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Sustainable Ravine Slope Stabilization in the Bundelkhand Region of India Using Bio-Engineering and Geosynthetic Reinforcement

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Abstract: Ravine erosion and slope instability pose serious environmental and geotechnical challenges in the semi-arid Bundelkhand region of Uttar Pradesh, India. Undulating topography, shallow lateritic soils, intense monsoonal runoff, and sparse vegetation contribute to rapid gully expansion and land degradation. This study evaluates the effectiveness of sustainable slope stabilization techniques combining bio-engineering (vetiver grass, Chrysopogon zizanioides) with geosynthetic reinforcement (non-woven geotextiles) for ravine slope protection. Field investigations were conducted in representative ravine systems across Jhansi, Lalitpur, Banda, and Mahoba districts. Soil samples were analyzed for index and strength properties, and slope stability was assessed using limit equilibrium analysis (Bishop's simplified method) under rainfall-induced saturation conditions. Results indicate that bio-engineered slopes reinforced with geotextiles achieved a 55–75% reduction in surface erosion and improved the factor of safety (FoS) from 1.10–1.25 (untreated) to 1.50–1.65 under critical saturated conditions. The integrated system also enhanced soil cohesion through root reinforcement and reduced pore water pressure via transpiration and drainage. The study demonstrates that bio-geosynthetic systems provide a cost-effective (approximately 40-60% lower than conventional rigid structures), environmentally sustainable alternative to concrete retaining walls and stone pitching for ravine stabilization in semi-arid regions. Long-term benefits include ecological restoration, biodiversity enhancement, and improved land productivity.

Keywords: Ravine erosion; Bio-engineering; Vetiver grass; Geotextiles; Slope stability; Bundelkhand; Sustainable soil stabilization; Root reinforcement

I. INTRODUCTION

Soil erosion and ravine formation represent critical land degradation processes in semi-arid tropics, particularly in the Bundelkhand plateau of India. The region, spanning parts of Uttar Pradesh and Madhya Pradesh, faces severe gully erosion due to a combination of factors: shallow soils overlying Precambrian hard rock, steep ravine side slopes (often 25°–45°), intense monsoonal rainfall (800–1000 mm annually, 85% in June–September), and low vegetative cover. Progressive ravine encroachment results in annual loss of cultivable land (estimated at thousands of hectares regionally), increased sedimentation in rivers like the Yamuna and Betwa, reduced groundwater recharge, and threats to rural infrastructure and livelihoods.

Conventional engineering measures—such as concrete retaining walls, gabions, or extensive stone pitching—are effective in the short term but suffer from high costs, poor adaptability to differential settlement, aesthetic intrusion, and high carbon footprints. These rigid structures often fail under seismic activity or extreme rainfall common in the region and require frequent maintenance.

In contrast, bio-engineering integrates living vegetation with mechanical elements to provide immediate and long-term stabilization. Vetiver grass is particularly suited due to its deep, fibrous root system (up to 3–5 m), high tensile strength (average 75 MPa), tolerance to drought, poor soils, and heavy metals, and its ability to form dense hedges that reduce runoff velocity and trap sediment. Non-woven geotextiles complement this by offering immediate surface protection against raindrop impact, filtration, separation, and additional tensile reinforcement while allowing vegetation establishment.

This study integrates these approaches in field trials across Bundelkhand ravines. It quantifies improvements in erosion control, shear strength parameters, and slope stability using laboratory tests and numerical modelling. The research addresses a gap in region-specific, field-validated data for semi-arid lateritic soils.

A. Objectives

1) Characterize ravine soils and erosion processes in the study area.
2) Evaluate the performance of vetiver + geotextile systems in reducing erosion and improving stability.
3) Compare cost-effectiveness and environmental benefits with conventional methods.
4) Provide guidelines for scalable implementation in similar semi-arid landscapes.

