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ASSESSMENT OF TECHNICAL EFFICACY AND ECONOMIC IMPACTS OF BENCH TERRACES IN SOIL EROSION CONTROL FOCUS ON GREEN GICUMBI PROJECT, GICUMBI DISTRICT

Theoneste BIZIMENYERA[1]
Dr Pancras NDOKOYE[2]
NTAKIRUTIMANA Theogene[3]
[1]Rwanda Green Fund (FONERWA), Project Infrastructure Specialist and Graduate in Master of science, option of Environmental Economics and Natural Resources Management at University of Lay Adventist of Kigali (UNILAK)
[2]Lecturer at University of Lay Adventist of Kigali (UNILAK)
[3]Watershed protection Specialist at Rwanda Green Fund (FONERWA)

Abstract: Soil erosion is a major cause of soil loss and one of the most serious problems threatening human well-being and environmental sustainability. In developing countries like Rwanda, where agriculture is the backbone of the economy, conservation practices have been implemented to combat soil erosion. Bench terraces in the highland regions of Rwanda are considered one of the most effective solutions to address accelerated soil erosion and its related problems. This research evaluated the technical conformity and cost-effectiveness of bench terraces in Gicumbi District, an area highly susceptible to erosion and climate hazards. The study focused on the Green Gicumbi Project, which plays a key role in implementing bench terraces to mitigate soil erosion. The study population of 44,326 households was considered within a sample size of 112 respondents comprising 12 project implementers and stakeholders and 100 beneficiaries. A mixed-method approach combining both quantitative and qualitative data was used. The technical standards and models provided by Food and Agriculture Organization were tested on 108 purposively sampled bench terraces across eight sectors, and the terraces were compared to the current practices implemented by the Green Gicumbi Project in the Gicumbi District. The results showed that most terraces adhered to technical guidelines, with average riser slopes of 65.5%, riser heights of 1.6 m, and widths of around 4.1 m. However, 18% of the terraces displayed technical flaws, particularly on steep slopes exceeding 44%, where instability and lack of check dams and maintenance were observed. Correlation analysis between FAO-calculated and field-measured terrace dimensions showed weak alignment r = 0.479 for vertical interval and a moderate positive correlation r = 0.675 for width. Economic analysis using Cost-Benefit Analysis showed that, with proper farming practices, terraces are economically viable, with a Benefit-Cost Ratio of 1.58 by the second year after construction. Maize and bean yields increased by 25–30%, and over 60% of farmers reported increased crop yields, reduction of soil erosion, improved soil moisture, and greater fodder availability. The study concludes that bench terraces are both technically and economically effective when properly designed and maintained. These findings offer valuable guidance for policy-makers and practitioners seeking to expand sustainable land management practices in Rwanda. The study supports the importance of adhering to construction standards and ensuring regular maintenance. It also emphasizes the need for continued support from the Ministry of Agriculture to sustain results beyond project completion, including efforts to strengthen supervision, farmer training, and long-term monitoring in future soil conservation programs.

Keywords: Technical efficacy, economic impacts, soil erosion, Green Gicumbi Project.

0. Introduction

Rwanda is a small landlocked country spanning an expanse of 26,338 Km2 with approximate total population is 13,798,561 contributing to a considerable population density of around 525 people per km² (NISR, 2022).

This substantial populace heavily depends on agriculture, a promising expansion potential sector. However, although agriculture remains paramount in the Rwandan economy, it also presents formidable challenges (Ministry of Health, 2014). The pressure on natural resources, including land, forests, and water, continues to rise due to the need for extensive agriculture to support a growing population and urban settlements. This increasing strain on resources, combined with poor land management practices, has led to widespread land degradation, particularly in rural areas. The consequences of erosion in these regions are severe, resulting in reduced crop yields, hazardous settlements, and diminished income for rural populations.

Globally, Rwanda is among African countries most highly vulnerable to water erosion, mainly driven by a rapidly growing population with limited economic and agricultural options on a fragile soil, steep slopes and intense rainfall. Natural resources are under increasing pressure due to the extensive agriculture to feed a growing population, and settlement for the shelter (GoR, May 2022).

Of 1,080,168 hectares of agricultural land, about 746,898 hectares (70%) are affected by soil erosion. Estimating cost of soil fertility loss, and productivity loss for commodity crops are key parameters that translate severity of soil erosion into the national economy and therefore show the crucial needs for erosion control (GoR, May 2022)

The main drivers of erosion include unsustainable land use, insufficient erosion control measures, and climate change, which exacerbates existing environmental degradation (GoR, May 2022)

Soil erosion remains one of the most pressing environmental challenges in Rwanda, particularly in the Northern and Western regions, where steep terrain, heavy rainfall, and unsustainable agricultural practices exacerbate the problem. The soil erosion causes the loss of 23.6 million tons of topsoil annually, with over 60% of the population living in erosion-prone areas (MoE, 2015).

Rwanda's erosion control mapping highlighted areas at high risk of erosion, including the Gicumbi District in the Northern Province is among the areas highly susceptible to soil erosion due to its mountainous terrain even though is the least susceptible to erosion compared to other districts in the region (GoR, May 2022).

Erosion risk mapping of Green Gicumbi area was done based on Revised Universal Soil Loss Equation model. The 30.88% of the total area is under very Low risk, 10.46 % low risk, 5.81% moderate risk, 3.98% high risk, 8.53 % very high risk and 40.34% extremely high risk. The 58.66 % of the total area are threatened by moderate to very high risk of erosion with soil loss rate ranging from 16.5 to 293 tons of soil per hectare per year (FONERWA, 2020).

However, the district has made progress in mitigating erosion through the construction of bench terraces and forest conservation practices, it still faces significant risks, with about 17% of its land vulnerable to erosion. Erosion control measures alone, such as bench terraces, are insufficient without a broader focus on integrated soil management systems. A shift towards conservation agriculture, which combines sustainable land management practices with agricultural productivity, is necessary for long-term success. Bench terraces, a key erosion control measure in Gicumbi District, are recommended for areas with high to extreme erosion risks. Grassed waterways are also suggested to prevent the destruction of terraces caused by water runoff (GoR, May 2022).

In response to these challenges, the Rwandan government and various development partners have prioritized sustainable land management practices. One of the key strategies employed to combat soil erosion is the construction of bench terraces. Historically, the concept of bench terraces was introduced in 1972 by Syrille Wieme, a religious figure in Rwanda's Kisaro Sector, located in the Rulindo District of the North Province. By 1979, the Rwandan Government officially recognized and promoted the adoption of bench terraces among all Rwandan farmers, targeting numerous households for implementation (Bizimana, 2011) bench terraces involve cutting into the slope of the land to create level steps, which reduce runoff velocity and promote water infiltration.

