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Evaluating the Effectiveness and Adoptability of Mulching Technology to Control Soil Erosion: Case Study of the Nyabugogo Catchment in Rwanda.

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abstract

This research examines mulching as an effective soil erosion control measure in the Nyabugogo catchment of Rwanda. To assess soil erosion causes, effects, and control, this study made use of literature reviews, interviews, and on-site visits. Findings based on the responses of 96 farmers revealed that intense rainfall (32.4%), soil type (31.7%), and steep slopes (30.7%) are the major contributors to soil erosion, while other factors were found to have a minimal influence of 5.2%. Mulching materials are sourced from crop and vegetative residues and differ in various geographical locations. By using the Universal Soil Erosion Equation (USLE) model to simulate the suggested Soil Erosion Control Measures (SECM), the study observed a significant reduction in soil loss from 35.86 t/ha/y to 17.84 t/ha/y. The use of mulching technology further decreased soil erosion rates to permissible levels, reducing the rate from 17.84 t/ha/y to 9.83 t/ha/y. Based on the results, the study recommends the implementation of the site-specific SECM combined with mulching, drainage channels, and stabilizing grasses on the same farmland to effectively reduce soil erosion to acceptable levels within the Nyabugogo drainage area. The study advocates soil erosion control measures as the optimal choice for enhancing soil productivity while minimizing sedimentation in downstream rivers and lakes.

Introduction

Soil erosion is a critical environmental issue that affects agricultural productivity and ecological balance worldwide (Pimentel and Burgess, 2013; Molla and Sisheber, 2017).

Among different SECM, mulching technology has emerged as a promising tool for controlling soil erosion and maintaining soil health. In practice, mulching involves the application of various materials, such as crop residues, plastic films, or biodegradable covers, to shield the soil from raindrop impact, reduce water runoff, and enhance moisture retention (Issaka and Ashraf, 2017; Iqbal et al., 2020; Mgolozeli et al., 2020; El-Beltagi et al., 2022).

In Rwanda, soil erosion is primarily due to its hilly terrain, high population density, and intense agricultural practices (RWB, 2022). Approximately 70% of Rwanda's population relies on agriculture for their livelihoods, leading to extensive land cultivation on steep slopes, making the soil vulnerable to erosion during heavy rainfall (RWB, 2022). Soil erosion is a pervasive issue in Rwanda, where it is exacerbated by deforestation, overgrazing, unsustainable land use practices, and climate variability (Karamage et al., 2016).

Located in a region highly susceptible to erosion due to its hilly terrain and heavy rainfall, Nyabugogo catchment is characterized by diverse agricultural practices and a reliance on subsistence farming (REMA, 2018).

This study aims to comprehensively assess the performance and adoptability of mulching technology as a strategy to control soil erosion within the Nyabugogo catchment in Rwanda.

Furthermore, this research endeavors to explore the perceptions, attitudes, and constraints of local farmers regarding the adoption of mulching techniques.

Data and methodology

Study area representation

The Nyabugogo catchment area (1661 km^2) overlaps on the Central, Eastern, And Northern Provinces of Rwanda. It accounts for 6.31% of the country's total area (Figure 1). It is a rural, densely populated area marked by urbanization, featuring flat clay soils in the central region and valley bottom, causing poor infiltration. The climate mirrors Rwanda's temperate tropical pattern with annual rainfall ranging from 992 mm to 1128 mm, temperatures averaging 19 to 21◦C, distinct rainy seasons from September to December, and a peak from March to early May. Fed by various rivers, the Nyabugogo River runs 45.97 km from Lake Muhazi to its convergence with the lower Nyabarongo River. Agriculture, fishing, and forestry are the primary economic activities in the catchment.

Sampling procedures and sample size definition

They aimed to gather direct insights from farmers regarding their perspectives on the causes of soil erosion, its impacts, and their practices related to preventing soil degradation in the Nyabugogo drainage area. A sample of 96 participants was meticulously chosen to be interviewed using a systematic random selection process with a reliability level of 95%, a variability of 0.5 degrees, and a 10% permissible error while using the Cochran formula (Neilson, 2011) as shown in Equation (1).

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Equation (1).

$$n = \frac{z^2 \hat{p}\hat{q}}{e^2} = \frac{(1.96)^2(0.50)(0.50)}{(0.10)^2} = 96 \text{ farmers}$$

Eq.1

Data gathering

The study utilized various methodologies, including literature reviews, government reports, and extensive fieldwork. Field visits involved the use of the Global Positioning System (GPS) for mapping the topographic and socio-economic aspects, alongside detailed observations of soil conditions, land use patterns, hydrographic network analysis, crop assessments, and the examination of the existing Soil Erosion Control Measures (SECM).

Furthermore, the study incorporated interviews and focus group discussions with local farmers to understand their perceptions, knowledge, and willingness to adopt mulching technology. Rainfall, Digital Elevation Model (DEM) data, and shapefiles (soil texture and administrative boundary) were obtained from the University of Rwanda's Center of the Geographic Information System (UR-CGIS) and from the Rwanda Water Resources Board (RWB) to create topographic and soil texture maps. In addition, the shapefiles obtained from RWB contained various additional data such as "existing soil erosion control measures together with the distribution of soil erosion rates at the national scale and site-specific recommended soil erosion control measures required in unprotected areas" to create soil erosion and soil erosion control practices maps.

The USLE model, with its specific parameters shown in Equation (2)., was employed to estimate soil erosion rates, contributing to a comprehensive assessment of mulching technology's effectiveness and potential adoption in soil erosion control within the Nyabugogo catchment.

$$A = R \times K \times LS \times C \times P \qquad \text{Eq.2}$$

Where:

A(t/ha*y) is the average annual soil loss; K(ton*ha*h/ha*MJ*mm) is the soil erodibility or K-factor; R(MJ*mm/ha*h*y) is the rainfall erosivity or R-factor; LS(Dimensionless) is the slope length factor or LS- factor; C(Dimensionless) is the crop management factor or C-factor and P(Dimensionless) is the erosion-control practice factor or P-factor.

Step1: Using Equation (3) as proposed by Hassan (2011), the rainfall erosivity in the Nyabugogo drainage area, with an annual mean rainfall of 1064.47mm (IWRM, 2018) is approximately 486 MJ x mm/h/y.

$$R = 81.50 + 0.38\overline{P} \qquad \text{Eq.3}$$

Step2: The minimum and maximum K-factors associated to various soil types are 0.03 and 0.3 (Oruk et al., 2012) with an average of 0.14.

