Vetiver grass-based bioengineering for slope reinforcement and carbon sequestration: a sustainable innovation in bioresource science

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Abstract. Landslides and soil erosion on unstable slopes are worsened by land degradation and extreme climates, which threaten ecological and human systems in tropical regions. Conventional slope stabilization methods, which use concrete structures and heavy machinery, are costly and emit CO_2 through material production and fossil fuel use. In contrast, vetiver grass (Vetiveria zizanioides) provides an eco-friendly bioengineering alternative that protects slopes while sequestering atmospheric CO_2 via physiological activity and biomass development. This study evaluated the dual function of vetiver in enhancing slope stability and capturing carbon under tropical conditions and quantified the organic carbon stored in its aboveground biomass. Photosynthetic traits were measured using the LI-COR 6800 system, and organic carbon was analyzed using the Loss on Ignition (LOI) method. Root characteristics and slope coverage were recorded using field observations. Vetivers exhibited high net photosynthetic rates and efficient stomatal conductance, indicating strong CO_2 absorption. LOI analysis confirmed a significant organic carbon content in shoot biomass. Its dense, fibrous roots improve soil cohesion and minimize runoff. Unlike conventional methods that emit CO_2, vetiver enhances carbon capture while reinforcing the slopes. In conclusion, vetiver-based bioengineering offers a cost-efficient and climate-positive approach for sustainable slope stabilization in tropical regions.

1 Introduction

Bogor Regency is a region in West Java Province with a high level of vulnerability to landslides. In 2022, 415 landslide incidents were recorded, increasing to 487 events in 2023 [1]. One of the villages frequently affected by landslides is Petir Village, which spans an area of 448.25 hectares and features hilly topography with steep slopes of ≥ 9°, resulting in a moderate to high potential for ground movement. This condition is exacerbated by the limited availability of flat land, which forces residents to build houses on slopes, thereby increasing the risk of landslides. This risk is heightened during the rainy season, as high rainfall saturates the soil, making it more susceptible to shifting. Slope cutting for residential development also

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contributes to reduced slope stability. Therefore, slope reinforcement is essential to ensure the safety of housing and infrastructure.

Various slope reinforcement methods have been applied to improve slope stability, including the use of concrete and bioengineering technologies. Concrete-based solutions such as shotcrete, concrete canvas, and gravity retaining walls contribute significantly to carbon emissions, with shotcrete emitting 65.73 kg-CO_2/m³ and gravity walls reaching up to 1025.58 kg-CO_2 [2,3]. The long production process, from material transportation to on-site pouring, also contributes to environmental degradation. Additionally, concrete affects the environment by lowering the soil pH and creating a barren visual impression. On the other hand, methods such as hydroseeding are more environmentally friendly and capable of absorbing CO_2, but they are not yet optimal in terms of slope reinforcement. Technical challenges, such as water accessibility, extreme rainfall, and animal disturbances, further hinder the success of this method [4].

As an alternative, the use of vetiver grass (*Vetiveria zizanioides*) can enhance slope stability while simultaneously absorbing atmospheric CO_2. This plant has a fibrous root system that can grow up to 5.2 meters deep, enabling it to intercept slope slip planes and increase the safety factor [5]. Vetivers can thrive in various soil types, including sand, gravel, shale, and acidic soils. Its strong root system binds soil particles, slows surface runoff, and naturally forms gentle terraces. Beyond its slope stabilization function, vetiver possesses stomata with a density of 108.26 per unit area, allowing efficient CO_2 absorption for photosynthesis [6]. This CO_2 absorption contributes to increased carbon storage within plant tissues. Therefore, vetiver grass has potential as an effective green material for erosion control and climate change mitigation. However, an optimal planting pattern is required to ensure the effectiveness of the plant in erosion control.

This study was conducted to determine a suitable vetiver grass planting pattern based on soil conditions in Petir Village using soil erodibility values and CO_2 absorption rates during the photosynthetic process. This research focuses on the application of vetiver grass for erosion control in the landslide-prone area of Petir Village. The determination of soil erodibility values was based on the Circular Letter of the Minister of Public Works No. 01/SE/M/2012. Tests conducted included sieve analysis, organic carbon content by the Walkley & Black method, soil permeability, and carbon stock measurement through the Loss on Ignition method. The LI-COR 6800 device was used to precisely measure the CO_2 uptake rates. This study aimed to provide planting recommendations for vetiver grass adapted to the site's conditions and support the implementation of environmentally friendly technologies. The results are expected to contribute to the development of disaster mitigation policies and sustainable civil engineering planning aligned with the Sustainable Development Goals, particularly SDG 13 (Climate Action), SDG 11 (Sustainable Cities and Communities), and SDG 15 (Life on Land).

