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Impact of reinforcing vetiver grass roots on controlling soil erosion

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Article

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Abstract

Significant fatalities, infrastructure destruction, resource depletion, and land degradation are all consequences of landslides. Growth and adequate mitigating efforts are sometimes blamed for their increasing prevalence. Conventional control methods also contribute to environmental imbalance due to their massive carbon footprint. Soil erosion from slopes and plant loss caused by human activity increase the frequency of landslides. Vetiver grass (Chrysopogon zizanioides) and other sustainable and environmentally acceptable techniques are therefore essential for erosion management. For this study, eight 45° small-scale slope models were constructed, four of which were bare (later planted with vetiver) and four of which were reinforced with jute geotextile and vetiver roots. In order to assess runoff control and erosion, four types of soil - red, black cotton, laterite, and sandy soils were utilized in the models. Following 90 and 365 days of planting, high, moderate, and low intensities of artificial rainfall were applied. The results showed that vegetation reduced cumulative runoff by 21 - 26% and increased infiltration by 25 - 45% for black cotton, red, and laterite soils. Silty sand performed even better, with 60% greater infiltration and 30% less runoff. Additionally, compared to other soils, the amount of soil eroded in sandy soil is reduced to 0.018 kg. The protection of canopy and root reinforcement significantly reduced runoff and erosion. In the early days, erosion was discovered to be successfully reduced by the combination of vetiver and jute geotextile. Vetiver generally performed better in soils with more sand, indicating that soil type had a major influence on erosion processes. All four soils reached stable cumulative erosion after runoff and erodibility increased linearly with rainfall intensity above a particular threshold.

1. Introduction

One major form of land degradation is soil erosion, which leads to the loss of rich topsoil, reduced agricultural productivity, and environmental hazards such flooding and water body sedimentation (Pimentel & Burgess, 2013). Millions of hectares of land are impacted by erosion each year, and one of the most destructive processes in tropical and subtropical regions is surface erosion caused by rainfall (Lal, 2019). The fact that conventional erosion control methods like stone bunds, contour trenches, and geosynthetics are often costly and less ecologically friendly emphasizes the need for nature-based alternatives.

Vetiver grass (Chrysopogon zizanioides), a perennial grass native to India, has attracted a lot of attention because of its potential uses in soil conservation and bioengineering. It provides exceptional soil strengthening and protection against detachment forces caused by runoff and rainfall due to its massive and deep root system, which can grow three to four meters vertically (Truong & Loch, 2004). Vetiver's fibrous roots serve as a natural erosion barrier, increase apparent cohesiveness, and increase shear strength on slopes and riverbanks (Nguyen et al., 2019). In addition to mechanical reinforcement, vetiver grass provides ecological benefits such as carbon sequestration, improved groundwater recharge, and sustainable land management practices (Chen et al., 2020).

According to Noorasyikin & Zainab (2016), vetiver roots have a higher tensile strength than Bermuda grassroots, which allows them to offer more shear strength and cohesiveness for reducing erosion. The usefulness of vetiver grass mulch for soil and water conservation under artificially induced rainfall of varying intensities has been tested, in addition to vetiver's better performance over native species (Donjadee & Tingsanchali, 2013). The literature study has been carefully expanded to distinguish between studies on vegetation-based slope stabilization, biodegradable geotextile reinforcement, and their combined use.

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Based on these studies, the current work examines how well an integrated vetiver–biodegradable geotextile system performs in red soil, black cotton soil, sandy soil, and lateritic soils under different rainfall intensities, providing a thorough evaluation of erosion mitigation, concentrating on Indian soils, monsoon conditions, and a comparative experimental approach that hasn't been carried out before.

Karnataka is an example of how powerful short-duration incidences and alternating high annual rainfall in coastal and western regions increase the risk of erosion. West coast of Karnataka experiences extremely high mean annual totals in some places. Notwithstanding the encouraging results, there are still issues with measuring vetiver's effectiveness for Indian soil types across the spectrum of monsoon rainfall intensities and connecting root morphological metrics to engineering parameters used in slope-stability design. As a result, this study examines how vetiver root reinforcement affects soil erosion control, with a focus on Indian contexts: (i) ascertain whether vetiver grows well in soils selected and how it affects erosion and runoff reduction under conditions of extreme, moderate and low rainfall; (ii) ascertain how vetiver and jute geotextile work together to reduce runoff and soil loss; and (iii) evaluate the effectiveness of a vetiver system for four distinct soil types.

2. Materials and methods

2.1 Study soil location

Black cotton soil from Raichur district, Karnataka; red soil from Kyatanahalli village, Pandavapura taluk, Mandya district, Karnataka; laterite soil from Sullia, Dakshina Kannada district, Karnataka; and sandy soil from the vicinity of the MIT campus in Halekesare, Mysore district, Karnataka were used in the study. The soil samples were procured from four locations of Karnataka. Figure 1 notifies the districts of Karnataka from where the soil samples were collected.

Karnataka has a tropical climate. Sullia is located in a very wet zone, Dakshina Kannada has an annual rainfall of about 3,900 to 4,030 mm, while Mandya has 700 mm, Mysore district has about 800 to 1,060 mm, and Raichur has semi-arid climate with low to moderate rainfall, averaging between 600 and 700 mm annually (IMD, 2022). Regional Western-Ghats analyses reveal increased erosive rainfall intensity, which, when coupled with land-use change, causes erosion failures (Chinnasamy & Honap, 2023).

In order to depict a wide range of geotechnical and hydrological behaviour frequently found in both natural and artificial slopes, red soil, lateritic soil, sandy soil, and black cotton soil were chosen. Tropical and semi-tropical areas are home to red and lateritic soils, which are extremely vulnerable to surface erosion during periods of heavy precipitation. Because sandy soil is prone to quick infiltration and particle separation due to its high permeability and low cohesion, it was included. The selection of black cotton soil was based on its expansive properties, low shear strength in wet conditions, and noticeable volume change characteristics. Examining these disparate soils allows for a thorough assessment of erosion processes under various rainfall scenarios.

