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REVIEW ON SOIL BIOENGINEERING IN ADVANCING SUSTAINABLE LAND MANAGEMENT: INNOVATIONS AND CHALLENGES IN NEPAL

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ABSTRACT

In Nepal, a country profoundly vulnerable to natural disasters, the agricultural sector faces significant challenges due to landslides, floods, earthquakes, and extreme climatic events. These natural calamities, particularly acute in mountainous regions, exacerbate soil erosion, diminishing the fertility and integrity of topsoil. The monsoon season further intensifies these issues, leading to increased desertification and the transformation of fertile lands into riverbeds. This study delves into the role of vegetation in soil bioengineering as a sustainable solution to these challenges. It focuses on how plant roots anchor soil, reduce runoff, and bolster resistance against lateral earth pressures. Emphasizing the use of indigenous plant species for their multifunctional benefits, the paper explores specific plant requirements, prevalent bioengineering techniques, and successful initiatives within Nepal. However, it also identifies key challenges such as limited data availability, the specific applicability of techniques, and concerns regarding short-term structural integrity. The paper concludes by advocating for comprehensive, strategic bioengineering methods that integrate traditional knowledge and long-term monitoring, aiming to enhance Nepal's agricultural resilience against environmental adversities.

Key words: Agriculture, bioengineering, soil conservation, soil erosion, landslides

INTRODUCTION

Nepal, situated amidst the dynamic landscape of the Himalayas, is inherently prone to a variety of natural disasters. This susceptibility is heightened by its complex topography, vigorous river systems, and the annual cycle of monsoonal rains. Consequently, the nation frequently confronts devastating landslides, destructive floods, and seismic events such as earthquakes and avalanches (Tuladhar et al., 2015). These natural disasters have profound implications, particularly for the agricultural sector, which forms the backbone of Nepal's economy and sustenance.

Agriculture in Nepal, especially in its terraced mountainous regions, is severely impacted by soil erosion. Factors contributing to this erosion include rainfall-induced erosivity, inherent soil erodibility, and land management practices that often fail to counteract these natural processes (Koirala et al., 2019). The annual monsoon season exacerbates these challenges, leading to extensive land inundation and river course alterations. The resultant deposition of sand and debris not only contributes to the desertification of cultivable lands but also transforms fertile croplands into barren riverbeds, posing a significant threat to food security and livelihoods (MoFE, 2021b).

Particularly affected are the Siwalik Hills and the Terai belt, regions that face acute soil erosion and flooding issues. In the Siwalik Hills, the erosion rate is alarmingly high, compounded by the exploitation of natural resources such as riverbed materials, forest products, and timber, further destabilizing the landscape (Ghimire et al., 2013; The Kathmandu Post, 2019). The Terai belt, known for its fertile plains, confronts similar challenges, jeopardizing its agricultural productivity.

In this context, soil bioengineering emerges as a sustainable and ecologically sound approach to land management. By leveraging the natural properties of vegetation, soil bioengineering presents an innovative solution to mitigate the impacts of soil erosion and enhance agricultural resilience. This paper aims to explore the potential of soil bioengineering techniques in the Nepalese context, highlighting the role of indigenous plant species and the integration of traditional knowledge with modern practices for sustainable land management. Future studies should focus on collecting region-specific data to tailor bioengineering practices to Nepal's diverse geographical areas. Recognizing the need for region-specific approaches, this paper will explore the application of soil bioengineering techniques tailored to Nepal's diverse landscapes. Additionally, it will consider the economic impacts of these practices and the importance of integrating them with traditional agricultural methods.

ROLE OF VEGETATION IN BIOENGINEERING

Vegetation is the assemblage of plant life in a particular area. It encompasses all the plants, from robust trees to tiny mosses, that call that place their habitat. It's not just about the diversity of plant species, but also their abundance, their arrangement, and how they interact with each other and the environment. The key aspects of vegetation are species diversity, plant community structures like trees, herbs, shrubs, fungus, and the presence of different layers like canopy, understory, and underground. Vegetation plays key ecological functions like nutrient recycling, water cycle, microclimate and climate regulations, and habitat provision for heterotrophs like insects, birds, and mammals. Vegetation assumes vital roles in soil formation, hydrological characteristics, and engineering function.