Step3: Using Equation (4) with GIS applications (Ganasri & Ramesh, 2016, the calculated steepness (LS) factor, is approximately 21.8 (unitless). In the Equation (4), As denotes the upstream area, β the slope angle, and coefficients "m" and "n".

$$LS = \left(\frac{A_s}{22.13}\right)^m \times \left(\frac{\sin\beta}{0.0896}\right)^n \qquad \text{Eq.4}$$

Step 4: The P and C factors typically vary from 0 to 1, where 0 indicates no erosion control, and 1 signifies complete erosion control. On the other hand, 0 for the C-factor signifies that there is no vegetative cover while 1 signifies that there is vegetative cover. Table 1 provides a compilation of typical crop cover (C) and control practices (P) factors values for different SECM aiming at mitigating extreme soil loss amounts within the Nyabugogo drainage area and adopted from different researchers (Kuok et al., 2013; Panagos et al., 2015; Basnyat et al., 2020; Endalamaw et al., 2021).

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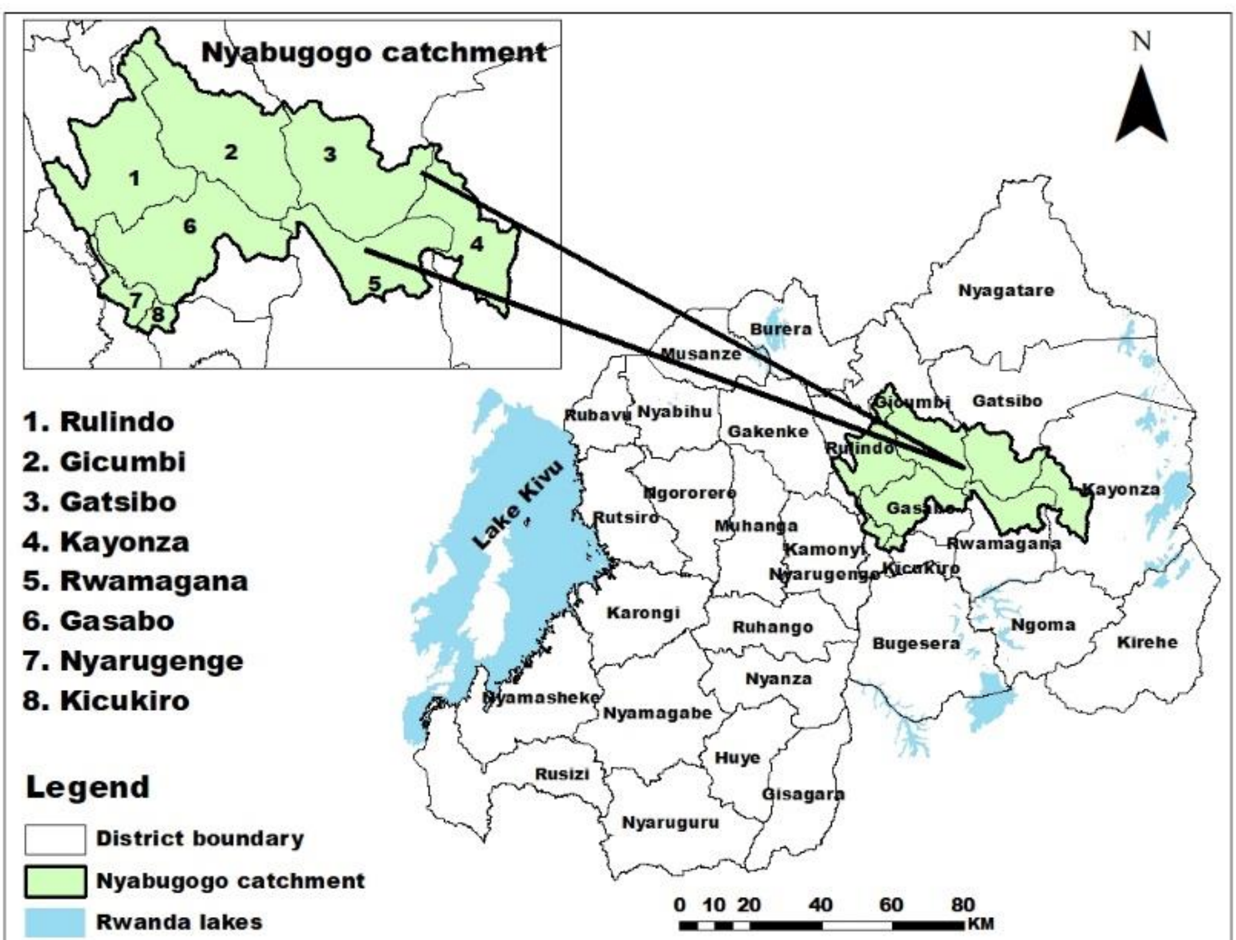

Figure 1: Location of the study areas

Data interpretation

The research extensively examined indicators, causes, and consequences of soil erosion, utilizing diverse data sources and tools such as shapefiles from the Rwanda Water Resources Board and the USLE-type model to evaluate the effectiveness of the suggested Soil Erosion Control Measures (SECM) in the Nyabugogo drainage area. ArcGIS and Excel tools were employed for data analysis, including mapping and tabulation.

Results

Farmers' socioeconomic characteristics

Table 2 summarizes the qualitative findings from analyzing various socioeconomic traits of 96 farmers in the Nyabugogo catchment using SPSS. It covers gender, age, marital status, education level, residence distance, farm size, fertilizer types, and satisfaction with agricultural income. The frequency distribution reveals demographic compositions and farming practices. For instance, male respondents accounted for 47% compared to 51% of female farmers. The 28-37 age group represented 30.2%, with 94.8% being married and 66.7% having primary education. Most farmers had small plots (≤1.0 hectares, 92.9%) and used organic/compost manure with industrial fertilizers (95.8%). Notably, 57.3% expressed dissatisfaction with their agricultural income. Table 2 provides a comprehensive view of socioeconomic and agricultural aspects in the Nyabugogo catchment, offering insights for targeted interventions and policy-making to address local farming community needs and challenges.

Table 1. Different SECM with their typical values of C and P from literature

Suggested SECM	C	P
Afforestation	0.020	0.001
Agroforestry	0.080	0.500
Bamboo to close gullies	0.010	0.500
Bench terraces	0.150	0.128
Contour bank terraces	0.150	0.150
Contour banks	0.500	0.600
Grassed channels	0.200	0.100
Hedgerows	0.200	0.000
No-till	0.250	0.100
Perennial crops	0.230	0.800
Reforestation	0.020	0.001
River side bamboo	0.010	0.500
Silvopastoralism	0.090	0.000
Rainwater reservoirs	0.000	0.800
Drainage waterways	0.580	0.800
Forestry	0.000	0.000

Table 2. The qualitative outcomes derived from the analysis of various socioeconomic traits of farmers within the Nyabugogo catchment area (n = 96) using SPSS software