Figure 2 shows the landslide events that were documented during the field surveying of the locations identified while the soil sample were collected for the study. Localized slope failures and erosion are observed near rivers, reservoir banks, steep cut slopes, and small hill escarpments, according to district reports from Mandya, Mysore, and Coorg.

2.2 Properties of soil and jute geotextile

Table 1, presents the index and engineering characteristics of the soil samples, determined using standard test procedures of the BIS.

Table 1. Geotechnical properties of soils used in present study.

Index Properties			BCS (S-1)	RS (S-2)	SS (S-3)	LS (S-4)
			Values			
Colour			Grey	Red	Yellowish orange	Orange red
Grain Size Distribution	Gravel		0	2.8	20.88	29
	Sand	Coarse	3.33	15.2	24.65	36
		Medium	15.65	15.6	19.21	5.5
		Fine	21.63	27.4	31.73	8.5
	Clay & Silt		59.4	39	3.52	21
Specific gravity of soil solids			2.84	2.66	2.5	2.7
Consistency limits	Liquid limit (%)		75	29	-	-
	Plastic limit (%)		31	16	-	-
	Shrinkage limit (%)		10	32	-	-
Plasticity Index (%)			44	13	-	-
IS standard compaction Test	Optimum Moisture Content (%)		30.5	13.5	9.5	15
	Maximum Dry Unit Weight (kN/m^3)		14.4	20	16	18
Shear strength Parameters	Cohesion, c (kN/m^2)		50	28	13	18.02
	Angle of internal Friction, ϕ (Degrees)		10	30	36	29
Indian Standard Soil Classification			CH	CL	SP	SM
Water content (%)			30	10.67	5.98	12.61

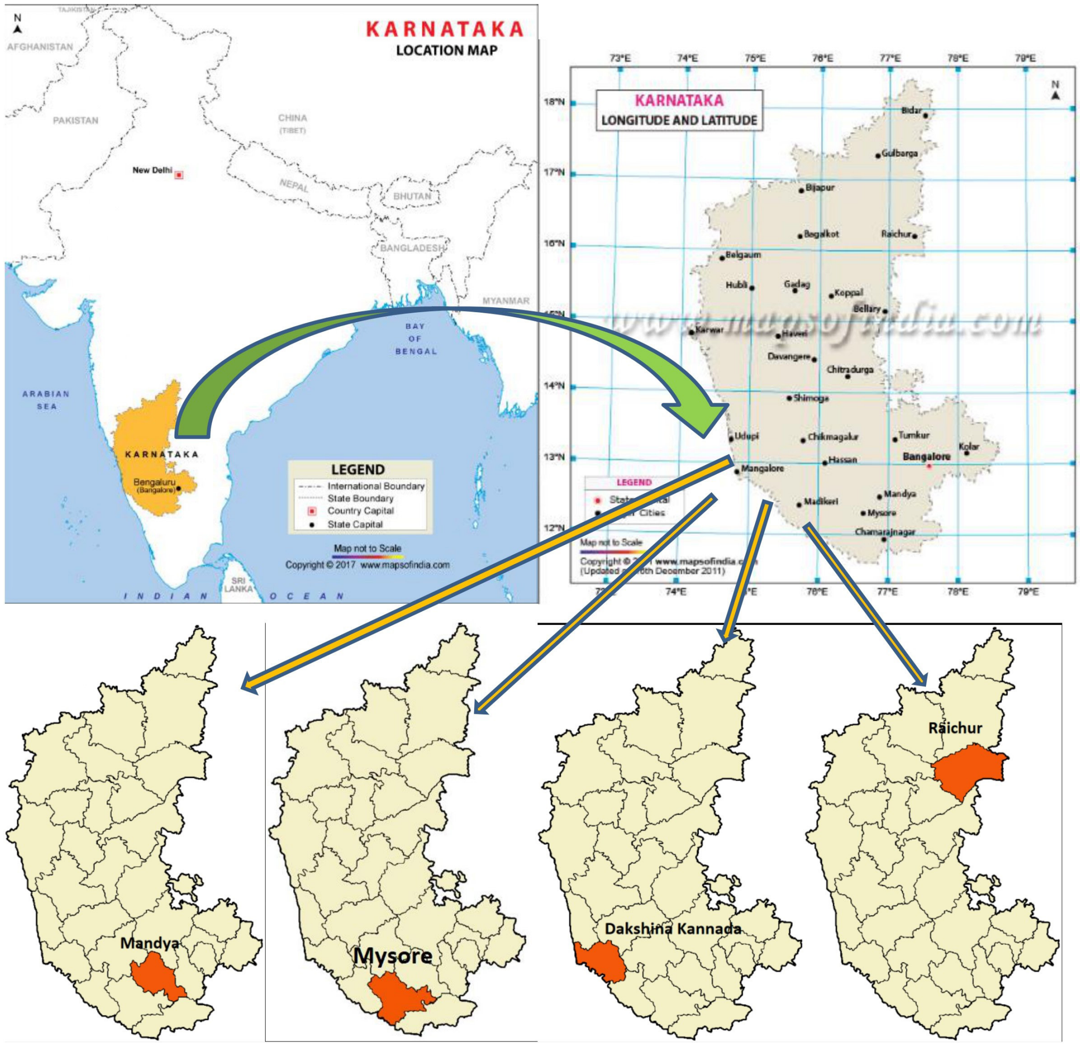

Figure 1. Location map of the four different soils collected.

Figure 2. Landslide at Coorg.

Two of the soils were cohesive, while the other two were cohesion-less and non-plastic. The Unified Soil Classification System (USCS) classified S-1 (BCS) as clay with high plasticity, S-2 (RS) as clay with low plasticity, S-3 (SS) as poorly graded sandy soil, and S-4 (LS) as silty sand (SM). The cohesiveness (c) and angle of internal friction (ϕ) were determined using the direct shear test. The woven jute-geotextile, which weighed 625 g per square meter was utilized as a protective layer in the current study.