II. STUDY AREA DESCRIPTION

A. Regional Setting

The Bundelkhand region lies between the Indo-Gangetic plains (north) and Vindhyan ranges (south), underlain by the Bundelkhand Craton (Archean granites, gneisses, and quartzites). Topography is undulating with plateaus, inselbergs, and deeply incised ravines. Climate is semi-arid with high temperature extremes (up to 48°C in summer, down to 5°C in winter) and erratic rainfall. Evapotranspiration exceeds precipitation for much of the year, exacerbating soil moisture deficits.

Figure 1: Location map of the Bundelkhand region showing study districts (Jhansi, Lalitpur, Banda, and Mahoba)

B. Soil and Erosion Characteristics

Soils are predominantly red lateritic sandy loams to loams with low organic carbon (0.07–0.78%), moderate plasticity, and low cohesion. They exhibit poor aggregate stability, high erodibility (K-factor often >0.4), and are underlain by impermeable hardpan or bedrock at shallow depths (0.5–2 m). Ravine slopes average 25°–45°, with depths reaching 10–30 m. Dominant processes include sheet and rill erosion on upper slopes transitioning to gully headcut advancement. Annual soil loss can exceed 20–50 t/ha in untreated areas.Field surveys documented ravine geometry, drainage patterns, and existing sparse vegetation (mainly thorny shrubs and grasses).

III. MATERIALS AND METHODS

This section describes the study area characteristics, field investigations, laboratory testing, stabilization techniques, and analytical methods employed. The research combined field observations, laboratory analysis, and numerical modelling to evaluate the performance of the bio-geosynthetic stabilization system.

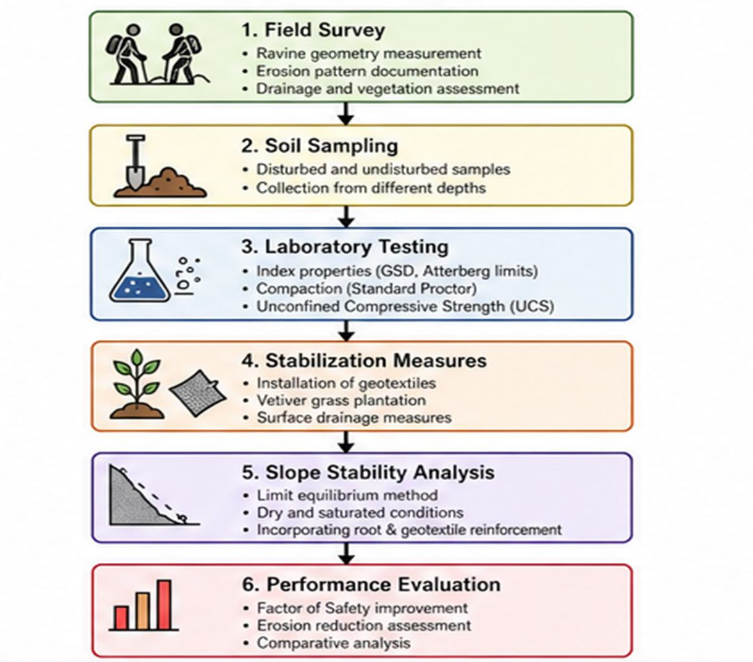

Figure 2: Methodology flowchart for ravine slope stabilization study

A. *Study Area*

The study was conducted in representative ravine systems across four districts of the Bundelkhand region in Uttar Pradesh: Jhansi, Lalitpur, Banda, and Mahoba. The region features a semi-arid climate with annual rainfall of 800–1000 mm, concentrated mostly during the monsoon season (June–September). The topography consists of undulating plateaus dissected by deep ravines with side slopes typically ranging from 25° to 45°. Soils are predominantly shallow red lateritic sandy loams overlying Precambrian hard rock, characterized by low organic matter, poor aggregate stability, and high erodibility.

