

CRITIQUE OF VETIVER ENGINEERING AND INTEGRATED SLOPE STABILIZATION IN THE HIMALAYA

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Abstract. This review critically examines the role of Vetiver grass (*Chrysopogon zizanioides*) in Himalayan slope stabilization and the emergence of what the authors term Vetiver Engineering the monocultural, geotechnically unsupported deployment of Vetiver as a standalone slope stabilization solution. Drawing upon a systematic synthesis of geotechnical, ecological, hydrological, and policy literature, this paper evaluates where Vetiver is mechanistically effective, where it is structurally inadequate, and why its uncritical proliferation in Nepal and adjacent Himalayan regions represents a critical gap between evidence and practice. Vetiver provides measurable benefits for surface erosion control and shallow root reinforcement in cohesive soils, but it cannot substitute for geotechnical drainage, structural reinforcement, or discontinuity-controlled failure analysis in complex Himalayan terrain. Integrated bioengineering approaches combining geotechnical screening, hydrological control, structural reinforcement, and mixed species vegetation are demonstrated to deliver more resilient, cost-effective, and ecologically sustainable outcomes. The paper synthesizes engineering perspectives, root mechanics, regional case evidence, material durability data, comparative performance analyses, and critiques of Vetiver Engineering institutional drivers. It proposes a stepwise integrated design framework, standardized monitoring protocols, and a policy reform agenda. The conclusion calls for evidence-based procurement reform, interdisciplinary research, and regional knowledge-sharing to guide Himalayan slope management in an era of increasing climate driven rainfall intensity and seismicity.

Keywords: *Nepal, bioengineering, geotechnical design, landslide management, root reinforcement*

Introduction

The Himalayan Mountain belt is among the most geologically dynamic, seismically active, and hydro-meteorologically intense landscapes on Earth. Spanning over 2,500 km across South and Central Asia, it encompasses Nepal, northern India, Bhutan, and southern Tibet, traversing lithologies that range from Siwalik mudstones and unconsolidated alluvial fans to metamorphic quartzites, phyllites, and high-grade crystalline rocks. Road networks penetrating these corridors are critical lifelines for millions of people and are essential for trade, governance, and disaster response. Yet these roads cut through slopes that are inherently predisposed to failure due to steep gradients, weathered and fractured rock masses, deep colluvial deposits, and exposure to the South Asian monsoon (Shrestha et al., 2025). Landslides and road-slope failures in Nepal alone cause hundreds of fatalities annually and impose economic losses estimated at hundreds of millions of US dollars per monsoon season (Taylor and Francis, 2026). The problem is compounded by rapid population growth, unplanned road expansion, and climate-driven intensification of monsoon rainfall. Under climate projections, rainfall intensities are expected to increase significantly across the Hindu Kush Himalaya, escalating the frequency and magnitude of shallow and deep-seated slope failures (Taylor and Francis, 2026; Immerzeel et al., 2020). These dynamics make slope stabilization one of the most pressing engineering and environmental challenges of the region.

Slope failures in the Himalaya are governed by a complex interplay of geological structure, lithological heterogeneity, groundwater dynamics, and surface hydrology. Siwalik formations comprising interbedded sandstones, mudstones, and siltstones are particularly susceptible to shallow translational slides and debris flows owing to their weak cohesion, rapid weathering rates, and susceptibility to pore-pressure buildup during intense rainfall events (Bhandari and Dhakal, 2019). In the Lesser Himalaya, quartzites and schists are more durable but heavily fractured, producing wedge and planar failures along persistent discontinuities. Higher Himalayan crystalline rock masses can exhibit catastrophic rock avalanches when discontinuity networks are adversely oriented relative to slope geometry (Singh and Pradhan, 2025; Phuyal, 2024). Engineering responses to these failures must therefore be calibrated to failure mode, material properties, and hydrological context. Yet in practice, slope management in Nepal and many adjacent Himalayan regions has increasingly converged on a single, low-cost intervention: the planting of Vetiver grass (*Chrysopogon zizanioides*) in monocultural hedgerows along slope contours.

Vetiver grass has been widely promoted as a cost-effective, ecologically benign bioengineering measure for erosion control and slope stabilization since the 1980s, largely through advocacy by the World Bank's Vetiver Grass Technology (VGT) program and The Vetiver Network International (Truong, 2000). Its deep fibrous root system, tolerance to harsh edaphic conditions, and rapid canopy establishment have made it attractive to practitioners, donor agencies, and government programs seeking low-cost, visible deliverables. In Nepal, Vetiver has become the dominant bioengineering measure along road corridors, promoted by government agencies, NGOs, and development banks alike (Timilsena, 2023). However, the increasing reliance on Vetiver as a one-size-fits-all remedy often deployed without prior geotechnical assessment, without attention to drainage, and in monocultural continuous hedgerows has prompted growing concern among engineers, geoscientists, and ecologists. We introduce the term "Vetiver Engineering" to describe this practice: the monocultural, engineering-light deployment of Vetiver grass as a universal solution to slope instability, characterized by the absence of geotechnical screening, hydrological analysis, structural measures, and performance monitoring. This practice has proliferated for reasons that are as much institutional as technical. Procurement systems that reward planting area rather than slope performance incentivize rapid, visible planting over careful, site-specific design (World Bank, 2016). Donor project cycles that prioritize short-term visibility over long-term resilience further entrench this dynamic. As a result, thousands of kilometers of road slopes in Nepal are now stabilized nominally by Vetiver hedgerows that are structurally inadequate for the failure modes they face.

This review addresses three interlinked objectives. First, it evaluates the mechanistic role of Vetiver in slope stability across Himalayan settings identifying where Vetiver is demonstrably effective and where it is structurally or hydrologically inadequate. Second, it critiques the emergent practice of Vetiver Engineering, examining its technical limitations, ecological risks, and institutional drivers. Third, it proposes a practical, evidence-based framework for integrated slope stabilization that combines geotechnical assessment, hydrological control, structural reinforcement, mixed-species vegetation, and systematic monitoring. The paper is structured to provide a comprehensive literature synthesis appropriate to a high-impact review article. Sections 2 through 5 establish the engineering, biological, regional, and material science

foundations. Sections 6 through 8 develop the critique of Vetiver Engineering and propose an integrated design framework. Sections 9 through 11 address monitoring, policy reform, and future research. Section 12 concludes with a synthesis and call to action. This review draws on peer-reviewed literature in geotechnical engineering, engineering geology, plant ecology, hydrology, and policy science, supplemented by technical reports from government agencies and international development organizations. Wherever possible, studies from Nepal and the broader Himalayan region are prioritized, with global evidence drawn on to fill gaps and provide comparative context.

Literature review

Historical development of bioengineering for slope stabilization

Bioengineering the use of living plant materials as engineering elements for slope stabilization and erosion control has a long history in both traditional and formal practice. Indigenous communities across the Himalaya have long used terracing, vegetated check dams, and mixed-species planting to manage slopes (Gurung and Khatri-Chhetri, 2019). The formalization of bioengineering as an engineering discipline emerged in Europe during the twentieth century, particularly in alpine regions of Austria, Switzerland, and Germany, where practitioners developed systematic approaches combining live plant materials with inert structural elements (Schiechtl and Stern, 1997, as cited in Stokes et al., 2009). In South and Southeast Asia, bioengineering gained formal recognition in the 1980s and 1990s, largely driven by the World Bank's promotion of Vetiver Grass Technology and the establishment of national bioengineering programs in Nepal, India, and Thailand (Truong, 2000). Nepal Department of Soil Conservation and Watershed Management (DSCWM) pioneered community-based bioengineering for roadside slope stabilization in the 1990s, producing influential technical guidelines that emphasized mixed-species planting, brush layering, and live stake installation alongside Vetiver hedgerows (Department of Soil Conservation and Watershed Management [DSCWM], 2013). These early programs recognized bioengineering as a complement to, not a substitute for, geotechnical engineering. However, as implementation scaled up and procurement systems evolved, the nuanced multi-technique approach was often replaced by simplified monocultural Vetiver planting, driven by cost considerations, contractor capacity limitations, and the appeal of a single, universally recognized species (Timilsena, 2023).

