https://doi.org/10.17221/124/2025-RAE

Vetiver grass for road slope protection through soil erosion and runoff reduction in a haor area of the Sunamganj district

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Citation: Akter T., Acharya S., Al-Hossain S.J., Robbani G.K. (2026): Vetiver grass for road slope protection through soil erosion and runoff reduction in a haor area of the Sunamganj district. Res. Agr. Eng., 72: 195–203.

Abstract: Erosion control on slopes and embankments is a global concern, with vetiver planting emerging as an effective solution. This study investigated vetiver grass as a potential alternative for reducing runoff and soil erosion in protecting road embankments. In a small-scale model on a 1 V : 2 H slope, simulated rainfall was applied through a perforated sheet. The runoff was collected, and the eroded soil samples were dried using the sand bath method. The runoff and soil loss were compared with and without vetiver grass. The results showed that the vetiver grass significantly reduced the soil erosion, preventing about 87% more soil loss than the bare soil. During 60 min of simulated rainfall, the bare soil plot lost 27.056 $kg.m^{-2}$ per unit area, whereas the vetiver-covered plot lost only 3.606 $kg.m^{-2}$. This soil retention is due to vetiver's strong, deep root system and its hedge-like structure that effectively holds the soil. Additionally, the runoff was reduced by 14% in the plots covered with vetiver. For the 60 min of cumulative rainfall, the total runoff in the bare soil micro-plot was 81.15 cm, compared to 70.35 cm in the vetiver micro-plot. Therefore, vetivers are expected to be a sustainable and eco-friendly solution for runoff and erosion control within the lowland haor context.

Keywords: erosive force; flood risk; soil quality; soil stability; vegetation

Vetiver grass (*Chrysopogon zizaniodes*) is a deep-rooted, perennial bunchgrass that thrives in warm, sunny climates and a wide range of soils from acidic to alkaline. It has been recognised by the World Bank since the 1980s for its effectiveness in conserving soil and managing water runoff and infiltration (D'Souza et al. 2019). Its upright stem and root system are ideal for preventing soil erosion, reducing it by up to 90%, and conserving rainfall runoff by as much as 70%, thereby helping to reduce flooding risks (Truong et al. 2008). Vetiver grass helps decrease the structural deformation and failure (Kumar and Bahadur Roy 2021) and improves the soil shear strength, increasing the soil cohesion and internal friction by 119.6% and 81.9%, respectively (Hamidifar et al. 2018). The root character-

Received financial support through the National Science and Technology (NST) fellowship of the Government of the People's Republic of Bangladesh for this work.

https://doi.org/10.17221/124/2025-RAE

istics of vetiver contribute to a 50% increase in the shear strength and provide an eco-friendly solution for slope stability (Badhon et al. 2021). This perennial tussock grass is tolerant of various climates, thriving in annual rainfall ranging from less than 300 mm to over 6 000 mm, and temperatures from −15 °C to over 55 °C (Truong and Loch 2004). The annual average precipitation in the Sylhet division is a little under 3 700 mm (Noorunnahar and Hossain 2019). Using vegetation contour hedges, vetiver grass slows the silt-laden runoff (Islam et al. 2008) and functions as a bioengineering method to reduce the runoff velocity, trap sediment, and restore the soil physical properties (Ejor and Oku 2024). Therefore, the use of vetiver grass should be studied extensively in Bangladesh to address the existing problems such as erosion, floodwater accumulation caused by runoff, waterlogging, and related issues. The runoff is made to move more softly down the slope over the surface of the soil, where it is intercepted and dispersed by a vetiver strip (Figure 1).

