWC	73.24 ± 1.36a	2.50 ± 0.69a	1.31 ± 0.35a
PSCW	63.76 ± 1.55b	1.93 ± 0.06b	0.98 ± 0.04b
UNC	57.34 ± 1.14c	1.49 ± 0.03c	0.77 ± 0.02c
LSD	3.59	0.16	0.08
p-value (≤0.05)	0.002	0.001	0.001
Slope factor			
Foot slope	68.92 ± 1.73a	2.28 ± 0.12a	1.19 ± 0.05a
Middle slope	64.50 ± 1.63b	1.94 ± 0.08b	1.00 ± 0.05b
Upper slope	60.92 ± 1.43b	1.69 ± 0.04c	0.86 ± 0.02c
LSD	3.59	0.16	0.084
p-value (≤0.05)	0.001	0.004	0.003
CV	7.78	22.14	19.49

Note: Means followed by the same lowercase letters within a column are not significantly different at $p < 0.05$.
Abbreviations: BSWC, biological soil and water conservation; CV, coefficiant of variation; LSD, least significance difference; PSWC, physical soil and water conservation; UNC, unconserved; SE, standard error.

Increased crop yield on the treated fields was due to reduced soil and nutrient losses and enhanced soil fertility because of SWC practices (Fantahun et al., 2024). This study is also in line with the previous study conducted by Taye et al. (2024), which reported that grain yield for plots with SWC structures increased by 4.2% to 33% when compared to control plots in terms of cropland area occupied by SWC structures.

The variation in plant height, biomass, and yield of finger millet among foot slope, middle slope, and upper slope in the study area can be attributed to several key factors related to soil properties, water availability, and microclimatic conditions. Plants at the foot slope generally might exhibit greater height due to better water retention, deeper soils, and higher nutrient availability. Although plant height, biomass, and grain yield were reduced at the upper slope. This is likely due to higher erosion rates, lower soil moisture, and nutrient deficiencies. Another study also confirmed that the accumulation of water and nutrients at the foot slope enhances plant growth and overall biomass (Guadie et al., 2020).

3.2 | Interaction effects of SWC with slope gradient on finger millet yield and yield components

The ANOVA indicated that the interaction effects of soil conservation methods (physical, biological, and untreated) with slope class on crop yield can significantly influence plant height, biomass yield, and grain yield (Table 2). The longest plant height (79.71 cm), followed by 71.73 cm, was obtained from the interaction of BSWC + foot slope and middle slope, respectively. Similarly, the highest biomass and grain yield (3.08 and 1.57 t ha^{-1}) were followed by 2.46 and 1.31 t ha^{-1} from the interaction of BSWC + foot slope and middle slope, respectively (Table 2). The result of plant height, biomass, and grain yield indicated that the interaction of biological soil conservation practice + foot slope showed a highly significant difference ($p < 0.05$) over untreated (control) + upper slope (Table 2). This variation might be because of topsoil and nutrient loss from upper slopes by erosion and deposition at the lower slope. That means slopes can affect the distribution of nutrients in the soil, with steeper slopes leading to nutrient loss through erosion and reduced nutrient availability for crops. This result is in line with another study that reported that the highest yield of teff (Eragrostis tef) and wheat (*Triticum aestivum*) grain was obtained from foot slope positions rather than hill slopes (Agegnehu et al., 2023).

In addition, steep slopes can be more difficult to farm, leading to increased labor intensity and potentially reduced crop yields. The result agrees with Kebede et al. (2023), who reported that available phosphorus, TN, and soil organic matter leached from higher slopes. An investigation by Wubie and Assen (2020) reported that TN, available phosphorous, soil organic carbon (SOC), and cation exchange capacity (CEC) reduced as the slope gradient increased. Due to those reasons, the yield decreased as the slope gradient increased in the study area. The combination of soil bunds and grass strips leads to increased crop productivity. By controlling erosion, improving soil health, enhancing water retention, and suppressing weeds, these conservation practices create favorable growing conditions for crops, resulting in higher yields and improved agricultural sustainability. The result is supported by Gebremedhin et al. (2022), who reported that BSWCPs

TABLE 2 Interaction effects of soil and water conservation and slope on growth and yield of finger millet yield.

