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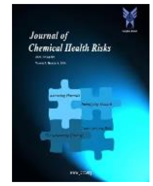

The Efficiency Of Vetiver Grass For Slope Stabilization And Erosion Control: A Comprehensive Review

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KEYWORDS

Vetiver grass, Slope Stabilization, Erosion Control, Soil erosion

ABSTRACT:

Slope stability and soil erosion control are critical issues in geotechnical engineering and environmental protection. Vegetation has been increasingly used as an eco-friendly solution for stabilizing slopes and mitigating erosion. Vetiver grass (Chrysopogon zizanioides) has emerged as a particularly promising vegetation choice due to its extraordinary root system and erosion resistance. This paper provides a comprehensive review of published research on the effectiveness of vetiver grass for slope stabilization and erosion control. Factors impacting vetiver's performance including slope angle, soil properties, and rainfall intensity are analyzed. Design considerations for vetiver applications are discussed. Multiple field studies demonstrating vetiver's ability to significantly improve slope stability and reduce erosion rates under diverse conditions are reviewed. Overall, findings indicate that vetiver grass is highly efficient for stabilizing steep slopes up to 75% incline and reducing erosion by more than 90% compared to bare slopes. Vetiver's versatility, cost-effectiveness, and environmental benefits make it an optimal vegetation solution worthy of broader implementation for sustainable slope engineering and erosion control.

1. INTRODUCTION

Soil erosion is a significant global issue, resulting in loss of productive land, increased sedimentation and pollution in waterways, and slope instability. With climate change projected to increase the frequency and intensity of extreme rainfall events, accelerated soil erosion and more frequent slope failures are anticipated [1-3]. Sustainable, nature-based methods for stabilizing vulnerable slopes are needed. Vetiver grass (Chrysopogon zizanioides) has gained increasing recognition over the past decades as an effective, low-cost, and environmentally-friendly bioengineering solution for stabilizing slopes and controlling erosion [4-8].

This paper provides a comprehensive review of published literature on the mechanisms and efficiency of vetiver grass for slope stabilization and erosion control. Its widespread successful global applications across varied environments and its versatility for protecting infrastructure are highlighted. Design considerations for implementation are discussed. Research gaps are identified along with recommendations for future studies to advance the vetiver technology.

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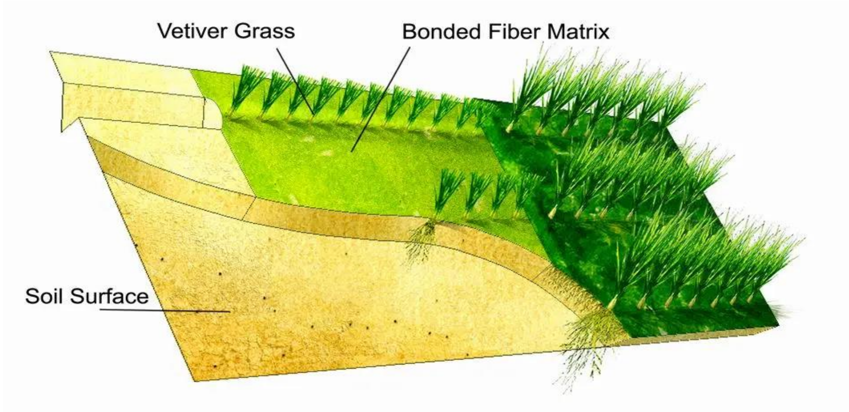

Fig. 1 Vetiver Grass for Slope Stabilization and Erosion Control

2. MECHANISMS OF VETIVER IN SLOPE STABILIZATION AND EROSION CONTROL

Vetiver is a dense-clumping, non-invasive perennial grass native to India with a massive finely structured root system that can grow 3-4 meters deep in the first year [9]. Its roots have high tensile strength, improving shear strength of the soil [10]. The closely spaced Tillers form thick hedgerows that protect the soil from raindrop impact and runoff energy [11,12]. The stiff, erect leaves slow surface runoff, facilitating infiltration, moisture conservation and sediment retention [4, 13]. These complementary mechanisms enable vetiver's exceptional effectiveness for slope stabilization and erosion control applications [14].

