

Effectiveness of Soil and Water Conservation Measures on Degraded Mountain Ecosystems: Enhancing Soil Moisture, Seedling Growth, and Biodiversity in Baka-Dawla Aari District, Southern Ethiopia

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Abstract

This study examines the short-term impacts of soil and water conservation measures on soil moisture, seedling growth, soil properties, and species diversity in the Baka-Dawla Aari District, Southern Ethiopia. The techniques investigated include level bench terraces, level soil bunds, and stone-faced bunds, compared to non-conserved plots. Soil samples were collected from both treated and non-conserved plots, with soil moisture analyzed using the gravimetric method after two rainy seasons. Growth parameters of *Grevillea robusta* seedlings were measured seasonally, and soil physico-chemical properties were assessed before and after interventions. Results showed that bench terraces significantly increased soil moisture content to 14.2%, compared to 7.8% in non-conserved plots. Soil organic carbon increased by 79.31%, total nitrogen and available phosphorus by 40.01%, and potassium by 20.01% in bench terraces. Bench terraces also supported higher growth rates of *Grevillea robusta* trees and improved species diversity and evenness. These findings confirm the effectiveness of bench terraces in rehabilitating degraded mountain ecosystems. Future research should extend the monitoring period to capture long-term changes.

Keywords: *Degraded mountain ecosystems, Conservation effectiveness, Ecosystem rehabilitation Soil moisture enhancement, Species diversity.*

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Introduction

Mountain ecosystems are particularly vulnerable to degradation due to their steep slopes, fragile soils, and often intense land use pressures (Price, 2013). Degradation in these regions can lead to reduced soil moisture (Lal et al., 2015), soil fertility, increased erosion, loss of biodiversity and diminished water resources (UN Environment, 2019).

Livelihood security in Ethiopia, particularly in the highlands depends strongly on local resources (Sharma, 2018) particularly those related to climate, soil and water (Field et al., 2014) for providing basic needs such as food, fuel, and income. Direct dependency on local natural resources for livelihoods is particularly high in rural regions with widespread poverty and where agriculture is the main living strategy (Malmberg et al., 2018).

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Soil erosion is the primary cause of land degradation in the rain-fed agricultural landscapes of Ethiopia. It is the most dangerous ecological process observed in Ethiopia, degrading the precious soil resources that form the basis of agricultural production and food for the country's people, while also providing numerous other ecosystem services. As soil productivity decreased due to increased erosion, the issues of soil and water conservation became a question of human survival (Hunri et al., 2015).

Securing the sustainability of agriculture and ecosystem services is paramount for meeting the challenge of enhancing yields while safeguarding environmental integrity and public health (Tilman et al., 2002). Soil and water conservation measures (SWCMs) play a vital role in mitigating these impacts and restoring ecosystems (Zhang et al., 2023). SWCMs directly affect plant productivity and indirectly influence functional traits and community structure, typically leading to reduced plant diversity but increased productivity. Vegetation measures promote biomass per plant growth, while engineering measures favor the growth of dominant species (Yang et al., 2023).

In Ethiopia, addressing soil erosion has been a significant focus for the government and development agencies, with substantial resources invested in promoting soil and water conservation (SWC) measures to enhance agricultural production and environmental conditions, ultimately combating land degradation (Gebrenichael et al., 2005). So, many efforts were undertaken by the Ethiopian government to combat the land degradation problem (Gadisa, 2021). However, the adoption of soil erosion control measures has been hindered by various challenges, including labor shortages, limited capital, insufficient incentives (such as food-for-work programs), insecure land tenure policies, inappropriate technology choices, lack of quick-return technologies for subsistence farmers, inadequate technical support, and low community participation due to top-down policies (Nigussie et al., 2017).

In the study area of this research, Baka-Dawla Aari District, South Ethiopia, the distribution of SWCMs is higher on the horizontal plane compared to plains and mountainous areas, particularly in hilly regions with slopes exceeding 35%. Historically, mountain areas were regarded as forest lands, making them highly prone to erosion (FAO, 2011). Furthermore, soil erosion is more severe in upland areas due to their lower soil and water retention capacity. Therefore, increasing the proportion of SWCMs in mountainous regions, especially where overland flow initiates, is vital for enhancing ecosystem service functions.

