Geotechnical Engineering Journal of SEAGS & AGSSEA

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Optimization Vetiver Root Growth Using Modular and Root Biostimulants Combination in Soil Bioengineering Method for Slope Reinforcement

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ABSTRACT: The degradation of slope stability caused by earth-cutting activities during highway construction is a geotechnical problem that requires systematic, sustainable management. Conventional concrete-based slope stabilization methods, while structurally effective, generate significant CO_2 emissions, thereby contradicting the principles of sustainable development. This study aims to examine the effectiveness of soil bioengineering methods that integrate vetiver (*Chrysopogon zizanioides*) with modular jute fiber geotextiles, arbuscular mycorrhizal fungi (AMF) biostimulants, and soil moisture control to optimize root system development for slope stabilization. The study was conducted on a laboratory scale with eight treatment combinations covering variations in the use of jute fiber modular units, application of mycorrhizal biostimulants, and two soil moisture regimes (25–35% and 35–45%), with observations at 30, 60, and 90 days after planting (DAP). The parameters analyzed included vegetation biometrics, side root area ratio (RAR_{side}), root tensile strength, and shear strength of vegetated soil. The results showed that the combination of jute fiber modules and a mycorrhizal biostimulant produced the highest root growth response, with root length reaching ±54 cm and RAR values up to 29% at 90 DAP, and a strong positive correlation between root length and RAR_{side} (R^2 = 0.9216). The highest root tensile strength was obtained in the treatment combining modular geotextiles and a mycorrhizal biostimulant at a soil moisture content of 25–35%, reaching 72.5 MPa at a root diameter of 0.4 mm. At 90 days after sowing, treatment A1 achieved the highest cohesion value of 7.70 ± 0.32 kPa, with a root weight of 4.24 ± 0.07 grams, representing an increase of approximately 3.6 times compared to the control. The research results indicate that synergy among modular geotextiles, mycorrhizal biostimulants, and optimal moisture management has the potential to be an effective, environmentally friendly slope-stabilization solution for highway infrastructure projects in Indonesia.

KEYWORDS: Vetiver Grass, Soil Bioengineering, Modular, Arbuscular Mycorrhizal Fungi, and Slope Reinforcement.

1. INTRODUCTION

Infrastructure development in Indonesia has grown significantly in recent years. Large-scale infrastructure projects have been implemented to accelerate national strategic projects. (Rasyid et al., 2022). One of the major infrastructure projects currently underway is the construction of toll roads in various regions, such as the Trans-Sumatra, Java, and Papua Toll Roads. However, toll road construction in Indonesia faces various challenges, including deterioration of slope stability due to excavation along the toll road route (Tugo et al., 2024). Slope cutting activities can reduce slope safety factors, potentially leading to landslides (Kurnia et al., 2024). This indicates that slope mitigation and stabilization efforts are necessary to reduce the likelihood of such disasters. Various protection and reinforcement methods that have been applied to improve the stability of excavation slopes generally employ conventional methods using concrete materials such as retaining walls, shotcrete, concrete blocks, concrete canvas, and various other mechanical techniques (Ikrimah et al., 2020; Li et al., 2016; Pangemanan et al., 2014; Putro and Agustina, 2023). Structurally, concrete materials have proven effective in enhancing slope strength; however, their use in construction faces various challenges, particularly regarding sustainability goals. The use of cement in concrete can result in CO_2 emissions of 0.7–0.99 tons per ton of cement produced (Hasanbeigi et al., 2012). Therefore, negative environmental impacts have driven the search for more sustainable, eco-friendly alternatives, such as soil bioengineering methods.

Soil bioengineering is an environmentally friendly technology that uses vegetation to improve soil (Leknoi and Likitlersuang, 2020). Soil bioengineering is applied to prevent various disasters, such as protecting the soil surface from erosion, preventing landslides, slowing surface runoff along slopes, and other slope stabilization activities (Sittadewi, 2017). One environmentally friendly slope stabilization technique is hydroseeding. The application of hydroseeding as a slope reinforcement method can increase the slope safety factor by up to 5.87% (Sari and Dharmawansyah, 2023). However, the field application of hydroseeding faces challenges such as water control issues, steep slope contours, and extreme weather conditions, so the method has not yet effectively enhanced slope strength (Sunandar and Prananda, 2020). Therefore, the limitations of current soil improvement methods necessitate alternative approaches, such as planting vegetation that retains water to prevent erosion and has root systems that enhance slope stability.