Root reinforcement mechanics: Theoretical foundations

The mechanical contribution of plant roots to slope stability has been extensively studied since the pioneering work of Waldron (1977) and Wu et al. (1979), who developed the first analytical models of root reinforcement. These models conceptualize roots as flexible tensile elements that are mobilized when a potential slip surface crosses the root network. The apparent cohesion contributed by roots (c_r) is related to root tensile strength, root area ratio (RAR), and root-soil mobilization angle. The Wu et al. (1979) model, and its subsequent refinements by Pollen and Simon (2005), Schwarz et al. (2010), and Docker and Hubble (2008), have been widely applied to estimate root cohesion in shallow slope stability analyses. These models show that root cohesion can add between 1 and 30 kPa of apparent cohesion to near-surface soils, depending on

species, root density, and depth a contribution sufficient to raise the factor of safety (FoS) of marginally stable shallow slopes above the critical threshold of 1.0 (Stokes et al., 2009). For Vetiver specifically, tensile strength values of roots have been measured at 75-115 MPa, comparable to mild steel and significantly higher than most herbaceous species (Kumar and Kumari, 2023; Aziz and Islam, 2022). The high tensile strength combined with deep vertical root penetration reaching 2-3 m under favorable soil conditions, and up to 5 m in some tropical settings gives Vetiver a root reinforcement profile that is exceptional among grasses (Truong, 2000). However, as emphasized by Nicoll and Ray (1996) and Stokes et al. (2009), the effective depth of reinforcement is typically concentrated in the upper 0.5-1.0 m of soil, and reinforcement decays rapidly below this zone due to decreasing root density and the reduction in tensile force mobilization with depth. This depth limitation is critical for Himalayan applications, where failure planes of concern may occur at depths of 1-5 m or more along weathered rock-soil interfaces, bedding planes, or persistent joint sets. In such contexts, Vetiver root reinforcement is mechanistically irrelevant to the primary failure mechanism and cannot contribute meaningfully to slope stability (Singh and Pradhan, 2025).

Hydrological effects of vegetation on slopes

Vegetation affects slope hydrology through multiple pathways: interception of rainfall by canopy and litter, evapotranspiration from root zones, and modification of infiltration and runoff patterns. These effects can reduce pore-water pressure in near-surface soils, thereby increasing effective stress and shear strength. Studies in humid tropical and subtropical settings have documented that vegetated slopes maintain lower average soil moisture contents than bare slopes, with canopy interception accounting for 10-30% of annual precipitation (Sidle and Ochiai, 2006, as cited in Stokes et al., 2009). For Vetiver specifically, transpiration rates are high due to its dense clump structure and deep root access to soil moisture. Under Indian and South Asian conditions, Vetiver has been shown to significantly reduce near-surface soil moisture during dry spells, creating a suction-driven cohesion effect (Allen and Smith, 2020). However, this benefit is intermittent: during the intense rainfall of the South Asian monsoon, rainfall rates routinely exceed infiltration capacity even in vegetated soils, and the hydrological benefit of vegetation is rapidly overwhelmed by positive pore-pressure generation (Khadka and Dahal, 2026). A critical, and often overlooked, hydrological risk of dense hedgerow plantings is the potential for water impoundment. Continuous horizontal rows of Vetiver create a physical barrier to overland flow, which can be beneficial for sediment trapping but detrimental if drainage is insufficient to evacuate trapped water rapidly. Several studies in Nepal have observed that Vetiver hedgerows planted without associated drainage channels create perched water zones immediately upslope of the hedge, saturating the soil profile and triggering shallow slides that would not have occurred on undisturbed or properly drained slopes (Timilsena, 2023). This mechanism represents a direct iatrogenic hazard a stabilization measure that generates the very instability it was intended to prevent.

Comparative bioengineering: Vetiver and native species

A substantial body of literature addresses the comparative performance of Vetiver versus native species and mixed-species plantings in slope stabilization. Meta-analyses by Stokes et al. (2009) and subsequent reviews by Reubens et al. (2007) demonstrate

that mixed-species plantings consistently outperform monocultures in both mechanical and ecological dimensions. Mixed plantings develop more complex, complementary root architectures combining deep-rooted shrubs and trees with shallow-rooted grasses thereby reinforcing a greater depth range of the soil profile and bridging the gap between Vetiver's upper root reinforcement and deeper failure planes (Borgaonkar and Sinha, 2018). Ecologically, mixed plantings provide greater biodiversity, enhance soil microbial communities, improve litter decomposition and nutrient cycling, and reduce vulnerability to pest and disease outbreaks all of which support long-term sustainability (Reubens et al., 2007). In contrast, Vetiver monocultures have been shown to suppress native seedling establishment through allelopathic effects and competitive exclusion, reducing the potential for natural vegetation succession and long-term ecological integration (Borgaonkar and Sinha, 2018). The Asian Development Bank's (2019) guidelines for slope stabilization in South Asia explicitly recommend against monocultural Vetiver planting, emphasizing the integration of native species appropriate to local soil and climate conditions. Similarly, Nepal own DSCWM technical guidelines identify at least twelve native species suitable for integration with Vetiver in road slope bioengineering, including *Eulaliopsis binata* (bhabar grass), *Saccharum spontaneum* (kans grass), *Dendrocalamus hamiltonii* (bamboo), and *Dalbergia sissoo* (rosewood) species with diverse root architectures and successional roles (DSCWM, 2013).

Geotechnical frameworks for Himalayan slope assessment

The geotechnical literature on Himalayan slope stability has grown substantially over the past two decades, driven by both the expansion of road networks and the increasing frequency of catastrophic failures. Key contributions include the development and application of Rock Mass Rating (RMR) systems for Himalayan lithologies (Acharya and Dhital, 2023), kinematic analysis of discontinuity-controlled failures using stereonet and DEM methods (Khadka and Dahal, 2026; Singh and Pradhan, 2025), and slope stability modeling using limit equilibrium and numerical methods (Shrestha et al., 2025). RMR classification, originally developed by Bieniawski (1989), has been widely adapted for Himalayan rock masses, which are often highly weathered, closely jointed, and anisotropic. Studies in Nepal Siwalik, Lesser Himalaya, and Higher Himalaya zones consistently document RMR values ranging from 15- 40 (very poor to poor) in weathered mudstones and phyllites, 35-55 (poor to fair) in jointed quartzites and metasediments, and 50-70 (fair to good) in massive crystalline rocks at higher elevations (Phuyal, 2024; Acharya and Dhital, 2023). These classifications have critical implications for remediation: slopes with RMR below 40 require structural intervention (anchors, bolts, retaining structures) and cannot be stabilized by vegetation alone. Limit equilibrium analyses of Himalayan slopes under saturated conditions using infinite slope, Bishop's simplified, or Morgenstern-Price methods consistently show that shallow failure planes in Siwalik materials have FoS values in the range 0.8-1.3, rising to 1.0-1.5 in Lesser Himalayan soils (Shrestha et al., 2025). Root cohesion contributions of 2-8 kPa from Vetiver can shift these values by 0.1-0.2, a meaningful but often insufficient margin when failure is driven by groundwater pressure spikes during intense rainfall (Kumar and Kumari, 2023). For deep-seated failures, root cohesion is negligible and the dominant controls are rock mass strength, discontinuity orientation, and groundwater pressure (Singh and Pradhan, 2025).

Seismic hazard and combined triggering

Nepal's position at the collision boundary of the Indian and Eurasian tectonic plates makes it one of the most seismically active regions on Earth. The April 2015 Gorkha earthquake (Mw 7.8) triggered more than 20,000 co-seismic landslides across the Himalayan arc, overwhelming existing slope stabilization measures and exposing the inadequacy of vegetation-only approaches under seismic loading (Kargel et al., 2016, as cited in Taylor and Francis, 2026). Seismic shaking reduces effective shear strength through a combination of cyclic pore-pressure generation, structural degradation of root-soil contact, and inertial loading of the slope mass mechanisms against which Vetiver root reinforcement provides negligible resistance. In seismically active corridors, slope stabilization design must incorporate pseudo-static seismic analysis, applying a horizontal seismic coefficient ($k_h = 0.10-0.25$, depending on peak ground acceleration) in limit equilibrium analyses to assess post-seismic FoS. This analysis typically reveals that slopes with FoS barely above 1.0 under static saturated conditions have post-seismic FoS well below 1.0 (Singh and Pradhan, 2025). Integrated designs with structural reinforcement (anchors, bolts) are far more effective at maintaining post-seismic stability than vegetation-only measures, as structural elements can be designed to resist seismic inertial forces that roots cannot. This is a dimension of slope management that Vetiver Engineering entirely fails to address.

Bioengineering standards and international guidelines

International guidelines for bioengineering in mountain environments have evolved substantially over the past two decades, converging on a set of principles that strongly align with the integrated approach advocated in this review. The International Erosion Control Association (IECA), the European Federation of Geologists (EFG), and the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) all emphasize that bioengineering must be underpinned by geotechnical assessment and that vegetation must be understood as a component of a system rather than a standalone solution (Stokes et al., 2009). The Food and Agriculture Organization (FAO) guidelines on slope stabilization for watershed management in Asia explicitly state that vegetation selection must be preceded by soil characterization, topographic analysis, and rainfall assessment, and that drainage infrastructure should be installed before or simultaneously with planting (FAO, 2005, as cited in DSCWM, 2013). The Asian Development Bank's (2019) technical notes for South Asian slope stabilization recommend a minimum of three complementary species in any bioengineering planting, with one species providing deep root reinforcement, one providing surface coverage, and one providing nitrogen fixation or soil-building functions. None of these standards support the monocultural, drainage-free approach that characterizes Vetiver Engineering. Nepal own DSCWM (2013) guidelines which predate the widespread proliferation of Vetiver Engineering and reflect the more sophisticated understanding that prevailed in Nepal early bioengineering program provide a rich, ecologically grounded toolkit of 22 bioengineering techniques ranging from brush layering and live stakes to fascines and wattling, integrated with drainage design and structural slope preparation. The progressive abandonment of this rich toolkit in favor of simplistic Vetiver hedgerows represents a regression in practice that is not supported by the country's own technical standards.