The degradation of mountain ecosystems leads to environmental problems such as sedimentation, flooding, and crop loss, impacting nearby residents and downstream communities. Thus, the objective of hillside rehabilitation is to restore the intricate ecosystem of the hillside and create a healthy environment for inhabitants. Urgent action is imperative to manage mountain resources effectively and foster the socioeconomic development of mountain-dependent populations. However, rehabilitating degraded mountain areas faces numerous challenges, including limitations in suitable physical structures for rehabilitation. This is particularly evident in our study area. Therefore, this study aims to explore the short-term impact of soil and water conservation measures on soil moisture enhancement, soil physicochemical properties, vegetative composition, and the growth of *Grevillea robusta* A Cunn. Seedlings planted for the rehabilitation of degraded mountains, as well as its effect on biomass and emerging vegetation indices.

Material and Methods

Site Selection and Research Design

The study was conducted on degraded mountains in midland agro-ecologies in the Baka-Dawla Aari District of Southern Ethiopia (Fig 1), which is 10km far from the capital town of Aari zone, Jinka and



794 Kms from Addis Ababa, capital town of Ethiopia. The study site is geographically situated as shown in (Figure 1) at 5.672°- 5.886° N latitude and 36.451°- 36.686° E longitude.

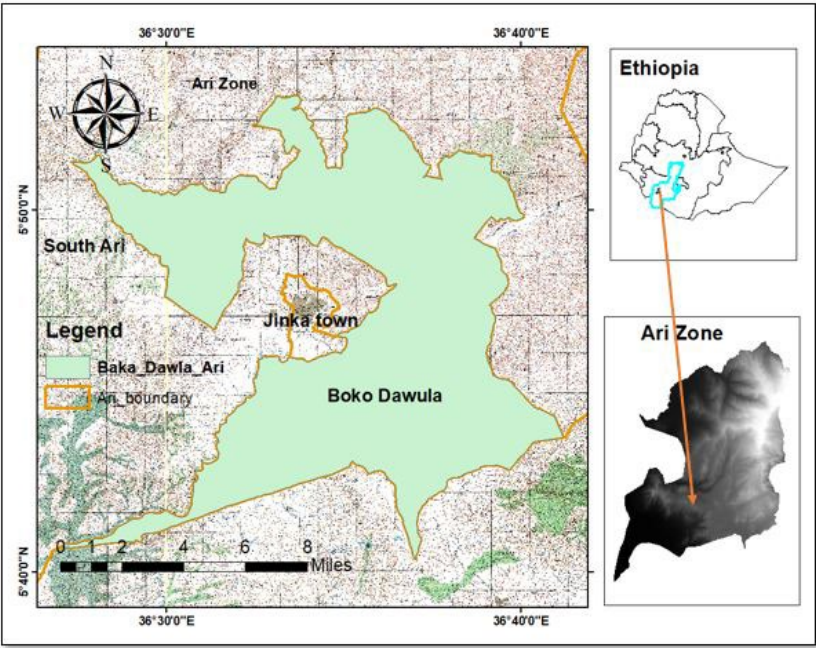


Figure 1. Map of the Study Area

Climatic Characteristics

Figure 2 illustrates the agro-ecology of the area that was midland with the mean annual rainfall of 1339 mm with a bimodal nature and maximum and minimum temperatures of 27.62 ° C and 16.32 ° C respectively.