Vetiver hedges reduce the water flow velocity, which reduces the erosive force. The vetiver root can penetrate the hardpan by up to 0.15 m, with its tendon enabling the vetiver to penetrate through the relatively hard layer of weathered rock, boulders, asphalt, concrete, etc. The tensile strength of the vetiver ranges from 40 MPa to 180 MPa, with the average tensile strength being 75 MPa. The shear strength is also about 6–10 kPa.kg^{-1} per cubic metre of soil (Truong et al. 2008). Therefore, due to its unique morphological, physiological, and ecological traits, vetiver grass is emerging as an effective solution for erosion control in tropical and temperate regions (Islam et al. 2021). Despite its potential, few studies have explored vetiver's effectiveness for slope protection in Bangladesh (Islam et al. 2013); however, runoff and erosion control research using vetiver has rarely considered lowland haor areas. Vetiver grass has shown promise in protecting slopes from rain-cut erosion and sliding, particularly on road embankments. Its ability to slow down and distribute concentrated runoff creates a dense hedge that significantly reduces the soil erosion and runoff when planted along contour lines (Nasrin 2013; Aziz and Islam 2023). It is time to investigate the potential uses of vetiver grass in preserving the haor lowlands and its function in reducing erosion on road slopes. This research serves as an initial field trial in a massive study on a road embankment and roadside mild slope stabilisation and erosion using vetiver. Reliable model study results can be an effective way to support the expansion of an erosion control plan to the field level, as large-scale erosion evaluation project implementation also requires more costs, time, and effort. Thus, the objectives include investigating the impact of vetiver grass on soil erosion and runoff through a small-scale physical model study and assessing its efficacy in road embankment protection without compromising the aesthetics.

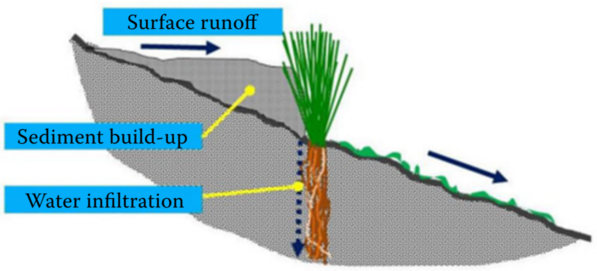

Figure 1. Illustration of sediment build-up and water infiltration on vetiver (Vanoh 2020)

MATERIAL AND METHODS

Description of the study area. Chhatak Upazila in Sunamganj was selected for this study as it experiences heavy rainfall and hill runoff, resulting in severe flooding that damages the infrastructure, submerges homes, and disrupts road connectivity and agriculture. It is located at a latitude of 25.0417°N and a longitude of 91.6750°E (Figure 2).

The soil sample was collected from the nearby area of the Surma River, Sunamganj, Bangladesh, and was tested by the Soil Resources Development Institute (SRDI), situated in Sylhet. The soil test result showed that the soil used in the experiment was Sandy Clay Loam. It consists of 56.56% sand, 19.60% silt, and 23.84% clay. The pH of the soil was 8.1. The average temperature of the locality during the experiment was approximately 25 °C, and the average rainfall was 52 cm. The experiment was conducted from October 2023 to March 2024. The micro-model was kept under study for about three months. During the first month, an experiment on the bare soil was performed, and data were collected. Similarly, the experiment on the vetiver-rooted soil was completed in the following two months.