Climate change and escalating slope instability

Climate projections for the Hindu Kush Himalaya indicate significant increases in extreme precipitation events under both moderate (RCP4.5) and high (RCP8.5) emissions scenarios (Immerzeel et al., 2020). Taylor and Francis (2026) demonstrate, using a slope unit-based susceptibility model for Nepal, that landslide susceptibility is projected to increase by 15–35% by mid-century under high-emission scenarios, driven primarily by intensifying monsoon rainfall. These projections have profound implications for slope stabilization design, which must account not only for current forcing but also for future hydrological extremes that may exceed the design envelope of existing interventions. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) identifies the Hindu Kush Himalaya as one of the global regions most vulnerable to climate change impacts on hydrological systems, with projected increases in the frequency and intensity of extreme rainfall events, increased glacial lake outburst flood (GLOF) activity, and shifts in seasonal snowmelt timing all of which interact with slope instability dynamics (IPCC, 2014, as cited in Taylor and Francis, 2026). Bioengineering designs that are calibrated to historical rainfall frequencies will progressively underperform as climate shifts the intensity distribution of triggering events beyond the range for which designs were optimized. Vegetated slopes including Vetiver hedgerows are particularly vulnerable to climate-driven destabilization if root systems are shallow and drainage inadequate. As rainfall intensities increase, the temporary pore-pressure spike generated by intense events will more frequently push FoS below 1.0 in shallow soil profiles, overwhelming the marginal cohesion contribution of roots. These dynamic underscores the necessity of integrated approaches that address drainage as the primary defense against hydrological forcing, with vegetation serving as a secondary, complementary measure (Khadka and Dahal, 2026; Taylor and Francis, 2026).

Results and Discussion

Lithology and rock mass behavior

The Himalayan Road corridors traverse three major tectonic zones, each with distinctive lithological and geomechanical characteristics. The Siwalik Group, occupying the southernmost and lowest-elevation zone, comprises Neogene interbedded sandstones, siltstones, and mudstones deposited as Himalayan foreland basin fill. These rocks are weakly cemented, rapidly weathering, and characterized by low intact strength (UCS typically 10–30 MPa for sandstones, <10 MPa for mudstones), high smectite clay content in mudstone horizons, and abundant colluvium at slope toes (Bhandari and Dhakal, 2019). Siwalik slopes are dominated by shallow translational slides, debris flows, and bank erosion. The Lesser Himalayan Zone contains older, more competent Proterozoic metasedimentary rocks quartzites, phyllites, schists, and carbonate rocks overlain by thick residual soils and colluvium. Rock mass quality varies widely (RMR 25-60) depending on weathering grade and discontinuity density. Failure modes include planar slides along bedding or foliation, wedge failures at joint intersections, and toppling in steeply dipping formations (Shrestha et al., 2025; Acharya and Dhital, 2023). The Higher Himalayan Crystallines consist of high-grade metamorphic and igneous rocks that are generally competent in fresh condition (RMR 50-75) but subject to catastrophic block failures along persistent joints and contact zones (Phuyal, 2024). Material properties set the envelope of feasible stabilization solutions. Where intact rock strength is low and weathering pervasive, vegetation can address surface processes but

cannot substitute for drainage or structural support. Geotechnical investigation including lithological mapping, RQD assessment, Schmidt hammer testing, and slake durability analysis must therefore precede any design decision (Acharya and Dhital, 2023).

Discontinuities and kinematic failure modes

Discontinuity networks, comprising bedding planes, joints, faults, and foliation exert primary control over failure kinematics in Himalayan rock slopes. Planar slides occur when a single persistent plane daylights on the slope face with a dip direction within $\pm 20^\circ$ of the slope face and a dip angle steeper than the friction angle of the discontinuity surface. Wedge failures develop at the intersection of two discontinuity sets whose line of intersection plunges toward the slope face at a shallower angle than the slope but steeper than the effective friction angle. Toppling occurs when steeply dipping planes dip into the slope face and lateral release joints allow forward rotation (Singh and Pradhan, 2025). Kinematic feasibility screening using stereonet projection should be a mandatory first step in slope assessment. Khadka and Dahal (2026), studying joint-controlled failures in Lamjung District, Nepal, demonstrate that discontinuity orientation data obtained from scanline surveys can reliably predict failure mode and guide remediation design a step that is routinely omitted in Vetiver Engineering practice. Their analysis of Udipur slope failures showed that persistent NW-SE trending joints with dip angles of $35\text{--}55^\circ$ were the dominant failure control, and that Vetiver planting had no mechanical effect on these deep-seated wedge failures, which continued to displace at rates of 10-20 mm/month despite vegetative cover.

Hydrological forcing and pore pressure dynamics

Monsoon rainfall is the dominant external forcing driving slope failures in Nepal. The South Asian monsoon delivers 80% of annual precipitation between June and September, with peak intensities reaching 50-150 mm/day in the middle hills and up to 200-300 mm/day during extreme events (Taylor and Francis, 2026). Infiltration of this rainfall through soil profiles and fractured rock masses generates transient pore-water pressures that reduce effective normal stress and trigger failure along pre-existing or developing shear surfaces. Pore pressure dynamics are strongly controlled by antecedent rainfall, soil permeability, drainage network characteristics, and the geometry of low-permeability layers within the slope profile. Perched water tables commonly develop above clay-rich horizons in Siwalik profiles, producing rapid positive pore-pressure spikes during intense events. Sub-horizontal drainage the installation of perforated pipe drains penetrating 5-15 m into the slope is the most cost-effective measure for reducing groundwater pressure and stabilizing slopes against pore-pressure-driven failures (Khadka and Dahal, 2026). Vegetation can reduce antecedent soil moisture through evapotranspiration, thereby providing a modest buffer against early-monsoon pore-pressure buildup. However, this benefit is quickly exhausted during sustained monsoon rainfall, and dense hedgerow plantings without associated drainage can aggravate water accumulation by impeding surface flow and concentrating infiltration (Timilsena, 2023). Integrated design must therefore prioritize drainage installation before vegetation planting.

Worked example: RMR-based screening and FoS calculation

The following worked example illustrates how RMR screening should inform remediation design. Consider a road cut in weathered sandstone in the Siwalik zone. Field observations yield: intact rock strength (UCS 15 MPa, score 4); RQD 30% (score 3); discontinuity spacing 50–150 mm (score 5); condition poor rough, weathered, clay-coated (score 8); groundwater wet (score 4); joint orientation unfavorable (adjustment - 5). Total RMR = 4+3+5+8+4-5 = 19, indicating very poor rock mass quality. At this RMR value, the slope requires structural intervention; vegetation alone including Vetiver is insufficient to maintain long-term stability. For a shallow soil layer overlying this rock mass, a limit equilibrium analysis under saturated conditions (infinite slope model) yields (Eq. (1)). Both values represent marginally stable conditions, and a further pore-pressure increase of 10-15 kPa during an intense storm would reduce FoS below 1.0 regardless of vegetation. This analysis demonstrates that drainage not planting is the critical intervention for such slopes (Shrestha et al., 2025; Kumar and Kumari, 2023).

$$FoS = \frac{c + \gamma z \cos^2 \beta \tan \phi}{\gamma_{sat} z \sin \beta \cos \beta} \quad \text{Eq. (1)}$$

Botanical characteristics and adaptive ecology

Chrysopogon zizanioides (formerly *Vetiveria zizanioides*), commonly known as Vetiver or khus, is a perennial C4 grass belonging to the family Poaceae. Native to India, it has been widely naturalized across tropical and subtropical regions. Unlike most grasses, Vetiver produces no stolons or rhizomes, growing exclusively in dense clumps from a fibrous root crown. This growth habit prevents Vetiver from spreading invasively but also limits its colonization of adjacent bare ground a consideration relevant to slope rehabilitation where full slope coverage is desired (Kumar and Kumari, 2023). Vetiver is exceptionally tolerant of environmental extremes: it can withstand soil pH ranging from 3.3 to 12.5, sustained drought conditions, waterlogging, salt stress, heavy metal contamination, and temperatures from -9°C to 55°C (Truong, 2000). This tolerance has made it attractive for mine rehabilitation, wastewater treatment, and roadside stabilization in diverse climatic settings. In the Himalayan context, Vetiver establishes rapidly on disturbed road cuts, providing canopy cover within 6-12 months of planting, which makes it particularly useful for initial erosion control during construction and early post-construction periods (Timilsena, 2023).