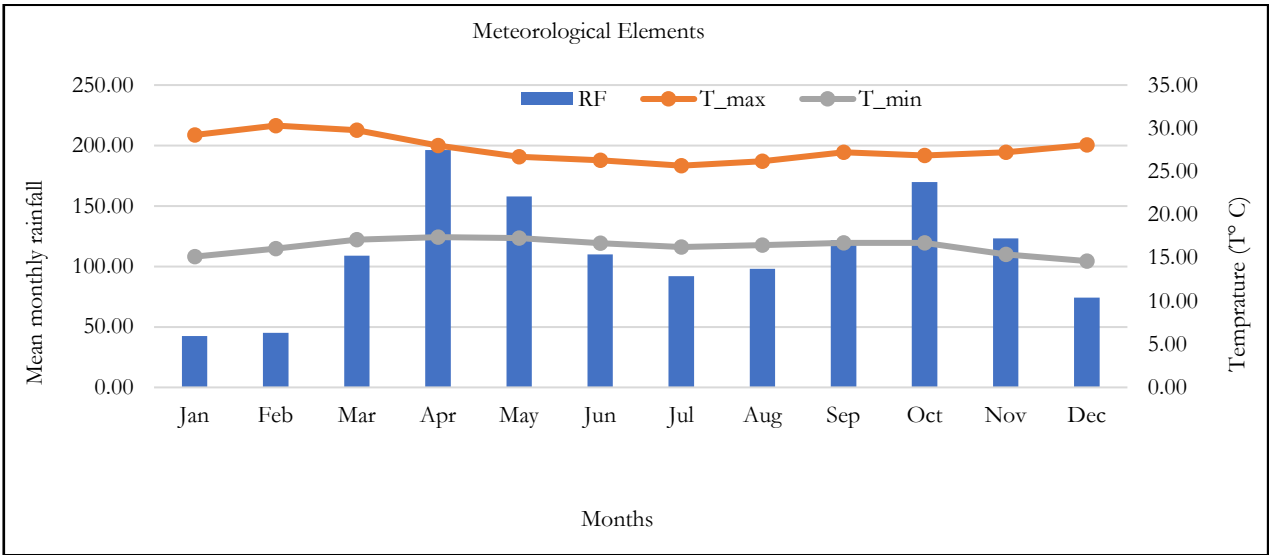


Figure 2. Monthly Rainfall and Maximum and Minimum Temperatures of in Experimentation Period



Research Design

Before choosing the degraded mountains, we discussed with the district's office of agriculture and natural resources to select a mountain with high degradation and to address the challenge of executing sustainable mountain development. Then, field observation of the mountain was made on slope measurement, topography and other obstacles to select the experimental area and plots.

The experiment was implemented on degraded land with an average slope gradient of 35%. The research was designed or laid out in randomized complete block design (RCBD) under farmers as replications block with four (4) treatments including soil level bund, stone-faced bund, level bench terrace and control (only tree planting or farmers practice to restore degraded land. The size of each plot in the experiment was 10m by 10m, with a 2m distance between the plots. The experiment was conducted on the degraded mountain, with one replication of treatments laid outside by side and replicated at different positions along the mountain. Attention was given to minimizing the variation between the plots due to the topographic effect, level of degradation, slope steepness, and other factors that maximize the variation between plots. Construction of soil and water conservation structures was carried out according to the specifications provided by the Ministry of Agriculture (Hurni et al., 2016).

Grevillea robusta A. seedlings were planted uniformly in each of the structures on the catchment between the structures as a test tree to help monitor the rehabilitation.

Data Collection

Soil sampling and analysis

Composite soil samples (100 g) were collected from a depth of 0-30 cm at the start of the study, before implementing soil and water conservation measures, to assess changes in fertility. Samples were air-dried, ground, and sieved (2 mm) before analysis for soil texture, pH, organic carbon (SOC), total nitrogen (TN), cation exchange capacity (CEC), available phosphorus (P), and potassium (K) at the Jinka Agricultural Research Center. Soil pH was measured in a 1:2.5 soil-to-water suspension, available P was analyzed using sodium bicarbonate extraction (Olsen, S. R. (1954), SOC was determined by the Walkley and Black method, total N was measured by the semi-micro Kjeldahl method, available K was determined by flame emission spectrophotometry, and CEC was assessed by titration of ammonium displaced by sodium. Soil texture was evaluated using the hydrometer method. Samples were collected using consistent methods across treatment types for impact evaluation

The method of percentage change (δ) in soil nutrients as a result of soil conservation was calculated from the relationship (Equation 1): given the beginning and end levels of soil nutrients over a study period following the equation below (Lal, R. (2001).

$$\text{Percentage change } (\delta) = \frac{(P_{\text{SWC}} - P_{\text{W_SWC}})}{P_{\text{W_SWC}}} * 100 \quad (1)$$

Where, P_{SWC} is the soil property measured after SWC is implemented $P_{\text{W_SWC}}$ is the soil property measured before SWC without.

Soil moisture determination

Soil moisture content was determined at two depths (0– 20 and 20 - 40cm). Measurements were carried out after seasons of rain period. The samples were oven dried at 105°C in an electric oven for 24 hours and weighed to determine moisture content on dry basis using gravimetric method (Hillel, D. (2004).



$$SMC = \frac{(W_w - W_d) * 100}{W_d} \quad (2)$$

Where;

MC = Moisture content (%)

W_w = Weight of wet soil (g)

W_d = Weight of dry soil (g)

The efficiency of soil conservation measures in the months towards the end of the rainy season was used for monitoring.

Vegetation Survey

Quadrat Method: Lay quadrats (e.g., 1m x 1m for herbaceous plants, 10m x 10m for shrubs/trees) randomly within the study sites.