Adopting bench terraces as a farming practice enables Rwandan farmers to cultivate in areas with hilly or mountainous terrain where traditional farming methods are not feasible. This practice has been widely adopted in Rwanda due to its proven effectiveness in controlling soil erosion, improving soil fertility, and enhancing agricultural productivity. According to UNDP (2007), erosion in Rwanda leads to approximately 15 million tons of soil loss annually, resulting in a decline in the capability to feed around 40,000 inhabitants yearly sustainably. To address this concern, the radical terraces project was initiated to protect land and increase farm productivity for the highland population (Murwanashyaka, September 2023)

In light of this, between 2008 and 2022, 4831 hectares of bench terraces were developed as erosion control practices in Gicumbi District (GoR, May 2022)

The Green Gicumbi Project, initiated as part of Rwanda's efforts to mitigate climate change and promote climate-resilient agriculture, has played a critical role in implementing bench terraces as a land management intervention by promoting sustainable land management practices, including the construction of bench terraces, the project seeks to restore degraded landscapes, enhance water resource management and promote sustainable agricultural practices aims to prevent soil erosion, increase crop yields, and improve the livelihoods of farmers in Gicumbi District (MoE, 2019).

Despite the perceived benefits of bench terraces, there is limited research on their technical efficacy and long-term economic impact, particularly in the context of large-scale interventions like the Green Gicumbi Project. While bench terraces have been successful in reducing soil loss, questions remain regarding their maintenance, the financial cost to farmers, and the overall economic returns. Furthermore, understanding the technical performance of these terraces in varying environmental conditions is critical to ensuring their sustainability and effectiveness (MoE, 2019)

This study, therefore, seeks to assess the technical efficacy and economic impacts of bench terraces constructed under the Green Gicumbi Project. By evaluating both the environmental and economic outcomes of these terraces, the research will provide valuable insights into their role in soil conservation and rural development in Gicumbi District. The findings of this study will contribute to policy recommendations on best practices for soil erosion control and inform future land management projects in Rwanda and similar regions.

1. Statement of the problem

Soil erosion is a critical environmental challenge in Rwanda, primarily due to its steep terrain, high population density, intensive agricultural activities, and heavy rainfall. These factors, coupled with deforestation and unsustainable land management practices, accelerate the loss of fertile topsoil, particularly in districts like Gicumbi, Musanze, and Rulindo. This soil loss reduces agricultural productivity, causes food insecurity, and threatens the livelihoods of rural communities (MoE, 2019). Rwanda loses an estimated 1.4 million tons of soil annually due to erosion, with the Northern and Western parts of Rwanda are highly exposed to soil erosion because they have steep slope and high precipitation although some areas have good land cover (MoE, 2018).

This has direct consequences, including reduced agricultural productivity, sedimentation of water bodies, and increased poverty among smallholder farmers who rely heavily on soil resources for food security and income (Bugenimana, 2017).

To combat soil erosion, various measures have been implemented in Rwanda, including biological measures like mulching, reforestation, and agroforestry, as well as engineering measures like bench terraces and progressive terraces (Twagiramungu, 2006). Bench terracing is the most common engineering measure, covering 42% of all implemented measures in Rwanda while other measures such as agroforestry cover around 10% (Bizoza, R. de Graaff, J., 2012).

Despite its widespread use, bench terracing has limitations. It requires high implementation and maintenance costs, can generate adverse environmental impacts, and may lead to a false sense of security (Boojh, 2012). Additionally, the long-term technical efficacy and economic implications of bench terraces remain poorly documented. Factors like terrace design, slope gradient, soil type, and rainfall patterns influence their effectiveness, raising concerns about their economic feasibility and sustainability.

The Green Gicumbi Project mainly focuses on reducing vulnerability to climate change by enhancing the adaptive capacity of the targeted groups in the project intervention area as well as reducing their exposure to climate risks through establishment of soil conservation measures including bench terraces and progress terraces. However, the construction of these terraces often faces challenges, including being built on slopes or cuts with sandy, rocky, or highly erodible soils (MoE, 2019).

Despite their widespread implementation, there is a need for comprehensive research to assess the technical efficacy and economic impact of bench terraces in controlling soil erosion and improving agricultural outcomes. Moreover, the economic implications of constructing and maintaining terraces remain poorly documented. Costs such as labor, materials, and ongoing maintenance may pose a financial burden on farmers, raising concerns about their economic feasibility and sustainability. This research should consider the diverse environmental conditions and evaluate whether the economic benefits outweigh the costs incurred by farmers.

However, few studies have assessed the technical efficacy and economic impacts of bench terraces in soil erosion (Bugenimana, 2017). Further research is needed to bridge the knowledge gap and inform decision making regarding the scalability and sustainability of bench terraces in soil conservation initiatives. In conclusion, tackling soil erosion in Rwanda requires continued investment in soil conservation technologies, community participation, and sustainable land management practices to safeguard the country's natural resources and agricultural productivity.

This includes linking the onsite and offsite effects of soil erosion with the economic impacts to provide valuable information to stakeholders for effective mitigation measures. This research will focus on assessing the technical efficacy and economic impact of bench terraces constructed under GGP in Gicumbi District. It has also examined the perception of local farmers towards bench terraces for soil erosion control.

2. Objectives of the study

The general objective of this study was to assess the technical efficacy and economic impact of bench terraces in controlling soil erosion focus on Green Gicumbi Project. And specifically this study intends:

i. Evaluate the bench terraces and their technical design parameters in the Green Gicumbi Project intervention sectors.

ii. Evaluate the performance of bench terraces in the soil erosion control in the Green Gicumbi Project intervention sectors.

iii. Analyze the economic benefits and costs associated with the implementation and maintenance of bench terraces for the supported local farmers of the project.

iv. Assess the perceptions of local farmers on the effectiveness and financial feasibility of bench terraces.

3. Literature review

There are several research gaps in the assessment of bench terraces for erosion control in Rwanda. First, most studies focus on short-term results, with limited research on the long-term effectiveness and sustainability of bench terraces, particularly under changing environmental conditions like climate variability. Additionally, there is a lack of comprehensive economic analysis that considers all costs associated with construction, maintenance, and labor compared to the long-term benefits. Research on the long-term impact of bench terraces on soil health, including organic matter and fertility, is also insufficient. Furthermore, the socio-cultural factors influencing the adoption of bench terraces, such as community attitudes, gender roles, and local knowledge, remain underexplored. The resilience of bench terraces to extreme weather conditions, particularly in the context of climate change, is another gap in the research. Comparative studies between bench terraces and other soil conservation methods are needed to assess relative effectiveness. Moreover, there is limited understanding of how government policies, extension services, and local institutions impact the adoption and success of bench terraces. Lastly, regional variations in topography, soil types, and farming practices across Rwanda have not been thoroughly examined in relation to the success of bench terraces. Addressing these gaps will provide a more comprehensive understanding of the effectiveness and economic impacts of bench terraces in Rwanda.

Before a problem can be addressed, it must be perceived. Addressing soil erosion with the adoption of conservation practices is no exception. The literature on the technical, economic and farmer's perception of bench terraces in Rwanda has given little attention to perception variables especially in Northern province. considering the findings reported in the literature reviewed above it is still not comprehensible whether the technical and how farmers perceive the bench terraces as shown in different studies carried out on soil conservation, farmers' participation in soil conservation rather on technical, economic and farmers' in worldwide as well as in Rwanda.