Vegetation cover significantly improves the predictability of the relationships between soil health, soil loss, and rainfall characteristics, emphasizing the importance of maintaining ground cover to minimize runoff and erosion (Gardner and Gerrard, 2003). Plant roots act as essential anchors, firmly holding surface soil and preventing them from being easily eroded (ICIMOD, 2012). Plants and soil have mutual benefits against each other. By reinforcing the soil, plant roots increase their shear strength. Large and mature plants provide support against lateral earth pressure, preventing the outward movement of slope materials (ICIMOD, 2012). Moreover, the plant cover acts as a protective shield by absorbing the kinetic energy of raindrops, mitigating their erosive impact on the surface (ICIMOD, 2012). Plants also play a role in absorption, drawing up water from the ground, which helps maintain optimal soil moisture levels and reduces the risk of soil saturation and slope failure. Infiltration, facilitated by plants and their residues, maintains soil porosity and permeability, delaying the onset of runoff (ICIMOD, 2012). Furthermore, plants engage in evapotranspiration, a process where they absorb water through their roots and release it into the air, contributing to a balanced moisture level in the ecosystem (ICIMOD, 2012). Further research is needed to evaluate the long-term sustainability and maintenance requirements of these bioengineering methods in various Nepalese ecosystems. Considering these roles, future research should also assess the long-term sustainability and maintenance requirements of vegetation in bioengineering, ensuring that these natural systems continue to support soil health over time.

PLANT REQUIREMENTS FOR BIOENGINEERING

The importance of plants and vegetation and their roles in soil bioengineering is categorically summarized below.

Sturdy, numerous, and flexible stems for structural robustness and resilience.
Possessing the capability to recover from damage, ensuring long-term effectiveness.
Demonstrating a dense vegetation cover that bolsters protection against erosive forces.
Maintaining a low canopy and small leaves to optimize erosion control efficiency.
Displaying strong, fibrous roots that contribute significantly to erosion resistance.
Cultivating deep roots, characterized by strength and vertical orientation, enhances overall stability.
Possessing an extensive, deep, and wide-reaching root system that further fortifies erosion control capabilities.

(Source: ADB, Bioengineering for Green Infrastructure, 2020)

It is vital to integrate these bioengineering strategies with traditional agricultural practices, aligning modern techniques with the rich local knowledge of Nepal's farming communities. Integrating these plant characteristics with Nepal's traditional agricultural practices can create a synergy between modern bioengineering and time-tested local knowledge, leading to more sustainable land management solutions.

SELECTION OF PLANT HABITS AND SPECIES FOR BIOENGINEERING

Employing indigenous plant species in bioengineering is advisable due to their inherent adaptation to local growing conditions, increased resistance to regional diseases, greater availability, and potential cost-effectiveness (ICIMOD, 2012). Additionally, selecting species that serve different purposes as bearing fruit, and providing firewood, fuel, and timber can enhance the benefits (ICIMOD, 2012).

An economic analysis is essential to understand the cost-effectiveness of these bioengineering practices and their potential impact on Nepal's agricultural economy. To fully realize the potential of these species, a detailed economic analysis is necessary to evaluate the cost-effectiveness and potential economic benefits of employing indigenous plant species in bioengineering, particularly in enhancing Nepal's agricultural productivity.

Some commonly used plants for bioengineering techniques in Nepal are given below:

Grasses	Vetiver grass (*Chrysopogon zizanioides*) Napier Grass (*Pennisetum purpureum*) Buffel Grass (*Cenchrus ciliaris*) Amliso (*Thysanolaena maxima*) Dubo (*Cynodon dactylon*) Kans (*Saccharum spontaneum*) Setaria (*Setaria anceps*) Molasses (*Melinis minutiflora*) Stylo (*Stylosanthes guianensis*) Nigalo Bans (*Drepanostachyum intermedium*) Phurke (*Arundela nepalensis*) Padang Bans (*Calamus hookerianus*) Khar (*Cymbopogon microtheca*) Narkat (*Arundo donax)* Babiyo (*Eulaliopsis binate*) Sito (*Neyraudia arundinacea*) Bluegrass (*Poa pratensis*)
(Source: Amatya and Shrestha, 2002 cited in Kafle et.al.,2005)	
Shrubs	Bains (*Salix tetrasperma*) Bhujetro (*Butea Minor*) Dhanyero (*Woodfordia fruticosa*) Namdi Phul (*Colquhounia coccinea*) Tilka (*Wendlandia puberula*)
Trees	Chilaune (*Schima wallichii*) Khayer (*Acacia catechu*) Lankuri (*Lagerstroemia parviflora*) Sisau (*Dalbergia sissoo*) Uttis (*Alnus nepalensis*) Bakaino (*Melia azedarach*)