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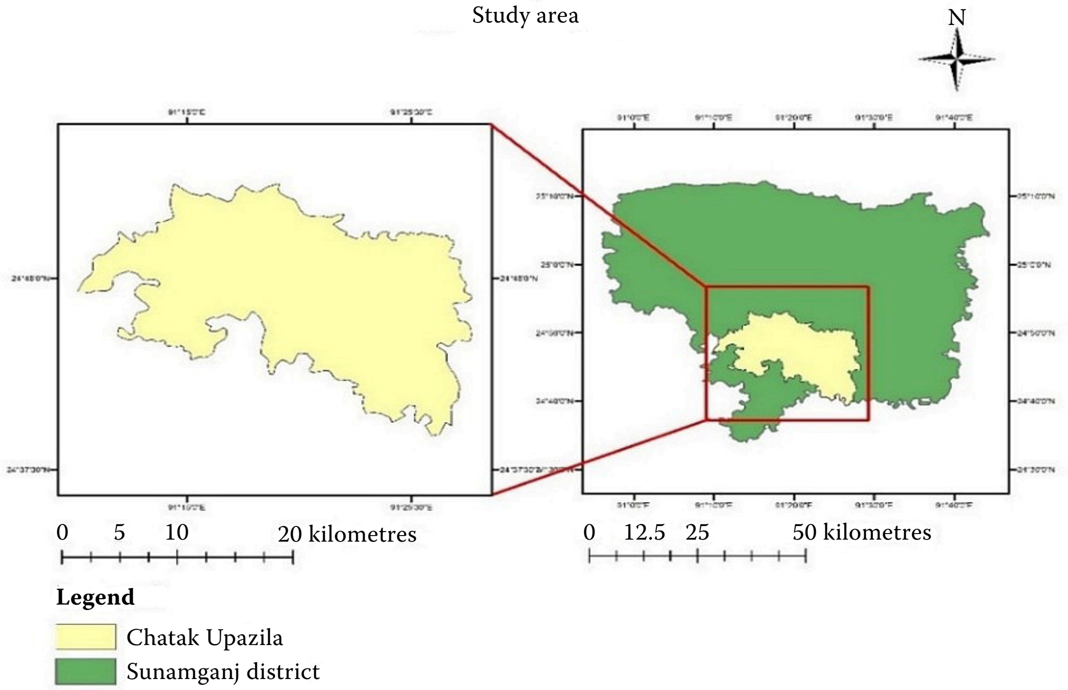

Figure 2. Experimental area

Micro-model plot. The micro-model used for the study was about 0.91 m in length, 0.61 m in width, and 0.61 m in height. Therefore, the total micro-model plot area was 0.558 m^2. The simulated structure was about 0.91 m in length and 0.61 m in height. The slope of the plot was about 1 V : 2 H. The slope angle (α) was estimated as 27° by using the equation: $\tan^{-1}$ (1.5/3). The runoff collector for the micro-model was about 0.91 m in length, 0.61 m in width, and 0.127 m in height. The runoff collector collected the accumulated runoff water resulting from the simulated rainfall. Figure 3 shows the overall experimental setup, including the micro-model and runoff collector. A perforated steel sheet was used to simulate the rainfall. It was 1.2 m in length and 0.91 m in width. Each perforated hole is about 5 mm in diameter. The distance between one of the holes and the other is about 15 mm.

Experimental procedure. The simulated rainfall was applied to the experimental plot over a single day for 60 minutes. The runoff resulting from the rainfall was listed as X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10} (cm), etc. The runoff collector collected runoff samples at suitable intervals until the rainfall stopped. The height of the accumulated runoff was measured with a scale. Then, the amount of runoff water was removed to collect the lost soil sample, allowing for the eroded wet soil samples to be collected for each rainfall. The wet sample was then dried by the sand bath method, and the dry weight

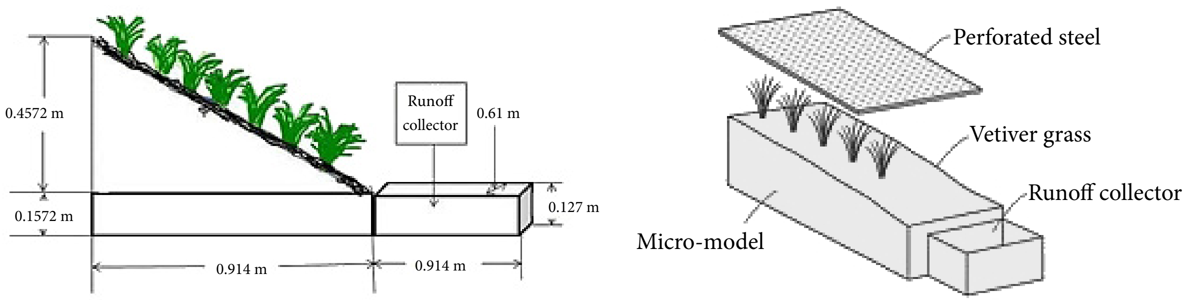

Figure 3. Experimental setup for the runoff and erosion measurement

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of the soil sample was taken. The experiment was conducted for both the bare soil plot and the vetiver plot. Finally, the runoff data and soil loss data were compared to observe the impact of vetiver on the soil and water conservation.