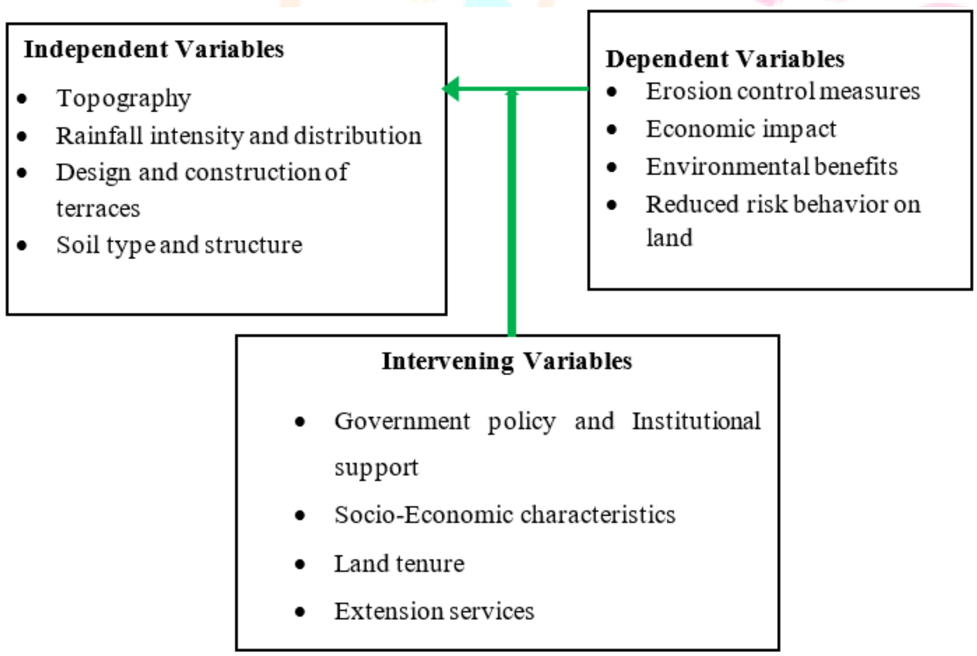
As reported by (Yamoah, 1987), there are many constraints for the promotion of bench terraces in the high-altitude regions of Rwanda. (Sheng, 2000) also stated that using land slope and the width of the bench as two starting points, the design proceeds step by step with basic arithmetic that can be easily understood by field workers, land users, or farmers (MINAGRI, 2010).

4. Conceptual framework of the study

Soil erosion remains a critical environmental and socio-economic challenge in Rwanda, particularly in hilly regions like Gicumbi District, Bench terraces, a widely promoted soil conservation measure have emerged as a key intervention for mitigating soil erosion, enhancing agricultural yields, and improving rural livelihoods.

The conceptual framework guiding this research explores the interplay between dependent, independent, and intervening variables influencing the effectiveness of bench terraces. Dependent variables include the erosion control measures implemented, their economic impacts, environmental benefits, and reduced risk behaviors on land use. Independent variables such as topography, rainfall intensity and distribution, terrace design and construction, and soil type and structure significantly affect the performance of terraces. Intervening variables, including government policy and institutional support, socio-economic characteristics, climate change, land tenure systems, and extension services, also mediate these relationships.

Figure 1: Conceptual Framework of the Study



Source: Compiled by the researcher, 2024

5. Methodology of the study

Research cannot carry out a study without the robust methodological approach is crucial for ensuring the legitimacy and genuineness of research results.

5.1 Reserch design

The study employed a descriptive research design combining both quantitative and qualitative approaches to assess the technical and economic impacts of bench terraces in controlling soil erosion within the Green Gicumbi Project area. Quantitative data were gathered through structured questionnaires administered to farmers using bench terraces, while qualitative data were collected via interviews and focus group discussions with farmers, Agricultural Officers, and project staff. This mixed-methods approach allowed for a comprehensive analysis by capturing both statistical evidence and personal experiences related to bench terrace implementation.

5.2 Study area

Gicumbi District, one of five districts in Rwanda's Northern Province, was established by Organic Law No. 29/2005 of 23/12/2005 governing administrative entities. It spans 829 km² and consists of 21 sectors, 109 cells, and 630 villages.

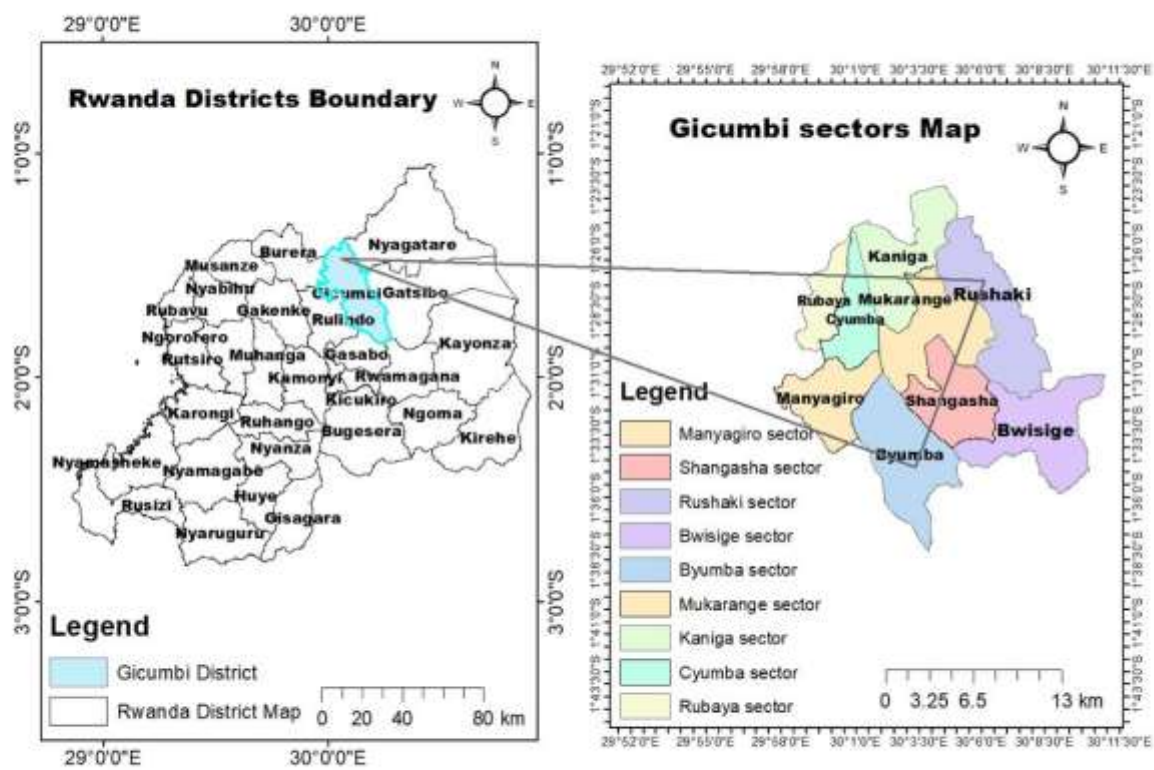
The district lies in the Buberuka highlands at elevations between 1,800 and 2,500 meters. It features steep mountainous slopes, lateritic soils, and receives high rainfall, conditions that make it highly prone to soil erosion. Around 17% of its land is classified as highly susceptible to erosion (Gicumbi District, 2018). However, today soil erosion problem is being alleviated through implementation of soil erosion control measures like bench terracing, excavation of anti-erosion trenches, tree planting among other environment protection mechanisms, Gicumbi is the least susceptible to erosion compared to other districts in Northern Province (MoE, 2020).