Plant selection is based on several criteria, including the ability to stabilize slopes, prevent erosion, and slow runoff, as well as the capacity to grow rapidly and develop deep, extensive root systems (Sinarta, 2014). Vetiver grass (Vetiveria zizanioides), also known as fragrant root, is one of the most effective plants for addressing erosion and landslide issues. Vetiver excels at controlling soil erosion and stabilizing slopes due to its deep, extensive root system, which effectively reduces erosion rates and holds soil particles in place (Elahi et al., 2019; Rouhou et al., 2023). Additionally, vetiver has fibrous roots capable of penetrating hard soil layers up to 15 cm thick and extending to a depth of 5.2 meters (Hamdhan et al., 2020). Vetiver has demonstrated excellent resilience under extreme

https://doi.org/10.14456/seagj.2026.25 Published on 19 October 2026

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environmental conditions, including drought, flooding, and poor soil, making it a strategic solution for soil and environmental conservation (Mahmoudpour et al., 2021). However, during the early growth stage of vetiver, the process faces several challenges, including slope conditions that can lead to soil erosion and make the plants more easily carried away. Additionally, nutrient deficiencies on excavation slopes challenge vegetation-based methods for improving slope stability and protecting highway excavation sites. Slope conditions consisting of fill soil reaching 15 meters in depth result in nutrient-deficient soil, as nutrients are typically concentrated in the topsoil layer, which is essential for plant growth (Pratama et al., 2022). Therefore, alternative methods are needed, such as using geotextiles as a temporary medium to prevent erosion from carrying away plants and applied nutrients.

The use of geotextiles is often combined with other materials, such as in canvas concrete, which is used to stabilize slope contours (Li et al., 2016). However, in this study, geotextiles were used as a growing medium for vetiver planting. Geotextiles were applied to protect the plants and nutrients from slope erosion during the early stages of vegetation growth (Kalibová et al., 2016). Several types of geotextiles were used, including synthetic, composite, and natural fiber materials. The use of geosynthetic materials on the soil surface can increase soil strength by up to 18.2% (Ogundare et al., 2018). However, synthetic geotextiles are not environmentally friendly because they are made from chemicals and do not degrade naturally. Therefore, selecting geotextiles made from jute fiber can be a solution as they have a lower environmental impact. Modular geotextiles made from jute fibers degrade, thereby providing additional nutrients as they decompose (Kalibová et al., 2016). However, there is currently no in-depth research on optimizing vetiver growth. Consequently, the application of specific vegetation management methods is also a critical factor in the growth of slope-protection plants.

The effectiveness of using vetiver for slope stabilization depends on the development of an optimal root system. Plant root system growth is influenced by the amount of water and nutrients the plant can absorb, allowing the roots to grow optimally and form a dense root network (Dwicaksono, 2023). Therefore, optimal water management is a key factor in supporting the growth and development of the vetiver root system. Meeting the water requirements for plant absorption must be managed efficiently so that plant roots can grow well (Marsha et al., 2014). A good water management system includes regulating surface drainage to control rainwater flow, managing water infiltration and percolation to maintain soil moisture balance, and implementing water and soil conservation techniques to reduce the risk of erosion. However, water alone is not sufficient to support vetiver root growth. Meeting nutrient requirements is also a key factor in accelerating root growth (Priherdityo et al., 2016). The use of biostimulants can be a potential solution for the development of vetiver cultivation. These biostimulants stimulate plant root growth and development, thereby promoting faster growth. One widely used biostimulant is mycorrhiza, or Arbuscular Mycorrhizal Fungi (AMF), which enhances plant growth, particularly by improving water and nutrient uptake. In soils with low nutrient content, the application of mycorrhizae can increase root surface area and the efficiency of nutrient uptake by plants (Pop-Moldovan et al., 2022; Ramana et al., 2023). This indicates that the application of mycorrhizae can enhance root growth by increasing root diameter and expanding root networks, enabling plants to access soil resources (Song et al., 2012). The integration of vetiver planting with specialized treatments is expected to create optimal synergy, developing a stronger root system for slope stabilization. Therefore, this study is important to conduct through a comprehensive analysis regarding the effectiveness of vetiver planting with geotextiles treated with special treatments as a method for highway slope stabilization.