Parameters and conditions of the experiment. The test was conducted on the bare soil and the vetiver-rooted soil. The slope angle was 27°. The simulated rainfall was more intense than the usual rainfall for experimental purposes. The artificial rain through the 15 mm × 15 mm perforated sheet produced an average rainfall intensity of 20 mm.min^{-1} (i.e. equivalent to 1 200 mm.h^{-1}), which resulted in excessive soil loss on the micro-model plot. The rainfall duration was 60 minutes. The rooted soil section was prepared by placing the vetiver at 10 cm × 10 cm spacing. The minimum space was kept for the vetiver hedge formation. During the experiment, the average root length was approximately 0.25 m, the average shoot length was approximately 0.564 m, and the average clump diameter was approximately 0.06 m.

The growth rate of vetiver was found to be relatively rapid. The average shoot length of vetiver was recorded as 0.933 m after the 53rd day of its establishment. Thus, 0.37 m increases in shoot length are observed in less than 2 months. If the growth continues in this manner, by the end of the year, the vetiver growth will be equivalent to more than 2 m. It was observed that the average height of the vetiver shoots was 0.93 m. The vetiver was established at an interval of 0.1 m × 0.1 m, which facilitated the formation of the vetiver hedge. The average root diameter of the vetiver was found to be 0.65 mm, and it ranged from 0.54 mm to 0.79 mm for ten random samples.

Ultimate tensile force and tensile strength of vetiver root. For the determination of the tensile root strength (Burroughs and Thomas 1977; Abe and Iwamoto 1986; Nilaweera 1994), the power regression analysis of the relationship between the ultimate root tensile force and the root diameter provides the best fit with the following equation:

$$F_1 = 46.93\, d^{1.4217} \tag{1}$$

where: F_1 – the ultimate tensile root force (N); d – the root diameter (mm).

This power regression function can be used to predict the ultimate tensile force of a vetiver root with a known diameter. The tensile root strength, T_s (MPa), decreases with the increasing root diameter d (mm) following the power regression relationship.

$$T_s = 59.80\, d^{-0.5785} \tag{2}$$

Data collection. After the application of the simulated rainfall, the runoff data and the wet weight of the filtered soil sample were taken. The soil sample was taken 26 times for both the bare soil plot and the vetiver plot, and the data for runoff (cm) and soil erosion were collected. Later, the wet sample of the soil was dried using the sand bath method, and the dry weight of the soil was obtained. The soil loss per unit area was calculated by dividing the total dry soil mass by the micro-model plot surface area. The following procedure was used for determining the dry weight (Wt.) of the soil and the moisture content of the soil sample:

Step 1: Oven dry method

$$\text{Wt. of the wet sample} = (\text{Wt. of the container} + \text{Wt. of the wet sample}) - \text{Wt. of the container} \tag{3}$$

Step 2: Sand bath method

In the present study, the dry weight and the moisture content of the soil sample were determined by the sand bath method. A small vessel with a 50 mm thick sand layer was used to dry the wet soil sample. The wet soil sample was kept in the vessel and was heated on the stove for one hour. A sand layer was used to give the sample a uniform heating layer. Once the sample dried, the following formula was used to calculate the dry weight of the soil:

$$\text{Wt. of the dried soil sample} = (\text{Wt. of the container} + \text{Wt. of the dry sample}) - \text{Wt. of the container} \tag{4}$$

therefore,

$$\%\text{Moisture content} = \frac{\text{Wt. of the wet soil sample } (i) - \text{Wt. of the dry soil sample } (ii)}{\text{Wt. of the dry soil sample } (ii)} \times 100 \tag{5}$$

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Runoff and erosion data (soil loss) collection on the bare soil plot and the vetiver plot. The accumulated runoff for each sample was first stirred, then measured using a scale, and the average runoff depth was recorded. The vetiver grass was established in the micro-model for two and a half months before the experiment was conducted. After the acquisition of sufficient strength by the vetiver root and shoot, the experiment was conducted.