2.3 Model construction

For the current investigation, eight cylindrical small scale models with dimensions of 600 mm in diameter and 800 mm in height were built. In order to depict a critical and conservative slope condition that is frequently linked to severe erosion during rainfall, a 45° slope angle was chosen in the current investigation. Because slopes at or around 45° roughly resemble the angle of internal friction of many natural soils, they are especially vulnerable to shear strength losses brought on by pore pressure development and moisture intrusion. Steeper slopes increase erosion rates and fasten failure onset, according to earlier experimental and analytical research. Meaningful relative comparisons between planted and bare systems are made possible by using a 45° slope. In order to reduce water stagnation and promote drainage, the model's base was removed and set on the ground to come in contact with the soil in the model. For the present investigation, the soil was placed in test setup using a standard compaction method as employed by Aziz & Islam (2023). A 2.5 kg hammer with a 30-cm fall height was used to compact each 7.5 cm layer 12 times in order to maintain the density of the prepared models near the in-situ density. The average moisture content of the eight models, which had soil samples S-1, S-2, S-3 and S-4 was found to be 30%, 13%, 10% and 15%, respectively.

The model was first left bare in order to examine the erosion in each of the four soil types. After that, vetiver was planted in four of them, and in four more, a single layer of jute geotextile was placed along with vetiver. Summary of the prepared plots for the study is tabulated in Table 2. According to a study by Islam et al. (2021) on scale models of hill tracts, the greatest runoff reduction was produced by 150 mm centre to centre (*c/c*) spacing between rows and columns of vetiver when compared to the control run. The current study's 150 mm *c/c* spacing and corresponding number of rows and columns were selected based on earlier research.

Using a wooden peg, holes of 4 cm in diameter were made in 8 models in order to plant these plants. Additionally, in order to prevent dislocation, the jute geotextile was fastened to the model's sloping surface for models M-5, M-6, M-7 and M-8.

The primary objective of the investigation is to assess the relative efficacy of various erosion control strategies (vetiver grass and jute geotextile) under the same circumstances rather than forecasting absolute field performance.

2.4 Calibration of drip-type artificial rainfall simulator

In the current investigation, a drip-type portable rainfall simulator with a 700 mm diameter perforated circular steel tray and a pipe-based water supply was utilized. The raindrop fall was two meters high. Additional comprehensive parameters are available from Chowdhury et al. (2017). In the study bigger drop sizes might have overestimated erosion while producing more impact energy.

The current study chose to model the extremely vulnerable conditions by achieving a total rainfall of 200 mm in 30 minutes, the intensity was 400 mm/hr, High (H). Rainfall of 100 mm and 50 mm, with intensities of 200 mm/hr, Moderate (M) and 100 mm/hr, Low (L) respectively, was also considered in the current study in order to determine the variance in erosion with varying rainfall intensities. The soil layer was 0.8 meters deep at the crest and 0.2 meters deep at the slope's base. Additionally, the hollow base of the model prevented water from standing still. As a result, the soil layer could support the artificial rainfall. To create simulated rainfall with the necessary intensity, numerous experiments were conducted collecting the rainfall into the empty tray by adjusting the inflow of water from pipe to the perforated steel tray with the help of inlet water valve fit at the bottom of the water supply line and calibrating the rainfall simulator, by determining the water inflow required from the opening by the valve adjustment to simulate the required rainfall intensity. The applied intensity was calculated using the volume of water collected in the tray kept below the perforated steel tray during a predetermined period of time.

Table 2. Summary of the prepared plots.

Model No.	Soil type	Protective layers	Layout of planting (C *x* R) 150 c/c	Moisture content	Density
1	S-1	Vetiver	4 *x* 5	31	10.50
2	S-2	Vetiver	4 *x* 5	14	15.20
3	S-3	Vetiver	4 *x* 5	10.5	12.40
4	S-4	Vetiver	4 *x* 5	16	11.60
5	S-1	Vetiver + Jute Geotextile	4 *x* 5	31	11.00
6	S-2	Vetiver + Jute Geotextile	4 *x* 5	14	15.50
7	S-3	Vetiver + Jute Geotextile	4 *x* 5	10.5	12.50
8	S-4	Vetiver + Jute Geotextile	4 *x* 5	16	12.8

After 30 minutes, the water collected in the tray was measured, trials were done till the rainfall intensity was obtained by judging the inlet valve adjustment and was been able to fix the inflow of water to simulate the required rainfall intensity for the study.

2.5 Rainfall simulation on the models

Each model had a 30 minutes rainfall simulation, providing 200 mm, 100 mm, and 50 mm of total rainfall. To reduce the amount of rainfall lost throughout the simulations, the top surface of the models was completely covered by its vertically projected area. Along the edge of the model's front side, a PVC-covered sheet was created to route the runoff water and the eroded soil to the tray, ensuring their minimal loss. At every 10 minutes intervals, samples of eroded soil and discharge were taken. The accumulated runoff water was left aside for two to three days to allow the suspended soil particles to settle and collected samples were filtered, and then the volume of the clean runoff was measured and the weight of eroded soil weighed after oven drying for 24 hours. This helped measuring the runoff coefficient (C) by knowing the volume of rainfall (Equation 1).

$$C(\%) = \frac{SR}{p} \tag{1}$$

where: SR is the volume of surface runoff (m^3), p is the volume of rainfall (m^3), and C is the runoff coefficient (%).

2.6 Determination of vetiver properties

Because vetiver plays a significant role in reducing erosion and runoff, its root characteristics were measured such as diameter of root and root density etc. In order to verify its growth trend under the current soil conditions, the growth was tracked for 90, 180, 270, and 360 days following the initial planting in February 2023. The grass was watered twice a day with potable water, and then twice a week after a month, when it was observed to be growing healthily. However, no more water was supplied during the dry season Ramakrishnegowda et al. (2025).