2. MATERIAL AND METHOD

2.1 Materials

The tools used in this study were 130-liter container boxes (53×76 ×45 cm). The container box was used to simulate field conditions, where plants can grow without restrictions on their growth area. Additionally, modular jute fiber units measuring 53×10×10 cm were used. The dimensions of the modular have been adjusted to fit the container box and the planned planting spacing. Additionally, several tools will be used, such as soil property testing equipment (particle size distribution test, soil bulk density test, soil moisture content test, Atterberg limit test), direct shear testing equipment, root tensile strength testing equipment, and a roll meter. The materials to be used include vetiver seeds, growing media consisting of compost and NPK fertilizer (16:16:16), and mycorrhizal biostimulants. Meanwhile, soil samples were collected from the slopes of the Cikabayan Garden at IPB University. A map of the sampling locations is shown in Figure 1.

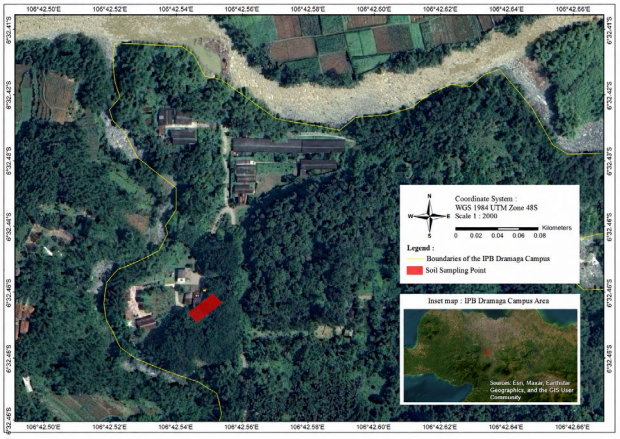


Figure 1 Map of soil sampling locations

The study began with soil property tests, including gradation, moisture content, specific gravity, and Atterberg limit tests. Subsequently, the vetiver planting and maintenance process was carried out with several treatments, including the use of jute fiber geotextile, two irrigation volumes corresponding to moisture ranges of 25–35% and 35–45%, and the application of 20 grams of mycorrhizal biostimulant per inoculum. Subsequently, biometric vegetation analysis was conducted, including root length, leaf length, and root area ratio on samples aged 30, 60, and 90 days after planting (DAP), as well as mechanical testing, including root tensile strength tests with diameter variations of 0.4 mm, 0.6 mm, 0.8 mm, and 1 mm, as well as soil shear strength tests using the direct shear method on samples 60 and 90 days after planting (DAP).

Based on soil property testing results, the initial soil moisture content was determined to be 35.11%. Changes in moisture content can affect soil density. The field density obtained from testing using a core cutter sample was 1.50 g/cm^3, while the dry density was also 1.11 g/cm^3. Furthermore, the specific gravity (Gs) was determined to be 2.52. The Gs value is related to soil density and can affect soil shear strength parameters. Atterberg limit tests yielded a liquid limit of 40.42%, a plastic limit of 29.09%, and a plasticity index of 11.33%. The analysis of sand, silt, and clay content was conducted by mixing the soil with water and allowing it to settle for 24 hours. The results showed sand content of 7.14%, clay content of 34.52%, and silt content of 58.33%. Based on the texture triangle classification, it was determined that the analyzed soil sample falls into the clay category. According to the USCS classification system, this soil sample is classified as CL, indicating clay with low to moderate plasticity. The materials used in this study are depicted in Figure 2.



Modular Jute



Biostimulant AMF



Vetiver Seeds



Growing Media

Figure 2 Materials used in this study

2.2 Vetiver Grass Planting Scheme

The vetiver planting process begins by filling the container boxes with soil samples. Vetiver is planted in an open area so that the plants can receive direct sunlight. The soil conditions are adjusted to match the soil density (γ_w) at the sampling site, ensuring they accurately reflect field conditions. The soil requirements per container are calculated, yielding 151.87 kg/box. Next, modular units containing the growing medium are placed on top of the container boxes and equipped with 5 cm diameter holes spaced 10 cm apart for the planting area. The growing medium consists of a 3:1 mixture of soil and compost. Subsequently, NPK fertilizer and mycorrhizal biostimulant were added to the planting area. The amount of NPK fertilizer applied was 3 grams. At the same time, the dose of mycorrhizal biostimulant followed the protocol from Chen et al. (2018), specifically 20 grams of inoculum per plant, applied by broadcasting over the planting area. Next, the vetiver seeds were planted in the prepared planting holes. The vetiver planting scheme using a modular pipe system is shown in Figure 3.