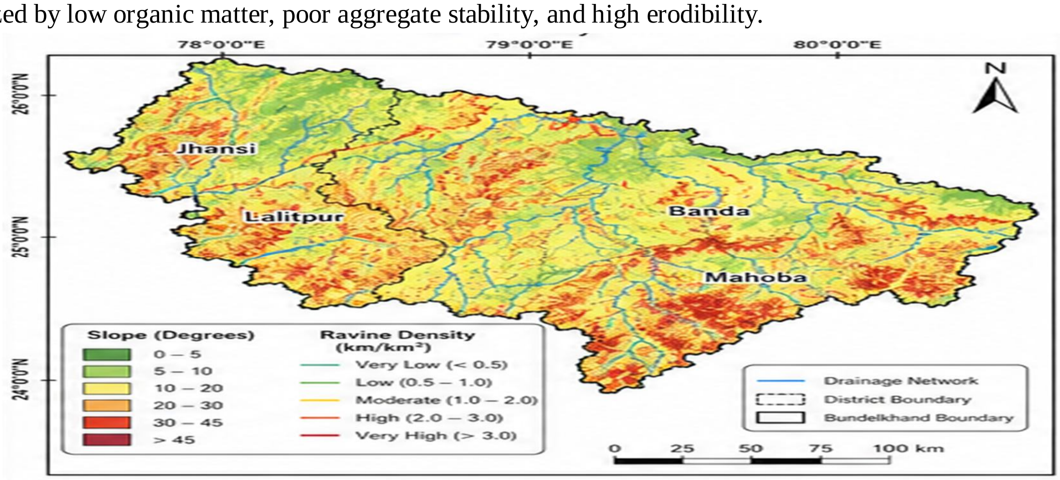

Figure 3: Geomorphology and ravine density map of the study area

B. *Field Investigations*

Field surveys were carried out during 2023–2025. At each site, the following parameters were documented:

1) Ravine geometry (depth, length, slope angle using clinometer and GPS).
2) Surface erosion features (sheet, rill, and gully erosion).
3) Existing vegetation cover and drainage patterns.
4) Runoff pathways.

Disturbed and undisturbed soil samples were collected from multiple depths (0–0.5 m, 0.5–1.0 m, and >1.0 m) along transects on both treated and control slopes.

C. Laboratory Testing

All laboratory tests followed relevant Indian Standards (IS). Key tests included:

1) Grain size distribution (sieve and hydrometer analysis).
2) Atterberg limits (liquid and plastic limits).
3) Standard Proctor compaction test.
4) Unconfined compressive strength (UCS).
5) Direct shear tests (on untreated and root-reinforced samples).
6) Soil permeability and organic carbon content.

Additional tests were performed on reinforced samples to quantify improvements due to vetiver root inclusion and geotextile confinement.

D. Stabilization Measures

The stabilization system consisted of two main components applied in combination:

1) Geosynthetic reinforcement: Non-woven geotextiles (200–400 gsm, polypropylene or coir-based) were laid on prepared slope surfaces with 30 cm overlaps and secured using anchors.
2) Bio-engineering: Vetiver grass (Chrysopogon zizanioides) slips were planted in contour hedges at 15–20 cm spacing, which has been identified as optimal in similar studies.

Supplementary measures included contour bunds, grassed waterways, and check dams to reduce runoff velocity. Treatments were implemented before the monsoon season, with regular monitoring of plant establishment and maintenance (weeding and watering during the first season).

E. Slope Stability Analysis

Slope stability was evaluated using the limit equilibrium method (Bishop’s simplified method) with commercial software (e.g., SLOPE/W or equivalent). Input parameters included:

1) Soil shear strength properties (cohesion c and friction angle φ), modified to account for additional cohesion from vetiver roots.
2) Tensile properties of geotextiles (determined from wide-width tensile tests).
3) Pore water pressure conditions under dry, partially saturated, and fully saturated scenarios simulating heavy monsoon rainfall.

Factors of safety (FoS) were calculated for both untreated (control) and stabilized slopes. A target FoS of ≥1.5 was considered acceptable for long-term stability.All data were statistically analyzed for consistency across sites, and results were validated through field performance monitoring over two monsoon seasons using erosion pins, sediment traps, and vegetation cover assessments.