(Source: Howell 1999b; Devkota and others, 2006, cited in Dhital et.al, 2012)

COMMON BIOENGINEERING TECHNIQUES

Soil bioengineering employs a variety of techniques utilizing living plant materials to address challenges such as soil erosion, slope instability, and ecological restoration. Key methods include:

- Brush Layering: This involves strategically placing live branches or cuttings along slopes. It's a method to promote root growth and enhance slope stabilization.
- Live Fascines: This technique involves bundling live or freshly cut branches to form barriers, crucial for slope stabilization and erosion prevention (Franti, 2013).
- Planted Pole Walls: In this approach, poles like larch are used to support the growth of deciduous trees, aiding in the gradual correction of soil movement.
- Live Slope Grids: Comprising vertical and horizontal logs nailed together and filled with live branches and soil, these grids create a dense vegetation cover for effective erosion control (Florineth and Christoph, 2023).
- Live Wooden Crib Walls: Constructed from logs and anchor logs, these structures provide immediate support for stabilizing slopes (Florineth and Christoph, 2023).
- Vegetated Stone Walls: Incorporating live plants into the joints of stone walls, this method is adaptable to various angles and is effective in stabilizing the lower parts of slopes (Florineth and Christoph, 2023).
- Vegetated Gabions: Consisting of wire mesh filled with plant materials, these structures offer flexible and efficient solutions for slope stabilization and drainage improvement.

Other techniques such as jute netting, bamboo fencing, and Sloping Agricultural Land Technology are also employed based on specific requirements. These diverse bioengineering techniques capitalize on the natural strength of plants to reinforce soil structures, combat erosion, and support sustainable environmental stewardship. The selection of a particular technique is guided by factors including the characteristics of the slope, soil composition, and overall project goals. Further studies should examine the impact of these bioengineering techniques on local biodiversity, ensuring ecological balance is maintained. Given the diverse range of techniques available, further studies are needed to assess their impacts on local biodiversity and ecological balance. This will ensure that bioengineering practices contribute positively to the environment while achieving their intended goals.

Figure 1. Bamboo Fencing (Source: Anil Gautam) 2. Jute Netting (Source: Sandbag) 3. Brush Layering (Source: LaRiMiT)

NOTEWORTHY SOIL BIOENGINEERING INITIATIVES IN NEPAL

Several noteworthy soil bioengineering initiatives in Nepal have demonstrated the effectiveness of using vegetation for soil stabilization and erosion control:

Siwalik Hills Initiative: A study in the Siwalik region of Nepal revealed significant stabilization of ephemeral stream banks within three growing seasons. The use of vegetative check dams led to a natural coverage of shrubs and grasses over previously bare ground, showcasing their superiority in controlling soil erosion and managing floods compared to traditional mechanical stream bank stabilization methods (Dhital and Tang, 2015).

Lalitpur Landslide Management: In a landslide-prone area of Lalitpur, the implementation of vegetated bamboo crib walls was observed to be highly effective. Within two monsoon cycles, these structures not only remained intact but also supported the vigorous growth of vegetation, resulting in minimal soil erosion over three years. This case study underlines the success of soil bioengineering in managing shallow slope instabilities in Nepal's Middle Mountains (Acharya, 2020; Lammeranner, Rauch, and Laaha, 2005).

Dipayal Mallekh Road Project: This project in Nepal is notable for its efficient application of soil bioengineering techniques to strengthen roadside slopes and mitigate erosion while preserving the local environment. Utilizing indigenous plants and simple bio-structural measures offers a viable and practical solution for sustainable roadside soil management (Ojha and Shrestha, 2008).

Krishnaveer Soil Bioengineering Program in Dhading: This program stands out for its efforts in curbing soil erosion and environmental degradation. By integrating native vegetation and modest bio-structural interventions, it has successfully stabilized slopes, controlled erosion, and fostered biodiversity. The program exemplifies a harmonious combination of traditional practices with basic bioengineering, serving as an exemplary model for small-scale soil management endeavors. The success of these initiatives also depends on addressing policy and implementation challenges, including community acceptance and governmental support. These initiatives highlight the need for policies that support bioengineering methods and their acceptance by local communities. Understanding and addressing these policy and implementation challenges will be crucial for the broader adoption of soil bioengineering practices in Nepal.