Attribute (variables)	Frequency	Attribute (variables)	Frequency
1. Gender		5. Distance from residence	
Male	45(47.0%)	Less than 10 min walk	21(21.9%)
Female	51(53.0%)	Between 10-30 min walk	53(55.2%)
2. Age		Greater than 30 min walk	22(22.9%)
18-27	11(11.5%)	6. Total farm land size	
28-37	29(30.2%)	<=1.0ha	89(92.9%)
38-47	28(29.2%)	>1.0ha	7(7.3%)
48-57	11(11.5%)	6. Types of fertilizer	
>57	17(17.7%)	Organic or compost manure (O)	3(3.1%)
3. Marital status		Industrial fertilizers (I)	0(0.0%)
Married	91(94.8%)	Both fertilizers (O and I)	92(95.8%)
Single	4(4.2%)	No fertilizers use	1(1.0%)
Divorced	1(1.0%)	7. Satisfaction of net income from agriculture	
Widowed	0(0.0%)	No	55(57.3%)
4. Education		Yes	41(42.7%)
Illiterate	26(27.1%)		
Primary education	64(66.7%)		
Secondary education	4(4.2%)		
University education	2(2.1%)		

Based on the outcomes from the interview and data illustrated in Table 3, this study demonstrated that the overall income per household (in kilograms) from sorghum, maize, beans, soybeans, and banana fell within the ranges of 0 to 1000, 0 to 5000, 0 to 700, 0 to 80, and 0 to 400, respectively. The average values were respectively 37.20, 352.36, 60.26, 1.15, and 5.94 kilograms per household seasonally. In addition, this research quantitatively highlighted the variation in the number of domestic animals per household, ranging from 0 to 10 cows, 0 to 4 pigs, 0 to 12 goats, 0 to 4 sheep, 0 to 6 chickens, and 0 to 10 rabbits.

On the average scale, each household in the Nyabugogo catchment area possesses approximately 0.83 cows, 0.30 pigs, 1.26 goats, 0.06 sheep, 0.51 chickens, and 0.17 rabbits.

The quantitative data and statistical analysis outcomes were gathered by the researchers and represented in Table 3.

Table 3: The numerical findings concerning diverse socioeconomic attributes of farmers within the Nyabugogo catchment area (n = 96), analyzed utilizing SPSS software

Parameter	Minimum	Maximum	Mean	Std. Deviation
Income from sorghum per household (kg/season)	.00	1000.00	37.198	153.282
Income from maize per household (kg/season)	.00	5000.00	352.365	550.357
Income from beans per household (kg/season)	.00	700.00	60.260	145.545
Income from soybeans per household (kg/season)	.00	80.00	1.146	8.444
Income from banana per household (kg/season)	.00	400.00	5.937	43.469
Number of cows per household	.00	10.00	.833	1.652
Number of pigs per household	.00	4.00	.302	.796
Number of goats per household	.00	12.00	1.260	2.502
Number of sheep per household	.00	4.00	.063	.455
Number of chickens per household	.00	6.00	.510	1.361
Number of rabbits per household	.00	10.00	.167	1.073

Farmers' perceptions on soil erosion in the Nyabugogo catchment

Analysis of the questionnaire

1. What are the tangible indicators of soil erosion in the drainage area?

Soil erosion can be identified by a range of indicators, from initial signs such as splash erosion caused by raindrops to more severe outcomes like gully formation, landslides, and river sedimentation. Remarkably, the most significant contributors to soil erosion include the decreasing productivity of land (26.2%), gully formation (25.9%), and landslides (25.0%), highlighting their significant prevalence in the erosion context. Other indicators such as reduced soil depth (5.9%) and river sedimentation (6.2%) also have noteworthy impacts, illustrating the diverse and impactful nature of soil erosion across landscapes. This distribution emphasizes the complex challenges presented by erosion, encompassing both immediate surface changes and far-reaching environmental transformations, which affect ecosystems and agricultural productivity. Similarly, Biratu and Asmamaw (2016) stated that 93.1% of participants acknowledged an extreme soil impairment in their farmlands.

2. What are the primary causes of soil erosion in the Nyabugogo drainage area?

The causes of soil erosion are complex and can arise from a range of natural and human factors. Natural factors like the slope of the terrain (25.7%) and rainfall coupled with runoff (28.5%) emerge as predominant natural influential factors of soil erosion. Several studies have identified these factors as the primary causes of soil erosion (Belay and Mengistu, 2019); Leta and Megersa, 2021), while (Shit et al., 2015) confirmed that heavy rainfall and steep slopes were the primary and secondary causes of soil erosion, respectively. Additionally, the scarcity of land for farming and settlements is a significant factor contributing to the deforestation in the Nyabugogo drainage area (IWRM, 2017). Human activities, including building and road construction, mining, and non-agricultural uses account for 40.5%.

3. What are various factors influencing soil erosion in the Nyabugogo catchment?

Figure 2 illustrates the primary influential factors on soil erosion: rainfall at 32.4%, soil type at 31.7%, and steep slopes at 30.7%. In addition, human-induced factors (deforestation, lack of erosion control, continuous cultivation) collectively contribute at 5.1% to soil erosion. The inventory of these diverse drivers of soil erosion emphasizes the need for the implementation of SECM to mitigate soil erosion and protect land productivity.

4. What kind of Best Management Practices (BMPs) of erosion control do you have in your farmland?

This study aims to identify the existing SECM in the Nyabugogo farmlands. Among the agricultural technologies, the use of compost fertilizers (24.2%) and industrial fertilizers (23.2%) is the most common practice that appears as the firstly appreciable agricultural practice. Mulching (23.4%) is considered as the primary method of controlling soil because it helps in soil enrichment and conservation. Field runoff prevention is also crucial by using diversion ditches (20.3%). Afforestation (2.3%), contour bunds (1.3%), and grass-lined channels (1.6%) represent other existing soil erosion control techniques in the Nyabugogo catchment, while contour tillage, terraces, and roof runoff and cisterns collectively account 5.7%.