The study focused on areas targeted by the Green Gicumbi Project, which includes nine sectors: Bwisige, Byumba, Cyumba, Kaniga, Manyagiro, Mukarange, Rubaya, Rushaki, and Shangasha (Figure 9). These sectors span 322 km² within the hilly terrain of the Buberuka highlands, making them particularly vulnerable to environmental degradation. effective natural resource management is needed in the form of terracing, watershed protection and rehabilitation, wetland protection, and sustainable forest management (Gicumbi District, 2018). The area is home to approximately 44,326 households, with women accounting for 52% of the population and men comprising to 48% (NISR, 2022).

This region is highly exposed to the adverse effects of climate change, including floods and landslides. Its vulnerability is compounded by low adaptive capacity, heavy reliance on rainfed agriculture, limited access to climate information, and declining forest cover (REMA, 2018).

The project was selected for its exemplary implementation of erosion control measures, especially bench terraces. These efforts offer a unique opportunity to evaluate the technical effectiveness and economic impact of such interventions, as well as to engage with experienced farmers. experienced farmers, conduct a comprehensive assessment of the effectiveness and economic impacts of this erosion control technique.

Figure 2: Map of the study area, source: primary data 2025



5.2 Study population

According to Panneerselvam (2005), a study population refers to the total group of people from whom the information is needed. In this study, the population comprised households from nine Green Gicumbi Project intervention sectors within Gicumbi District: Bwisige, Byumba, Cyumba, Kaniga, Manyagiro, Mukarange, Rubaya, Rushaki, and Shangasha, collectively covering 44,326 households (NISR, 2022). These sectors were selected based on their agricultural significance and the extent of bench terrace adoption. The distribution of households is as follows: Bwisige (4,328), Byumba (10,762), Cyumba (4,023), Kaniga (4,003), Manyagiro (5,479), Mukarange (4,431), Rubaya (2,954), Rushaki (3,644), and Shangasha (4,522). This purposive selection provided a representative sample of the district's agricultural population engaged in bench terrace practices, enabling the study to capture diverse experiences and perspectives related to soil erosion control. The study population included households benefiting from bench terraces constructed on agricultural lands, as well as those involved in their implementation, maintenance, and use under the Green Gicumbi Project. This focus ensured the viability of data collection and the relevance of findings to the broader agricultural community of Gicumbi District in assessing the technical efficacy and economic impact of bench terraces for soil erosion control.

Table 1: Distribution of respondents

Institution	Sample Sector	Households	Sample size	Type of sampling
Gicumbi District	Bwisige	4,328	$n = \frac{4{,}328 * 100}{44{,}326} = 10$	Stratified sampling
Gicumbi District	Byumba	10,762	$n = \frac{10{,}762 * 100}{44{,}326} = 24$	Stratified sampling
Gicumbi District	Cyumba	4,203	$n = \frac{4{,}203 * 100}{44{,}326} = 10$	Stratified sampling
Gicumbi District	Kaniga	4,003	$n = \frac{4{,}003 * 100}{44{,}326} = 9$	Stratified sampling
Gicumbi District	Manyagiro	5,479	$n = \frac{5{,}479 * 100}{44{,}326} = 12$	Stratified sampling
Gicumbi District	Mukarange	4,431	$n = \frac{4{,}431 * 100}{44{,}326} = 10$	Stratified sampling
Gicumbi District	Rubaya	2,954	$n = \frac{2{,}954 * 100}{44{,}326} = 7$	Stratified sampling
Gicumbi District	Rushaki	3,644	$n = \frac{3{,}644 * 100}{44{,}326} = 8$	Stratified sampling
Gicumbi District	Shangasha	4,522	$n = \frac{4{,}522 * 100}{44{,}326} = 10$	Stratified sampling
Gicumbi District	Key Informants		9	Purposive Sampling
GGP	Project Agronomist		3	Purposive Sampling
Total population		**44,326**	**112**	

5.3 Instrument of data collection

The study employed a mix of data collection procedures and instruments to assess the technical and economic impacts of bench terraces in soil erosion control. Primary data were collected through questionnaires, interviews, focus group discussions (FGDs), field observations, and GIS-based erosion assessments, while secondary data were sourced from literature, project reports, and institutional records. Structured questionnaires captured quantitative data from 100 farmers, and interviews with 12 participants provided deeper insights. FGDs explored community perceptions, while field measurements and GIS technology assessed terrace effectiveness using RUSLE. Data validity and reliability were ensured through expert reviews, stratified sampling, and pilot testing, with a high Content Validity Index (CVI) of 0.9 confirming instrument accuracy and consistency.

5.4 Data Processing and Analysis

The study followed a structured data processing and analysis approach to ensure clarity, accuracy, and reliability. Raw data were first edited to correct errors and fill gaps, then coded to categorize responses and identify patterns, and finally tabulated for clear presentation. Quantitative data were analyzed using cost-benefit analysis and productivity measurements, while qualitative data from interviews and FGDs enriched the understanding of bench terraces' technical and economic impacts. Ethical considerations were strictly observed, including informed consent, confidentiality, and institutional approval, ensuring respect for participants and integrity throughout the research process.

6. Findings

This section presents and analyzes the demographic and socio-economic profiles of respondents in the Green Gicumbi Project to understand their perspectives on the technical efficacy and economic impacts of bench terraces. The study involved mostly male (65%) and married (86%) respondents, with the majority aged between 46–60 years and having primary-level education (65%). Most were smallholder farmers (83%) with land sizes ranging from under 0.5 to over 2 hectares. The analysis revealed that gender, age, education, marital status, income source, and land size significantly influence the adoption and perception of bench terraces. These factors shape farmers' engagement in soil erosion control, their understanding of bench terrace benefits, and their capacity to invest in and maintain them, highlighting the need for inclusive, tailored interventions in conservation agriculture.

6.1 Evaluation of technical conformity of bench terraces

This study evaluated bench terraces (BTs) constructed in the Green Gicumbi Project areas through a multidisciplinary approach, focusing on technical and socioeconomic aspects to assess their stability and sustainability. Onsite measurements of key parameters such as bench type, width, length, riser height, slope, water availability, and maintenance—were taken to analyze their technical efficacy against FAO standards. Results showed that terraces closely followed contour lines, effectively reducing runoff and soil loss. An inverse relationship was observed between terrain slope and bench width: steeper slopes had narrower benches, while gentler slopes featured wider benches, aligning with recommended design principles. Most sites demonstrated appropriate bench dimensions matching slope gradients, indicating sound, adaptive construction. However, variations in slope, embankment height, and maintenance were noted, impacting terrace stability and overall effectiveness.