Root architecture and mechanical properties

The root system of Vetiver is its primary engineering attribute. Unlike most grasses that produce shallow lateral roots, Vetiver develops a dense, vertically oriented fibrous root mass that can penetrate 2-3 m under typical conditions and up to 5 m in deep, well-drained tropical soils (Truong, 2000). Root diameter ranges from 0.3 to 2.5 mm, and root length density (root length per unit soil volume) in the upper 0.5 m can reach 5,000-15,000 cm/cm³-among the highest recorded for any grass species (Aziz and Islam, 2022). The tensile strength of Vetiver roots has been measured at 40-180 MPa across multiple studies and growing conditions, with typical values of 75-115 MPa reported for roots of 0.5-1.5 mm diameter (Kumar and Kumari, 2023; Aziz and Islam, 2022). These values are comparable to mild steel wire and significantly higher than most herbaceous species. Root tensile strength decreases with increasing root diameter, following a power-law relationship consistent across species (Nicoll and Ray, 1996).

Mechanisms of slope stabilization

Vetiver contributes to slope stability through four distinct mechanisms. First, root reinforcement: roots increase apparent cohesion in the near-surface soil by tensile resistance to shear displacement across potential slip surfaces. Based on the Wu et al. (1979) fiber bundle model, effective root cohesion contributions from Vetiver in Himalayan soils have been estimated at 2–8 kPa in the upper 0.5–1.0 m, decreasing to 0.5–2 kPa at depths of 1.0–1.5 m and approaching zero below 2.0 m (Kumar and Kumari, 2023). Second, surface protection: the dense clump structure of Vetiver intercepts raindrop impact and reduces surface runoff velocity, limiting detachment and transport of surface soil particles. On road cuts with gradients of 35–50°, Vetiver cover of 60–80% has been shown to reduce surface erosion rates by 70–90% compared to bare slopes (Rahman and Islam, 2015). Third, sediment trapping: Vetiver hedgerows act as permeable check structures, reducing downslope sediment transport and promoting deposition of eroded material behind the hedge. This function is valuable for reducing downstream sedimentation but can create negative hydrological effects if drainage is inadequate. Fourth, hydrological regulation: Vetiver deep roots access subsoil moisture, supporting sustained transpiration that can reduce near-surface soil moisture during inter-event periods (Allen and Smith, 2020).

Global applications and performance evidence

Vetiver has been applied for slope stabilization and erosion control across more than 100 countries (The Vetiver Network International, 2020). In Asia, it has been used extensively on highway embankments and road cuts in Thailand, India, China, and Vietnam. In Thailand, a long-running national Vetiver program initiated by His Majesty King Bhumibol Adulyadej and supported by the Royal Department of Public Works has integrated Vetiver with drainage and structural measures, producing well-documented case evidence of success on embankments and cut slopes (Truong, 2000). In China, Vetiver has been applied to gully rehabilitation and highway slope stabilization in Yunnan and Guangdong provinces, with documented reductions in erosion rates of 60–85% (Kumar and Kumari, 2023). In Africa, Vetiver has been applied for agricultural terrace stabilization in Ethiopia and Kenya, and for embankment protection in South Africa. In Latin America, it has been used for riverbank protection in Colombia and slope stabilization in Central American coffee-growing regions. Meta-analyses of Vetiver performance across diverse settings consistently confirm its effectiveness for surface erosion control and sediment trapping, particularly when combined with engineered drainage (Stokes et al., 2009). These analyses also consistently confirm that Vetiver's effectiveness is limited to shallow surface processes and that it cannot substitute for structural or hydrological measures where deep-seated failures dominate.

Overview of bioengineering practice in Nepal

Nepal has been a global pioneer in formalized bioengineering for road slope stabilization. The Department of Soil Conservation and Watershed Management, established in 1974, developed systematic bioengineering guidelines in the 1990s that became influential across South Asia (DSCWM, 2013). These guidelines emphasized mixed-species planting live stake installation, brush layering, and wattling a rich toolkit that positioned vegetation as a complementary component of integrated slope

management. During this period, Vetiver was one of many species recommended, typically for lower slope zones and drainage channels. However, from the 2000s onward, a convergence of factors led to the progressive simplification of bioengineering practice toward monocultural Vetiver planting. Donor-funded road improvement projects financed by the Asian Development Bank, World Bank, and bilateral donors adopted Vetiver as a standard specification item across diverse slope types without site-specific assessment. Procurement contracts rewarded hectares planted rather than geotechnical outcomes. Contractor capacity to implement multi-technique integrated designs diminished as simplified Vetiver planting became the industry norm. By the 2010s, Vetiver Engineering had become the de facto standard for roadside bioengineering across much of Nepal road network (Timilsena, 2023).

Case study synthesis: Siwalik zone

The Siwalik zone of Nepal road network traversed by the East-West Highway (Mahendra Highway) and multiple feeder roads provides extensive evidence of Vetiver Engineering limitations. Bhandari and Dhakal (2019) documented debris flows and shallow translational slides on Siwalik road cuts following extreme rainfall events in the 2017 and 2018 monsoon seasons. Their analysis showed that slopes treated with Vetiver hedgerows without drainage failed at the same rate as untreated slopes during peak monsoon events, while integrated slopes with drainage channels and regraded bench cuts showed significantly lower failure frequencies. The mechanism of failure in Vetiver-treated Siwalik slopes follows a consistent pattern: intense rainfall generates rapid surface runoff that is partially intercepted by Vetiver hedgerows; water ponds upslope of the hedge, infiltrating into the already-saturated soil; pore pressure at the soil-mudstone interface spikes above critical levels; and shallow translational slides initiate immediately upslope of the hedgerow, exploiting the saturated zone created by the planting itself (Timilsena, 2023). This iatrogenic hazard pattern has been documented at multiple sites along the Prithvi Highway and Tribhuvan Highway corridors.

Case study synthesis: Lesser Himalayan zone

In the Lesser Himalayan zone, road cuts through weathered quartzites and phyllites present a different failure regime dominated by discontinuity-controlled kinematics. Shrestha et al. (2025) investigated cut slope failures along the Narayangadh–Muglin Highway, where deeply weathered quartzite with RMR values of 25-45 hosts persistent NE-SW trending joints that create planar and wedge failure conditions. Their study documented 23 active failure sites, of which 18 had received Vetiver planting within the past five years. At all 18 Vetiver-treated sites, surface erosion was measurably reduced relative to untreated slopes, confirming Vetiver effectiveness for surface protection. However, kinematic analysis showed that 15 of the 18 sites were subject to active planar or wedge sliding along joint planes at depths of 1.5-4.0m well below the effective root reinforcement zone of Vetiver. Displacement monitoring using crack gauges and inclinometers confirmed continued deformation at rates of 5-25 mm/month during monsoon periods, indicating that the underlying kinematic failure modes were entirely unaddressed by the bioengineering treatment (Shrestha et al., 2025).

Case study synthesis: Higher Himalayan zone

In the Higher Himalayan zone, Phuyal (2024) conducted a comprehensive rock mass characterization study at the Tatopani Liping road corridor in Myagdi District, a critical link to the Mustang and Manang districts. The study area comprises high-grade metamorphic rocks (gneisses and schists) with RMR values of 35-65, intersected by multiple joint sets and a prominent fault scarp. Vetiver planting on road cut faces had been carried out by a donor-funded project in 2019–2021. Phuyal's (2024) assessment found that Vetiver had established successfully on the cut face soils, reducing surface erosion and providing aesthetic cover. However, field evidence indicated continued deep-seated deformation along a basal shear zone at 3.5-6.0 m depth, associated with the fault contact. Three sites showed progressive displacement of 15-40 mm/month, with associated tension cracks, bulging at slope toes, and fresh scarp development. The Vetiver hedgerows had survived the surface deformation but provided no resistance to the underlying mechanism. Phuyal (2024) concluded that structural intervention specifically, pre-stressed anchor installation and sub-horizontal drainage was required, and that the Vetiver planting had created a false impression of stability that delayed appropriate remediation.

Procurement patterns and institutional drivers

A consistent theme across Nepal bioengineering literature is the role of procurement incentives in driving Vetiver Engineering. World Bank (2016) analyzed procurement practices across 14 road slope stabilization contracts in Nepal and found that 12 of 14 contracts rewarded area of planting as the primary performance metric, with no contractual requirement for geotechnical investigation, drainage installation, or post-planting performance monitoring. In this context, rational contractors maximize planting area with the lowest-cost, fastest-establishment species Vetiver regardless of site-specific conditions. Training gaps compound the procurement problem. Surveys of contractors implementing bioengineering works in Nepal found that fewer than 20% had received formal training in geotechnical assessment, and fewer than 10% had access to RMR classification tools or slope stability analysis software (DSCWM, 2013). Without training and tools, contractors default to the simplest available specification: plant Vetiver in horizontal rows along slope contours and submit area-based progress claims. The resulting gap between the potential of integrated bioengineering and the reality of Vetiver Engineering represents a systemic institutional failure rather than a technical misunderstanding.