2.7 Determining erodibility of soil

The Universal Soil Loss Equation (USLE: Equation 2) was used to determine the erodibility of four different soil types in order to examine how they behaved under bare and vegetated circumstances with a 45° slope angle.

$$A = R \times K \times LS \times C \times P \tag{2}$$

$$R = \frac{E \times I_{30}}{100} \tag{3}$$

where R is the rainfall erosion index as determined by Equation 3 (RUSLE), the RUSLE rules have been used to calculate the remaining four factors. In all cases, the vegetative cover factor C (which takes into account no vegetation cover) was 1.0 for all four bare soils, 0.04 for plants tested for 90 days, and 0.01 for plants tested for 365 days based on the vegetation growth. In addition, the erosion control practice factor P (which takes into account irregular cuts along the slope) was 1.0 for bare soils, 0.1 for S-1, 0.2 for S-2, 0.3 for S-3, and 0.25 for S-4. On the other hand, the slope length and steepness factor LS varied with slope height and length, whereas the soil erodibility factor, K, varied with soil type, calculated using the RUSLE guidelines.

3. Results and discussion

3.1 Soil loss in varying vegetated conditions

Table 3 shows that, among the eight models with poorly graded sand (S-3), the unprotected model produced the most soil loss. S-1, S-2, and S-4 produced the runoff less than S-3, as shown by the observable degraded surface, following the rainfall simulation in Figure 3 and the oven dried collected runoff samples justifies it.

When measured for 90 days of plant development, the soil loss for models M-1, M-2, M-3, and M-4 is decreased by 65% when vegetation was added to the same four models of the bare soil. Similarly, when tested for 365 days of plant growth, models M-1, M-2, M-3, and M-4 reduce soil loss by 99.9%, 99.8%, 99.7%, and 99.75%, respectively.

Table 3. Calculated soil loss per event (g) under various condition and soil.

Soil Type	Soil Loss g/event								
	Soil Alone			3 Month Vetiver			1 Year Vetiver		
	H	M	L	H	M	L	H	M	L
Black Cotton Soil	18.03	8.33	3.82	6.31	2.92	1.34	0.018	0.0083	0.0038
Red Soil	21.06	9.73	4.47	7.37	3.41	1.56	0.042	0.019	0.0089
Sandy Soil	22.60	10.44	4.79	7.91	3.65	1.68	0.068	0.0313	0.014
Laterite Soil	12.16	5.62	2.58	4.26	1.97	0.90	0.030	0.014	0.0064

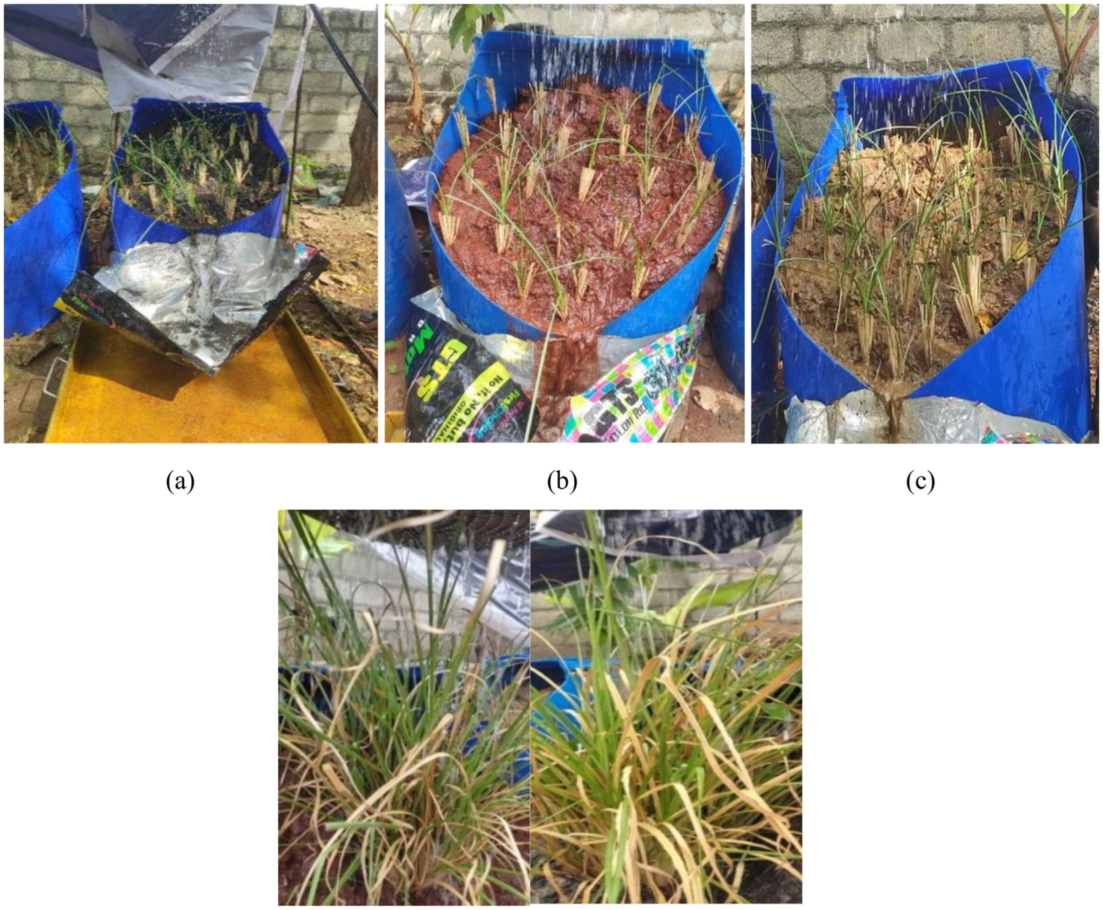

Figure 3. Eroded soil and runoff from model at different growth rate (a) Testing on BCS (b) Testing on LS (c) Testing on SS (d) 360d vetiver in red soil (e) 360d vetiver in BCS soil.