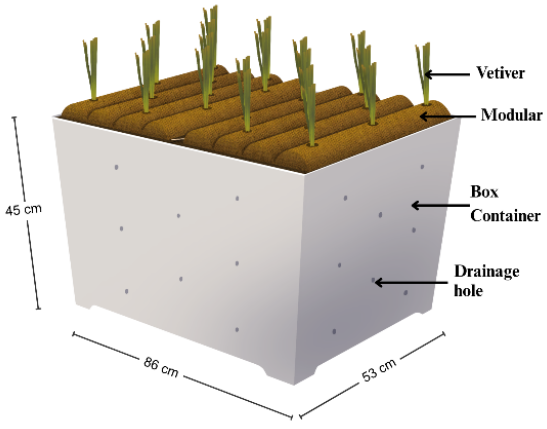


Figure 3 Schematic of vetiver planting with modular jute on box container

Next, maintenance was carried out through regular watering and fertilization. Watering was performed under two soil moisture conditions: 25–35% and 35–45%. Watering was conducted after determining the soil moisture level, allowing the irrigation volume to be adjusted to match the planned moisture regime. Subsequently, watering should be performed routinely, at least once a day (before 9:00 AM or after 4:00 PM) until the plants are 3 months old. Furthermore, plants were fertilized 2 weeks after planting with NPK fertilizer (16:16:16) at a rate of 3 grams per hole. Subsequently, analysis and observation of the vetiver plants were conducted at 30, 60, and 90 days after planting (DAP) by measuring root dimensions, conducting root tensile strength tests, and performing direct shear strength tests on a laboratory scale. The experimental design for vetiver planting is presented in Table 1.

Table 1 Experimental design

Sample Code	Planted Aged (DAP)	Note
A1	30, 60, 90	A = Modular with biostimulant B = Modular without biostimulan C = Non-modular with biostimulan D = Non-modular without biostimulan 1 = Soil moisture 25-35% 2 = Soil moisture 35-45%
A2	30, 60, 90	
B1	30, 60, 90	
B2	30, 60, 90	
C1	30, 60, 90	
C2	30, 60, 90	
D1	30, 60, 90	
D2	30, 60, 90	

2.3 Testing Procedure

2.3.1 Side Root Area Ratio (RAR_{side}) Analysis

The effect of vetiver on soil shear strength can be assessed using the root area ratio. The side root area ratio (RAR_{side}) was used to characterize the two-dimensional projected root area of the washed and flattened root system. The cleaned roots were placed on a transparent medium and photographed from the side at the same height and shooting position. The images were analyzed using ImageJ, and RAR_{side} was calculated as the ratio of total root pixels to the total pixels within the analyzed area. The side root area ratio (RAR_{side}) is a parameter that describes the degree of root penetration into the soil matrix (Mahima et al. 2025). Side root area ratio analysis was conducted to estimate the contribution of roots to soil shear strength at specific root depths (Adu et al. 2025). The observation began with preparing root samples separated from their shoots. Next, the cleaned root samples were placed on a transparent medium. Then, images of the root samples were taken at the specified planting ages for analysis: 30, 60, and 90 days after planting (DAP). Images were taken at the same height and from the same shooting position. The images were then analyzed using ImageJ. Image processing with ImageJ software begins by converting the photograph into an 8-bit monochrome image; next, the image's brightness and contrast are adjusted so that cracks or fracture lines can be clearly distinguished. The final step involves thresholding the image so that it consists only of black and white pixels. This simplifies image analysis by allowing the crack area to be calculated using only black pixels. The number of pixels in the crack area could be determined through gray-level thresholding and pixel statistics. The side root area ratio was then calculated using Eq. (1).

$$RAR_{side} = \frac{total\ plant\ root\ pixels}{total\ number\ of\ pixels} \quad (1)$$

2.3.2 Root Tensile Test

Tensile strength testing of vetiver roots was conducted to characterize the roots used in the soil reinforcement process using plants. Vetiver roots interacting with the soil form a composite to reinforce the soil by converting shear stress within the soil matrix into tensile stress. The tensile strength of these roots can be influenced by several factors, including their physical and chemical characteristics and environmental factors that affect root growth in a given area. The root tensile strength test is conducted by measuring the maximum force

(F_{max}) until the root breaks. Root tensile-strength (T_r) testing begins by measuring the root sample's diameter. Next, the root tensile strength test is performed using a Universal Testing Machine (UTM). An illustration of the equipment used in the root tensile strength test is shown in Figure 4.