The simulated rainfall was applied on the sloped model at an average intensity of 20 mm.min^{-1}. Then, the runoff and soil erosion data were collected by the same processes previously described for the bare soil plot. After the simulated rainfall on the vetiver micro-model, the runoff water accumulated in the runoff collector. The volume of the accumulated runoff was equivalent to (0.61 × 0.91 × h) m^3, where "h" is the height of the runoff water. Then, the runoff data was taken accordingly (Figure 4).

Figure 4. Vetiver grass plot on a micro model plot and the runoff accumulation after the simulated rainfall on the vetiver grass plot

RESULTS

Ultimate tensile force and tensile strength of vetiver root. How the vetiver root reduces the soil erosion and runoff by significantly influencing the root's ultimate tensile force and tensile strength is presented in Table 1.

As root diameter increases, the tensile root strength decreases, while the ultimate tensile force increases. For instance, the vetiver root with the smallest diameter (0.54 mm) exhibited a tensile root strength of 85.41 MPa and an ultimate tensile force of 19.54 N. In contrast, the root with a larger diameter (0.79 mm) demonstrated an ultimate tensile force of 33.57 N, but a reduced tensile root strength of 68.54 MPa. The average values were 25.44 N for the ultimate tensile force, 76.72 MPa for the tensile root strength, and an average root diameter of 0.65 mm. These results are consistent with previous studies (Turmanina 1965; Wu 1976; Burroughs and Thomas 1977), which report that the tensile strength decreases as the root diameter increases. This is particularly important for levee and stream bank stability, where finer roots, with their higher tensile strength and pull-out resis-

Table 1. Ultimate tensile force and tensile strength of vetiver root at different diameters

Sample No.	Diameter, d (mm)	Ultimate tensile force, F_1 (N)	Tensile root strength, T_s (MPa)
1	0.61	23.24	79.60
2	0.57	21.10	82.78
3	0.64	24.88	77.42
4	0.73	30.00	71.74
5	0.79	33.57	68.54
6	0.64	24.88	77.42
7	0.70	28.26	73.50
8	0.57	21.10	82.78
9	0.54	19.54	85.41
10	0.67	26.56	75.39
Average	0.65	25.44	76.72

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tance, offer better protection against soil erosion compared to larger roots. Additionally, thinner roots play a key role in soil stabilisation, as they are more effective in resisting pull-out, supporting the findings by Machado et al. (2015). In this study, the root diameters ranged from 0.54 mm to 0.79 mm, with the tensile strengths ranged between 68.54 and 85.41 MPa and the tensile forces ranged from 19.54 N to 33.57 N. These results demonstrate that vetiver roots possess significant strength, making them suitable for stability studies using discrete element modelling (DEM), finite element (FE) methods, or similar techniques.

Soil loss on the bare soil plot and the vetiver plot. The vetiver grass reduced the soil loss by nearly 87% compared to the bare soil, with only 2.002 kg lost versus 15.097 kg, as shown in Figure 5.

During 60 min of simulated rainfall, the bare soil plot lost 27.196 $kg.m^{-2}$ per unit area, whereas the vetiver-covered plot lost only 3.606 $kg.m^{-2}$. This effectiveness is due to its canopy intercepting the rainfall, dispersing the runoff, and slowing the surface water, which enhances the infiltration. In contrast, the bare soil lacked any protective cover, making it highly vulnerable to erosion.

Percentage of erosion reduction due to vetiver grass. Vetiver grass has an extensive root system that binds the soil, making it less susceptible to water and wind erosion. Furthermore, the grass slows down the runoff, allowing more time for the water to infiltrate and reduce the soil loss (Table 2).