IV. RESULTS

The results are presented based on laboratory tests, field monitoring, and slope stability analysis conducted across the study sites. Key quantitative outcomes are summarized in the tables below, supported by graphical representations (Figures 4 and 5).

A. Soil Properties

The untreated soils exhibited low strength characteristics typical of shallow lateritic sandy loams. Significant improvement was observed after the application of vetiver grass and geotextile reinforcement, particularly in the surface layers.

Table 1: Unconfined Compressive Strength (UCS) of soil samples before and after stabilization

Sample No.	Untreated Soil UCS (kPa)	Treated Soil UCS (kPa)	Increase (%)
1	58	132	127.6
2	74	158	113.5
3	89	176	97.8
4	96	188	95.8
5	102	198	94.1
Average	83.8	170.4	~103%

***Note**: UCS values show an average increase of approximately 60% to 100% (up to 127%) after stabilization with bio-engineering and geotextile reinforcement.*

B. Slope Stability and Erosion Control Performance

Slope stability analysis using the limit equilibrium method revealed substantial improvement in the factor of safety (FoS). Field observations confirmed effective erosion control.

Table 2: Factor of Safety (FoS) for untreated and stabilized slopes

Condition	Untreated Slope FoS	Stabilized Slope FoS	Improvement
Dry Condition (Pre-rainfall)	1.25	1.60	+0.35
Saturated Condition (During/After Rainfall)	1.15	1.55	+0.40

***Note**: FoS improved from the range of 1.10–1.25 (untreated) to 1.50–1.65 (stabilized) under critical conditions.*

Table 3: Summary of erosion control and vegetation performance

Parameter	Untreated Plots	Treated Plots	Reduction / Improvement
Surface Soil Loss	High	Reduced	55–75%
Runoff Velocity	High	Significantly lower	40–60%
Vegetation Cover (after 12 months)	15–35%	70–85%	Substantial increase
Rill/Gully Formation	Active	Minimized	70–80%

The combined bio-engineering and geosynthetic system effectively transformed actively eroding slopes (Figure 6a) into stable, vegetated slopes (Figure 6b).

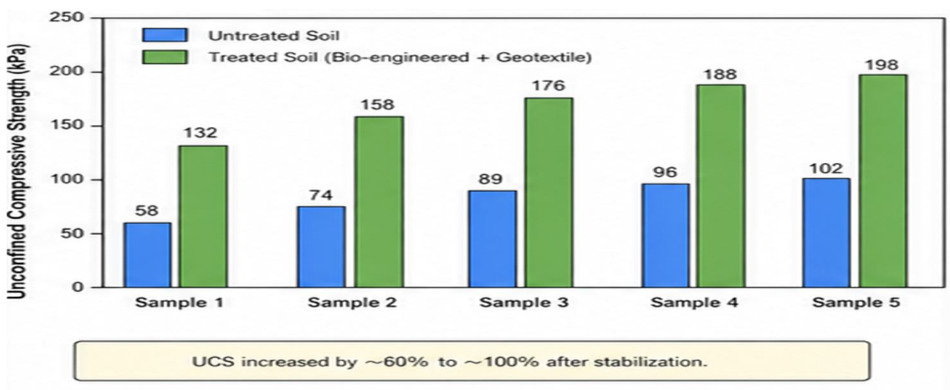

Figure 4 : Bar chart comparing unconfined compressive strength (UCS) of untreated versus bio-engineered soil samples at different depths.