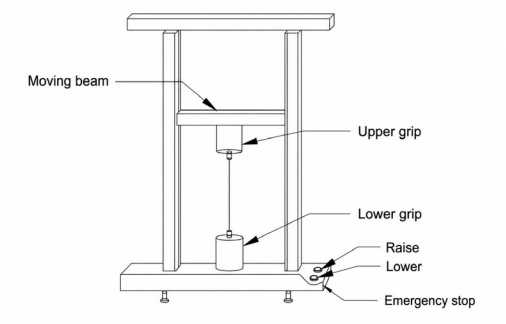


Figure 4 Illustration of tensile strength (T_r) testing of roots using a universal testing machine (UTM)

Subsequently, the root tensile stress value is calculated using Eq. (2).

$$T_r = \frac{F_{max}}{\pi\left(\frac{D^2}{4}\right)} \quad (2)$$

where T_r is root tensile strength (MPa), F_{max} is the maximum force (N), and D is the root diameter (mm).

2.3.2 Direct Shear Test

Direct shear strength tests were conducted to determine the effect of vetiver planting on cohesion, interparticle attraction, and the angle of internal friction (the angle between the soil particles). These tests were performed in accordance with SNI 3420:2016 regarding the Method for Direct Shear Strength Testing of Unconsolidated and Undrained Soils. Direct shear strength testing was performed on control samples (without vegetation) and on samples with vegetation under various treatment conditions, including the use of modular systems, application of a mycorrhizal biostimulant, and soil moisture management, with samples tested 60 and 90 days after planting (DAP).

Direct shear strength testing was performed on control samples (without vegetation) to represent field soil conditions prior to soil reinforcement using vegetation. Subsequently, soil samples were collected at a depth of 0–15 cm from each plant under different treatment conditions. Direct shear tests were conducted in triplicate for each treatment. The results were expressed as mean values, and the variability among the three replicate measurements was evaluated using the standard deviation (SD). The SD was calculated based on the three replicate measurements and presented as error bars in the corresponding figures. The direct shear test scheme for a single specimen is illustrated in Figure 5.

Soil shear strength analysis was performed using the Mohr-Coulomb equation. Eq. (3) shows the relationship between normal and shear stresses on the soil plane, where the shear stress (τ) (kPa), cohesion (c) (kPa), normal stress (σ) (kPa), and friction angle (φ) (°). Furthermore, soil shear strength analysis with additional vegetation influence was conducted using Eq. (4), with soil cohesion influenced by roots is the (c_R) (kPa), and the internal friction angle influenced by roots is the (φ_R) (°). This root influence is represented by increment c, which is the additional cohesion from plant roots. The calculation of the value (Δc_R) is performed using Eq. (5).