LIMITATIONS OF SOIL BIOENGINEERING

While soil bioengineering has made significant strides in habitat restoration and damage recovery, it is important to acknowledge its limitations:

- **Data Gaps**: There is often a lack of comprehensive data regarding soil characteristics, climatic conditions, and vegetation types. This gap poses challenges in designing and implementing effective soil bioengineering solutions that are tailored to specific environmental needs (Simon and Steinemann, 2000).
- **Limitations of Conventional Methods:** The effectiveness of soil bioengineering can be constrained by the limitations inherent in traditional erosion control methods. This restricts the scope of these solutions in complex environmental scenarios (Simon and Steinemann, 2000).
- **Applicability Concerns**: Soil bioengineering may not be universally suitable, especially in areas facing severe erosion or landslide risks. In such extreme cases, the effectiveness of bioengineering approaches can be limited (Lewis, 2000).
- **Structural Challenges**: Bioengineering projects can face short-term challenges, such as the potential for damage or failure of the structures soon after installation. This can undermine the immediate effectiveness of these interventions (Simon and Steinemann, 2000).

- **Soil Saturation Issues:** The growth of roots in deep soil layers can be hindered by anaerobic conditions in consistently saturated soils. Therefore, implementing proper drainage measures is crucial for the success of these bioengineering projects (Bischetti et al., 2021).
- **Monitoring Deficiencies:** A lack of adequate long-term monitoring can adversely impact the performance and effectiveness of soil bioengineering projects. Continuous oversight is essential to ensure the long-term success of these interventions (Mickovski and Slobodan, 2021).
- **Strategic Framework Shortcomings**: The absence of a comprehensive strategic framework for soil bioengineering hampers its broader adoption as a sustainable solution to combat climate change and other environmental challenges (Mickovski and Slobodan, 2021).

Soil bioengineering projects, exemplified by initiatives such as the Krishnaveer Soil Bioengineering Program, demonstrate the success of employing vegetation-based techniques for ecological restoration, particularly in stabilizing stream banks and landslide-prone areas. However, this field faces certain gaps and challenges. Notably, there is a need for more comprehensive data regarding the interaction between soil physics and vegetation, which is critical for tailoring bioengineering solutions to specific environmental contexts. Additionally, the absence of a well-defined strategic framework for implementing these practices limits their broader application and effectiveness, particularly in addressing the impacts of climate change.

These limitations highlight the need for enhanced research, better data collection, and the development of more robust frameworks to maximize the potential of soil bioengineering in diverse ecological contexts. There is a need to adapt these bioengineering practices to the emerging challenges posed by climate change, ensuring their effectiveness in a changing environment. To overcome these limitations, it is imperative to adapt bioengineering practices to the challenges posed by climate change. Developing a strategic framework that encompasses these adaptations will be crucial for the future success of bioengineering in Nepal.

CONCLUSION

In conclusion, the application of vegetation in soil bioengineering stands out as a pivotal element in addressing various environmental and infrastructural challenges, including habitat destruction, land degradation, civil engineering problems, and associated economic impacts. The ability of plant roots to anchor soil effectively combats erosion, while the overall vegetation cover plays a crucial role in reducing surface runoff. The strategic selection of indigenous plants, particularly those with multiple functions, is vital for adapting to local environments and reducing the introduction of invasive species.

Moreover, sustained success in soil bioengineering requires continuous monitoring and assessment of projects to ensure long-term viability and adaptability. The integration of local plant species and the incorporation of traditional land management practices with contemporary bioengineering methods offer practical solutions, especially for small-scale soil management endeavors.

Looking ahead, adopting a holistic and strategic approach to vegetation-based soil bioengineering is imperative. Such an approach should not only focus on immediate ecological benefits but also consider the long-term resilience of Nepal's diverse and fragile landscapes against the increasing threats posed by climate change and other environmental challenges. This comprehensive strategy would better equip Nepal to protect and sustain its natural resources, ensuring environmental stability and the well-being of its communities. Future research should also include a comparative analysis with alternative soil conservation methods to assess the relative effectiveness of bioengineering techniques. The implementation of these techniques should be accompanied by robust training and capacity-building programs for local communities and practitioners. Future publications should aim to include quantitative metrics or case studies to demonstrate the tangible impacts of bioengineering on soil stabilization and agricultural productivity in Nepal. The future of soil bioengineering in Nepal also hinges on comparative analyses with other soil conservation methods, offering insights into the most effective practices for different environments. Moreover, establishing robust training and capacity-building programs for local communities and practitioners will be essential. Such efforts, combined with quantitative assessments of bioengineering's impact on soil stabilization and agricultural productivity, will provide a clearer picture of the effectiveness of these techniques in Nepal's unique landscapes.

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