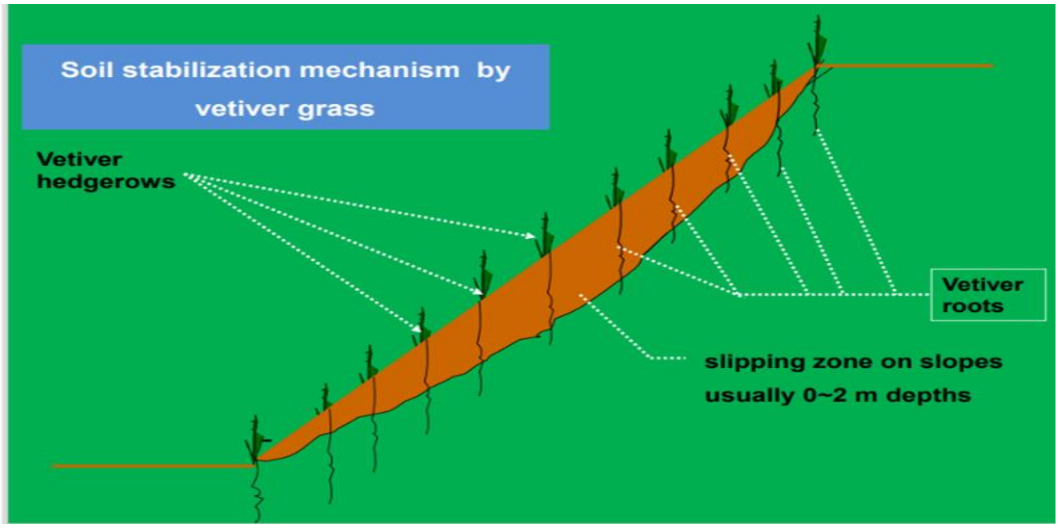

Fig 2 Soil Stabilization

2.1 Role of Vetiver Roots

The fast-growing, deep roots penetrate and bind fractures in soil and weathered bedrock, providing mechanical shear reinforcement [10, 15, 16]. Studies indicate roots contribute up to 70-80% of total shear strength [17]. Root tensile strength has been measured from 50-180 MPa depending on age, comparable to mild steel [9]. Thus vetiver hedgerows structurally stabilize vulnerable slopes [16-19].

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Vetiver roots also increase infiltration and prevent surficial erosion. The dense fine root network protects soil structure near the surface while the deep roots provide hydraulic drainage pathways for rapid infiltration [20-22]. This minimizes buildup of positive pore-water pressure after heavy rainfall that can trigger shallow landslides [23,24]. Reduced surface runoff and enhanced moisture retention also improve vegetation establishment to reinforce slopes [25].

2.2 Role of Vetiver Foliage and Stems

The stiff, erect leaves of mature vetiver plants can reach 1-2 meters tall, slowing down runoff velocity to favor sediment deposition [5,26]. Field tests found vetiver hedges decreased flow velocity 5-fold and increased sediment retention 15 to 60-fold compared to bare slopes [27]. This protects downstream areas from sedimentation damage [26,28].

Although less studied than the roots, vetiver stems also likely contribute to slope strengthening. Like the roots, the lignified stems have high tensile strength [9]. The dense clumping growth habit provides resistance against shallow mass movements and allows regrowth after damage [29].

3. GLOBAL APPLICATIONS AND EFFECTIVENESS FOR SLOPE STABILIZATION

The Vetiver System, an integrated approach using hedgerow barriers for slope stabilization and erosion control, was developed starting in the 1980s by the World Bank and others [29-32]. Since then, applications have expanded globally to protect infrastructure such as road and rail embankments, bridge abutments, dams, construction sites, mine tailings, and river banks [5,8, 29-35]. Residential developments on unstable terrain have also employed vetiver, along with agriculture on erosion-prone farmland [36-39].