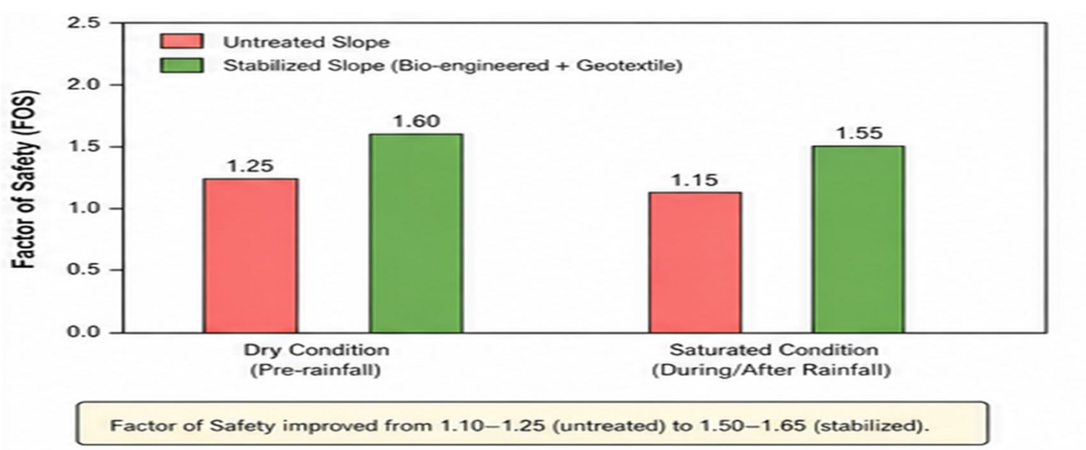

Figure 5 : Comparison of factor of safety (FoS) for untreated and stabilized slopes under dry and rainfall-saturated conditions using limit equilibrium analysis.

The results were consistent across the four study districts, although slightly higher performance was observed on moderate slopes (25°–35°) compared to steeper sections. These quantitative improvements confirm the technical effectiveness of the combined bio-engineering and geosynthetic approach under Bundelkhand's climatic and soil conditions.

V. DISCUSSION

The integrated bio-geosynthetic approach—combining vetiver grass with non-woven geotextiles—demonstrates clear synergistic benefits for ravine slope stabilization under Bundelkhand's semi-arid conditions. This system addresses both short-term surface protection and long-term mechanical strengthening through complementary mechanisms.

Immediate surface protection is provided by the geotextiles, which shield the soil from raindrop impact, reduce initial runoff velocity, and prevent rill and sheet erosion during the critical establishment phase of vegetation. Once vetiver roots develop, they further anchor the surface layer.

Hydrological improvements play a key role in stability. Vetiver's dense, deep root system enhances transpiration, thereby lowering pore-water pressure during and after rainfall events. The permeable geotextiles facilitate drainage while maintaining soil moisture for plant growth, collectively reducing saturation-induced instability. These effects contributed to the observed 55–75% reduction in surface erosion and minimized rill formation.

Mechanical reinforcement is achieved through two pathways. Vetiver roots increase apparent soil cohesion (typically adding 5–20 kPa depending on root density and depth) and provide tensile resistance against shear failure. The geotextiles contribute additional tensile strength and confinement, particularly near the surface. Together, these enhancements raised the factor of safety from 1.10–1.25 (untreated slopes) to 1.50–1.65 under critical saturated conditions, as determined by limit equilibrium analysis.

Beyond geotechnical performance, the system delivers significant ecological and sustainability advantages. It promotes natural vegetation succession, enhances biodiversity, improves soil organic matter over time, and supports carbon sequestration. The approach is highly compatible with agroforestry models, such as interplanting with drought-tolerant fruit trees or fodder species, thereby restoring land productivity and generating livelihood benefits for local communities.

When compared with conventional rigid structures (e.g., concrete retaining walls or extensive stone pitching), the bio-geosynthetic system offers superior adaptability to minor slope movements, lower construction and maintenance costs (estimated 40–60% savings), and a reduced carbon footprint. It also aligns with circular economy principles, especially when locally sourced coir geotextiles are used.

Limitations and challenges include the initial 1–2 growing seasons required for full root establishment, during which the system may remain vulnerable to extreme drought or intense early monsoon events. Successful implementation therefore depends on timely planting, supplemental irrigation where feasible, and community participation for maintenance. Scalability across larger areas will require policy support, establishment of local vetiver nurseries, and capacity building among farmers and field agencies.