Table 2 demonstrates how introducing vetiver grass vegetation could effectively minimise the soil erosion in 60 min by 97.71% to 86.74%.

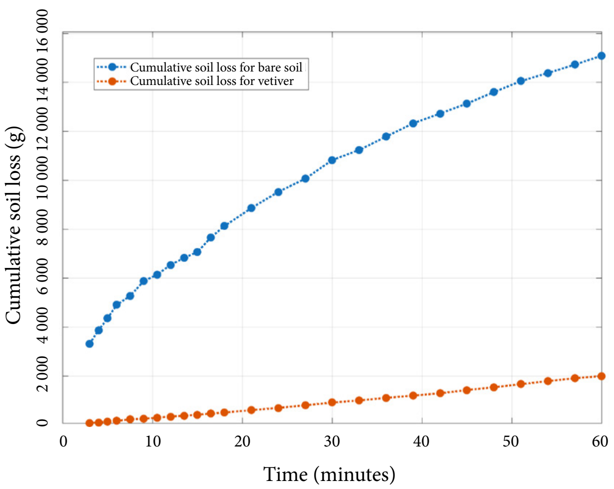

Figure 5. Soil loss on the bare soil plot and the vetiver plot

Additionally, the average erosion reduction percentage was 92.46%. This investigation found excellent erosion reduction because, in the micro-model, the infiltration rate was higher, and the runoff rate was low. However, in the natural system, this erosion reduction will be less than this micro-model. Comparing the vegetated models to the bare ones, studies by Aziz et al. (2020) and Islam et al. (2021) found that the soil loss was reduced by about 75%.

Runoff on the bare soil plot and the vetiver plot. Figure 6 represents the gradual increase in the runoff accumulation over time. The runoff resulting from 60 min of simulated rainfall is shown in the figure.

The runoff on the bare soil plot increased rapidly, reaching 81.15 cm after 60 min due to the

Table 2. Erosion reduction by vetiver grass in the field investigation

Time (min)	Bare soil erosion rate (g)	Rooted soil erosion rate (g)	%Reduction
3	3 324	76	97.71
4	3 879	104	97.32
5	4 364	134	96.93
6	4 908	168	96.58
7.5	5 276	229	95.66
9	5 876	255	95.66
10.5	6 146	301	95.10
12	6 541	343	94.76
13.5	6 830	381	94.42
15	7 067	422	94.03
16.5	7 672	466	93.93
18	8 132	512	93.70
21	8 867	607	93.15
24	9 527	699	92.66
27	10 067	807	91.98
30	10 830	919	91.51
33	11 241	1 004	91.07
36	11 784	1 109	90.59
39	12 329	1 201	90.26
42	12 727	1 298	89.80
45	13 137	1 430	89.11
48	13 605	1 542	88.67
51	14 054	1 671	88.11
54	14 386	1 795	87.52
57	14 726	1 911	87.02
60	15 097	2 002	86.74

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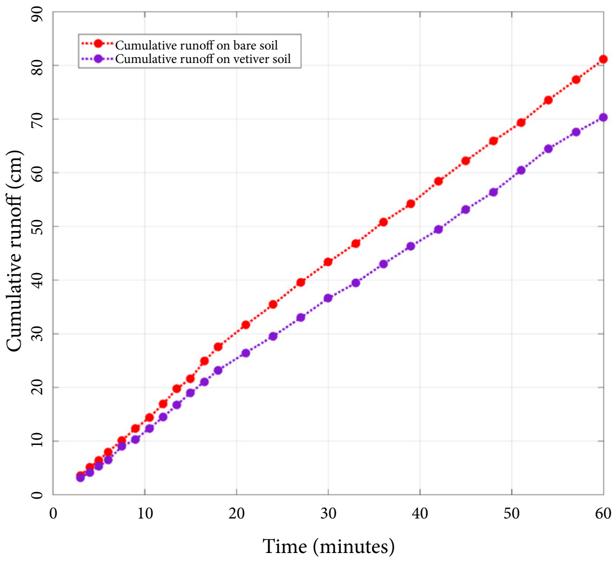