Figure 3: Assessment of land use change in Bahimba wetland

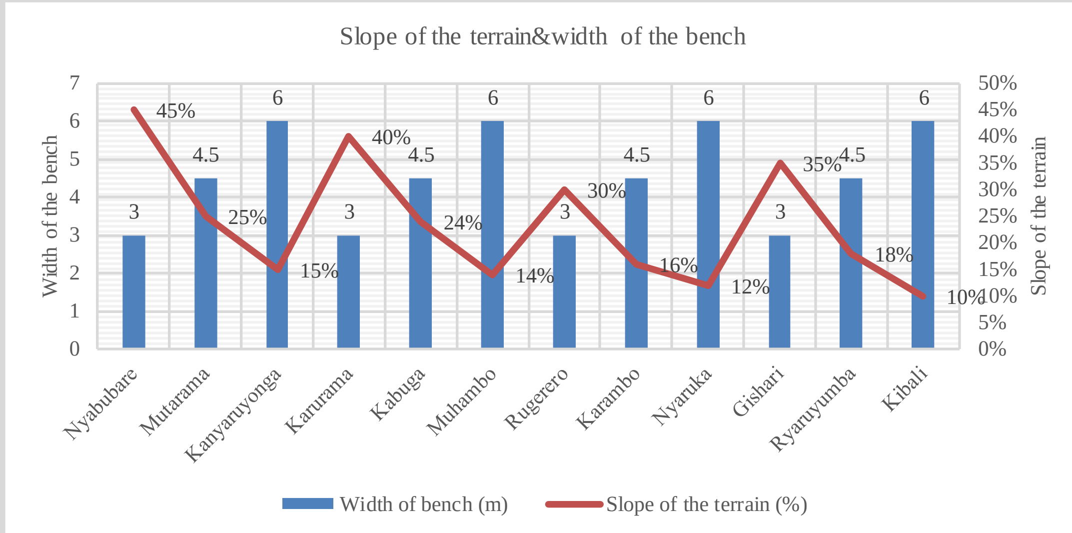


Figure 3 shows that the technical design parameters of bench terraces across twelve Green Gicumbi Project sites generally align well with FAO recommendations, with most measurements falling within acceptable ranges. Vertical intervals (VI) and bench widths closely match the standards, though some sites show slight variations likely due to local slope conditions or construction limitations. Riser heights and slopes vary more widely, with some exceeding typical guidelines, which could increase erosion risks if not properly stabilized. Bed slopes remain gentle and within safe limits to control runoff. Overall, the terraces are technically sound and effective, with minor site-specific adaptations that do not significantly affect their functionality, though steeper risers may require additional stabilization for long-term durability.

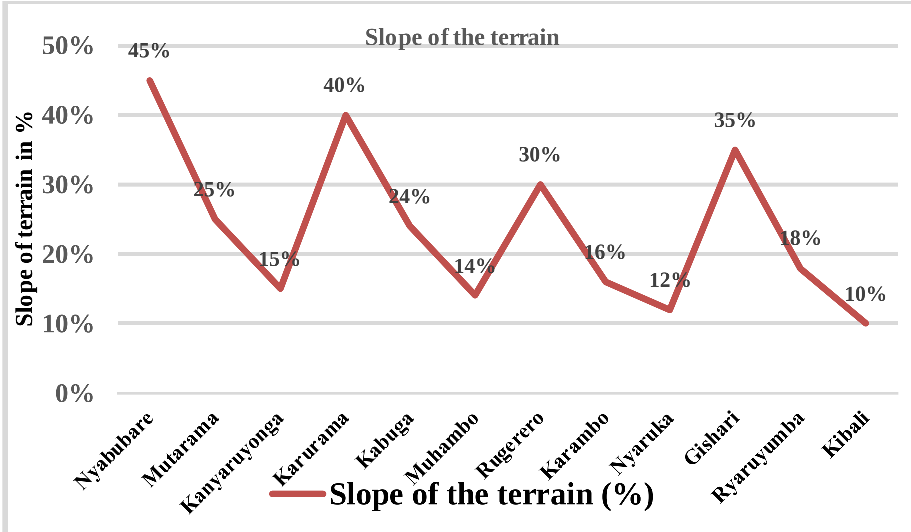
Table 2: Field measured Versus given FAO formulas parameters, researcher 2025

No	Site	Slope of bed (%)	Slope of riser (%)	Height of riser(m)	VI(m)given by FAO formula	VI measured on the field in m	Width(m) given by FAO formula	Width (m) measured on the field
1	Kibali	3.6	65.5	1.6	1.2	1.5	4.0	4.1
2	Nyaruka	3.0	63.1	1.5	1.2	1.4	4.2	4.2
3	Muhambo	3.0	61.0	1.6	1.3	1.6	3.8	4.1
4	Kanyaruyonga	3.2	56.8	2.2	1.1	1.4	2.9	4.2
5	Karambo	3.0	65.5	1.9	1.2	1.6	4.1	3.5
6	Ryaruyumba	4.0	66.1	1.2	1.4	1.3	4.2	4.3
7	Kabuga	3.9	62.1	1.0	1.3	1.2	4.1	4.4
8	Mutarama	4.6	67.8	1.0	1.2	1.1	4.2	4.7
9	Rugerero	3.2	82.8	0.9	0.8	1.3	4.6	4.4
10	Gishari	3.7	89.8	1.0	0.7	1.3	4.9	4.6
11	Karurama	1.6	71.7	1.4	1.4	1.5	4.8	4.5
12	Nyabubare	3.2	75.8	1.7	1.3	1.4	5.0	4.2

According to FAO guidelines, the suitability and design of bench terraces depend heavily on the degree of slope, with general recommendations as follows: From the figure 18 provided, the terrain slopes across the 12 sites range from 10% to 45%, showing a diversity of conditions: Gentle slope sites: Kibali (10%) and Nyaruka (12%) ideal for broad-based terraces that support crop cultivation with minimal erosion risk. Moderate slope sites: Karurama (15%), Muhambo (14%), Karambo (16%), Rugerero (30%), Ryaruyumba (18%) suitable for narrow-based terraces with moderate investment in stabilization. Steep slope sites:Gishari (35%), Kabuga (40%), Kanyaruyonga (25%), Nyabubare (45%) these require strong erosion control measures, such as reinforced risers, drainage channels, and possibly vegetative stabilization.

This distribution confirms that bench terraces were implemented across a wide range of terrain gradients, and according to FAO recommendations, steeper areas demand more technical precision and structural reinforcement to ensure long-term functionality and resistance to erosion. Therefore, the construction of terraces in the Green Gicumbi Project appears to be aligned with FAO best practices, demonstrating both technical feasibility and adaptability to varied topographical conditions.