Weathering processes in Himalayan climates

The durability of both natural slope materials and engineering interventions in Himalayan climates is fundamentally limited by intense physical and chemical weathering. Physical weathering processes repeated wetting-drying, freeze-thaw cycles, thermal expansion and contraction, and hydrofracturing are particularly aggressive in the transitional zone between the monsoon-dominated middle hills and the periglacial higher elevations (Acharya and Dhital, 2023). Chemical weathering hydrolysis of feldspars and micas, oxidation of iron-bearing minerals, dissolution of carbonates progressively reduces rock cohesion and produces expansive clay minerals, particularly in Siwalik mudstones and Lesser Himalayan phyllites. Slake durability testing of Siwalik sandstones has shown that intact rock strength can decrease by 40-70% after just five wetting-drying cycles a process that occurs annually on road cut faces exposed

to monsoon rainfall and dry-season desiccation (Bhandari and Dhakal, 2019). This rapid degradation means that design parameters measured at construction may be significantly overestimated relative to in-service conditions after five to ten years. Designs that are marginally stable at construction may become unstable as weathering progresses, unless monitoring and adaptive maintenance are systematically implemented.

Root reinforcement vs. rock mass strength: The critical gap

The relationship between root reinforcement magnitude and rock mass strength parameters defines the mechanical niche within which bioengineering is effective. For soils and heavily weathered saprolites, shear strength parameters ($c' = 5\text{--}25$ kPa, $\phi' = 25\text{--}35^\circ$) are comparable in magnitude to root cohesion contributions ($c_r = 2\text{--}8$ kPa from Vetiver), meaning that vegetation can provide a meaningful, though not decisive increment to stability (Kumar and Kumari, 2023). For intact rock or rock masses with RMR above 40, shear strength parameters ($c' = 50\text{--}500+$ kPa, $\phi' = 30\text{--}50^\circ$) are orders of magnitude greater than root cohesion, and vegetation contributes nothing to rock mass stability. The critical gap in Vetiver Engineering practice is the failure to match the engineering solution to the failure regime. Where failure is governed by rock mass strength and discontinuity kinematics, root reinforcement is irrelevant. Where failure is governed by shallow soil shear strength, root reinforcement is relevant but must be accompanied by drainage to control pore-water pressure, which is typically the dominant destabilizing factor (Shrestha et al., 2025; Singh and Pradhan, 2025).

Implications for design life

Design life considerations are often absent from bioengineering project specifications in Nepal. Vegetation-only measures on rapidly weathering slopes create a false sense of stability that may last only one to three monsoon seasons before the combination of progressive weathering, pore-pressure accumulation, and root senescence leads to failure. Established Vetiver plants have a field lifespan of 15-20 years, but their root reinforcement effectiveness diminishes after 5-8 years as root density declines in senescent clumps (Allen and Smith, 2020). Maintenance including periodic trimming, gap-filling replanting, and division of overcrowded clumps is rarely budgeted or implemented in Nepalese road projects, further shortening effective design life. Integrated designs that combine structural elements (anchors, bolts, retaining walls) with drainage and vegetation extend design life to 20-50 years for structural components, with vegetation requiring periodic maintenance. Lifecycle cost analyses consistently show that integrated designs, while more expensive upfront, deliver lower total costs over 20-year horizons due to reduced failure, reconstruction, and network disruption costs (World Bank, 2016).

Defining the comparison

This section provides a structured comparison of Vetiver-only approaches (Vetiver Engineering) with integrated bioengineering, drawing on case evidence from Nepal and global settings. The comparison addresses technical performance, ecological outcomes, cost-effectiveness, and institutional feasibility the four dimensions most relevant to policy and practice decisions (*Table 1*).

Table 1. Comparative performance of vetiver-only vs. integrated bioengineering approaches.

Dimension	Vetiver Engineering (Monoculture)	Integrated Bioengineering
Surface erosion control	High effectiveness (70-90% reduction)	High effectiveness (75-95% reduction)
Shallow soil reinforcement	Moderate (cr = 2-8 kPa, upper 0-1 m)	Higher (cr = 3-15 kPa, upper 0-2 m with mixed species)
Deep-seated failure control	None (roots cannot reach failure planes)	Addressed by anchors, bolts, drainage
Hydrological management	Risk of water impoundment without drainage	Active drainage reduces pore pressure
Ecological resilience	Low (monoculture, allelopathic)	High (mixed species, successional)
Upfront cost	Low (USD 500-2,000/100 m run)	Higher (USD 3,000-15,000/100 m run)
20-year lifecycle cost	Higher (frequent reconstruction)	Lower (longer design life)
FoS improvement (shallow)	0.05-0.20	0.20-0.50
FoS improvement (deep)	~0.00	0.30-0.80 (structural)
Monitoring requirement	Often absent in practice	Essential-piezometers, inclinometers

Note: Cost ranges are indicative and based on Nepal-specific contractor rates. FoS improvements are approximate and depend on slope geometry, material properties, and failure mode.

Sources: Shrestha et al. (2025); Kumar and Kumari (2023); World Bank (2016); Stokes et al. (2009).

Case evidence from Nepal

The comparative evidence from Nepal strongly supports integrated approaches over Vetiver-only treatments. Timilsena (2023) compared 45 bioengineering intervention sites along the Prithvi Highway, classifying them as Vetiver-only (n=28) or integrated (n=17). Over a five-year monitoring period, 18 of 28 Vetiver-only sites (64%) experienced slope failures of varying magnitude, compared with 4 of 17 integrated sites (24%). The failure rate differential was most pronounced for slopes with RMR below 35 and for sites with evidence of perched groundwater—precisely the conditions where Vetiver Engineering is most commonly deployed and least effective. Shrestha et al. (2025) similarly found that integrated designs on Lesser Himalayan Road cuts in Narayangadh Muglin produced FoS values above 1.3 under saturated conditions when drainage was installed, compared with FoS values of 0.9-1.2 for Vetiver-only treatments on comparable slopes. These results are consistent with limit equilibrium analyses showing that drainage not root cohesion is the primary determinant of stability in pore-pressure-dominated failure regimes.

Regional comparisons: Thailand and India

Thailand's national Vetiver program, widely regarded as a global best-practice reference, provides a useful comparative baseline. The Thai approach, developed under royal patronage and supported by dedicated government infrastructure, explicitly integrates Vetiver with drainage and structural measures, requires site-specific assessment, and includes long-term maintenance provisions (Truong, 2000). Outcome monitoring in Thailand shows failure rates below 5% over 10-year periods for integrated Vetiver-based treatments, compared with failure rates of 30–60% reported for comparable Vetiver-only treatments in Nepal (Timilsena, 2023; Truong, 2000). The Thai experience demonstrates that Vetiver, when deployed as part of an integrated system with institutional support and sustained maintenance, can deliver excellent long-term outcomes. In India, Vetiver Engineering has similarly proliferated in national highway bioengineering programs without systematic geotechnical integration. A review by Kumar and Kumari (2023) of 35 highway bioengineering case studies across Indian hill states found that Vetiver-only treatments performed well on slopes with gradients below 30° and cohesive soils, but consistently underperformed on steeper

slopes with fractured rock, poor drainage, or deep failure planes. These findings closely parallel the Nepalese evidence and support the conclusion that Vetiver Engineering limitations are structural and universal, not context-specific.

A Formal Definition

We define Vetiver Engineering as the systematic deployment of monocultural Vetiver grass (*Chrysopogon zizanioides*) as a universal, engineering-light solution for road slope instability, characterized by: (a) absence of prior geotechnical screening or failure mode analysis; (b) continuous horizontal hedgerow layout without staggering or drainage integration; (c) no provision for sub-surface or surface drainage infrastructure; (d) procurement systems that incentivize planting area over slope performance; and (e) absence of post-planting performance monitoring. This definition distinguishes Vetiver Engineering from legitimate integrated bioengineering practice, which incorporates Vetiver as one of multiple, complementary measures within a geotechnically designed system.

Technical critique

The fundamental technical critique of Vetiver Engineering is that it mismatches the engineering solution to the failure mechanism. The three dominant failure mechanisms in Himalayan Road slopes pore-pressure-driven shallow slides, discontinuity-controlled planar and wedge slides, and progressive deep-seated deformation each require specific interventions that Vetiver cannot provide. For pore-pressure-driven failures, drainage is the critical intervention; for discontinuity-controlled failures, structural reinforcement (anchors, bolts) is required; for deep-seated deformation, comprehensive geotechnical analysis and multi-system response is necessary. Vetiver mechanical contribution surface erosion reduction and shallow root cohesion addresses only the most superficial layer of slope instability. In the absence of drainage and structural measures, Vetiver planting may temporarily improve the appearance of a slope while the underlying failure mechanism continues unabated. In the worst case, as documented at multiple Siwalik and Tatopani sites, the hedgerow itself creates hydrological conditions water impoundment, concentrated infiltration that accelerate rather than retard failure (Phuyal, 2024; Timilsena, 2023).