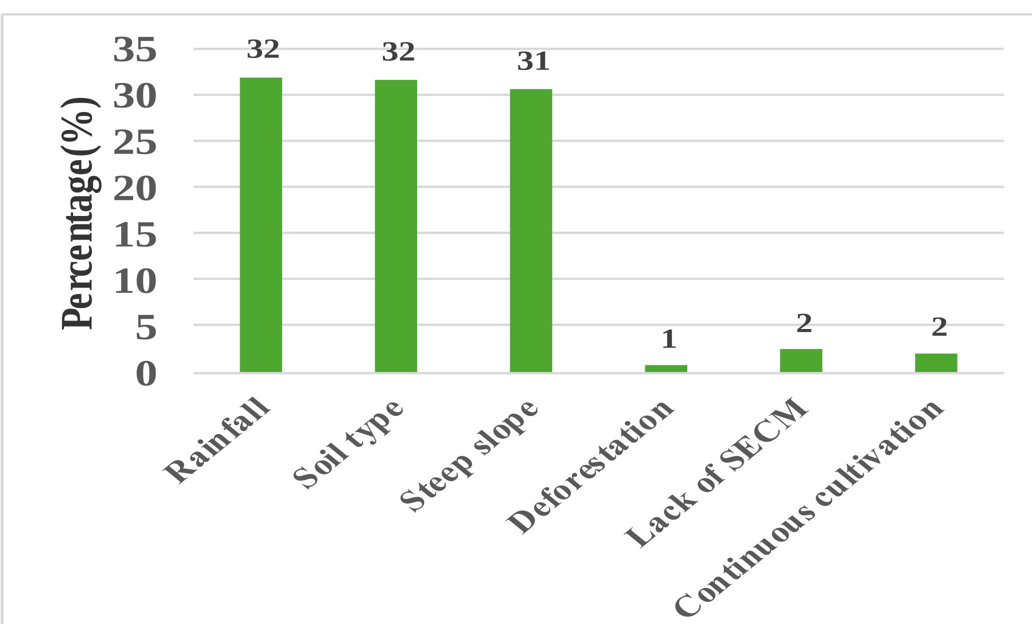

Figure 2. Various factors influencing soil erosion in the Nyabugogo catchment

5. Do you plan to implement sufficient SECM in your farmland?

The Nyabugogo catchment area has implemented various measures to control erosion. However, there is a need to implement additional SECM to reduce soil erosion to tolerable soil loss rates. Particularly, 13.5% of farmers confirm their willingness to plant additional trees, 14.7% and 14.9% for the use of compost and industrial fertilizers respectively, 14.9% for mulching, 14.6% for anti-erosive ditches, 12.2% for agroforestry, 12.5% for grass-lined channels. This farmers' willingness stands as a holistic approach toward soil erosion prevention and land conservation within the catchment area. The limited use of certain technologies, such as bench terraces, check dams, hillside water tanks, retaining walls, and sediment basins, is due to their high cost, making them unaffordable by individual farmers.

6. For which purpose farmlands are mulched?

Mulches play a crucial role in agriculture by serving various important purposes. (Figure 3). They are particularly effective in conserving soil moisture (20.5%), which helps to maintain optimal soil moisture levels. Mulches also help in preventing soil erosion (19.9%) and contribute significantly to soil stability. In addition, they protect the farmland from the excessive heat from the sun heat (20.1%) and increase organic matter in the soil (20.1%). By acting as a barrier against wild weed growth (19.4%), mulches support efficient crop management. These versatile functions address multiple agricultural needs such as moisture regulation, erosion prevention, soil enrichment, temperature moderation, and weed control, making them a valuable agricultural practice.