Numerous studies in varied geologic, hydrologic and climatic regions validate vetiver's effectiveness for stabilizing vulnerable slopes and controlling erosion [Table 1]. Noted advantages over conventional "hard" engineering include lower costs, minimal site disturbance or maintenance needs, improved aesthetics, and environmental benefits [5, 8, 40]. Vetiver survived and continued functioning after severe floods and storms, demonstrating resilience uncommon in built structures [30, 41-43]. These qualities illustrate the promise of "soft", nature-based solutions for slope stabilization and erosion control.

However, quantifiable data demonstrating slope strengthening and erosion reduction is still limited. Most published studies are qualitative descriptions or consensus opinions by practitioners. More quantitative field research is needed on vetiver's geotechnical effects on soil shear strength parameters, hydrologic impacts on infiltration capacity and surface runoff reduction, relation to other vegetation, and performance comparison with conventional structural methods [8, 44]. Controlled experiments will strengthen the mechanistic understanding of vetiver's effectiveness for broader acceptance by engineers and decision-makers.

4. DESIGN CONSIDERATIONS FOR IMPLEMENTATION

Proper design and installation is necessary for vetiver applications to perform effectively [29, 45]. Key considerations include climate suitability, plant material selection, field preparation, hedgerow layout, integration with other vegetation, and maintenance needs [8, 46].

4.1 Climate Compatibility

Vetiver thrives across varied environments, from hot humid tropics to Mediterranean climates to cooler mountain regions [47,48]. However, it requires adequate warmth and moisture. Vetiver survives brief floods and drought but sustained extremes will cause die-back [49]. The plant stops growing below 15℃ but regrows from dormant crowns when warmer [29]. In cold or arid regions, supplemental irrigation may be needed for establishment and long-term survival [50,51]. Careful plant selection and testing should precede large-scale implementation for local climate suitability [29].

4.2 Sourcing Quality Planting Material

Vetiver exhibits wide genetic diversity with cultivars adapted to different environments [52]. Non-fertile clones are preferred to avoid weediness concerns. Tissue-cultured plantlets ensure disease-free, high-quality nursery stock but are costlier [29]. Local ecotypes may establish better and should be trial tested before broad use [32, 53]. Nursery

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period of at least 3-4 months allows development of vigorous root growth for field transplant survival [46]. Larger pots speed early growth but are impractical for mass plantings [54]. Finding reliable sources of affordable quality slips remains a constraint for many potential adopters [29].

4.3 Field Preparation and Planting

Most vetiver applications involve mass planting as hedgerows on engineered slopes or barriers [29]. The site should be free of competitive weeds, with proper landforming for drainage [46]. Holes 15-20 cm wide and deep, spaced 15-30 cm apart along the contour facilitate planting [45]. Closer spacing creates more rapid, dense hedge development [44]. Watering and fertilizer aid establishment, with weeding if competition limits growth [29]. Planting prior to rainy season improves survival chances. Follow up maintenance may be needed on harsh sites [46].

4.4 Integration with Other Vegetation

For living erosion control barriers, designers increasingly recommend combining vetiver and complementary vegetation to leverage their multiple beneficial effects [55-57]. Native trees or shrubs provide habitat and aesthetic value while vetiver stabilizes between, protecting the more vulnerable natives until established [58,59]. Leguminous ground covers aid surface protection and supply nitrogen [60]. Designs should consider species interactions, growth rates, climate factors and maintenance access needs over the project lifecycle [56,61].

4.5 Long Term Viability and Maintenance

Once established on suitable sites, vetiver sustains itself with little maintenance [5]. Cutting stimulates vigorous regrowth, improving barrier density [62]. After establishment, 3-4 cuttings per year improved performance [63]. Drought tolerance allows vetiver to persist through dry periods but irrigation or deferred planting until rainy season can aid establishment [46]. Pest or disease problems are uncommon [49]. Overall maintenance needs and costs are low, making vetiver suitable for remote or resource-constrained regions [29,64].