Bare soil has a high rate of soil detachment, while vegetated soil has a lower rate. As a result, the vegetated soil exhibits around 65% lower soil detachment rates than the bare soil during a 90 days period and 99% lower rates over a 365 days period. Vetiver grass (Chrysopogon zizanioides) is arranged linearly along contour lines on a slope to create a dense, continuous vegetative barrier known as a vetiver hedge. Surface hedges decrease soil detachment during rainstorm events by lowering runoff velocity, increasing sediment deposition upslope of the hedge, and capturing nutrient-rich fine particles carried by overland flow (Islam et al., 2021). The hedges can be observed in the 365 days. Vetiver hedges can be used as an efficient natural option for reducing erosion in slopes that experience heavy rainfall. Bioengineering solution for slope stabilization, enhances unsaturated soil behaviour and limiting rainfall-induced instability (Satyanaga & Rahardjo, 2019)

Splash erosion, which is the first erosion in all models, is brought on by raindrop impact that separates soil particles (Quansah, 1981). Extreme rainfall intensities produce droplets with a larger median diameter and higher kinetic energy, which lead to maximal erosion, as per Chen et al. (2018). The current study replicated such an intense rainfall condition in addition to moderate and low rainfall, where the canopy prevents the direct impact of raindrops on the soil, hence providing resistance to the mechanical action. As a result, models M-1, M-2, M-3, and M-4 with vegetation experienced less soil loss and less raindrop kinetic energy than models M-1, M-2, M-3, and M-4 with bare soil. Because the created models had densities more in line with in-situ conditions, the generated erosion has been calculated to be nearer to actual conditions.

3.2 Runoff and infiltration in varying vegetated conditions

Percentage decrease in runoff in each model as well as the cumulative runoff and soil loss following 30 minutes of rainfall is tabulated in Table 4. The maximum runoff produced by the bare model is 0.07488 m^3 with S-1, 0.07104 m^3 with S-2, 0.06912 m^3 with S-4, and 0.0576 m^3 with S-3.

Table 4. Percentage decrease in runoff in each model as well as the cumulative runoff and soil loss, following 30 minutes of rainfall.

Model number	Soil sample	Soil loss g/event			Cumulative runoff (m^3)			Runoff coefficient (%)		
		Soil alone								
		200	100	50	200	100	50	200	100	50
M-1	S-1	18.034	8.332	3.824	0.073	0.033	0.013	95.000	85.000	70.000
M-2	S-2	21.065	9.733	4.467	0.063	0.026	0.012	82.500	68.000	64.000
M-3	S-3	22.597	10.441	4.791	0.038	0.019	0.008	50.000	50.000	40.000
M-4	S-4	12.157	5.617	2.578	0.058	0.027	0.011	75.000	70.000	56.000
Model number	**Soil sample**	**Soil loss g/event**			**Cumulative runoff (m^3)**			**% Reduction of Runoff**		
		3 months Vetiver								
		200	**100**	**50**	**200**	**100**	**50**	**200**	**100**	**50**
M-1	S-1	6.3119	2.9164	1.3384	0.0653	0.0265	0.0108	10.5263	18.8235	20.0000
M-2	S-2	7.3729	3.4066	1.5634	0.0557	0.0215	0.0100	12.1212	17.6471	18.7500
M-3	S-3	7.9090	3.6543	1.6770	0.0326	0.0161	0.0065	15.0000	16.0000	15.0000
M-4	S-4	4.2550	1.9660	0.9022	0.0492	0.0223	0.0088	14.6667	17.1429	17.8571
Model number	**Soil sample**	**Soil loss g/event**			**Cumulative runoff (m^3)**			**% reduction of Runoff**		
		12 months Vetiver								
		200	**100**	**50**	**200**	**100**	**50**	**200**	**100**	**50**
M-1	S-1	0.0180	0.0083	0.0038	0.0576	0.0253	0.0100	21.0526	22.3529	25.7143
M-2	S-2	0.0421	0.0195	0.0089	0.0480	0.0200	0.0088	24.2424	23.5294	28.1250
M-3	S-3	0.0678	0.0313	0.0144	0.0269	0.0146	0.0056	30.0000	24.0000	27.5000
M-4	S-4	0.0304	0.0140	0.0064	0.0422	0.0200	0.0077	0.0077	25.7143	28.5714

For a 200 mm rainfall, the reduction in runoff produced by the four vegetated models is 0.0653 m^3 with S-1, 0.0557 m^3 with S-2, 0.0492 m^3 with S-4, and 0.0326 m^3 with S-3. The greatest runoff produced by the bare model is 0.0326 m^3 with S-1, 0.0261 m^3 with S-2, 0.0269 m^3 with S-4, and 0.0192 m^3 with S-3. For a 100 mm rainfall, the reduced runoff produced by the four vegetated models is 0.0265 m^3 with S-1, 0.0215 m^3 with S-2, 0.0223 m^3 with S-4, and 0.0161 m^3 with S-3. For a 50 mm rainfall, the greatest runoff produced by the bare model is 0.0134 m^3 with S-1, 0.0123 m^3 with S-2, 0.0108 m^3 with S-4, and 0.0077 m^3 with S-3 and the reduced runoff produced by the four vegetated models is 0.0108 m^3 with S-1, 0.01 m^3 with S-2, 0.0088 m^3 with S-4, and 0.0065 m^3 with S-3. The cumulative runoff is lower for 90-day grown vetiver assessed for soil erosion than for model bare soils, and vegetation reduces the runoff by an average of 10–20% in S-1, 12–18% in S-2, 15–16% in S-3, and 14–17% in S-4. Figure 4 illustrates how, despite maintaining constant rainfall intensity throughout time, the runoff from models increased steadily.

A fraction of the water that falls during a rainfall events seeps into the soil, while the remainder creates runoff. In the vegetated models, less runoff is produced since less rainwater reaches the slope surface due to the canopy's ability to intercept it. The decreased runoff coefficients for the vegetated models suggest that the grass cover creates surface roughness and lowers runoff velocity (Donjadee & Tingsanchali, 2013). Additionally, the permeability and filtration capacity rise when the vetiver penetrates the soil through its roots (Saleh et al., 2018). The aforementioned factors work together to decrease initial and cumulative runoff.