Ecological critique

From an ecological perspective, Vetiver Engineering reliance on a single exotic species represents a significant departure from best-practice bioengineering, which emphasizes using locally adapted, native species that integrate with natural vegetation succession. While Vetiver is non-invasive in its sterile clonal form, its dense clumps suppress native seedling establishment through competition for light, water, and nutrients, and through possible allelopathic effects (Borgaonkar and Sinha, 2018). Long-term monocultural Vetiver plantations on Himalayan Road slopes show minimal natural succession, remaining as species-poor Vetiver stands indefinitely a condition that lacks the root architecture diversity, organic matter inputs, and ecological services of multi-species vegetation communities. From the perspective of climate resilience, monoculture plantations are inherently more vulnerable to environmental stress than diverse communities. A single pest, disease, drought stress, or climatic extreme that exceeds Vetiver's tolerance range can compromise the entire planting, leaving slopes

suddenly bare and vulnerable to rapid erosion. Mixed-species plantings with diverse physiological tolerances and life forms provide redundancy that buffers against such threats (Stokes et al., 2009).

Institutional critique

Perhaps the most fundamental critique of Vetiver Engineering is institutional: it reflects a systemic misalignment between procurement incentives and engineering objectives. When contracts are awarded on the basis of area planted and contractors are evaluated against delivery of hedgerow coverage targets, the rational response is to plant rapidly, cheaply, and ubiquitously regardless of geotechnical suitability. Geotechnical investigation, drainage installation, structural reinforcement, and performance monitoring are costly, time-consuming, and difficult to quantify in area-based procurement frameworks, and thus are systematically excluded. This institutional failure is compounded by weak regulatory oversight, limited technical capacity in government agencies, and the political visibility of planting as a tangible, photographable deliverable. Donor agencies have historically contributed to this dynamic by accepting area-planted metrics as proxies for slope stability outcomes, a practice that the World Bank (2016) has explicitly acknowledged and sought to reform through its updated procurement guidelines. However, reform has been slow and implementation inconsistent across Nepal road sector.

Evidence from post-failure forensic analysis

Post-failure forensic analysis of slopes treated with Vetiver Engineering provides some of the most compelling evidence for the critique developed in this section. Forensic investigations of Siwalik slope failures following the 2020 and 2022 monsoon seasons in Nepal documented a consistent pattern: slopes with intact, well-established Vetiver cover (60-80% canopy) failed along shallow translational planes at depths of 0.6-1.2 m, immediately below the main root zone. In all cases, failure occurred within hours of peak rainfall intensity, and piezometric back-analysis confirmed that pore pressures at the failure plane exceeded critical thresholds levels that would have been significantly reduced if sub-surface drainage had been installed (Timilsena, 2023). Post-failure investigation also consistently revealed the absence of any geotechnical investigation documentation in project files. No RMR assessments, no kinematic analyses, no stability calculations, and no drainage design drawings were available for any of the failed Vetiver Engineering sites audited. This absence is not attributable to poor record-keeping alone; in most cases, the investigations were never conducted. The sites were assessed visually as 'erosion-prone' and treated with Vetiver hedgerows without any systematic geotechnical analysis the defining characteristic of Vetiver Engineering. The forensic record thus confirms that the failures were not the result of design inadequacy in a technical sense, but of design absence: the application of a planting prescription in place of engineering judgment.

The false economy of vetiver engineering

Proponents of Vetiver Engineering often justify the approach on economic grounds, arguing that the low unit cost of Vetiver planting typically USD 500-2,000 per 100 linear meters of hedgerow makes it accessible to communities and government agencies with limited budgets. This economic argument, while superficially appealing, fails when

lifecycle costs are considered. A slope that fails following Vetiver Engineering incurs costs of failure investigation, emergency response, slope reconstruction (often at USD 15,000–80,000 per 100 m run for a properly engineered stabilization), disruption to road connectivity (with economic multipliers across the supply chains and communities dependent on that road), and potential loss of life. When these costs are amortized over a realistic failure probability documented at 30–64% for Vetiver Engineering in Siwalik and Lesser Himalayan settings the expected lifecycle cost of Vetiver Engineering consistently exceeds that of integrated bioengineering (Timilsena, 2023; World Bank, 2016). The economic case for integrated bioengineering is thus not simply about engineering performance it is about fiscal responsibility. Governments and donors that fund Vetiver Engineering as a cost-saving measure are, in effect, deferring the true cost of slope stabilization to a future reconstruction budget that will be larger and less predictable than the upfront cost of integration. This deferred cost dynamic is a recognized feature of risk management practice in infrastructure policy, where short-term budget optimization frequently generates long-term cost escalation (World Bank, 2016).

Principles of integration

An integrated slope stabilization framework rests on five principles that, taken together, address the full complexity of Himalayan slope failure. First, the principle of site specificity: design must be driven by site-specific geotechnical, hydrological, and topographic data rather than generic specifications. Second, the principle of hierarchy: interventions should address failure mechanisms in order of dominance drainage first, structural second, vegetation third, monitoring throughout. Third, the principle of complementarity: each measure should reinforce the others, creating a system whose resilience exceeds the sum of its parts. Fourth, the principle of ecological integration: vegetation should use native species alongside Vetiver to enhance biodiversity, succession, and long-term root reinforcement. Fifth, the principle of adaptive management: monitoring data should drive iterative improvement of design and maintenance throughout the project life.

Stepwise design process

Step 1 Site Investigation: Geological mapping of cut face lithology, structure, and weathering grade; discontinuity survey (scanline or window mapping) to characterize joint sets and failure kinematics; RMR classification to quantify rock mass quality; hydrogeological assessment including identification of perched water, seepage zones, and drainage pathways; and topographic survey using GPS and/or UAV photogrammetry to generate a high-resolution digital terrain model. Step 2 Hazard Assessment: Kinematic feasibility screening using stereonet projection to identify potential planar, wedge, and toppling failure modes; limit equilibrium analysis of FoS under dry and saturated conditions for identified failure modes; pore-pressure sensitivity analysis to determine critical groundwater levels; and erosion susceptibility assessment for surface processes. Step 3 Intervention Selection: Based on hazard assessment outputs, interventions are selected from a hierarchy. For slopes with RMR below 35: structural reinforcement (anchors, rock bolts, retaining walls or gabions) is mandatory, accompanied by drainage and surface protection. For slopes with RMR 35–55: drainage is the primary intervention, supplemented by structural reinforcement where kinematic

analysis identifies adverse failure modes, and integrated vegetation. For slopes with RMR above 55 without adverse kinematics: drainage and integrated vegetation may be sufficient. In all cases, vegetation includes Vetiver in combination with at least two to three native species. Step 4 Implementation Sequence: Install drainage infrastructure (surface channels, sub-horizontal drains, toe drains) before vegetation planting. Complete structural reinforcement (anchoring, bolting) before loading slopes with additional vegetation weight. Prepare planting substrate (scarification, pH amendment if required) before establishment. Plant Vetiver in staggered rows not continuous horizontal bands at 60-100 cm spacing, with native shrubs and trees at 1-2 m intervals. Install monitoring instruments (piezometers, crack gauges, inclinometers) immediately upon completion. Step 5 Monitoring and Adaptive Maintenance: Conduct baseline survey immediately after implementation. Pre-monsoon inspection checks drainage capacity and vegetation establishment. Monthly monsoon monitoring tracks pore pressure, displacement, and vegetation cover. Post-monsoon inspection assesses cumulative impacts and identifies maintenance needs. Trigger thresholds for escalated response: pore pressure rise above 20% of hydrostatic, displacement rate above 5 mm/month, crack aperture above 10 mm, or vegetation cover below 40%.

Example applications

Siwalik slope (poor rock mass): RMR = 20, failure mode = shallow translational slide, slope angle = 38°. Intervention: regrade to 45° with 3 m wide benches at 5 m intervals; install toe drain and longitudinal bench drains; apply coir geotextile for immediate surface protection; plant Vetiver in staggered rows on benches combined with *Saccharum spontaneum* and *Eulaliopsis binata*; monitor pore pressure monthly during monsoon. Expected FoS improvement from 1.05 (Vetiver only) to 1.45 (integrated) under saturated conditions. Lesser Himalayan slope (fair rock mass, adverse kinematics): RMR = 42, failure mode = planar slide along joint plane dipping at 40°, slope at 55°. Intervention: install pattern rock bolts at 1.5 m spacing, 6 m length, oriented perpendicular to joint plane; sub-horizontal drain holes at 3 m spacing, 8 m depth; surface protection with Vetiver combined with *Dalbergia sissoo* and *Dendrocalamus hamiltonii* on regraded benches; monitor displacement with inclinometers and crack gauges. Expected FoS improvement from 0.85 (no treatment) to 1.50 (integrated with bolts and drainage) (Table 2).

Table 2. Integrated design decision matrix by slope classification.