Recording Data includes; - identifying species within each quadrat/transect, recording the number of individuals per species, and weighing the biomass.

Data Analysis

The measured soil moisture content and seedling growth parameters data were subjected to analysis of variance (ANOVA) and Least Significant Difference (LSD) test was used for mean separation at 5% significance level by using a software program (SAS. 2010). The other species diversity and evenness data were subjected to their standard procedure as follows.

Species Diversity Indices (Shannon, C. E. (1949):

- Shannon-Wiener Index (H')

$$H' = -\sum_{i=1}^S (p_i \ln p_i) \quad (3)$$

Where p_i is the proportion of individuals belonging to species i.

- Simpson's Diversity Index based on (Simpson, E. H. (1949)

$$D = 1 - \sum_{i=1}^S (p_i^2) \quad (4)$$

Where p_i is the proportion of individuals belonging to species i.

Species Evenness

- Pielou's Evenness Index (Pielou, E. C. (1966)

$$J' = \frac{H'}{\ln S} \quad (5)$$



Where H' is the Shannon-Wiener index and S is the total number of species.

Statistical Analysis

The mean separation Comparison was made on species diversity and evenness between sites with and without intervention measures using Analysis of variance.

Results and Discussion

Effects of Soil and Water Conservation Measures on Soil Moisture Content

Table 1. The Effect of Soil and Water Conservation on Soil Moisture Content (SMC) Dynamics at the Early and Late Seasons of the Years 2020 and 2022

Treatments	2020		2022	
	SMC _{early}	SMC _{late}	SMC _{early}	SMC _{end}
Level Soil bund	8.13	9.13 ^{ab}	5.67 ^{ab}	11.18 ^{bc}
Stone faced bund	7.22	8.22 ^{ab}	4.84 ^{ab}	11.68 ^{ab}
Bench terrace	9.99	10.99 ^a	6.82 ^a	14.20 ^a
Control	5.31	6.31 ^b	3.92 ^b	7.80 ^c
CV (%)	---	12.04	8.40	9.5
LSD (0.05)	NS	3.12	1.94	5.32

Note: Means with the same letter are not significantly different; SMC is soil moisture content phases

Soil moisture content (SMC) was significantly influenced by soil conservation practices as presented in Table 1. All Soil bunds, stone-faced bunds, and bench terraces had significantly higher SMC compared to plots with no conservation measure.

Similarly, various studies reported that implementing soil conservation measures has a significant role according to (Gadana et al., 2020), soil moisture content was noticeably greater under SB compared to no conservation technique. Furthermore, in the last season of the trial, the bench terrace exhibited a significantly higher (SMC) (14.2%) than plots without, which had the lowest (SMC) of 7.8%.

Effect of SWC on Soil Physicochemical Properties

Table 2. Physico-Chemical Properties of the Soil Before and After Intervention Treatment

Treatments	pH (H ₂ O)	% OC	%TN	av.P ppm	av.K ppm	CEC (meq/100g soil)	Textural class
Before treatment	7.17	0.87	0.05	7.19	33.39	19.08	Sandy Loam
After intervention							
Level Soil bund	7.17	1.44	0.056	7.19	22.91	No data	Sandy Loam
Stone faced bund	7.17	1.49	0.056	7.71	21.92	No data	Sandy Loam
Bench terrace	7.17	1.56	0.07	10.06	22.92	No data	Sandy Loam
Control	7.17	0.93	0.033	7.04	19.43	No data	Sandy Loam

Note: OC: organic carbon, TN: total nitrogen and CEC: cation exchange capacity, av.P and av. K: available phosphorus and potassium

Table 3. Percentage Change in (δ) Soil Nutrients as Result of Soil Conservation Measures

Treatments	$\delta\%$ OC	$\delta\%$ TN	$\delta_{Av.P}$ ppm	$\delta_{Av. K}$ ppm
Soil Bund	65.52%	12%	0.07%	20.10%
Stone faced bund	70.69%	12%	7.31%	14.91%
Bench terrace	79.31%	40%	40.01%	20.16%
Control	6.90%	-44%	-2.02%	1.86%

Note: δ = % *Change in* soil nutrients

As illustrated in table 2 & table 3, the study found that soil and water conservation techniques (soil bunds, stone-faced soil bunds, and bench terraces) had a far-reaching positive impact on soil nutrients. Soil organic carbon in a control plot revealed an increase of 6.9%, while soil bund, stone-faced bund and bench terrace were increased by 65.52, 70.69 and 79.31% respectively. Similarly, the total nitrogen was increased by soil bund, stone-faced, and bench terrace, with respective increases of (12%, 12%, and 40%), over the (-44%) decline in the case of conservation plots. In the same manner, available phosphorus and potassium rose by intervention measures has shown a percentage increment with the recorded (-2%) reduction of phosphorous in no conservation measure condition.