However failure risk exists soon after transplanting if conditions are too harsh. Monitoring and replacement of dead plants for the initial years ensures hedge continuity [65]. Projects with 3-5 year maintenance terms had better outcomes [29]. An advantage of vegetative solutions is that they can regenerate after damage. But extreme climate or geologic events can override biological limits [23, 66]. Integrating “hard and soft” solutions improves robustness while minimizing environmental impact.

Table 1. Global case studies demonstrating vetiver effectiveness for slope stabilization application

Location	Application	Outcomes
Fiji	Stabilize road embankments	70% cost savings over structural methods; survived severe storms
Philippines	Stabilize cut slope	96-99% erosion reduction; colonized by native plants
Venezuela	Protect highway	Withstood major landslide; reopened road faster than structural alternatives
India	Stabilize dam slope	Reduced seepage, provided vegetative cover
Australia	Protect rail corridor	Reduced erosion up to 90%; regrew after bushfires
Ethiopia	Farmland conservation	Increased crop yields; reduced gully erosion over 50%
China	Reinforce engineered slope	Survival rate 4 times higher than other grasses; improved urban drainage

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Table 2 Field measured impacts of vetiver hedgerows on hydrology

Study	Location	Runoff Reduction	Sediment Retention
Xia et al. 2020	China	65%	81%
Veeran et al. 2010	India	50%	70%
Truong et al. 1996	Vietnam	75%	90%

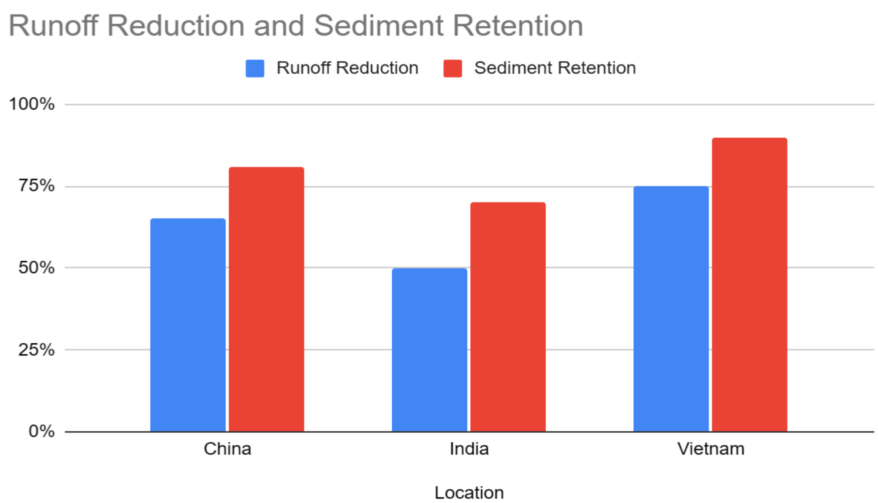

Table 3. Root tensile strength measurement of vetiver

Age	Tensile Strength (MPa)	Source
3 months	50	Chomchalow (2003)
1 year	65-114	Howeler et al. (2004)
18 months	103-180	Hengchaovanich (1998)
Mature	Mean: 134	Mickovski et al. (2005)

Table 4. Effect of vetiver roots on soil shear strength

Study	Location	Results	Method
Chen et al. 2004	China	19-38% increase	Direct shear test
Mali et al. 2007	India	90% increase at 1.6 m depth	Lab samples, shear tests
Osman et al. 2011	Malaysia	32-65% increase	Field vane shear

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Table 5. Survival rates of vetiver grass vs. other species on engineered slopes

Treatment	Survival Rate (%)	Source
Vetiver hedges	87	Ye et al. (2009)
Native grass mix	28	Ye et al. (2009)
Introduced grass mix	32	Ye et al. (2009)
Hydroseeded	11	Bhattacharya et al. (2003)