Figure 4: Slope of the bench terraces site, Primary data 2025



Field observations (Figure 5) and Focus Group Discussions (FGDs) revealed that some farmers, particularly those less familiar with the Green Gicumbi Project interventions, have engaged in the destruction of bench terrace embankments. Driven by the desire to expand cultivable land, these farmers perceive the embankments as occupying potentially productive areas. However, this practice severely compromises the integrity and functionality of the terraces, leading to increased soil erosion, reduced water retention, and eventual land degradation.

This issue was especially prevalent among farmers who had limited participation in terrace construction, maintenance training, or awareness programs. Many of them, including newly resettled farmers and those with minimal exposure to project activities, lacked understanding of the importance of the terraces in promoting sustainable land management.

The findings highlight a critical need for continuous farmer education, regular sensitization campaigns, and strong community-led monitoring efforts. Strengthening the enforcement of land management bylaws is equally essential to safeguard the investments made in soil conservation infrastructure and to ensure the long-term sustainability of bench terraces in enhancing agricultural resilience and combating soil erosion.

Figure 5: Destruction of embankment to increase cultivable area, Primary data,2025

Table 3 shows Pearson correlations between field-measured and FAO-calculated Vertical Interval (VI) and Width for 108 bench terraces in Gicumbi District. There was a moderate, significant correlation between field and FAO widths (r = 0.675), indicating the FAO formula reliably estimates bench width. However, the correlation for Vertical Interval was weaker (r = 0.479), suggesting the FAO formula is less accurate for VI without field verification. These results highlight the value of using both formula-based estimates and field measurements, especially for Vertical Interval, to improve bench terrace design and soil erosion control effectiveness.

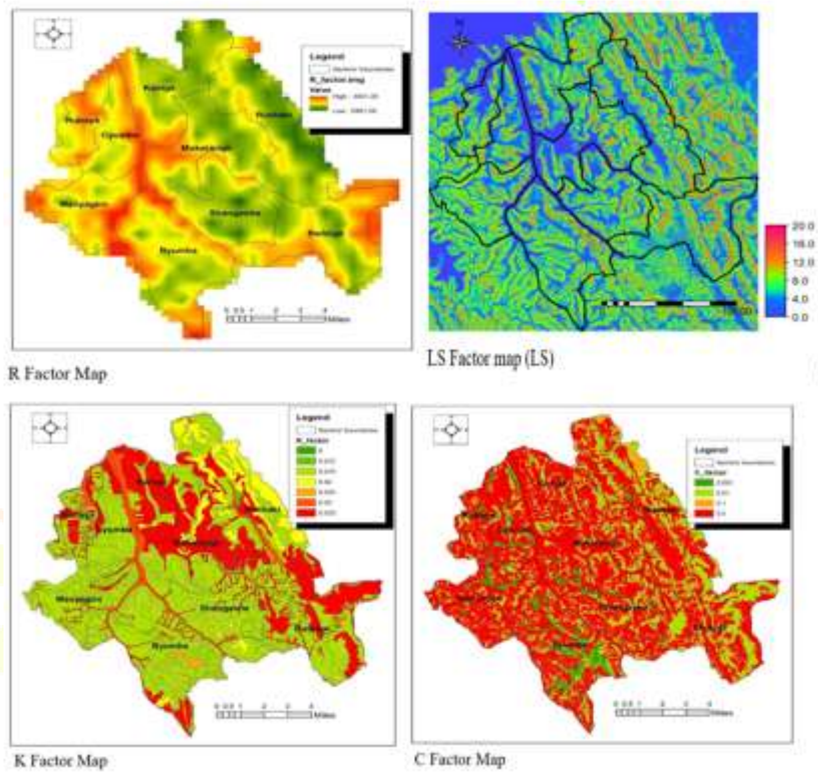
Table 3: Correlations between Parameters

Designation of parameters		**VI-FAO**	**VIF**	**WB-FAO**	**WBF**
VI_FAO	Pearson Correlation	1	.479**	-0.45	-0.2
	Number of terraces	108	108	108	108
VIF	Pearson Correlation	.479**	1	-0.3	0.6
	Number of terraces	108	108	108	108
WB_FAO	Pearson Correlation	-0.45	-0.3	1	.675**
	Number of terraces	108	108	108	108
WBF	Pearson Correlation	-0.2	0.6	.675**	1
	Number of terraces	108	108	108	108

Farmers in the Green Gicumbi Project area have been using bench terraces mainly for 3 to 5 years since the project began in 2019, with some terraces predating the intervention. The terraces have contributed to improved soil quality, including better moisture retention and increased organic matter, though improvements vary depending on maintenance. Soil tests revealed challenges such as acidity and nutrient deficiencies, highlighting the need for organic amendments and liming. While most farmers maintain the terraces due to their value and stability, some remove conservation structures because of the labor-intensive upkeep, high costs, and limited technical skills. Compared to other regions, the project's close collaboration with local authorities and extension services has resulted in higher retention rates of conservation measures. Overall, bench terraces are effective for soil erosion control and productivity improvement, but sustained success depends on ongoing farmer training, financial support, and strategies to reduce maintenance burdens.

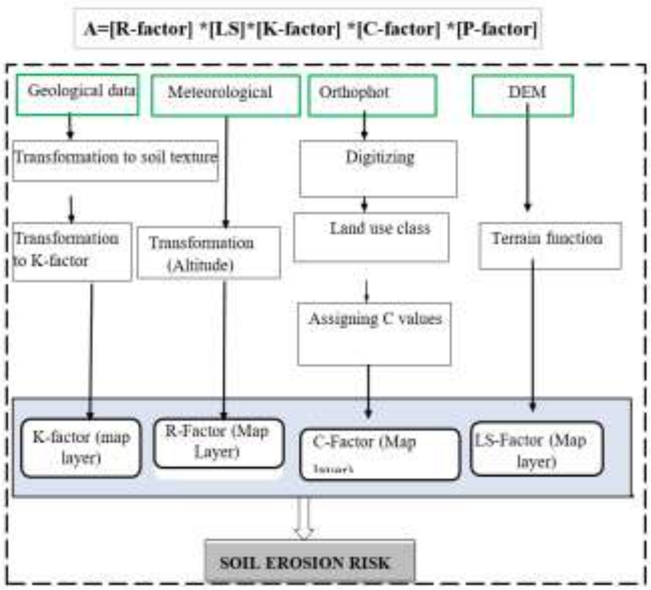
6.2 Evaluation of bench terraces in the soil erosion control in GGP area

Figure 6: Rainfall Erosivity – R; LS; K and C Factor Maps



The evaluation of bench terraces in the Green Gicumbi Project (GGP) area used the Revised Universal Soil Loss Equation (RUSLE) to estimate soil erosion rates post-implementation of land husbandry technologies. RUSLE calculates average annual soil loss (A) based on factors including rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and support practices (P). Each factor was derived from relevant data rainfall, soil type, topography, land cover, and management practices and integrated into GIS software to produce soil loss maps. Rainfall erosivity (R) was estimated using a regression model relating annual rainfall to erosivity; slope factors (LS) were computed via SAGA GIS algorithms applied to elevation data. Soil erodibility (K) was calculated based on soil texture, organic carbon, and other properties using soil maps. Cover management (C) values were assigned based on land use types such as cropland, forest, and grassland, reflecting their effectiveness in preventing erosion. This comprehensive approach enabled spatial assessment of soil erosion control effectiveness of the bench terraces within the GGP area.