Figure 6. Cumulative runoff versus time

lack of barriers and frequent scouring. In contrast, the vetiver plot had a lower runoff at 70.345 cm under the same rainfall intensity. This shows that vetiver effectively reduces the surface runoff. The experiment demonstrated that the vetiver grass reduced the runoff by 10.8 cm, or approximately 14%, compared to the bare soil plot. This reduction is attributed to the vegetation's ability to intercept the rainfall, reduce the runoff velocity, and enhance the infiltration, thereby limiting the soil erosion. However, the effectiveness was somewhat constrained by the closed boundary of the micro-model used, which trapped water and led to the early soil saturation and increased the direct runoff (Islam et al. 2021). In contrast, vetiver's performance is expected to be more efficient under open-field conditions. Supporting studies show that vetiver plots consistently experience a lower runoff than bare plots. Babalola et al. (2007) reported mean runoff values of 0.5% for vetiver-covered plots versus 6.5% for bare plots, while Donjadee et al. (2013) observed a runoff range of 6.6–98.2 mm for vetiver plots compared to 12.1–144.6 mm for bare plots across varying slopes. These findings suggest that, in natural settings, vetiver could potentially reduce the runoff accumulation by 40–70%.

Percentage of runoff reduction due to vetiver grass. Vetiver grass can act as a natural barrier. Also, it slows down the water flow and allows more water absorption. Besides this, vetiver roots improve the soil structure and increase the infiltration rate. In this way, it can reduce the runoff. Table 3 shows the effect of the surface runoff reduction due to the vetiver grass.

Table 3 demonstrates how introducing vetiver grass vegetation could effectively minimise the runoff. For 60 min, the percentage of the runoff reduction ranged was 10.89% to 19.38%. Additionally, the average runoff reduction percentage was 14.92%.

Relationship between runoff and soil loss on the bare soil plot and vetiver soil plot. The proportional relationship between the soil loss and runoff for the bare soil is shown in Figure 7.

Figure 7 presents the cumulative runoff and corresponding soil loss over a 60-minute simulated rainfall event. On the bare soil plot, a strong positive correlation was observed, with the soil loss

Table 3. The effect of vetiver on surface runoff reduction

Time (mins)	Bare soil runoff (cm)	Rooted soil runoff (cm)	%Reduction
3	3.60	3.20	11.11
4	5.10	4.13	19.12
5	6.40	5.28	17.58
6	8.00	6.45	19.38
7.5	10.10	9.00	10.89
9	12.35	10.33	16.40
10.5	14.38	12.35	14.09
12	16.90	14.45	14.47
13.5	19.77	16.75	15.28
15	21.67	19.00	12.32
16.5	24.90	21.08	15.34
18	27.55	23.23	15.68
21	31.65	26.45	16.42
24	35.45	29.55	16.63
27	39.60	33.00	16.66
30	43.35	36.63	15.50
33	46.85	39.50	15.69
36	50.85	43.02	15.39
39	54.20	46.32	14.53
42	58.40	49.42	15.37
45	62.25	53.17	14.58
48	65.92	56.42	14.41
51	69.37	60.47	12.83
54	73.60	64.50	12.36
57	77.35	67.60	12.61
60	81.15	70.35	13.31

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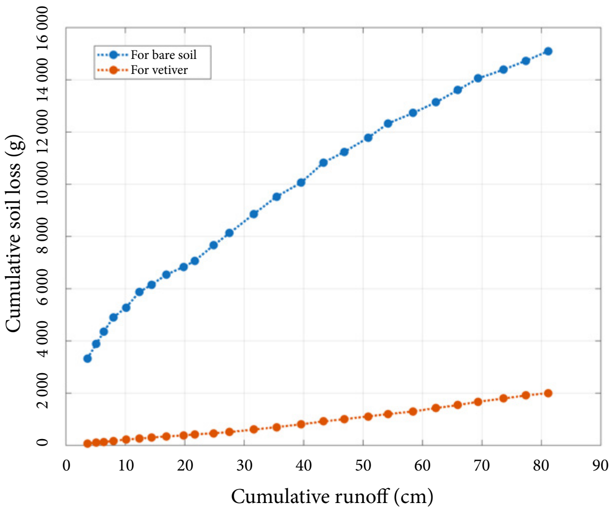