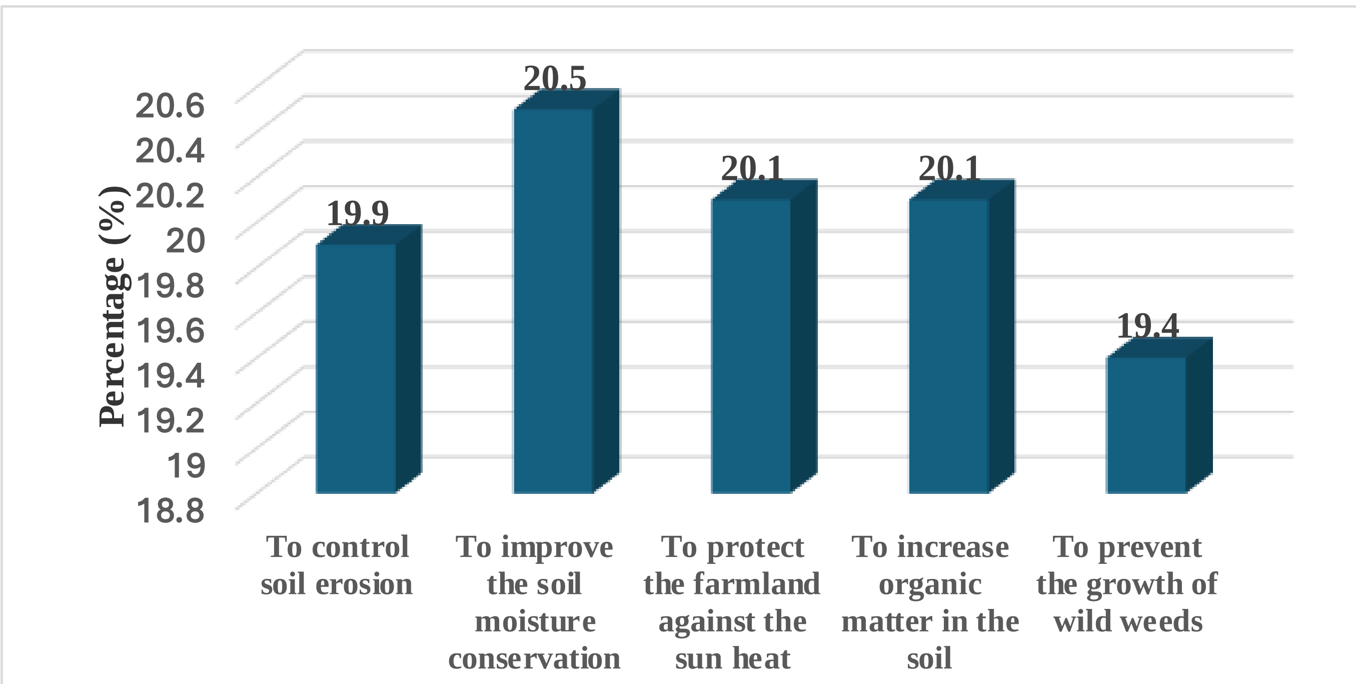

Figure 3. Various purposes of mulching

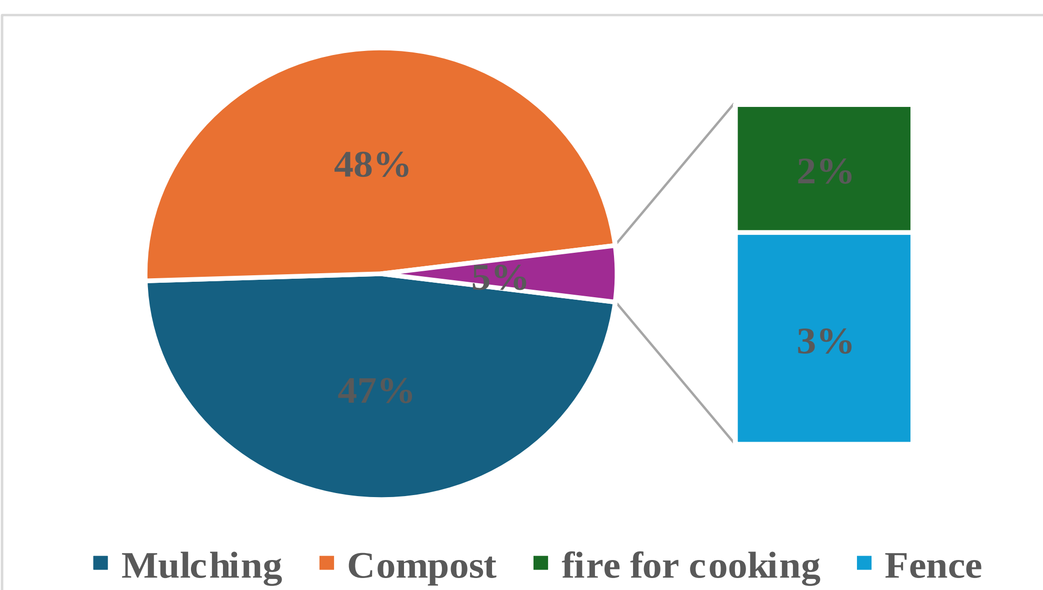

Figure 4. Various uses of crop residues

7. Indicate various uses of crop residues from your farmland
It is worth noting that crop residues have two main uses: mulching (47.5%) and composting (48.5%) as shown in Figure 4. Mulching is the practice of using crop residues to conserve soil and retain moisture, which helps to maintain soil health and regulate moisture levels. Composting, on the other hand, involves using a high percentage of crop residues to improve soil fertility and increase organic matter content, which in turn enhances soil structure and nutrient availability. A small portion of crop residues is utilized as a cooking fuel (1.5%), while another small fraction is utilized as fencing (2.5%), indicating their limited utilization beyond agriculture (Figure 4).

8. What are the main use of the vegetative residues from your farmland?
Farmers in the Nyabugogo catchment predominantly use vegetative residues for two purposes: mulching (47.5%) and composting (47.5%) as shown in Figure 5. A small portion of vegetative residues is utilized for cooking fuel (2.0%) and animal feed (3.0%), expending the range of uses beyond agriculture.

Actual soil loss rates in the Nyabugogo catchment
By utilizing various shapefiles obtained from the Rwanda Water Resources Board, Figure 6 illustrates various existing SECM and the induced soil erosion rates within the Nyabugogo catchment. Ultimately, Table 4 shows that the annual soil loss from the Nyabugogo catchment is approximately 35.86 t/ha/y.

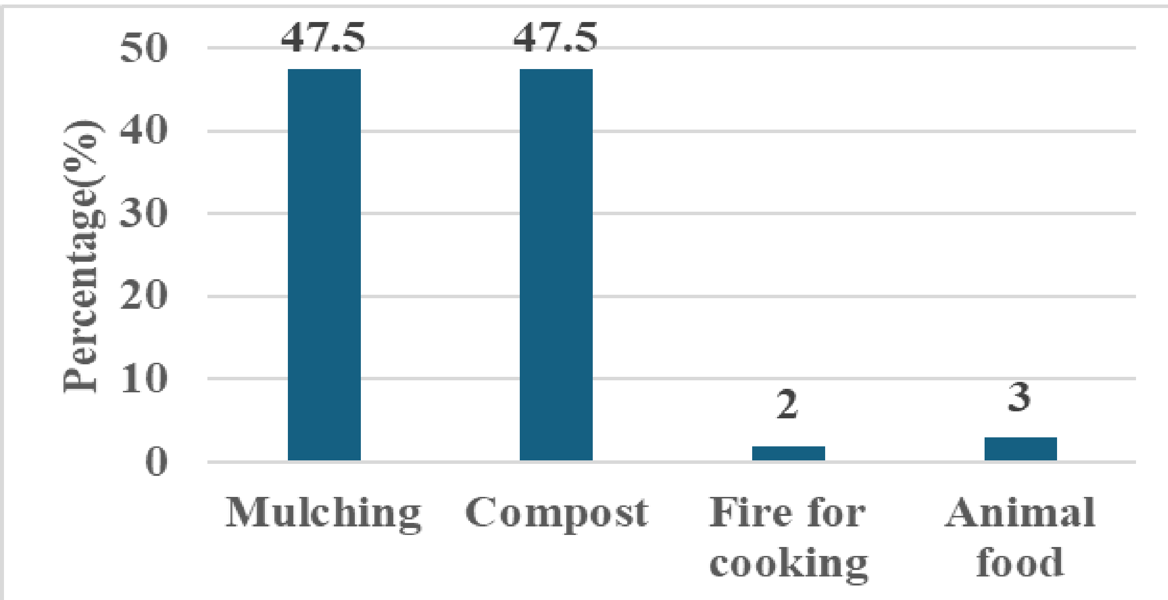

Figure 5. Various uses of vegetative residues

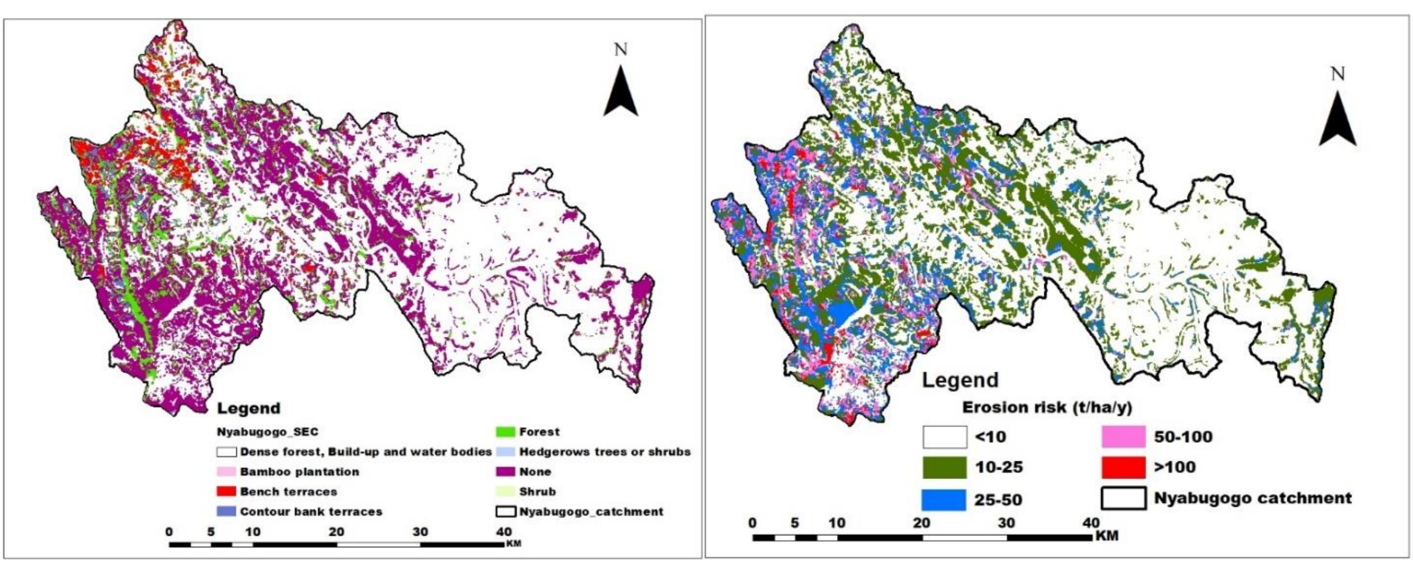

Figure 6. Current SECM and the induced soil loss rates within the Nyabugogo catchment area.