Slope Class	RMR Range	Failure Mode	Primary Intervention	Secondary Intervention	Vegetation
Very Poor	<25	Shallow slides, debris	Regrade + retaining wall	Sub-horizontal drains	Vetiver + native grasses
Poor	25–40	Planar/wedge + shallow	Anchors/bolts + drainage	Toe drain + surface channels	Vetiver + shrubs
Fair	40–55	Wedge/planar	Sub-horizontal drains	Pattern bolts if needed	Vetiver + native shrubs/trees
Good	55–70	Toppling/superficial	Surface drainage	None typically	Mixed native species + Vetiver
Very Good	>70	Surface erosion only	Drainage maintenance	None	Vetiver alone acceptable

Note: All slope classes require monitoring. Structural interventions should be designed by a qualified geotechnical engineer.

Sources: Singh and Pradhan (2025); Acharya and Dhital (2023); Asian Development Bank (2019).

The monitoring imperative

Monitoring is not an optional add-on to slope stabilization projects—it is a fundamental component of responsible slope management. In Himalayan contexts, where failure conditions can develop rapidly during intense rainfall and where design parameters are inevitably uncertain, monitoring provides the early warning signals necessary for adaptive intervention before failures occur. Without monitoring, interventions cannot be validated, designs cannot be refined, and institutional learning cannot accumulate (Khadka and Dahal, 2026). Despite this imperative, monitoring is systematically absent from most bioengineering projects in Nepal. World Bank (2016) found that fewer than 15% of 14 audited road slope contracts in Nepal included any provision for post-implementation monitoring, and that none had installed piezometric instrumentation. This absence creates a dangerous blind spot: slopes that appear visually stable under Vetiver cover may be experiencing accelerating subsurface deformation that will culminate in sudden failure.

Monitoring instruments and protocols

A comprehensive monitoring system for integrated slope stabilization includes hydrological, geotechnical, and remote sensing components. For hydrological monitoring: vibrating-wire piezometers installed in boreholes at two to three depths bracket the identified failure plane, logging pore pressure at 15-minute intervals during monsoon months and daily during dry seasons; tipping-bucket rain gauges at the slope crest provide rainfall correlation data; flow meters in drainage outlets monitor discharge capacity and identify clogging. For geotechnical monitoring: surface crack gauges across tension crack systems detect incipient slope movement; inclinometers in 10–15 m boreholes measure subsurface deformation profiles; extensometers at joint apertures in rock slopes detect dilation. For remote sensing: monthly UAV photogrammetric surveys generate point cloud and orthophoto datasets for surface erosion quantification and vegetation cover assessment; synthetic aperture radar (SAR) interferometry from Sentinel-1 satellites provides regional displacement mapping at 10–20 mm precision (Taylor and Francis, 2026). Trigger thresholds for escalated response should be pre-defined in monitoring protocols and linked to maintenance actions. A tiered alert system is recommended: Yellow alert (increased inspection frequency) at pore pressure rise of 15% above hydrostatic, displacement of 2-5 mm/month, or vegetation cover below 60%; Orange alert (engineering assessment required) at pore pressure rise of 20% above hydrostatic, displacement of 5-10 mm/month, or crack aperture of 5-10 mm; Red alert (emergency intervention) at pore pressure rise above 25%, displacement above 10 mm/month, or crack aperture above 10 mm (Khadka and Dahal, 2026; Acharya and Dhital, 2023).

Community-based monitoring

Given the extensive road network in Nepal and the limited institutional capacity for systematic technical monitoring, community-based monitoring offers a valuable and cost-effective complement to instrument-based approaches. Trained community monitors can conduct regular visual inspections, record crack development using simple photographic protocols, and report changes in spring flow or drainage pattern all indicators of slope instability (DSCWM, 2013). Community monitoring programs in Nepal middle hills have successfully detected early-warning indicators of landslide

activity weeks to months before failure, enabling proactive evacuation and infrastructure protection. Effective community monitoring requires investment in training, reporting systems, and institutional linkages to ensure that community-generated data reaches qualified engineers who can interpret it and trigger appropriate response. Mobile phone-based reporting applications, adapted to local languages and low-connectivity environments, have shown promise in Himalayan contexts for linking community monitors with district disaster management offices (Taylor and Francis, 2026).

Diagnosing the policy gap

The proliferation of Vetiver Engineering in Nepal and adjacent Himalayan regions is fundamentally a policy failure, manifested through misaligned procurement incentives, inadequate regulatory standards, insufficient technical capacity, and weak monitoring and accountability mechanisms. Addressing this failure requires coordinated action across procurement, regulation, capacity building, and institutional design areas that have received far less attention in the slope stabilization literature than technical design questions. A systematic review of road sector procurement documentation in Nepal (World Bank, 2016) identified five specific policy gaps that enable Vetiver Engineering: (1) Slope stabilization specifications that mandate vegetation planting but do not require geotechnical investigation reports; (2) Performance metrics expressed as area planted or slope length vegetated rather than as FoS targets or failure rate benchmarks; (3) No requirement for drainage design or drainage installation as a precondition for vegetation payment; (4) No post-implementation monitoring requirement in contract documents; (5) No independent verification of slope performance outcomes before project closure and payment of retention.

Procurement reform recommendations

Procurement systems must be restructured to align financial incentives with slope performance outcomes. Specific recommendations include: (a) Mandate geotechnical investigation reports including at minimum RMR classification, kinematic analysis, and FoS calculation under saturated conditions as a precondition for approval of any slope stabilization design; (b) Require integrated design plans that explicitly identify the suite of measures to be implemented (drainage, structural, vegetation) with quantities and specifications for each; (c) Replace area-planted payment metrics with performance-based payment linked to verified FoS achievement, piezometric targets, or monitored failure rate benchmarks; (d) Require post-implementation monitoring plans with specified instruments, frequency, and trigger thresholds as a mandatory component of contract documents; (e) Include a three-year defect liability period for slope stabilization works, with contractor responsibility for monitoring and corrective action during this period.

Institutional capacity building

Procurement reform will only be effective if supported by institutional capacity to implement more demanding design and monitoring requirements. Specific capacity-building recommendations include: training programs for government engineers in RMR classification, kinematic analysis, and limit equilibrium calculation, delivered through partnership with Tribhuvan University Institute of Engineering and

international technical organizations; establishment of a slope monitoring unit within the Department of Roads with UAV survey capability, GIS-based slope inventory, and real-time piezometer data management; development of a national slope failure database that records failure locations, geological context, stabilization measures applied, and performance outcomes; and engagement of international technical assistance to support advanced design and review for complex slopes on national highway corridors.

Donor alignment and regional cooperation

Donor agencies including the Asian Development Bank, World Bank, and bilateral donors must align their project design, procurement standards, and performance monitoring requirements with best-practice integrated bioengineering principles. This means: requiring integrated design documentation before approval of bioengineering components; funding monitoring equipment and technical capacity as project components rather than afterthoughts; commissioning independent performance audits of slope stabilization outcomes at project midterm and completion; and sharing technical evidence and case studies across regional programs in India, Bhutan, and Nepal to accelerate learning and avoid repeated mistakes (Asian Development Bank, 2019). Regional technical cooperation through platforms such as the South Asian Association for Regional Cooperation (SAARC) or the International Centre for Integrated Mountain Development (ICIMOD) offers an underutilized opportunity to harmonize standards, share monitoring data, and develop regionally adapted design guidance. Nepal own experience both the failures of Vetiver Engineering and the successes of integrated practice represents valuable evidence that should inform regional norms rather than remaining confined to project-specific technical reports.

Identifying critical knowledge gaps

Despite two decades of active bioengineering practice in Nepal, several critical knowledge gaps constrain evidence-based design and policy. These gaps span geotechnical-bioengineering integration, hydrological dynamics, material durability, ecological resilience, monitoring technology, and the social science of procurement and institutional behavior.

Priority research areas

Root reinforcement quantification in Himalayan soils: While global literature on root reinforcement is extensive, studies calibrated to specific Himalayan soil types Siwalik colluvium, Lesser Himalayan saprolite, Higher Himalayan glacial till are scarce. Research is needed to measure root tensile strength, root area ratio, and root cohesion under field conditions at Himalayan sites, using force mobilization models (Schwarz et al., 2010; Pollen and Simon, 2005) rather than the simpler Wu et al. (1979) model, which consistently overestimates reinforcement. These data are necessary to parameterize stability models accurately and to define the slope conditions under which Vetiver provides meaningful reinforcement versus negligible benefit. Pore pressure dynamics under Vetiver hedgerows: A controlled field study comparing pore pressure evolution behind continuous versus staggered Vetiver hedgerows, with and without drainage, would provide direct evidence of the water impoundment hazard currently documented only through post-failure forensic analysis. Such a study, instrumented with vibrating-wire piezometers at multiple depths and correlated with tipping-bucket rainfall

data, would generate the evidence base needed to specify safe hedgerow configurations and drainage requirements. This research priority directly addresses the most consequential unresolved technical question in Nepalese bioengineering practice. Long-term vegetation performance under climate change: Climate projections indicate that both rainfall intensity and drought severity will increase across Nepal under future emissions scenarios, creating more extreme wetting-drying cycles that may exceed Vetiver tolerance range or accelerate root senescence (Taylor and Francis, 2026; Immerzeel et al., 2020). Long-term monitoring plots comparing Vetiver monocultures with mixed-species plantings across a climate gradient would provide evidence on comparative resilience and inform species selection for climate-adaptive bioengineering design. Procurement and institutional behavior: The institutional drivers of Vetiver Engineering procurement incentives, training gaps, political visibility of planting, weak monitoring systems are as important as the technical factors in explaining its persistence. Research using surveys, semi-structured interviews with contractors and government engineers, and analysis of project documentation would generate evidence to support specific procurement reform recommendations. Comparative analysis of procurement systems in Thailand, India, and Nepal where Vetiver use ranges from well-integrated to pervasively monocultural would identify the institutional conditions that distinguish good practice from Vetiver Engineering. Socioeconomic and community dimensions: The adoption of bioengineering by local communities who often maintain road slopes under community-based maintenance contracts is shaped by economic incentives, knowledge access, and social organization. Research on community perceptions of Vetiver versus mixed-species planting, barriers to adoption of drainage-integrated approaches, and the effectiveness of community monitoring programs would strengthen the design of participatory bioengineering programs that extend beyond the contracted project period.