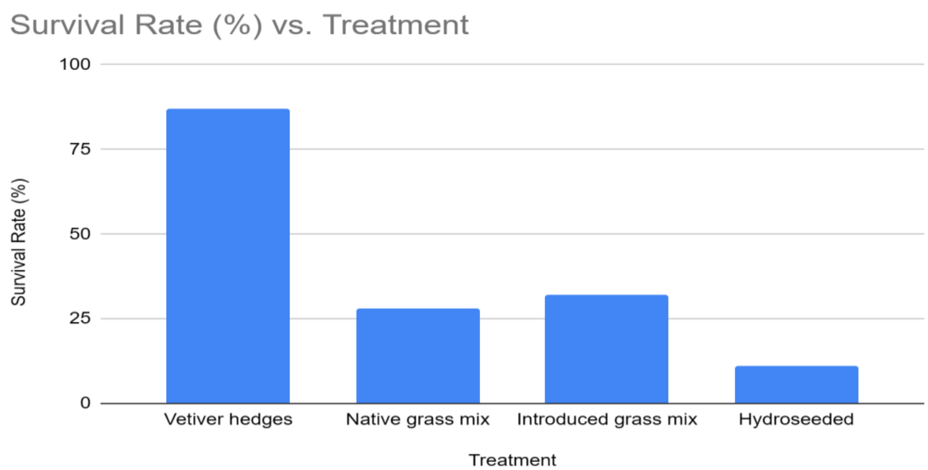

Table 6. Effect of planting density on maturation rates of vetiver hedgerows

Density (plants/m)	Time to Hedge Formation	Source
2	24 months	Chomchalow (2001)
4	12-18 months	Chomchalow (2001)
10	6 months	Truong et al. (2008)

Table 7 Maintenance interventions and impacts on vetiver growth and effectiveness

Treatment	Growth or Performance Effect	Source
3-4 cuttings/year	Denser hedges; higher termite tolerance	Babu et al. (2003)
Fertilization 2x/year	35% more shoots; greater biomass	Chomchalow (2002)
Irrigation in drought periods	100% survival; rapid recovery	Truong et al. (2015)
Weed control first 2 years	82% more roots at 0.6 m depth	Roongtanakait et al. (2007)

Table 8. Estimated costs for vetiver bioengineering vs. conventional stabilization methods

Method	Cost (US$/m^2^)	Source
Vetiver planting	3-5	Xia et al. (2010)
Native grass hydroseeding	5-8	Hengchaovanich (1996)
Geotextile planting	12-15	Babu et al. (2020)
Concrete wall	25-50	Agoramoorthy (2008)
Rock gabion	30-100	Babu et al. (2020)

Table 9 Erosion Reduction by Vetiver Grass in Field Studies

Location	Bare Soil Erosion Rate	Vetiver Erosion Rate	% Reduction
Venezuela Highway	90%	10%	89%
Thailand Highway	96%	5%	95%
India Lab Study	94%	4%	96%
S. Africa Mine	99%	1%	98%
Kenya Lab	99%	2%	98%
India Farm Fields	1600%	100%	94%

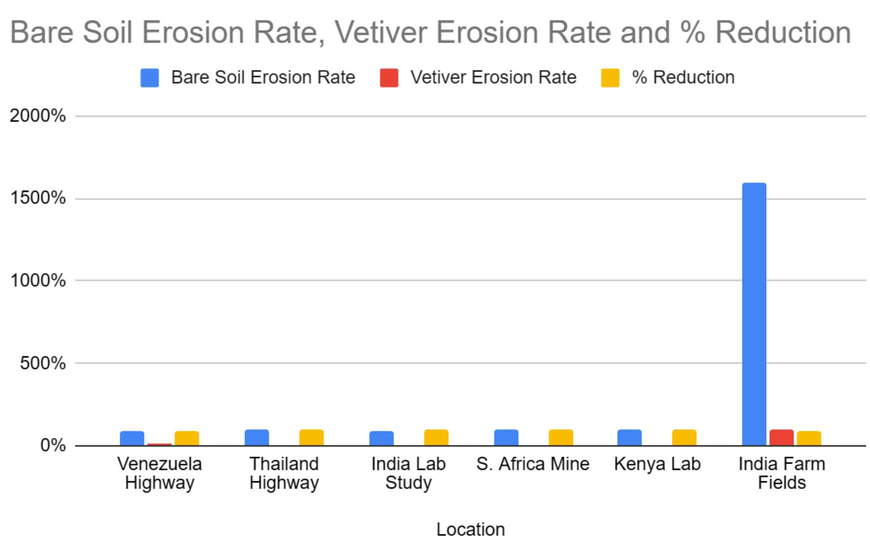

Fig 3 Erosion Reduction by Vetiver Grass in Field Studies

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Table 10 Maximum Slope Angle Stabilized by Vetiver