Table 4. Current SECM and their induced soil erosion rates from the Nyabugogo catchment

(a) Existing SEC			**(b) calculation of the actual soil loss**				
Existing SECM	Area covered (ha)	%	Erosion risk Ai(t/ha/y)	Peak value Ai(t/ha/y)	Coverage (ai)	(%)	Weighted value (Ai*ai)
Bamboo plantation	1.9	0.001	<10	10	91523	55	915230
Bench terraces	4141.0	2.493	,10-25	25	42265	25	1056625
Contour bank terraces	2267.9	1.365	25-50	50	18860	11	943000
Forest	14120.5	8.499	50-100	100	10099	6	1009900
Hedgerows trees or shrubs	26.6	0.016	>100	600	3389	2	2033400
None	54013.1	32.511			166136	100	5958155
Shrubs	41.9	0.025	**Total soil loss from the Nyabugogo is 5958155/166136= 35.86 (t/ha/y)**				
Dense forest and water bodies	91523.2	55.089					
Total	166136.1	100					

Site-specific suggested SECM and associated erosion rates in the Nyabugogo catchment

Without proper Best Management Practices (BMPs), soil erosion will continue to increase over time (NISR, 2019). Consequently, soil erosion control will always need improvement. A farmer's interview in Nigeria revealed that farmers required improvement of all SECM in the Kogi region (Onu & Mohammed, 2014). Using shapefiles from RWB, Figure 7 illustrates the suggested SECM aiming to achieve tolerable soil erosion rates in the Nyabugogo catchment. Using the USLE model described by Equation (1), the subsequent sections outline procedures to predict soil erosion rates that will be induced by the proposed SECM.

Figure 7 illustrates the site-specific SECM to mitigate the high soil erosion rates estimated as 35.86 t/ha/y in Table 4, while Table 5 predicts the soil erosion rates for the recommended SECM in the Nyabugogo catchment. Significantly, the recommended SECM reduced the soil loss from 35.86 to 17.84 t/ha/y, indicating an efficiency of 50.25%.

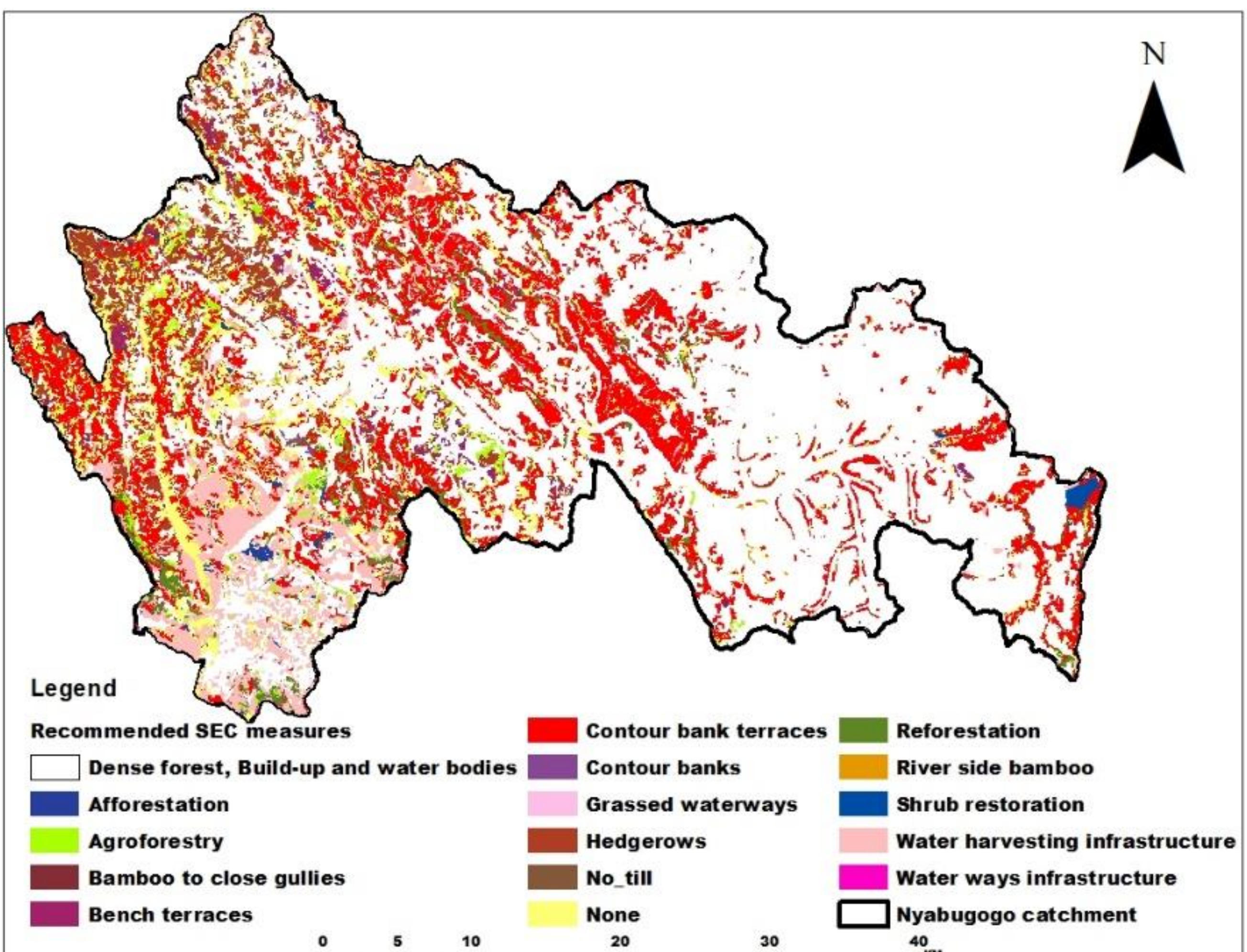

Figure 7. Suggested SECM in the Nyabugogo catchment

Table 5. Erosion rates induced by the site-specific suggested SECM in the Nyabugogo catchment