The current study's findings indicate that runoff for 90 days vetiver in highly clayey soil from high to low intensity rainfall is reduced by 10% to 20%, while runoff for 365 days vetiver is reduced by 21% to 26%. In contrast, low compressive clayey soil, such as red soil, is reduced by 12% to 19% from high to low intensity rainfall for 90 days vetiver, and 365 days vetiver is reduced by 24% to 29%. For 90 days vetiver, the runoff was reduced by 15% to 16% in poorly graded sandy soil from high to low intensity rain fall, and it was reduced by 24% to 30% for 365 days vetiver. Lastly, for laterite soil, which is classified as silty sand, the runoff was reduced by 14% to 17% for 90 days vetiver from high to low intensity rain fall, and by 25% to 29% for 365 days vetiver. It may be deduced that less runoff occurs in poorly graded sandy soil, laterite soil, low compressible clay soil, and black cotton soil, with the least reduction. The main factors influencing the decrease in runoff after vetiver reinforcement are surface flow resistance, root-induced porosity changes, and soil permeability. Due to their high infiltration capacity, which is strengthened by vetiver root pathways, coarse-grained soils, such as silty sand (laterite soil) and poorly graded sand, significantly reduce runoff. Because of their stable aggregation and efficient root penetration, red soil (low compressible clay) exhibits a minor improvement. On the other hand, because of their limited permeability, swelling behavior and susceptibility to surface sealing, which limit infiltration despite root reinforcement, fine-grained soils like black cotton soil exhibit relatively lesser runoff reduction.

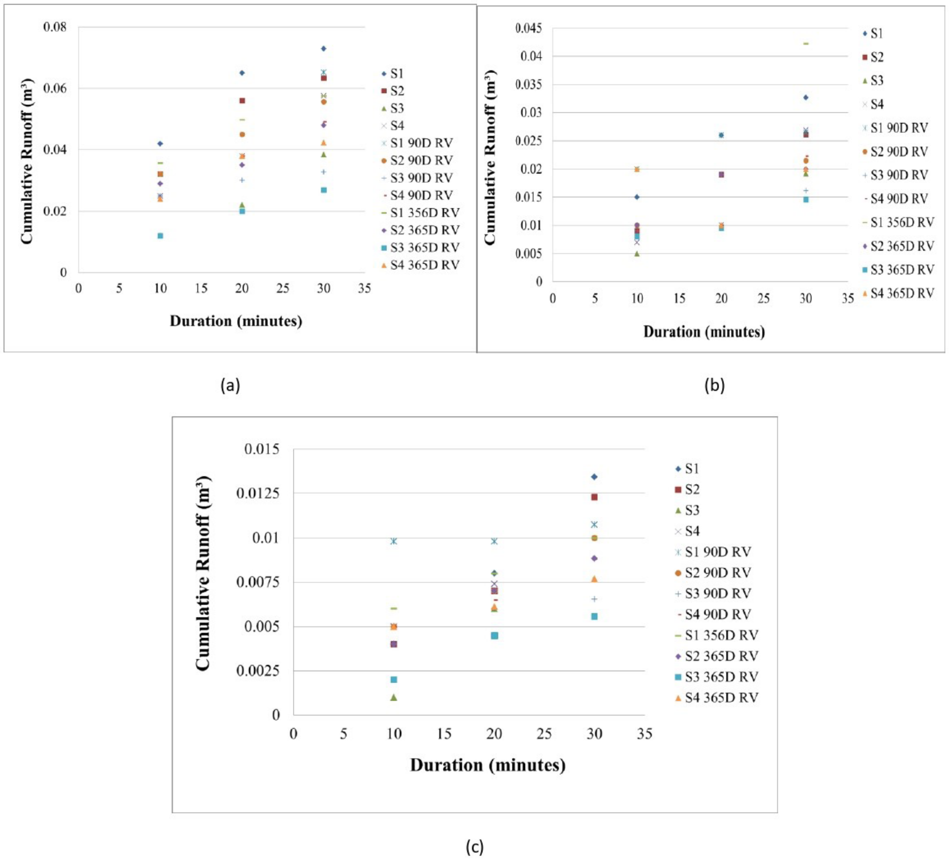

Figure 4. Runoff (m³) for both bare and planted models with varying rainfall intensities and rainfall durations (min) (a) under 200 mm rainfall, (b) under 100 mm rainfall, (c) under 50 mm rainfall.

Table 5. Runoff coefficient and cumulative runoff following 30 minutes of precipitation for all models with an extra layer of Jute geotextile protection.

Model number	Soil sample	Cumulative runoff (m³)			Runoff coefficient (%)			% Reduction of Runoff		Soil loss g/event	
		Soil alone	Soil + JGT	S + V + JGT 365D	Soil alone	Soil + JGT	S + V + JGT 365D	Soil + JGT	S + V + JGT 365D	Soil + JGT	S + V + JGT 365D
		200			200			200		200	
M-5	S-1	0.07	0.07	0.05	95.00	95.50	63.00	- 0.53	34.03	17.0	0.01
M-6	S-2	0.06	0.07	0.05	82.50	87.50	60.00	- 6.06	31.43	16.0	0.03
M-7	S-3	0.04	0.05	0.03	50.00	62.50	33.50	- 25.00	46.40	19.0	0.05
M-8	S-4	0.06	0.06	0.04	75.00	80.00	46.00	- 6.67	42.50	9.00	0.02

3.3 Effect of the composite system of JGT and vetiver on erosion and runoff reduction

Together with vetiver grass, jute geotextile was the most efficient erosion reduction technique for models M-5, M-6, M-7, and M-8, reducing soil erosion by 30–50% as compared to bare soil. Adopting jute geotextile increases runoff from models M-5, M-6, M-7, and M-8. The results of this extra layer of protection are summarized in Table 5, and variations are shown in Figure 5. As per the experimental results vetiver alone has provided good results which could be sufficient to lean towards vetiver.