Table 7: Conceptual framework of RUSLE Source: from Gitas, et al., 2009



The analysis reveals that extremely high-risk areas are the primary contributors to soil loss, with the highest rates observed in Kaniga (293.1 t/ha), Rubaya (272.3 t/ha), and Rushaki (256.9 t/ha). In contrast, moderate, high, and very high-risk zones exhibit lower and more consistent soil loss values.

Using the RUSLE model, as adapted through the CROM DSS and calibrated with the best available data, the study shows that 58.6% of the total area falls within medium to high-risk categories, with soil loss rates ranging from 16.5 to 293.1 tonnes per hectare per year (see Figure 15). These results underscore the urgent need for targeted erosion control interventions, particularly in the most affected sectors, to combat land degradation and promote sustainable land management.

The findings offer critical guidance for decision-makers to prioritize actions and allocate resources effectively for soil conservation across the study area.

Map 8: Soil loss potential map, Source researcher 2025

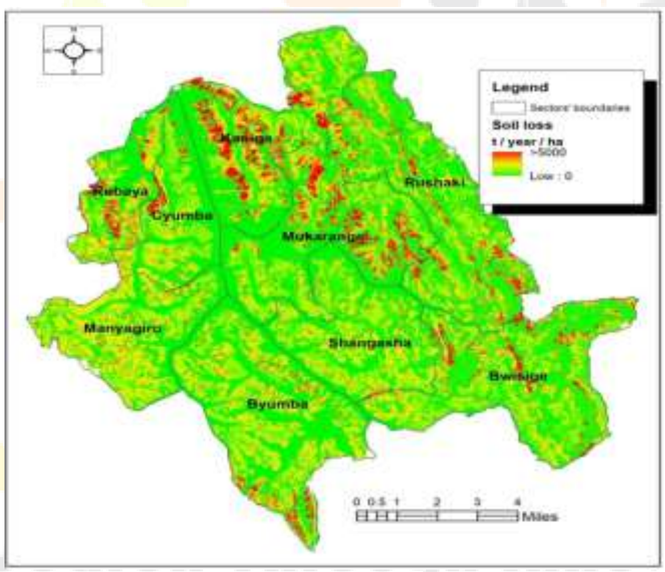
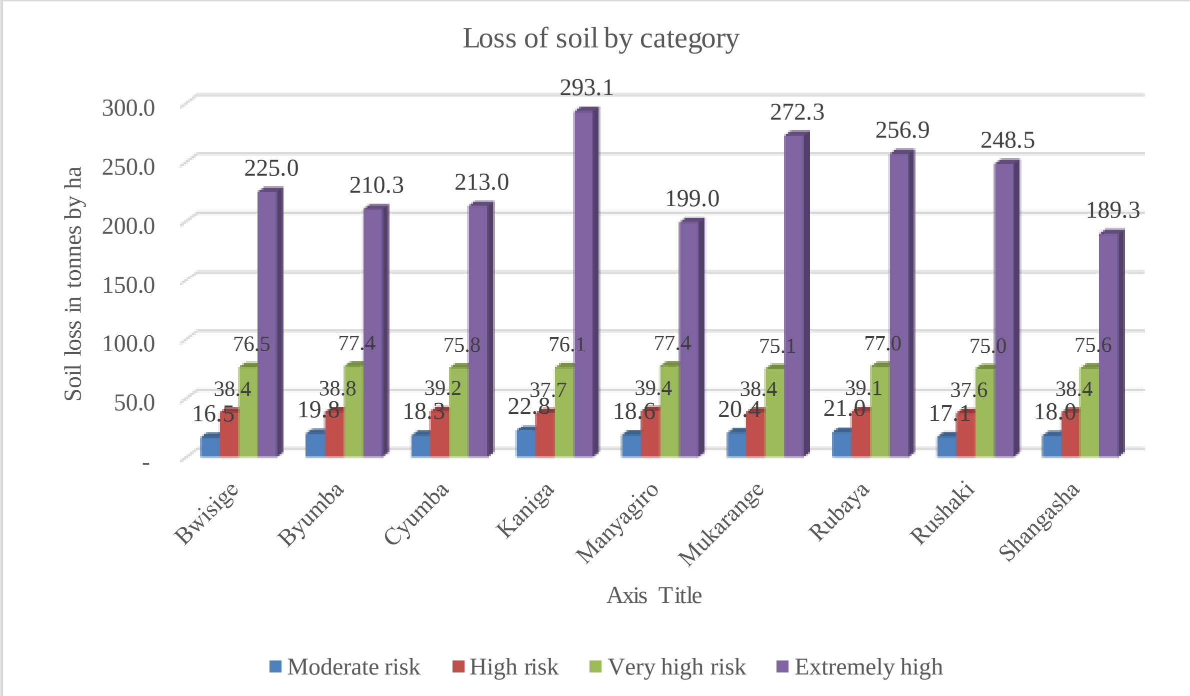


Figure 9: Loss of soil by category of slope



Before adopting bench terraces, farmers widely perceived severe soil erosion on their cultivated lands, especially on steep slopes where gullies were expanding and fertile topsoil was being washed away, leading to declining soil fertility and reduced crop productivity. This perception aligns with studies from Rwanda and other countries like Ethiopia, showing that recognizing erosion as a problem is crucial for adopting conservation measures. However, some farmers underestimated erosion's impact due to gentle slopes or concerns that terraces would reduce land size and increase labor. After bench terraces were introduced, farmers reported a significant reduction or complete cessation of erosion in terraced areas, attributing this to terraces retaining water and stabilizing runoff through waterways and gullies. Experts confirmed terraces' effectiveness in slowing water flow, enhancing infiltration, reducing soil loss, and improving soil structure and resilience against climate change. Survey data showed over half of farmers rated bench terraces as very effective in controlling erosion, with improved crop yields and sustainable land use noted. A small minority viewed terraces as less effective, often due to poor maintenance. Overall, the introduction of bench terraces under the Green Gicumbi Project markedly diminished soil erosion and boosted agricultural productivity.

6.3. Economic benefits and costs of bench terraces

Farmers reported multiple benefits from bench terraces, with 42% noting significant erosion control and soil moisture retention, 35% citing increased crop yields, 13% observing improved soil fertility, and 10% recognizing increased land value, reflecting both agricultural and economic gains. However, farmers also identified major costs, including high initial construction expenses (46%), costly maintenance (30%), labor intensity (18%), and reduced cultivable land (6%), highlighting economic trade-offs in adoption. Labor and material costs were the primary expenses, followed by time investment and maintenance. Focus group discussions revealed that most farmers experienced improved crop productivity due to better soil conservation and moisture, with some reporting substantial harvest increases, such as a farmer harvesting 12 tons of Irish potatoes after terrace installation. Nonetheless, some farmers faced challenges like poor maintenance and design flaws, which limited benefits. Beyond yield improvements, terraces reduced fertilizer needs, enhanced soil fertility, increased land value, and supported crop diversification, contributing to greater food security and income. An economic evaluation over two years showed promising yields for maize and beans, aligning with regional productivity standards when proper agricultural practices are applied. Overall, bench terraces offer significant agronomic and socio-economic advantages but require quality construction, ongoing maintenance, and technical support to sustain long-term benefits.