S.N	Recommended erosion control measures	R	K	L.S	C	P	Ai (t/ha/yr)	Area covered ai (ha)	Weighted soil loss (Ai*ai)
1	Afforestation	486	0.14	21.82	0.02	.001	0.030	654	19.419
2	Agroforestry	486	0.14	21.82	0.08	.500	59.385	2235	132726.2
3	Bamboo to close gullies	486	0.14	21.82	0.01	.500	7.423	27	200.425
4	Bench terraces	486	0.14	21.82	0.15	.128	28.505	2262	64478.2
5	Contour bank terraces	486	0.14	21.82	0.15	.150	33.404	32575	1088143
6	Contour bunds	486	0.14	21.82	0.5	.600	445.390	84	37412.8
7	Grassed waterways	486	0.14	21.82	0.2	.100	29.693	29	861.1
8	Hedgerows	486	0.14	21.82	0.2	.000	0.000	6434	0.0
9	No-till	486	0.14	21.82	0.25	.100	37.116	966	35853.9
10	Existing SECM*	486	0.14	21.82	0.22	.341	111.377	14221	1583894
11	Reforestation	486	0.14	21.82	0.02	.001	0.030	3075	91.3
12	River side bamboo	486	0.14	21.82	0.01	.500	7.423	441	3273.6
13	Silivo pastoralism	486	0.14	21.82	0.09	.000	0.000	323	0.0
14	Rainwater harvesting pond	486	0.14	21.82	0.00	.800	0.000	11260	0.0
15	Drainage channels	486	0.14	21.82	0.58	.800	688.870	25	17221.7
16	Build-up, dense forest, and water bodies	486	0.14	21.82	0.00	.000	0.000	91523	0.0
	Total							166134	2964176

Average soil loss = 2964176/166134 = 17.84 t/ha/y

Table 6: Performance of mulching in the Nyabugogo catchment

S.N	Recommended erosion control measures	R	K	LS	C	P	Ai (t/ha/y)	Area covered ai (ha)	Weighted soil loss (Ai*ai)
1	Afforestation	486	0.14	21.8	0.020	0.001	0.030	654	19.419
2	Agroforestry+ mulching	486	0.14	21.8	0.006	0.130	1.220	2235	2726.196
3	Bamboo to close gullies	486	0.14	21.8	0.010	0.500	7.423	27	200.4254
4	Bench terraces+ mulching*	486	0.14	21.8	0.012	0.033	0.585	2262	1324.382
5	Contour bank terraces+ mulching	486	0.14	21.8	0.012	0.039	0.686	32575	22350.46
6	Contour bunds + mulching	486	0.14	21.8	0.0395	0.156	9.148	84	768.458
7	Grassed waterways	486	0.14	21.8	0.200	0.100	29.693	29	861.087
8	Hedgerows	486	0.14	21.8	0.200	0.000	0.000	6434	0.000
9	No-till+ mulching	486	0.14	21.8	0.020	0.026	0.762	966	736.439
10	Existing SECM	486	0.14	21.8	0.220	0.341	111.377	14221	1583894
11	Reforestation	486	0.14	21.8	0.020	0.001	0.030	3075	91.305
12	River side bamboo	486	0.14	21.8	0.010	0.500	7.423	441	3273.615
13	Silivo pastoralism	486	0.14	21.8	0.090	0.000	0.000	323	0.000
14	Rainwater harvesting pond	486	0.14	21.8	0.000	0.800	0.000	11260	0.000
15	Drainage channels	486	0.14	21.8	0.580	0.800	688.870	25	17221.74
16	Build-up, dense forest, and water bodies	486	0.14	21.8	0.000	0.000	0.000	91523	0.000
	Total							**166134**	**1633468**

Average soil loss = 1633468/166134 = 9.83 t/ha/y

*Note: combined C (Bench terraces+ Mulching) and combined P (Bench terraces+ Mulching) were obtained by multiplication of C-bench terraces and C-Mulching:

- C (Bench terraces+ Mulching) = C(bench terraces)* C(Mulching)= 0.15*0.079=0.012 (Table 6)
- P (Bench terraces+ Mulching) = P(bench terraces)* P(Mulching)= 0.128*0.26=0.033 (Table 6)

This study evaluated the effectiveness of mulching in reducing soil erosion rates within the Nyabugogo catchment. The results showed that mulching reduced the soil erosion rates from 17.84 t/ha/y (under recommended SECM) to 9.83 t/ha/y, indicating 44.89% of efficiency in lowering erosion within the Nyabugogo catchment (Table 6). Mulching practice has a significant impact on reducing erosion rates, stabilizing soil structure, and improving water infiltration. Recent research by Solgi et al. (2022) also supports these findings.

Discussions

Benefits of mulching

Mulching is an essential practice that helps to prevent soil erosion by acting as a protective cover (Matisic et al., 2023). By preventing soil detachment due to droplet strikes and minimizing overland flow, it reduces soil erosion rates (Matisic et al., 2023; Shi et al., 2013). Mulching also plays a significant role in enhancing soil health by retaining moisture and regulating soil heat. It acts as insulator, reducing evaporation and maintaining optimal soil moisture levels (Iqbal et al., 2020). In addition, it suppresses weed growth by limiting light availability and enhancing nutrient availability for cultivated crops (Hüppi et al., 2015; Nwosisi et al., 2019; Iqbal et al., 2020). It helps to maintain a more stable soil heat, preserving plant roots from excessive heat or cold stress (Iqbal et al., 2020). Furthermore, mulching minimizes water usage by reducing evaporation and runoff, thereby improving water retention in the soil (El-Beltagi et al., 2022). These benefits make mulching an important agricultural practice that helps to protect soil quality and improve crop yields.

Field performance of different mulches on soil erosion

The effectiveness of mulching in controlling soil erosion varies depending on the type of mulch. Organic mulches such as crop residues, straw, and grass help to protect the soil by reducing soil detachment and erosion rates, while also improving soil moisture and stability (Kavian et al., 2020; Solgi et al., 2022). On the other hand, inorganic mulches such as plastic sheeting, gravel, and geotextiles act as physical barriers that minimize runoff and soil movement (Tibash et al., 2023). Living mulches, which include cover crops and perennial vegetation, offer erosion control by providing continuous soil cover and root binding, which enhances infiltration and stabilizes soil aggregates (Neri et al., 2021). Similar studies suggest combining mulching with other erosion control methods to reduce soil erosion to tolerable soil loss rates (Prosdocimi et al., 2016).

Adoptability of mulching technology in Nyabugogo catchments

The adoption of mulching technology is influenced by various factors such as socioeconomic, technological, cultural, and environmental factors (NGAIWI et al., 2022). Factors like affordability, accessibility, government incentives, and perceptions of cost-effectiveness have a significant impact on adoption rates (Murindangabo et al., 2021). Farmers' familiarity, ease of use, and alignment with traditional practices also play a crucial role in adoption decisions (Olum et al., 2020). Education, awareness programs, community engagement, and demonstration plots are crucial in shaping farmers' attitudes towards mulching (Bwalya et al., 2023).

Adoptability of SECM depends on environmental factors such as soil type, climate, topography, and land use practices (Iqbal et al., 2020). To promote mulching adoption in agricultural systems, targeted interventions, technological advancements, supportive policies, and community engagement are essential.