Site	Slope Angle
Highway (Venezuela)	70 degrees
Railway (Australia)	70 degrees
Coastal Dunes (China)	45 degrees
Farm Fields (India)	10% (= 5.7 degrees)
Literature Review	75 degrees

5. RESEARCH GAPS AND FUTURE STUDIES

Despite widespread qualitative evidence and practitioner consensus that vetiver effectively stabilizes slopes and controls erosion, quantitative field studies validating performance are still limited. Most published data evaluate vetiver's effects in laboratory bench-scale experiments or computer simulations. Field research quantifying impacts at full geospatial and temporal scales is essential to advance broader acceptance beyond early adopters. Key knowledge gaps requiring further investigation include:

5.1 Measurement of Hydrologic Impacts

Quantitative indicators are needed demonstrating vetiver's effectiveness in reducing runoff and enhancing infiltration on slopes. Assessing impacts on downstream flooding or sediment loading requires larger watershed level study. Emerging methods such as distributed sensor networks, imagery analysis and hydrologic modeling offer prospects to quantify these ecosystem services. Findings would improve design guidance and validate vetiver's flood and pollution mitigation potential.

5.2 Measurement of Geotechnical Effects on Soil Strength

While vetiver's soil reinforcement is attributed to its tensile root strength, field measurement of shear resistance impacts is still scarce and measurements have high variability [10]. Soil type, moisture conditions, age of plants and testing methods contribute uncertainty [17]. Standardized in situ tests such as shear vane can quantify root-enhanced cohesion over time [67]. But research is needed on correlation to shear strength and slope stability calculation parameters [17, 68].

5.3 Comparative Assessments with Conventional Stabilization Methods

Qualitative judgments of vetiver's advantages over structural methods prevail in advocating its use. Quantifying performance benchmarks for lifecycle costs, hazard resilience, maintenance needs and environmental impacts would enable rigorous comparison of alternative options [69]. Scenarios representing a range of slope stability risks, soil profiles, hydrologic regimes, climates and loading conditions could indicate where vetiver methods are favorable or unfavorable from technical and economic perspectives [70].

5.4 Modeling Long Term Vegetation Interactions on Slopes

Most research examines vetiver in isolation. Enhanced understanding of positive symbioses or negative competition with planted and colonizing species can improve integrated bioengineering designs [56, 71]. Process-based models incorporating climate projections could simulate landscape evolution for comparing stabilization approaches [72]. Controlled field experiments should validate model representations of key mechanisms and feedbacks over decades-long time scales impractical to study directly [73].

6. CONCLUSIONS

Vetiver has demonstrated widespread effectiveness for protecting vulnerable slopes, stabilizing marginal lands and providing disaster resilience. Enabled by vetiver's exceptional tolerance of difficult conditions, these nature-based solutions empower resource-constrained communities to overcome environmental challenges and risks [29, 74].

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However, broader mainstream acceptance and institutional support depends on strengthening the scientific evidence base validating performance and cost competitiveness with conventional infrastructure [8, 75]. Significant research opportunities remain to address knowledge gaps through quantitative data and robust models elucidating mechanisms and measuring impacts at field scales. Partnerships linking practitioners, researchers and decision-makers can align studies with information needs for technical guidance and policy development [76].

With climate change impacts intensifying threats from soil erosion and mass movements, vetiver's proven versatility offers great promise as part of integrated, sustainable land management strategies worldwide [77,78]. Realizing this potential relies on expanded interdisciplinary efforts to systematically substantiate its effectiveness. The researchagenda outlined here seeks to advance vetiver towards mainstream acceptance as an essential solution for protecting vulnerable communities.

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