Through vetiver growth, JGT's impact to erosion control does not show much variation at the end. A layer of geotextile serves as temporary protection for the soil against rainfall erosion in the early stages because vetiver takes time to grow and to fully control the erosion (Likitlersuang et al., 2020). The JGT lowers the kinetic energy by preventing raindrops from directly interacting with the soil surface (Li et al., 2020). As vetiver develops,

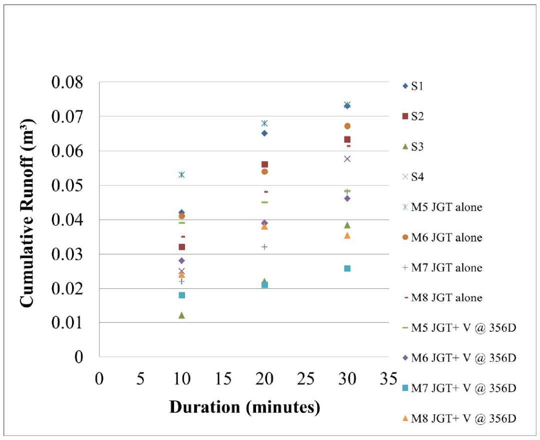

Figure 5. Runoff (m^3) of the vegetated, bare, and additional layer of JGT models after 30 minutes of intense rainfall.

the canopy and the geotextile layer both lower the kinetic energy of raindrops, which lessens the impact of splash erosion caused by rainfall. Therefore, the least amount of erosion was found in models M-5, M-6, M-7, and M-8. In contrast to traditional vegetation-based erosion control methods, the combination of Vetiver grass and jute geotextile offers a dual-function system that combines short-term surface protection with long-term root reinforcement. The current method tackles the crucial early-stage susceptibility of slopes by using jute geotextile to lessen soil detachment and runoff effects, whereas earlier research mostly concentrated on vegetation-induced stabilization. Furthermore, a composite reinforcement mechanism is introduced by the interaction between the growing root systems and the geotextile matrix, improving overall erosion resistance. When compared to plant alone, this hybrid, biodegradable system provides better hydraulic and mechanical performance, making it a more complete and long-lasting erosion control method.

From Figure 5, initial runoff for models M-5, M-6, M-7, and M-8 is higher than for the bare model (M-1, M-2, M-3, and M-4) before planting the vetiver. This could be because jute geotextile is used in these models. Because geotextiles may retain moisture, it's still possible that the vetiver grass will be soaking the geotextile at the beginning of the rainstorm (Aziz & Islam, 2023). Because of this, more runoff was initially produced and the JGT and soil may have achieved their infiltration capacity earlier.

3.4 Soil loss and runoff in varying soil conditions

Under similar conditions and with a one-year plant growth period, model M-1 produced an erosion load that was 99.9% lower than models M-2, M-4, and M-3, which were 99.8%, 99.75%, and 99.7% lower, respectively, under the same rainfall amount. Furthermore, from Figure 6, the erodibility of model M-1 is lower than that of model M-4, model M-4 is lower than M-2, and model M-2 is lower than model M-3 at the various rainfall intensities, vegetation plantings, and durations. For the vegetated models, the average cumulative runoff was 0.0269 m^3 for S-3 whereas it was almost 53.3% less for model S-1, S-4 was 0.0422 m^3 whereas it was almost 26.7% less for S-1, S-2 was 0.048 m^3 whereas it was almost 16.7% less for model S-1.

Further, M-1 had 42% greater erodibility, M-3 had 32% more erosion, and M-4 had 46% more erosion than M-2, even though the vegetative cover in the first four models was the same. Silt content is regarded as one of the most crucial elements for assessing soil erodibility (Goldman et al., 1986). Additionally, the mineral composition might also be responsible, which could be the subject of future research. For soil S-4 in its bare state, this cause might have resulted in decreased infiltration, increased runoff, and increased erosion. In the present study's low erosion results for the vegetated model on high compressible clay, laterite soil, red soil, and poorly graded sand with a higher proportion of fine sand particles. The reduction in erosion observed in vetiver-reinforced soils is primarily governed by root-induced cohesion, canopy protection and increased surface roughness. Fine-grained soils such as high compressible clay exhibit low erosion despite relatively higher runoff due to strong root binding and reduced particle detachment. Lateritic and red soils demonstrate effective erosion control due to stable aggregation and enhanced root–soil interaction. In poorly graded sand with fines, improved cohesion and root anchorage contribute to reduced soil loss. These findings indicate that erosion resistance in vegetated systems is influenced more by soil reinforcement and surface protection mechanisms than by runoff reduction alone. The soil's enhanced cohesiveness (Vannoppen et al., 2017; Owino et al., 2006) and the size of the particles that have contributed to this trend could be the reason for these results. The results are further validated by the RUSLE computations. Out of the five regulating factors utilized for RUSLE, the value of K is what causes this variation in sediment yields, while the other four factors remain more or less same due to the similar vegetation and type of growth in all models. K is a metric that depends on the soil's organic matter and particle size analysis. The degradation increases with the K value. According to Vannoppen et al. (2017), bare cohesive soils had lower rates of soil detachment than bare cohesion-less soil and the additional cohesion was found to be useful in reducing detachment, particularly for cohesion-less soil. Root reinforced soil exhibits improved hydraulic and mechanical behaviour (Rahardjo et al., 2020).

4. Conclusions

The role of vetiver grass in controlling erosion and surface runoff under artificially simulated rainfall of three different intensities was examined in a small-scale