Table 7: SWOT analysis on performance and adoption of mulching technology

Strength	**Weakness**
Erosion Control effectiveness*:* Mulching demonstrates significant efficacy in reducing soil erosion rates by preventing soil detachment, minimizing surface runoff, and enhancing soil stability.	***Degradation and Renewal*****:** Some mulching materials degrade over time, necessitating regular renewal or replacement, which could be a constraint for resource-limited farmers.
Soil Health Improvement*:* Mulching contributes to enhanced soil moisture retention, preservation of soil composition, and increased organic matter content, fostering improved soil fertility and microbial activity.	***Seasonal Variation in Effectiveness*****:** The effectiveness of mulching practices might fluctuate depending on seasonal changes, especially in extreme weather conditions.
Cost-Effective**:** Utilizing locally available materials for mulching, such as crop residues, can be cost-effective and sustainable for farmers, reducing the need for external inputs.	***Skill and Knowledge Gap*****:** Adequate knowledge and technical skills are crucial for proper mulching application and management, which can be challenging for some farmers.
Environmental Sustainability*:* Mulching aligns with sustainable agricultural practices by conserving water, sequestering carbon, and reducing the environmental impact associated with soil erosion.	***Technological Constraints inorganic mulches****:* Inadequate access to appropriate equipment or lack of technological advancements in mulching methods may hinder widespread adoption.
Opportunities	**Threats**
Degradation and Replenishment*:* Organic mulches require replenishment and maintenance, as they decompose over time, potentially leading to a need for frequent reapplication.	***Resource Constraints****:* Limited availability of mulching materials, high initial investment costs, and lack of financial support may hinder adoption, especially among resource-constrained farmers.
Education and Outreach*:* Awareness programs, farmer training, and extension services can improve knowledge dissemination and encourage greater adoption among farmers.	***Resistance to Change****:* Traditional farming practices (use of crop residues and vegetative grasses for cooking, composting, and fencing instead of using them as mulches in their farmlands) and reluctance to adopt new techniques could impede the uptake of mulching practices.
Policy Support*:* Supportive policies, incentives, and government initiatives promoting sustainable land management practices, including mulching, can favor an increased adoption.	***Environmental Challenges****:* Extreme weather events, soil degradation, and changing climate patterns may influence the effectiveness of mulching and pose threats to its long-term viability.
Integration with Agroforestry**:** Integrating mulching with agroforestry systems offers opportunities to enhance soil conservation, biodiversity, and overall ecosystem health.	***Inadequate Support Services*****:** Limited access to extension services, technical guidance, or financial support may impede farmers from adopting mulching technology.

Ill-effects (Disadvantages of Mulching Technology)

Mulching is a popular agricultural practice that offers many benefits but also has some drawbacks. One of the most significant concerns is the potential increase in pest and disease pressure due to the sheltered and moist environment created by the mulches (Iqbal et al., 2020). In addition, certain organic mulches like straw or compost can promote weed growth by harboring weed seeds (Du et al., 2022).

Improper or excessive mulch application can lead to soil compaction with reduced aeration, and hinder plant root respiration and nutrient uptake, ultimately affecting plant growth (Mbukwa et al., 2023). Therefore, it is critical to monitor and adjust the depth and type of mulch to avoid these adverse effects on soil texture and plant health (Pavlů et al., 2021).

In humid or high-rainfall areas, mulching may retain excessive moisture, leading to conditions that favor pests and negatively impact plant health (Panth et al., 2020; El-Beltagi et al., 2022; Chen et al., 2023).

Responsibility of Rwanda Water Resources Board (RWB) in the implementation of mulching technology

Rwanda Water Resources Board (RWB) is a non-commercial public Rwandan institution established on 29/01/2020 with the mission of ensuring the availability of enough well-managed water resources for sustainable development. One of its responsibilities is to establish strategies related to the protection of catchments and coordinate the implementation of erosion control plans.

Most of SECM (terraces, contour bunds, retaining walls, check dams, sediment basins, etc.) are costly to build. Because farmers are the most direct perceivers of soil erosion processes in their farmlands, the development of soil erosion rates greater than the acceptable soil loss tolerance rates can be prevented through some adaptive measures based on their indigenous knowledge. For effective sustainable agricultural and environmental management, this research recommends RWB to promote further studies to assess systematically and simultaneously all three aspects (planning, adoption, and implementation) of mulching technology as perceived by farmers themselves in Rwandan catchments.

To this end, RWB should sensitize farmers on the benefits of mulching in controlling soil erosion. Salomon (2016) indicated that when farmers do not have more information about a Soil Conservation Measure, they cannot be expected to adopt it. Also, the Government should facilitate farmers' access to microfinance credit. Many researchers reported that the limiting factors of the adoption of soil and water conservation techniques are related to poverty and limited knowledge (Bizoza and De Graaff, 2012; Debebe et al., 2013).

SWOT analysis on performance and adoption of mulching technology

A SWOT analysis is a tool used to evaluate the internal and external factors that affect the performance and adoption of mulching technology for soil conservation. This analysis highlights the strengths, weaknesses, opportunities, and threats associated with the use of mulching techniques (as listed in Table 7). By identifying these factors, it becomes easier to ascertain the advantages, challenges, areas for improvement, and external influences that impact the effectiveness and adoption of mulching techniques.

Future work

The ongoing research aimed to evaluate the effectiveness of mulching technology in controlling soil erosion. It has assessed the impacts of various mulching materials and methods on soil health and crop yield, as investigated by Prosdocimi et al. in 2016 and by Thakur and Kumar in 2021. Future endeavors should focus on scaling up mulching practices by overcoming socio-economic barriers, raising farmers' awareness, and tailoring customizing strategies to local conditions. In addition, further research should explore long-term effects on soil health, biodiversity, and ecosystem resilience. To encourage wider adoption, stakeholders' insights should be integrated, emphasizing socioeconomic and cultural aspects through surveys, community engagement, and collaboration. Targeted educational programs, training sessions, and demonstration plots are also crucial for raising awareness and promoting the adoption of mulching. Collective efforts from stakeholders, researchers, and policymakers are pivotal in enhancing mulching technology for sustainable land practices in Rwandan catchments.

Conclusion and recommendations

This study aimed to assess mulching technology's effectiveness in controlling soil erosion in the Nyabugogo catchment and promote its adoption. Initially projecting high soil loss (35.86 t/ha/y) due to various factors, the suggested Soil Erosion Control Measures (SECM) reduced it to 17.84 t/ha/y through simulations using the USLE model. A combination of mulching practices with the site-specific suggested SECM further decreased soil loss from 17.84 to 9.83 t/ha/y, showing a mulching efficacy of 44.89% in controlling soil erosion. For effective sustainable agricultural and environmental management, this research recommends the Rwanda Water Resources Board (RWB) to promote further studies aiming to assess systematically and simultaneously all three aspects (planning, adoption, and implementation) of mulching technology as perceived by farmers themselves in Rwandan catchments. Farmers' training and sensitization will enhance mulching adoption and implementation in their farmlands.

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