2 Methods

2.1 Location and materials

Soil samples used in this study were collected from landslide-prone areas in Petir Village, Dramaga. The materials used in this research included soil samples, H_2SO_3, $K_2Cr_2O_3$, glucose, deionized water, and vetiver grass (*Vetiveria zizanioides*). The equipment used in this study included tools for soil organic carbon testing (Walkley & Black method) such as acrylic tubes, 100 ml volumetric flasks, 10 ml graduated pipettes, 5 ml volumetric pipettes, 50 ml burettes, and 250 ml Erlenmeyer flasks; tools for soil sieve analysis including a sieve shaker, a set of sieves (No. 10–200), pan, analytical balance, brush, and stopwatch; tools for

soil permeability testing including falling head apparatus, extruder, thermometer, ruler, and vernier caliper; tools for measuring CO_2 uptake rate (LICOR LI-6800); and tools for carbon stock testing including an oven, porcelain crucibles, and a furnace.

2.2 Determination of soil erodibility value

Soil erodibility refers to the average amount of soil loss per year per unit index. The magnitude of soil erodibility is determined by soil characteristics, such as texture and structure, which are analyzed through particle-size distribution using the simple hydrometer method based on sedimentation principles, organic matter content (Walkley & Black), and soil permeability. The procedure for determining the soil erodibility value is illustrated in Fig. 1 and was calculated using Equation (1) from Wischmeier and Smith (1973) [7].

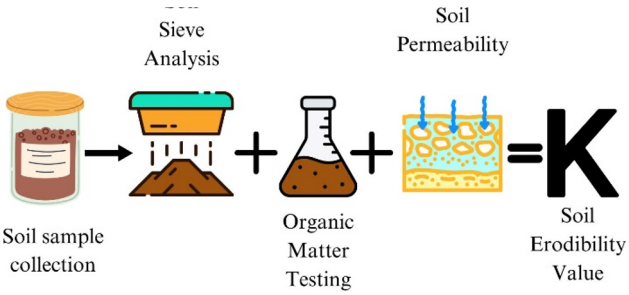

Fig. 1. Determination of Soil Erodibility Value.

$$100K = 1.292[2{,}1\ M^{1{,}14}(10^{-4})(12-a) + 3{,}25(b-2) + 2{,}5(c-3)] \quad (1)$$

Note:

K = Soil erodibility factor

M = (% silt + % fine sand) x (100 -% clay)

a = Percentage of organic matter (1.724 x % C-organic)

b = Soil structure classification code

c = Soil permeability class

2.3 Photosynthesis rate measurement

Measurements were carried out between 09:00 AM and 10:00 AM (Western Indonesian Time). Three vetiver grass plants grown in planting media contained in pipes with a diameter of 10 cm and length of 50 cm were selected as sample units. Photosynthesis rate was measured in fully expanded mature leaves using the LI-COR 6800 Portable Photosynthesis System (LI-COR Inc., Lincoln, Nebraska, USA). During the photosynthesis rate measurement, CO_2 uptake rate data were obtained. In this study, leaf area was calculated by multiplying the length and width of the leaf measured using a ruler, without applying a shape correction constant. This approach was adopted because of the absence of a specific correction factor developed for vetiver grass leaves.

2.4 Carbon stock testing

The Loss on Ignition (LOI) method was employed to measure the carbon stock in vetiver grass by combusting samples to eliminate organic matter. The difference in mass before and

after ignition reflects the organic matter content, which serves as an indicator of the carbon stock. Calculations were performed using Equation (2). Because the LOI method measures not only organic carbon but also other organic substances such as nitrogen and sulfur, a correction was applied using Equation (3).

$$\%LOI\ organic\ matter = \left(\frac{D-E}{D-C}\right) \times 100 \quad (2)$$

$$\%\ C - organik = 0.40 \times \%\ LOI - 0.21 \quad (3)$$

Note:

C = Weight of empty porcelain crucible

D = Weight of crucible + sample before ignition

E = Weight of crucible + sample after ignition (residue)

3 Results and discussion

3.1 *Soil properties*

Based on the results of soil property testing, the wet bulk density (γ_b) was found to be 1.51 g/cm³ and the dry bulk density (γ_d) was 1.12 g/cm³. These soil density values play a role in influence the soil permeability rate. The results of the permeability test showed a value of 0.12 cm/hour, which falls into the "very slow" category with a rating code of 6. In addition, soil moisture content also affects the organic matter content parameters. The soil organic matter content was 4.3%. Soil texture analysis showed that the soil fractions consisted of 0% sand, 97% silt, and 3% clay. According to the soil texture classification based on the textural triangle, the tested sample was categorized as silty soil. The moisture content was 35.79%. Based on the classification of the soil texture triangle, the tested sample was categorized as silty soil. The soil structure obtained from the test was very fine granular, with a rating code of 1. The detailed physical characteristics of the soil are presented in Table 1.

Table 1. Soil Sample Properties in Petir Village

Soil Properties	Value	Unit
Bulk density (γ_b)	1.51	g/cm³
Dry density (γ_d)	1.12	g/cm³
Coef. of permeability	0.12	cm/hour
Moisture content	35.79	%
Organic matter	4.2	%
Soil type	Silt	-

3.2 Soil erodibility

Based on soil texture triangle analysis, the soil was categorized as silt. Data from soil property testing, such as the percentage of organic matter, soil structure, and soil permeability, were used as parameters in Equation (1). The determination of the soil erodibility values using a nomograph is shown in Fig. 2. The erodibility values calculated using Wischmeier and Smith's (1973) equation (A) and the nomograph method (B) are presented in Table 2 [7].

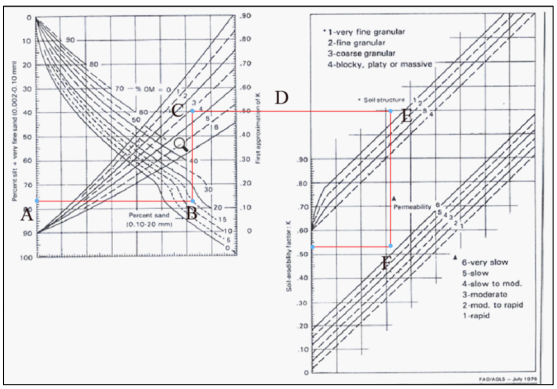

Fig. 2. Nomograph of Soil Erodibility Value in Petir Village

Table 2. Soil Erodibility Values Using the Wischmeier and Smith (1978) Formula (A) and Nomograph Method (B)

Model	Organic Matter (%) (A)	Soil Permeability(C)	K	K Class
A	4.3	6	0.51	5
B	4.3	6	0.50	5

In Table 2, based on the calculation and nomograph methods, the soil erodibility values (K) in Petir Village, Dramaga District, Bogor Regency, were 0.51 and 0.50, respectively. Although there was a slight difference in the K values between the two methods, both fell into Class 5 (high). This indicates that the soil in this category had a relatively high susceptibility to erosion. The high erodibility level was due to the high content of fine sand and silt, low organic matter content, and slow permeability. Soils with high fine sand and silt contents have low particle cohesion, making them more easily detached when exposed to surface runoff. This causes soil particles to be more readily dislodged and transported, thereby increasing the risk of erosion. In addition, low organic matter content contributes to weak aggregate stability. The lack of organic matter results in a less cohesive soil structure, making it more vulnerable to degradation and displacement by hydrological processes.

For soils categorized in the high erodibility class ($K \geq 0.20$), the plant layout recommendations were based on technical guidelines. One commonly used vegetative species is vetiver grass, which has a deep root system that is capable of enhancing soil cohesion. The selection and implementation of planting patterns must be adapted to the slope characteristics to ensure their effectiveness in reducing erosion rates and maintaining soil stability. The planting guidelines established by the Ministry of Public Works (2012) serve as a reference for determining appropriate planting distances, as shown in Table 3 [8].