Some studies reported that soil nutrients were improved due to soil conservation measures. According to (Sinore et al., 2022), %TN, available phosphorus, SOC, soil pH, and CEC, showed a significant difference in the different landscape positions between soil with management practices (soil bund and fanya-you with desho) over no-management practices.

Effects of Soil Conservation Measures on Test Tree (*Gravellia robusta*)

Table 4. Effect of SWC Structures under during Final (2022) Season's Growth of Test Seedling (*Gravellia robusta*) Diversity and Evenness on Species Level

Treatments	2020		2022	
	ph (cm)	rcd (mm)	ph(cm)	rcd (mm)
Soil bund	39.53	6.11b ^c	106.63 ^{ab}	20.12 ^b
Stone faced bund	35.39	6.39 ^{ab}	101.57 ^{ab}	19.17 ^{bc}
Bench Terrace	34.18	8.47 ^a	120.00 ^a	22.64 ^a
Control	32.43	5.73 ^c	83.50 ^b	15.76 ^c
LSD(0.05)	NS	1.82	26.8	1.37
CV	4.75	8.41	4.77	4.82

Note: ph-plant height, rcd:- root collar diameter

The growth parameters observed in 2021 indicated that the intervention measures did not have a significant impact on the height of *Gravellia Robusta* plants during the early planting season. However, in 2022, the seedling growth parameters, such as the plant height and root collar diameter (RCD), showed significant differences ($p < 0.005$) (Table 4). Due to the implementation of bench terrace conservation measures, the height of *Gravellia Robusta* grew significantly to 120cm compared to the plot without conservation measures in which the height was 83.5cm. However, there was no significant difference in plant height among the various conservation measures. The root collar diameter of 22.64mm was recorded in the bench terrace condition, which was significantly greater than the control plot and control. In agreement with this finding (Elhag Aydrous, 2015), reported that the plant height, stem thickness (for some cases), and the number of leaves/trees were significantly increased under the micro catchment techniques as compared to the control



According to (Gadana et al., 2020) integrating physical SWC measures with ex-closure in a watershed approach effectively restores tree species density and diversity, and improves SOM, TN, and soil moisture contents.

Effect of SWCMs on Emerging Vegetation Biomass, Richness and Evenness

Table 5. Biomass Mean for Emerged Grasses on Degraded Mountains

Treatments	2020	2022
	(bw /kg/m ²)	(bw /kg/m ²)
Soil bund	0.86	2.3 ^{cd}
Stone faced bund	0.89	3.1 ^b
Bench Terrace	0.91	4 ^a
Control	0.73	1.9 ^{cd}
LSD (0.05)	NS	0.82
CV(%)	8.3	7.21

Note: NS -No significant difference, bw- biomass weight

Table 5 illustrates the biomass weights across different treatments over two consecutive years. In 2020, no significant difference (NS) in biomass weight was observed among the treatments, indicating that variations were not statistically significant. However, by 2022, significant differences were evident in biomass weight (bw) among the treatments ($p < 0.05$).

Remarkably, the bench terrace treatment exhibited the highest biomass weight, measuring 4 kg/m², significantly surpassing other treatments. Following closely, the stone-faced bund treatment recorded a biomass weight of 3.1 kg/m². Comparatively, the soil bund and control treatments displayed lower biomass weights of 2.3 kg/m² and 1.9 kg/m², respectively.

These findings indicate an improvement in biomass weight across all treatments from 2020 to 2022. Particularly noteworthy is the substantial increase in biomass weight observed in the bench terrace treatment in 2022, followed by the stone-faced bund, soil bund, and control treatments in decreasing order.