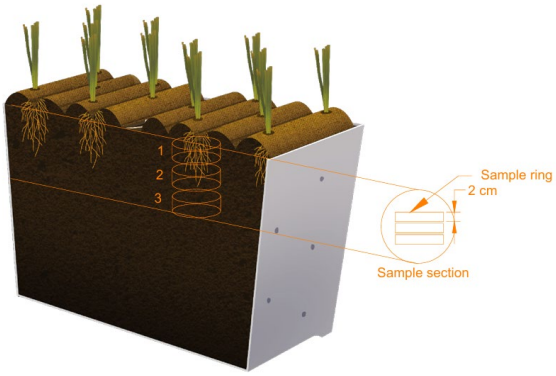


Figure 5 Direct shear testing procedure

$$\tau = c + \sigma \tan \varphi \quad (3)$$

$$\tau = (c + c'_R) + (\sigma_n).tan\,(\varphi + \varphi'_R) \quad (4)$$

$$\Delta c_R = (c + c_R) - (c_{control}) \quad (5)$$

3. RESULT AND DISCUSSION

3.1 Analysis of the Effect of Modular System and Root Biostimulants Application on Vegetation Biometrics

The combined application of jute bags and mycorrhizae as root biostimulants affected the biometric characteristics of vetiver vegetation. Vetiver growth analysis was conducted to determine the root growth rate under each treatment variation. In general, the combination of modular treatment with biostimulants yielded the optimal vetiver plant growth response compared to samples without modular treatment or biostimulants throughout the observation period, as shown in Figure 6, which compares vetiver plant growth responses at 30 days after planting (DAP). Data from biometric vegetation observations at 30, 60, and 90 days after planting (DAP) showed significant variations among treatments, as presented in Figure 7.

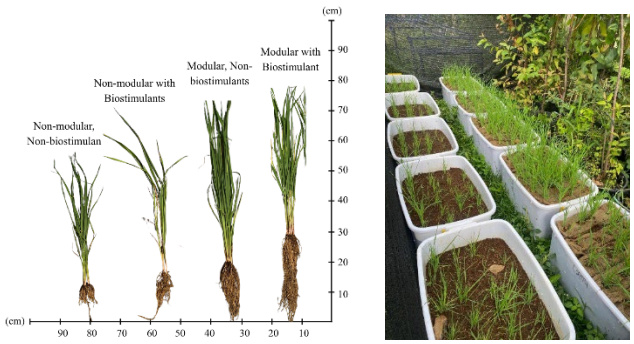


Figure 6 Comparison of vetiver growth responses at 30 days after planted

Based on the observation results, it was found that the biometric parameters of vetiver vegetation increased with plant age across all treatments. In general, the highest root length and leaf length parameters were obtained in the modular treatment with biostimulant (sample A), namely with a root length of approximately 51±4.24 cm and a leaf length of 113.67±2.83 cm, slightly higher than in the modular treatment without biostimulant, (sample B) which had a root length of 48.67±2.83 cm and a leaf length of 107.83±3.06 cm. Meanwhile, in the non-modular samples with biostimulants (Sample C), root length was 42.33±1.89 cm and leaf length was 101.67±0.47 cm, slightly higher than in the non-modular samples without

biostimulants (sample D), where root length reached 40.33±2.36 cm and leaf length was 95.5±4.84 cm. This suggests that during the early growth phase, a modular system has a more pronounced effect on root development than biostimulants.

In this study, jute fiber modules were used as a growing medium to maintain soil moisture and nutrient availability during the early stages of plant growth, thereby promoting optimal root development (Dwicaksono, 2023; Susilawati and Veronika, 2016). The jute modular geotextile serves as a temporary medium during the early growth stage by providing physical protection and retaining moisture and nutrients. As a natural fiber, jute gradually biodegrades, reducing its structural function as the vetiver root system becomes more established. In this study, the increase in root length and the root area ratio from 30 to 90 days after planting indicates progressive root development. However, because jute decomposition was not directly measured, the specific decomposition rate and stage cannot be quantitatively determined.