Table 3. Vetiver Grass Planting Layout in Petir Village

Planting Layout	Slope Gradient (°)		
	<30	30 - 45	>45 - 60
Strip Spacing (cm)	80 - 120	40 - 80	Planting vetiver grass independently is not recommended (it should be combined with mechanical methods)
Shoot spacing (cm)	10 - 15	10 - 15	

3.3 CO_2 uptake rate

The Loss on Ignition (LOI) method was used to measure the organic matter content in vetiver plant biomass, both in roots and leaves. This measurement provides an overview of the amount of organic carbon stored in plant biomass. Based on the test results, the organic carbon content in the combination of roots and leaves was 12%, with leaves contributing 14% and roots contributing 9%. These results were then compared with the leaf organic matter content of other soil conservation plant species, based on previous studies, as shown in Fig. 3.

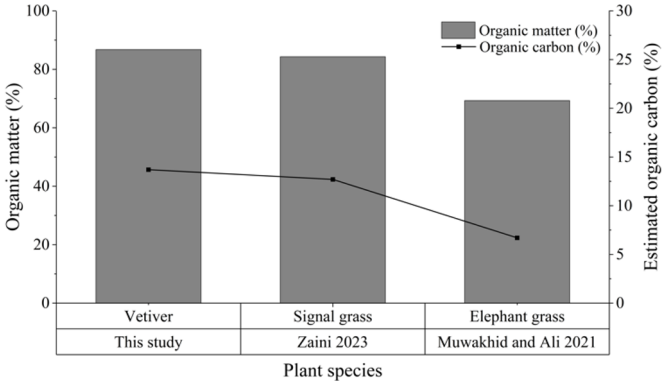

Fig. 3. Correlation Between Organic Matter and Soil Organic Carbon by Plant Type

The results indicate that vetiver leaves contain 86.75% organic matter and 13.7% organic carbon, which are higher than those of elephant grass (*Cenchrus purpureus)* (68% and 7.4%) and signal grass (*Brachiaria decumbens*) (84% and 12.7%). These differences are influenced by the lignin, cellulose, and aromatic compound contents in the plant biomass. Vetiver, which has a high lignin content, exhibits a slower decomposition rate, making its organic matter more stable [9,10].

The dense and deep root system of vetiver increases below-ground biomass and improves soil structure, enriching soil organic matter and carbon content. With a dry biomass of 44.9 g at 4 months after planting, it is estimated that vetiver can absorb 19.6 g of CO_2 per plant [11]. These data demonstrate the effectiveness of vetivers as conservation plants for erosion control and climate change mitigation. This is also supported by CO_2 absorption testing under different light intensities using the LI-COR instrument and the total leaf area, as shown in Fig. 4 and Fig. 5.

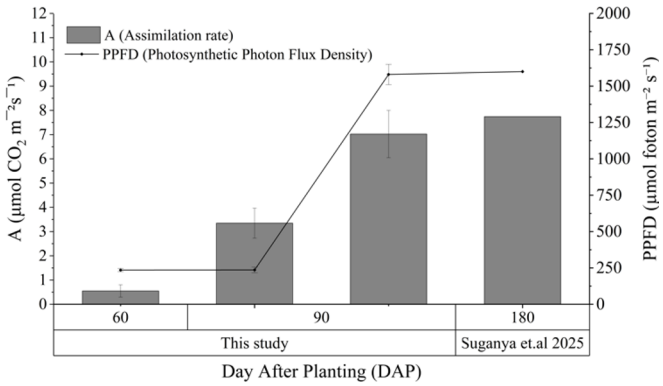

Fig. 4. CO_2 Absorption Rate Based on Light Intensity at Days After Planting (DAP)

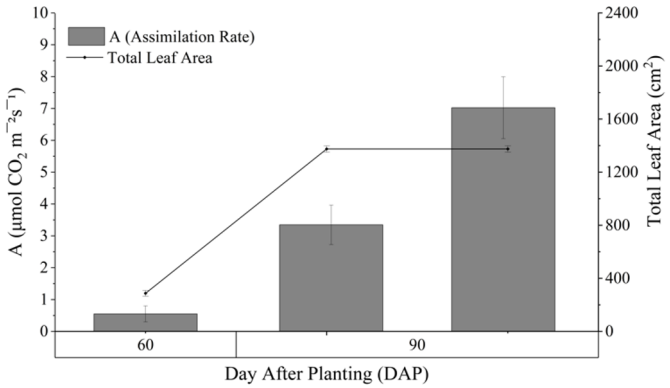

Fig. 5. Relationship Between Assimilation Rate and Total Leaf Area During Vetiver Growth