Table 6. Effect of SWCMs on Species Diversity and Evenness

Treatment	Species Diversity (2020/2022)	Species Evenness (2020/2022)
Soil Bund	0.5273 / 0.61	0.7124 / 0.961
Stone-faced Bund	0.851 / 0.961	0.81 / 1.02
Bench Terrace	0.913 / 1.33	0.901 / 1.2
Control	0.1181 / 0.21	0.0969 / 0.12

Table 6 demonstrates that plots subjected to soil and water conservation interventions exhibit superior plant species diversity compared to untreated fields. Remarkably, even the untreated fields show incremental changes, suggesting that controlling interference alone can induce restoration activity. This observation aligns with the findings reported by (Saavedra O. et al. (2024). The results make it evident that bench terrace-treated fields had the most significant positive effect on vegetation cover, plant species diversity, richness, and restoration on steeply landscapes. This could be due to (SWCMs) ensure a more even distribution of water resources, reducing the competitive advantage of certain dominant species. This can lead to more balanced species abundances. With more equitable access to water, less dominant species have a better chance of thriving, which increases species evenness (Woubet et al., 2011). Besides,



SWCMs can support the growth of a variety of tree species and understory plants, leading to a more diverse and evenly distributed plant community over time (Kumawat et al., 2022). Similarly, soil and water conservation structures, along with other watershed management interventions, have a positive impact on herbaceous plant species composition, diversity, biomass production, and the survival and growth of planted tree species in rangeland areas such as the Haro-Bake Sub-Watershed in Southern Ethiopia. These interventions result in increased indigenous plant species diversity and richness, improved survival and growth of planted tree species, and enhanced grass biomass and herbaceous basal cover (Siraj et al., 2023).

Conclusion

Based on the results and discussions presented, the adoption of soil conservation practices, such as soil bunds, stone-faced bunds, and bench terraces, markedly augmented soil moisture levels compared to untreated plots. Notably, bench terraces emerged as the most effective method for retaining water during the period spanning 2020 to 2022. Moreover, the implementation of these techniques resulted in discernible enhancements in soil physico-chemical properties. Soil organic carbon, total nitrogen, available phosphorus, and potassium exhibited substantial increases following the adoption of conservation measures, while control plots experienced declines in these essential nutrients. This underscores the role of soil and water conservation practices in fortifying soil fertility and nutrient availability. In terms of *Gravellia robusta* seedling growth, the utilization of bench terraces yielded the most significant improvements, manifesting in heightened plant stature and root collar diameter compared to untreated areas.

Across the two-year observation period, there was a substantial upsurge in biomass weight across all treatment groups, with the bench terrace treatment showcasing the highest biomass weight in 2022. Additionally, soil and water conservation interventions positively influenced species diversity and evenness, with bench terrace-treated fields displaying the most notable enhancements in vegetation cover and diversity.

Based on the current study result, some conclusions were drawn such as; all of the three soil and water conservation measures (soil level bunds, stone face soil bunds and level bench terraces) implemented have brought a significant advantage on soil moisture retention, soil organic carbon, total nitrogen, available phosphorus and potassium as compared to the conventional methods, while bench terraces are the best one as compared to other treatments. Besides this, bench terrace structures are also attributed to better results in higher tree growth as compared to conventional practices and others.

Recommendation

Based on the conclusion drawn from the study, several recommendations can be made to optimize soil conservation efforts and promote sustainable agricultural practices:

- **Promotion of Bench Terraces:** Given their significant impact on soil moisture retention in steeply slope landscapes, soil fertility improvement, and plant growth, prioritizing the adoption of bench terraces is recommended. This technique not only conserves soil and water but also enhances agricultural productivity.
- **Integration of Soil Conservation Practices:** While bench terraces proved highly effective, a combination of biological conservation practices can further augment soil moisture levels and nutrient availability. Implementing a holistic approach to soil conservation can maximize benefits.



- **Education and Training:** Farmers and agricultural practitioners should be educated and trained on the implementation and maintenance of soil conservation techniques. Providing workshops, demonstrations, and extension services can facilitate widespread adoption and ensure proper utilization of conservation measures.
- Continuous monitoring and evaluation of soil conservation efforts are essential to assess their effectiveness over time. Regular soil testing and assessment of vegetation cover and diversity can provide valuable insights for refining conservation strategies.
- **Research and Innovation:** Additionally, continued monitoring and assessment of the long-term impacts of these conservation practices are essential for sustainable land management and ecosystem restoration efforts.

Author Contributions

Abebe Hegano and Mitiku Ayele conceptualized and initiated the project and developed the methodology. Abebe Hegano also handled the software and visualization aspects, while Yenesew Animaw curated the lab data. Validation and formal analysis were collaboratively performed by Abebe Hegano, Mitiku Ayele, Belayneh Lema, and Yenesew Animaw. The original draft was written by Abebe Hegano, with review and editing contributions from Abebe Hegano, Mitiku Ayele, and Belayneh Lema. Supervision was provided by Belayneh Lema.

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