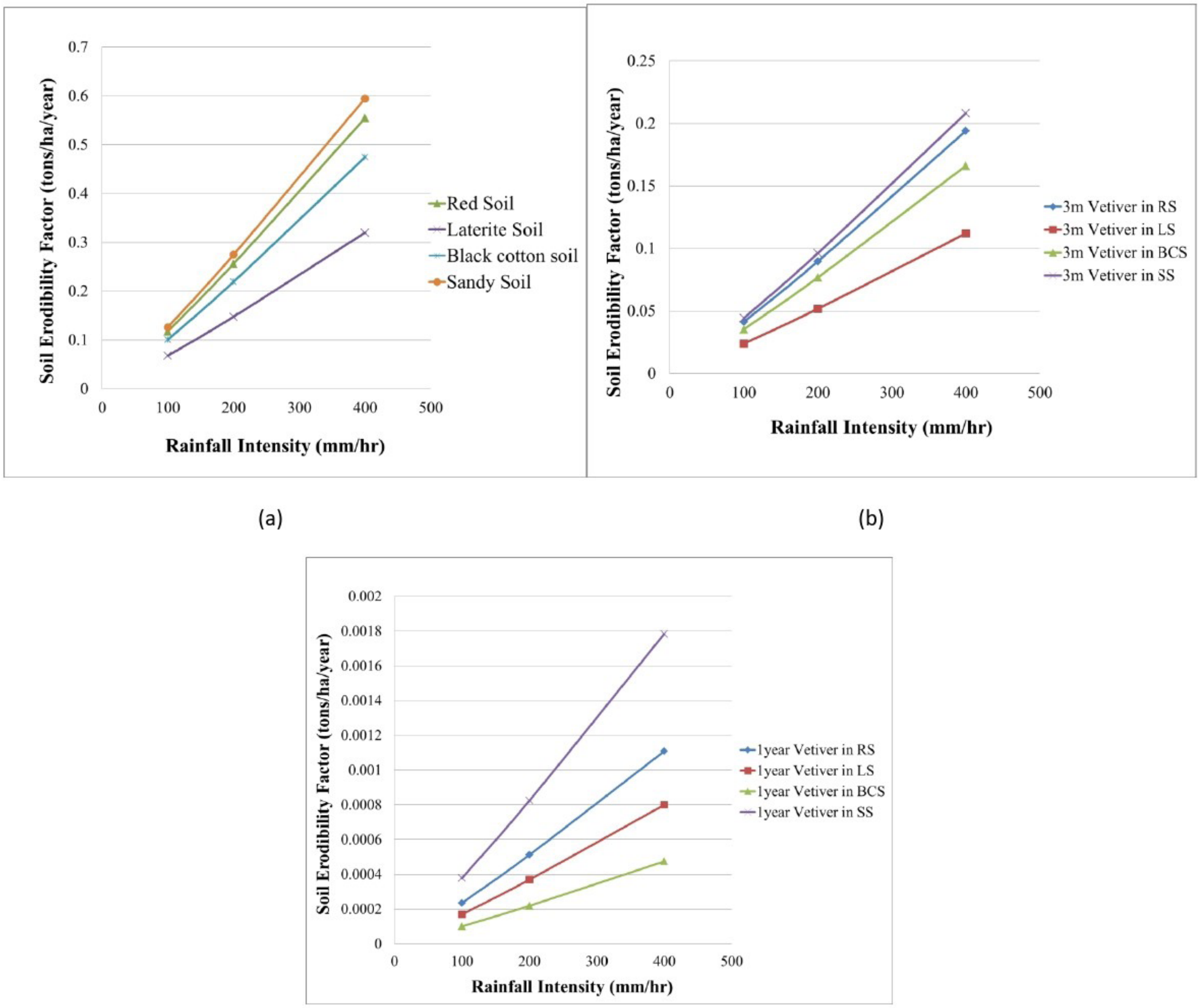

Figure 6. Soil erodibility with varying rainfall durations and intensities (a) soil alone (b) 3 month vetiver in different soil (c) 1 year vetiver in different soil.

model research. The present investigation has yielded the following findings:

In comparison to bare soil, vetiver decreased the erosion load by approximately 95% to 99% for clayey soil, 99.7% for laterite soil, 99.8% for red soil, and 98% for sandy soil. The vetiver grass must be given enough time to grow an ideal root system, which reduces soil loss.

The creation of a dual rain protection system made the vetiver and jute geotextile composite system very effective at reducing erosion in initial days supporting vetiver growth.

In comparison to the bare soil, vegetation decreased cumulative runoff by 21%, 24%, 26% and increased infiltration by 25%, 37%, 45% for black cotton soil, red soil and laterite soil respectively. Nonetheless, poorly graded sand has been found to have higher percentages under the same vegetative cover, increasing infiltration by 60% and producing nearly cumulative runoff by 30%. As a result, vetiver works best to conserve soil and water in coarse-grained soil that is primarily composed of sand.

In each of the four soils, runoff and erodibility rose linearly as rainfall intensity increased. Consistent cumulative erodibility was attained after a specific amount of rainfall.

Vetiver is essential for lowering soil loss and surface runoff during periods of rainfall. While the root network increases infiltration capacity and lowers overland flow velocity, the plant canopy aids in dispersing the impact of raindrops. Because of this, slopes reinforced with vetiver show reduced rates of erosion and enhanced resistance to instability caused by rainfall, especially when the root system is established and the jute geotxtile is added in the early stages while the vetiver is still unable to do so.

Ideal for slopes that are prone to erosion and it is ideal for long-term slope protection and erosion management in an environmentally conscious engineering context since it gradually creates a self-sustaining vegetative barrier.

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Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contributions

Dhanraj Ashwini: conceptualization, methodology, experimental setup, data analysis, validation, writing – original draft, reviewing and editing, investigation, resources, software. Chittanahalli Ramakrishnegowda: conceptualization, supervision, reviewing.

Data availability

The datasets generated and analysed in the course of the current study are available with the corresponding author upon experimentation results.

Declaration of use of generative artificial intelligence

This work was not prepared with the assistance of Generative Artificial Intelligence (GenAI).

List of symbols and abbreviations

c	Cohesion
c/c	Center to center
p	Volume of rainfall (m^3)
P	Support practice factor
A	Average annual Soil loss
ASTM	American Society for testing and Materials
BCS	Black Cotton Soil
BIS	Bureau of Indian Standards
C	Cover management factor
C x R	Column x Rows
C (%)	Runoff coefficient
CH	Clay with High Compressibility
CL	Clay with Low Compressibility
D	Days
E	Kinetic energy of rainfall (MJ/ha·mm)
H	High
I_{30}	Maximum 30-min rainfall intensity (mm/hr)
IS	India Standard
JGT	Jute geotextile
K	Soil erodibility factor
L	Low
L	Slope length factor
LS	Steepness factor
LS	Laterite soil
M	Medium
M	Model
MIT	Maharaja Institute of Technology
PVC	Polyvinyl chloride
R	Rainfall-runoff erosivity factor
RS	Red Soil
RF	Rainfall
RUSLE	Revised Universal Soil Loss Equation
S	Sample
S	Slope steepness factor
S	Soil
SM	Silty sand
SP	Poorly graded sand
SS	Sandy Soil
SR	Volume of surface runoff (m^3)
USCS	Unified Soil Classification System
V	Vetiver
V:H	Vertical to Horizontal
ϕ	Angle of Internal friction

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