Fig. 5 shows that CO_2 assimilation rates in vetiver increased with plant age and light intensity, as measured by the LI-COR 6800 device. At 60 days after planting (DAP) and light intensity of 200–300 µmol photons/m²/s, the assimilation rate was about 0.55 µmol CO_2/m²/s. At 90 DAP, this increased to 3.34 µmol CO_2/m²/s, and reached 7.02 µmol CO_2/m²/s at 1600 µmol photons/m²/s. This Fig. closely matches that reported by Suganya et al. (2025) [12] for 180 DAP, which recorded an assimilation rate of 7.74 µmol CO_2/m²/s. This difference is attributed to the more developed physiological characteristics of older plants, such as increased leaf area, chlorophyll content, and photosynthetic efficiency. Plant responses to light also improve with age because of better leaf structure and chloroplast capacity.

The LOI method of organic carbon measurement supports these findings, indicating that CO_2 is not only utilized in photosynthesis but also stored as stable biomass due to its high lignin content. This assimilation rate was used to estimate CO_2 absorption based on the leaf area. The total leaf area was measured for six individual vetiver plants categorized by planting age. Individuals 1, 2, and 3 were 60 days old, with leaf areas of 310 cm², 266 cm², and 284.5 cm², respectively, yielding an average leaf area of 286.83 cm². Individuals 4, 5, and 6 were 90 days old, with leaf areas of 1350.5 cm², 1375.6 cm², and 1397.8 cm², with an average of 1374.63 cm². The estimated CO_2 uptake per plant is shown in Fig. 6. The average assimilation rate at light intensities of 200–300 µmol photons/m²/s increased from 0.55 µmol/m²/s at 60 DAP to 3.34 µmol/m²/s at 90 DAP. At high light intensity (1600 µmol photons/m²/s) at 90 DAP, the rate reached 7.74 µmol/m²/s. Assuming active photosynthesis for 10 h/day, the daily CO_2 uptake was estimated at 0.024 g (60 DAP, low light), 0.728 g (90 DAP, low light), and 1.53 g (90 DAP, high light) per plant. This increase indicates that photosynthesis is strongly influenced by light intensity and plant age, with total leaf area (Fig. 6) playing a critical role. Sufficient light intensity promotes carbon assimilation, whereas older plants have larger leaf areas, more chlorophyll, and root systems that enhance photosynthetic efficiency.

Vetiver is also effective as a conservation plant on roadside slopes because of its dense and deep root system, which helps reduce surface runoff and strengthen the soil. Previous field experiments have shown that the mechanical reinforcement effect of vetiver roots is most pronounced at shallow soil depths and varies with land cover type. For instance, vetiver roots in bushland areas exhibited the highest root area ratio (0.108%) and root cohesion (up to 0.275 kPa), significantly outperforming those planted in bare land or shrubland [13]. The planting distance was adjusted based on slope steepness, as shown in Table 4. These recommendations align with the slope reinforcement guidelines, which suggest additional stabilization on steep slopes to prevent erosion and landslides. Vetivers perform optimally on moderate to steep slopes (30°–45°) but must be combined with civil engineering measures on very steep slopes (>45°), especially for road infrastructure protection in hilly areas.

Table 4. Estimated Number of Vetiver Grass Plants Suitable for Planting

Slope Gradient	Planting Layout		Number of Plants per 10 m² (units)	Number of Plants per Hectare (units)
	Strip Spacing (cm)	Shoot Spacing (cm)		
<30	80	10	237	237,000
	80	15	156	156,000
	120	10	158	158,000
	120	15	104	104,000
30-45	40	10	355	355,000
	40	15	234	234,000
	80	10	237	237,000
	80	15	156	156,000

Table 4 shows that the number of vetiver plants per unit area is influenced by the planting distance. On slopes <30°, a planting distance of 80 cm between strips and 10 cm between shoots yielded the highest population (237 plants/10 m² or 237,000 plants/ha), while a spacing of 120 cm × 15 cm yielded the lowest (104 plants/10 m² or 104,000 plants/ha). The wider the spacing, the lower the plant population. On slopes of 30°–45°, plant populations tended to be higher, particularly with closer spacing between strips. The 40 cm × 10 cm combination produced the highest overall population (355 plants/10 m² or 355,000 plants/ha), whereas the 80 cm × 15 cm combination yielded only 156 plants/10 m² (156,000 plants/ha), similar to the results on slopes <30° with the same spacing. The steeper the slope, the greater the vetiver population required per hectare to reinforce erosion control. Dense planting accelerates the formation of vegetative barriers, slows surface runoff, and enhances slope stability. The highest-density and most evenly spaced planting setup was used to calculate the CO_2 absorption potential, as shown in Fig. 6.