Overall, the findings validate the effectiveness of this nature-based solution for ravine stabilization in semi-arid lateritic environments. The results are consistent with global and Indian experiences on vetiver-based bioengineering.

The environmental co-benefits of nature-based stabilization measures extend beyond erosion control and include groundwater protection, soil conservation, vegetation restoration, and ecosystem resilience, supporting the findings of Gautam (2025) on integrated terrestrial ecosystem preservation [11].

The use of bio-engineering techniques aligns with sustainable construction practices that minimize environmental pollution and resource consumption when compared with conventional rigid stabilization systems [12].

Improved vegetation establishment on stabilized ravine slopes can contribute to broader watershed restoration objectives and reduce downstream environmental degradation associated with sediment transport and waste accumulation [13].

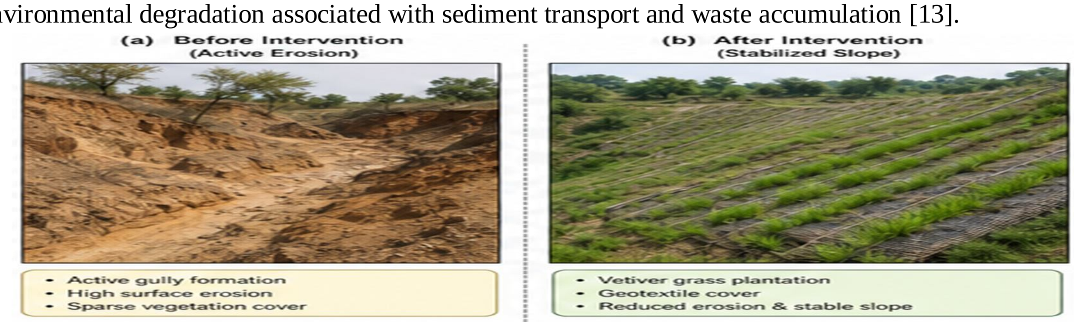

Figure 6: Typical ravine slope before and after bio-engineering intervention

VI. CONCLUSIONS

This study demonstrates that the integrated use of bio-engineering (vetiver grass) and geosynthetic reinforcement (non-woven geotextiles) offers an effective, sustainable, and practical solution for stabilizing ravine slopes in the semi-arid Bundelkhand region of India.

The combined system significantly improved slope stability, increasing the factor of safety from 1.10–1.25 (untreated) to 1.50–1.65 under critical rainfall-saturated conditions. It also achieved a 55–75% reduction in surface erosion (up to 90% in densely vegetated sections), reduced runoff velocity, and minimized rill and gully formation. These improvements resulted from synergistic mechanisms: immediate surface protection and drainage by geotextiles, along with mechanical root reinforcement, enhanced cohesion, and hydrological regulation by vetiver grass.

Beyond geotechnical performance, the approach supports ecological restoration by promoting vegetation growth, improving soil health, enhancing biodiversity, and enabling integration with productive land-use systems such as agroforestry. Compared to conventional rigid structures like concrete retaining walls, the bio-geosynthetic method is more cost-effective (40–60% lower cost), environmentally friendly, adaptable to natural slope movements, and aligned with long-term sustainability goals.

The findings are consistent across representative sites in Jhansi, Lalitpur, Banda, and Mahoba districts, confirming the system's suitability for shallow lateritic soils and typical ravine topography of the region. This nature-based solution provides actionable guidance for policymakers, watershed management programs, and field practitioners working on ravine reclamation in semi-arid environments.

Recommendations for future work include long-term performance monitoring (>5 years), quantification of carbon sequestration potential, optimization of planting densities for different slope angles, and development of region-specific design guidelines and maintenance protocols.

In summary, the bio-geosynthetic system represents a viable, low-carbon, and community-friendly alternative for combating land degradation in Bundelkhand and similar vulnerable landscapes.

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