Methodological innovations

Future research on Himalayan slope stabilization should exploit methodological innovations that are transforming geotechnical, ecological, and hydrological science. High-resolution UAV photogrammetry and LiDAR scanning enable millimeter-precision surface change detection over large slope areas, providing data on erosion rates, vegetation cover, and surface deformation that were previously impossible to obtain at this scale (Taylor and Francis, 2026). Machine learning algorithms applied to multitemporal remote sensing datasets can identify pre-failure deformation signatures and map slope susceptibility across entire road network corridors capability that could transform early warning and prioritization. Discrete element modeling (DEM) integrating root reinforcement effects through explicit simulation of root fiber inclusion in particle assemblies offers the possibility of mechanistically modeling the interaction between vegetation, soil, and potential failure planes at scales relevant to slope management (Singh and Pradhan, 2025). Such models, calibrated against field data, could significantly improve the predictive capability of integrated bioengineering design, moving beyond simplified limit equilibrium approaches to capture the full complexity of root-soil-failure plane interactions.

Building interdisciplinary research capacity in Nepal

A critical barrier to advancing the research agenda for Himalayan slope stabilization is the limited interdisciplinary research capacity within Nepal academic and government institutions. Tribhuvan University's Institute of Engineering offers programs in civil and geotechnical engineering, but formal training in bioengineering, plant root mechanics, and integrated slope management is largely absent from curricula. Similarly, Kathmandu University and Pokhara University have strong environmental science programs but limited geotechnical engineering depth. Building interdisciplinary capacity connecting geotechnical engineers with ecologists, hydrologists, and social scientists requires deliberate curriculum development, faculty exchange programs, and research collaboration frameworks that bridge disciplinary silos. The International Centre for Integrated Mountain Development (ICIMOD), based in Kathmandu, is uniquely positioned to host an interdisciplinary research consortium on Himalayan slope stabilization that could coordinate field research, share monitoring data, develop standardized assessment protocols, and translate research outputs into policy-relevant guidance. Such a consortium would also facilitate the regional comparative research across Nepal, India, Bhutan, and China needed to identify the lithological, climatic, and institutional conditions that determine integrated bioengineering success across the Himalayan arc. A dedicated funding stream for this consortium, supported by regional development banks and bilateral donors, would represent a high-leverage investment in evidence-based slope management.

Translating research into practice: The knowledge-action gap

Even where research evidence for integrated bioengineering is strong as it is for the core questions addressed in this review the translation of evidence into practice is frequently impeded by institutional barriers, knowledge access gaps, and the inertia of established procurement patterns. The history of bioengineering in Nepal demonstrates that technical guidelines, however well-grounded in evidence, are insufficient alone to change practice. Nepal DSCWM (2013) guidelines for integrated bioengineering have been available for over a decade but have had limited influence on procurement practice in the road sector. This knowledge-action gap is not unique to Nepal; it reflects a broader challenge in engineering practice where evidence rarely translates directly into behavioral change without supporting institutional mechanisms. Closing the knowledge-action gap requires strategies that go beyond guideline development to include: mandatory pre-qualification requirements for contractors that incorporate geotechnical training; peer-reviewed design checking by qualified engineers before contract approval; community of practice networks that connect practitioners with researchers and enable peer learning; and positive case study dissemination through government channels, professional associations, and donor knowledge management systems. These mechanisms have been effective in other engineering domains notably in structural engineering seismic design reform following the 1989 Loma Prieta and 1994 Northridge earthquakes in California and offer a model for accelerating the transition from Vetiver Engineering to integrated bioengineering in Nepal and the broader Himalayan region.

Conclusion

This review has critically examined Vetiver Engineering the monocultural, engineering-light deployment of Vetiver grass as a universal slope stabilization solution and demonstrated its fundamental inadequacy for the complex failure regimes

characteristic of Himalayan Road slopes. The synthesis of geotechnical, biological, hydrological, and institutional evidence leads to five principal conclusions. First, Vetiver grass provides genuine and valuable engineering functions surface erosion control, shallow root reinforcement, and sediment trapping that make it a legitimate component of integrated slope management. Its root mechanical properties are exceptional among grasses, and its performance in surface erosion control is well-documented across diverse climatic settings globally (Kumar and Kumari, 2023; Aziz and Islam, 2022; Stokes et al., 2009). The problem is not Vetiver itself, but its systematic misuse as a standalone solution. Second, the depth limitation of Vetiver root reinforcement effective primarily in the upper 0.5-1.0 m means that it cannot address the dominant failure mechanisms of Himalayan Road slopes, which operate at depths of 1-5 m along soil-rock interfaces, bedding planes, and joint systems (Shrestha et al., 2025; Kumar and Kumari, 2023). Deploying Vetiver without geotechnical screening to identify these deeper failure planes is mechanistically irrational and leads predictably to failure. Third, the hydrological risk of continuous Vetiver hedgerows without drainage is real and consequential. Multiple case studies in Nepal document the iatrogenic creation of saturated zones behind hedgerows that trigger the very failures they were intended to prevent (Timilsena, 2023; Bhandari and Dhakal, 2019). Drainage must precede, not follow, vegetation planting on all slopes with pore-pressure-sensitive failure regimes which encompasses the majority of Nepal road corridor slopes. Fourth, the proliferation of Vetiver Engineering is primarily an institutional failure, driven by procurement systems that reward planting area over slope performance, combined with weak regulatory oversight, limited technical capacity, and the political visibility of planting as a tangible deliverable (Timilsena, 2023; World Bank, 2016; DSCWM, 2013). Technical knowledge of integrated bioengineering exists and is available; the barrier to its implementation is institutional, not technical. Fifth, integrated bioengineering combining geotechnical screening, drainage, structural reinforcement where required, and mixed-species vegetation including Vetiver consistently outperforms Vetiver Engineering across all relevant dimensions: FoS improvement, failure rate reduction, ecological resilience, and 20-year lifecycle cost (Shrestha et al., 2025; Timilsena, 2023; World Bank, 2016). The evidence for integration is robust and consistent across Nepal, Thailand, India, and global settings (Kumar and Kumari, 2023; The Vetiver Network International, 2020; Stokes et al., 2009; Truong, 2000).

The path forward requires coordinated action by multiple stakeholders. Government agencies particularly Nepal Department of Roads and Department of Soil Conservation and Watershed Management must revise procurement standards to mandate geotechnical investigation, integrated design, and performance monitoring for all slope stabilization contracts (World Bank, 2016; DSCWM, 2013). Donor agencies must align project design, performance metrics, and accountability mechanisms with integrated bioengineering principles rather than planting-area targets (Asian Development Bank, 2019; World Bank, 2016). The research community must prioritize the specific knowledge gaps identified in Section 12, with particular urgency for pore-pressure dynamics under Vetiver hedgerows and long-term vegetation performance under climate change scenarios. And practitioner's engineers, contractors, community organizations must have access to training, tools, and institutional support to implement integrated approaches in place of Vetiver Engineering. Vetiver grass remains a valuable tool for the Himalayan toolkit when used as one component of a geotechnically designed, hydrologically sound, ecologically integrated, and systematically monitored

slope management system (Kumar and Kumari, 2023; The Vetiver Network International, 2020; Stokes et al., 2009). The challenge is to ensure that this valuable tool is used appropriately, rather than misused as a substitute for the engineering judgment, hydrological analysis, and structural intervention that Himalayan slope stability demands. Meeting this challenge is both a technical imperative and an institutional responsibility and it is one that will become only more urgent as climate change intensifies the hydrological forcing that drives slope failure across one of the world's most landslide-prone mountain belts (Immerzeel et al., 2020).

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Conflict of interest

The authors confirm that there is no conflict of interest involve with any parties in this research study.

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