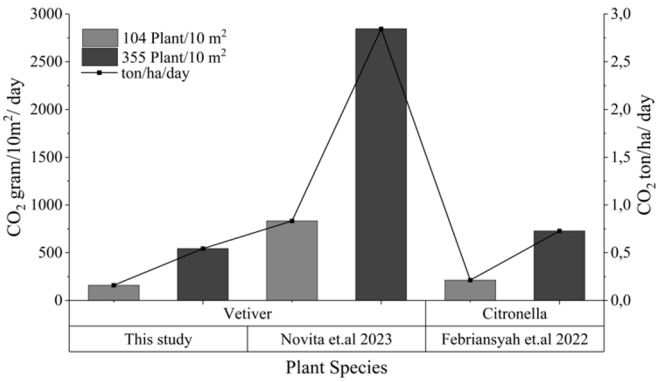

Fig. 6. Combined CO_2 Absorption Graph Based on Plant Type and Planting Density

Fig. 6 illustrates that the planting pattern significantly influences the total CO_2 uptake by the vetiver. With an average uptake rate of 1.53 g/plant/day under high light conditions, the densest planting pattern (355 plants/10 m²) can absorb approximately 543.15 g CO_2/10 m²/day or 0.543 tons/ha/day. In contrast, the sparsest pattern (104 plants/10 m²) only absorbs 159.12 g/10 m²/day or 0.159 tons/ha/day. Compared with the findings of Novita et al. (2023) [14], who used 50 × 50 cm polybag planting media in larger land areas versus a vertical pipe system (diameter 4 inches, height 50 cm) in this study, older 6-month seedlings were observed at 70 DAP, whereas younger 3-month seedlings were observed at 90 DAP. Their CO_2 uptake rate was significantly higher at 8.01 g/plant/day, nearly five times greater than

the younger plants in this study. This suggests that the CO_2 uptake potential of vetivers increases substantially with plant age. A larger planting medium allows for more optimal root and canopy development, which in turn increases leaf area and photosynthetic capacity.

Based on these rates, dense planting can absorb up to 2.844 tons CO_2/ha/day, while sparse planting absorbs 0.833 tons/ha/day, both significantly exceeding uptake rates at younger plant ages. In comparison, citronella grass only absorbs about 2.05 g CO_2/plant/day [15], resulting in 0.728 tons/ha/day for dense planting and 0.213 tons/ha/day for sparse planting—still lower than older vetiver in Novita et al. (2023) [14]. The advantage of vetiver lies in its high CO_2 absorption and long-term carbon storage capacity, owing to its high lignin and aromatic compound content. Measurements also showed that root length increased with plant age. The average root lengths at 60 and 90 DAP were 56.7 cm and 89 cm, respectively, —an increase of 30–40 cm, which functions to bind soil. Its deep root system also supports underground carbon accumulation and soil binding. Therefore, vetivers demonstrate greater potential than citronella in vegetation-based climate change mitigation strategies, especially when grown to optimal age.

4 Conclusion

Petir Village in Bogor is characterized by highly erodible, silt-textured soils, steep slopes, and low permeability, making it particularly susceptible to landslides. Vetiver grass (*Vetiveria zizanioides*) is recommended as the primary component of erosion control strategies. For slopes with gradients of less than 30°, a planting distance of 80–120 cm between strips and 10–15 cm between shoots is advised. For slopes with gradients between 30° and 45°, the recommended spacing is 40–80 cm between strips and 10–15 cm between shoots. On slopes steeper than 45°, vetiver grass should be combined with mechanical methods, such as gabions or slope-retaining structures. In addition to enhancing slope stability, vetiver demonstrates significant carbon sequestration potential, positioning it as a sustainable and environmentally sound alternative to conventional, concrete-based civil engineering methods. Therefore, its integration into local disaster mitigation and sustainable development policies supported by active community participation is strongly encouraged.

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