Figure 7. Cumulative soil loss vs. cumulative runoff curve

reaching approximately 10 kg at 39.6 cm of runoff (i.e. 66.6% of the total loss) and peaking at 15 kg at 81.15 cm of runoff. The absence of vegetation allowed rapid surface flow, leading to increased scouring, sheet erosion, and soil displacement. In contrast, the vetiver plot exhibited substantially lower erosion rates, with a soil loss of approximately 500 g at 23 cm runoff and 2 kg at 71 cm. The consistent linear relationship in the vetiver plot indicates that the vegetative barrier effectively reduced the flow velocity, promoted infiltration, and limited sediment transport. These findings align with previous studies (e.g. Babalola et al. 2007; Donjadee et al. 2013; Islam et al. 2021), which demonstrated that vetiver systems significantly mitigate runoff and soil erosion across varying slopes and rainfall intensities.

The statistical analysis (Table 4) confirmed that the differences in the soil loss and runoff between the bare soil and vetiver plots were highly significant (t = 12.05 and 8.14, $P < 0.001$). The soil erosion

Table 4. Statistical analysis

Paired t-test	Bare soil erosion rate and rooted soil erosion rate	Bare soil runoff and rooted soil runoff
Correlation	0.776	1.000
Significance	< 0.001	< 0.001
t	12.045	8.135
Cohen's d	2.362	1.595
Hedge's correlation	2.327	1.571

and runoff showed strong correlations (r = 0.78 and 1.00, respectively), indicating that vetiver grass effectively reduced the erosion and surface flow (IBM SPSS Statistics version 27).

CONCLUSION

The micro-model test showed that vetiver grass effectively reduces the runoff and soil erosion. Bare soil plots on slopes experienced high rates of soil loss and runoff, with up to 27.196 kg.m^{-2} of soil lost in 60 min, compared with about 3.606 kg.m^{-2} on vetiver plots, representing an 87% reduction. The lag time was shorter than in natural conditions, giving vetiver grass less time to conserve the runoff water. Planted in a 10 cm × 10 cm pattern, vetiver formed dense hedges that intercepted the rainfall and stabilised the soil with its strong root system. The grass significantly reduced the runoff accumulation, though the micro-model's limited slope and size slightly restricted its ability to conserve runoff. Still, in real-world conditions, larger areas and steeper slopes are likely to enhance vetiver's effectiveness. While the micro-model provided useful insights, it did not fully replicate natural slope variations, such as different angles, deeper roots, and wider infiltration zones. These limitations led to higher runoff and erosion rates than would normally occur in natural settings. Based on a micro-model area of 0.558 m^2 containing twelve vetiver clumps, the current establishment cost of the vetiver system is estimated at approximately USD 3.2 per m^2. In contrast, the equivalent mechanical barrier for the same protected area incurs a construction cost of around USD 16.3 per m^2. This results in a cost–benefit ratio of roughly 5.1 : 1, indicating that the vetiver-based system achieves comparable erosion control at nearly one-fifth the cost of a conventional mechanical barrier under the current economic conditions.

Future research should focus on quantifying the potential of vetiver grass for sustainable erosion control and slope resilience across diverse landscapes in Bangladesh.

Acknowledgement

The authors would like to express gratitude to the Soil Resource Development Institute (SRDI), Government of the People's Republic of Bangladesh, for allowing laboratory tests of the soil samples.

https://doi.org/10.17221/124/2025-RAE

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Received: August 2, 2025
Accepted: February 10, 2026
Published online: July 2, 2026