Table 4: Economic evaluation for selected crops Source: Primary data 2025

S/N	Description Cost Category	Unit	Qty	Unit Cost	Total Cost
1	**Initial investment Costs**				**1,609,460**
	Site Clearing	ha	1	6,000	6,000
	Topographic works	ha	1	25,000	25,000
	Terracing works	ha	1	1,000,000	1,000,000
	Cut off drains	m	220	250	55,000
	Manmade waterways	m	180	250	45,000
	Lining of Drainage systems,	m	400	250	100,000
	Construction of check dams	pce	30	2,500	75,000
	Embankment protection by pennisetum sp	ha	1	80,000	80,000
	Supply and planting shrubs	Seedling	767	50	38,350
	Supply and planting agroforestry	Seedling	383	50	19,150

S/N	Description Cost Category	Unit	Qty	Unit Cost	Total Cost
	supervision	ha	1	165,960	165,960
2	**Operation costs**				**4,605,000**
	Supply and application of lime	tone	10	55,000	550,000
	Supply and application of compost	tone	20	50,000	1,000,000
	Seeds maize for two seasons		50	2,000	100,000
	Seeds beans for two seasons		90	2,000	180,000
	Pesticides 10% of investment cost for two years		2	138,600	277,200
	Drying costs for 4 seasons		4	207,900	831,600
	Tillage per season (First and second)		4	207,900	831,600
	Planting		4	69,300	277,200
	Maintenance for 4 seasons		4	138,600	554,400
	Harvesting material for 4 seasons		5	600	3,000
3	**Total Costs**				**6,214,460**
4	**Total Revenue from Crop Yield (Over 2 Years)**				**9,790,000**
No	**Description Cost Category**	**Unit**	**Qty**	**Unit Cost**	**Total Cost**
	Crop yield productivity of maize in 2 seasons	kg	8,800	550	4,840,000
	Crop yield productivity of beans in 2 seasons	kg	6,600	750	4,950,000
5	**Summary of financial indicators**				
	Benefit Cost Ratio (BCR) Total Returns ÷ Total Costs				1.58
	Return on Investment (ROI)(Net Profit ÷ Total Cost) × 100				58%
	Net present value by considering discount rate of 10%				1,876,449
	Internal rate of return				25.49%

The economic analysis of bench terraces for soil erosion control and agricultural productivity demonstrates clear financial benefits despite substantial initial and operational costs. The project required an initial investment of about 1.6 million RWF for site preparation, terracing, and planting, with operational expenses totaling over 4.6 million RWF over two years. Revenue generated from maize and beans production reached nearly 9.8 million RWF, yielding a Benefit-Cost Ratio (BCR) of 1.58, a Return on Investment (ROI) of 58%, a positive Net Present Value (NPV) of approximately 1.9 million RWF, and a strong Internal Rate of Return (IRR) of 25.49%, indicating that bench terraces are a cost-effective and profitable agricultural intervention.

Crop yields increased notably due to the project, with maize rising from 3.5 to 4.4 tons per hectare and beans from 2.7 to 3.3 tons per hectare, alongside improvements in Irish potatoes and wheat. Farmers attributed these gains to enhanced soil moisture retention, reduced erosion, and better soil fertility. However, challenges such as labor-intensive maintenance, high costs, and the need for technical knowledge were highlighted. Women, in particular, spend significant time maintaining terraces, which can affect their engagement in other income-generating activities. Participation in decision-making varied among farmers, with those more involved showing greater commitment to terrace upkeep.

Overall, bench terraces are perceived as an effective soil conservation practice with substantial agronomic and economic benefits, including increased land value, reduced fertilizer use, and improved food security. Nevertheless, the sustainability of these benefits depends heavily on addressing maintenance challenges through financial support, technical training, and stronger community involvement. The study underscores the need for participatory approaches and targeted support to ensure long-term adoption and maximize the positive impact of bench terraces on sustainable agriculture and land management.

7. Conclusion

Soil erosion poses a significant challenge to Rwanda's agricultural productivity, food security, and environmental sustainability. The Government of Rwanda (GoR) has prioritized soil conservation, implementing bench terraces to rehabilitate degraded land, enhance food security, and improve farmers' livelihoods. This study evaluates the technical efficiency and economic viability of bench terraces in Gicumbi District.

Findings indicate that while bench terraces have reduced erosion and improved soil fertility, construction quality and maintenance remain critical concerns. In several locations, terraces exceeded recommended slope limits (10.7%), with risers often surpassing the 1.8–2.0 m threshold, increasing the risk of collapse. Some farmers altered risers to expand cultivated land, further destabilizing structures. While all 12 study sites had waterways and cut-off drains, check dams were often improperly constructed, heightening erosion risks.

Economically, the study reveals that bench terraces can be financially viable, achieving a break-even point in the second year with a benefit-cost ratio of 1.58. Farmers ranked fodder production and soil erosion control as the primary benefits, using harvested fodder for livestock or sale. Improved soil moisture retention and higher crop yields were also noted, reducing drought-related losses.

Despite these benefits, adoption and maintenance challenges persist. Farmers with larger plots are more likely to maintain terraces, while those engaged in off-farm activities show lower commitment. Addressing construction defects, strengthening technical supervision, and promoting proper maintenance practices will be essential for sustaining the benefits of bench terraces in soil conservation and agricultural productivity.

8. Recommendations

The recommendations emphasize the important role of bench terraces in controlling soil erosion and improving agricultural productivity in Gicumbi District and Rwanda at large. For the Government of Rwanda, it is advised to promote collaborative, participatory approaches involving farmers and experts to increase adoption of soil conservation techniques, respecting local knowledge and ensuring continuous sensitization. Additionally, the government should enhance technical supervision during terrace construction and maintenance, ensuring adherence to standards, and extend monitoring efforts over several years to guarantee long-term success.

For the Green Gicumbi Project and Gicumbi District authorities, the recommendations focus on expanding the adoption of bench terraces where they are not yet implemented, continuing community training especially targeting youth, and promoting sustainable energy use to prevent damage to conservation structures. Financial support mechanisms like facilitating access to bank loans for inputs are suggested to help farmers maintain terraces effectively and boost productivity. Continuous sensitization and support are highlighted as key to sustaining the terraces' benefits for soil erosion control and economic gains.

Further research is encouraged to evaluate the effectiveness of bench terraces nationwide and to investigate their role in soil erosion control more broadly. Expanding studies to cover all sectors in Gicumbi District with an emphasis on farmers' capacity for investment in terrace adoption and maintenance would provide valuable insights to scale up successful interventions. These recommendations aim to strengthen technical, financial, and participatory frameworks to ensure the long-term sustainability of bench terraces.

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