Treatment combinations	Parameters		
	Mean plant height (cm) ± SE	Mean biomass yield (t ha^{-1}) ± SE	Mean grain yield (t ha^{-1}) ± SE
BSWC + foot slope	79.71 ± 1.53a	3.08 ± 0.84a	1.57 ± 0.09a
BSWC + middle slope	71.73 ± 1.45b	2.46 ± 0.62b	1.31 ± 0.07b
BSWC + upper slope	68.26 ± 1.38bc	1.97 ± 0.55c	1.02 ± 0.05c
PSWC + foot slope	66.70 ± 1.32bc	2.30 ± 0.61b	1.21 ± 0.06b
PSWC + middle slope	64.6 ± 1.29cd	1.8 ± 0.526cd	0.95 ± 0.05c
PSWC + upper slope	59.95 ± 1.23de	1.60 ± 0.47de	0.78 ± 0.03d
UNC + foot slope	60.34 ± 1.25de	1.45 ± 0.43e	0.80 ± 0.04d
UNC + middle slope	57.15 ± 1.14e	1.50 ± 0.45e	0.73 ± 0.03d
UNC + upper slope	54.53 ± 1.12e	1.51 ± 0.46e	0.77 ± 0.04d
LSD	6.21	0.28	0.14
p-value (≤0.05)	0.003	0.007	0.006
CV	7.79	20.01	19.09

Note: Means followed by the same lowercase letters within a column are not significantly different at $p < 0.05$.
Abbreviations: BSWC, biological soil and water conservation; LSD, least significance difference; PSWC, physical soil and water conservation; UNC, unconserved; SE, standard error.

contribute to increased crop yield by improving soil health, water availability, nutrient supply, and erosion control. These practices create optimal growing conditions for crops, resulting in higher yields, improved crop resilience, and greater agricultural sustainability.

4 | CONCLUSION

This study showed that SWC practices significantly enhanced the growth and yield of finger millet. Biological SWC measures, particularly soil bunds stabilized with grass, produced the highest plant height, biomass yield, and grain yield compared with physical SWC and untreated plots. These improvements are attributed to enhanced soil organic matter, better moisture retention, and improved nutrient cycling, which collectively strengthened soil fertility and crop performance. Slope position also had a marked influence on crop productivity. Foot slope areas recorded the highest plant height, biomass, and grain yield due to deeper soils, greater moisture availability, and deposition of nutrients from upper slopes. In contrast, upper slopes produced the lowest yields, mainly because of severe erosion, reduced soil moisture, and nutrient depletion. Interaction effects confirmed that the combination of biological SWC practices with foot slope conditions resulted in the highest yield advantages, whereas untreated upper-slope plots performed poorest. The findings highlight that integrating biological conservation measures with slope-specific land management can substantially improve finger millet productivity. To enhance finger millet productivity, farmers and land managers are advised to prioritize biological SWC measures, particularly soil bunds stabilized with grass, while giving special attention to upper slope areas through intensified conservation efforts to reduce erosion and improve moisture retention.

AUTHOR CONTRIBUTIONS

Fekadu Debebe: Conceptualization; data curation; formal analysis; investigation; methodology; writing—original draft; writing—review and editing. **Wondwosson Kibrie**: Investigation; methodology; project administration; writing—original draft; writing—review and editing. **Habtamu Admas**: Project administration; resources; supervision; validation; writing—original draft; writing—review and editing. **Beletech Kindu**: Validation; visualization; writing—original draft; writing—review and editing. **Assaye Mehari**: Methodology; software; validation; writing—original draft; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data supporting the findings of this study are included in the main text. Raw datasets are available from the corresponding author upon reasonable request.

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