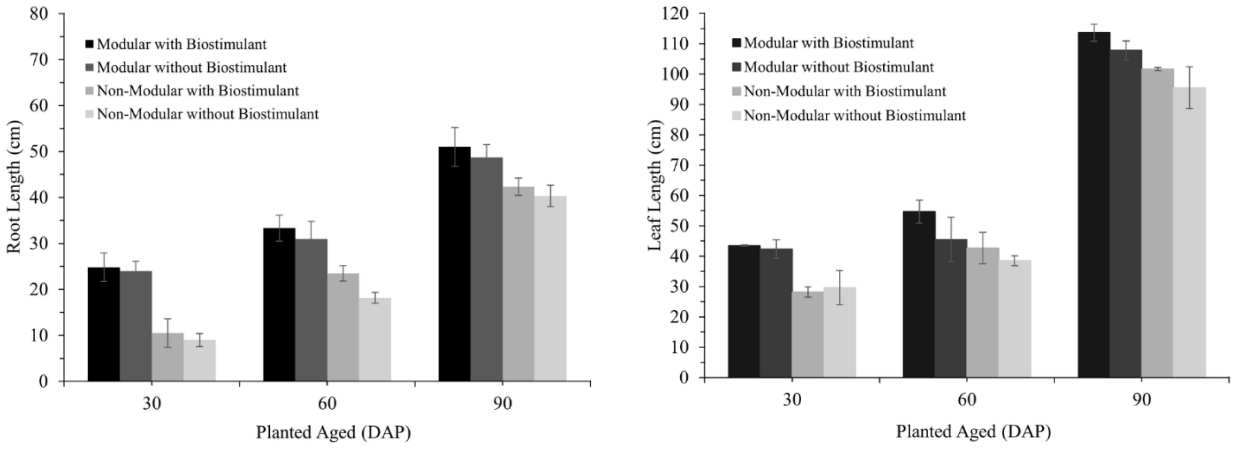


Figure 6 The effects of modular and biostimulants on vegetation biometrics: (a) root length; (b) leaf length

This occurs because the soil surface is not directly exposed to sunlight, preventing it from drying out too quickly. Additionally, nutrients derived from compost fertilizer remain retained within the modular layer, ensuring nutrient availability during the early growth stage of vetiver (Septyani et al., 2014). However, the use of the modular system alone is insufficient to optimize vetiver growth, particularly in soils with low nutrient content; therefore, this study also included a treatment with mycorrhizal biostimulants.

The application of biostimulants is expected to help strengthen the vetiver root system, particularly during the early growth stage. Biostimulants are known to stimulate the synthesis of plant growth hormones, enhance nutrient uptake efficiency, and strengthen the plant's response to abiotic stress (Chen et al., 2022). Arbuscular mycorrhizal fungi (AMF) are soil microorganisms that live in symbiosis with plant roots, including vetiver (*Chrysopogon zizanioides*), by entering root cortex cells and forming specialized structures such as arbuscules, vesicles, and hyphae as conduits for nutrient exchange between the fungi and the plant. In this symbiosis, the plant provides carbohydrates from photosynthesis to the AMF. At the same time, the AMF assists the plant in absorbing phosphorus (P) and water from the soil through its hyphal network, which in turn stimulates root tip cells to divide and elongate (Begum et al., 2021; Chen et al., 2018).

3.2 Analysis of the Effect of Soil Moisture Conditions on Vegetation Biometrics

Controlling soil moisture across various moisture conditions demonstrated an effect on vetiver vegetation growth. In this study, soil moisture control was based on two ranges: 25–35% and 35–45%. The selection of these two moisture ranges was based on field soil moisture tests, which indicated a soil moisture content of approximately 35%; therefore, the experiment involved increasing and decreasing the moisture content by 10% from the field conditions. The results of the soil moisture observations are shown in Figure 8(a) and (b). Therefore, these moisture settings were established to determine the optimal soil moisture level required by vetiver plants, ensuring optimal plant growth. Observations of the effect of soil moisture on root length were conducted at 30, 60, and 90 days after planting (DAP). The results of root length observations influenced by soil moisture are presented in Figure 8(c).

Based on observations of root length under the two soil moisture treatments, a consistent pattern of growth emerged: root length increased as plants matured, both at 25–35% and 35–45% soil moisture. At 30 days after planting (DAP), vetiver plants under the 25–35% moisture treatment had an average root length of 10–27 cm, whereas those under the 35–45% moisture treatment had a lower root length of 8–23 cm. This difference became more pronounced at 60 days after planting (DAP) and peaked at 90 DAP, where the 25–35% humidity treatment yielded average root lengths of 47–54 cm, while the 35–45% treatment reached only 38–44 cm. Overall, the treatment with lower humidity (25–35%) consistently produced longer roots compared to the treatment with higher humidity (35–45%) throughout the observation period.

Under soil moisture conditions of 25–35%, the plants experience a mild water deficit, a condition in which they face a slight water shortage, but one that is still sufficient for the plants to perceive as a stress signal, prompting the roots to explore deeper into the soil. These conditions promote primary root elongation as an adaptive response to enhance water uptake efficiency under deficit conditions, while simultaneously inhibiting lateral root formation (Ganeshan et al., 2024). Conversely, at soil moisture levels of 35–45%, higher water availability causes soil pores to become water-saturated, thereby reducing aeration and inhibiting root aerobic respiration. Hypoxic conditions in the root zone reduce the roots' ability to absorb water and nutrients, while the lack of oxygen due to overly saturated soil forces the roots to switch to anaerobic respiration, which produces significantly less energy (Yang et al., 2023; Zhang et al., 2025).

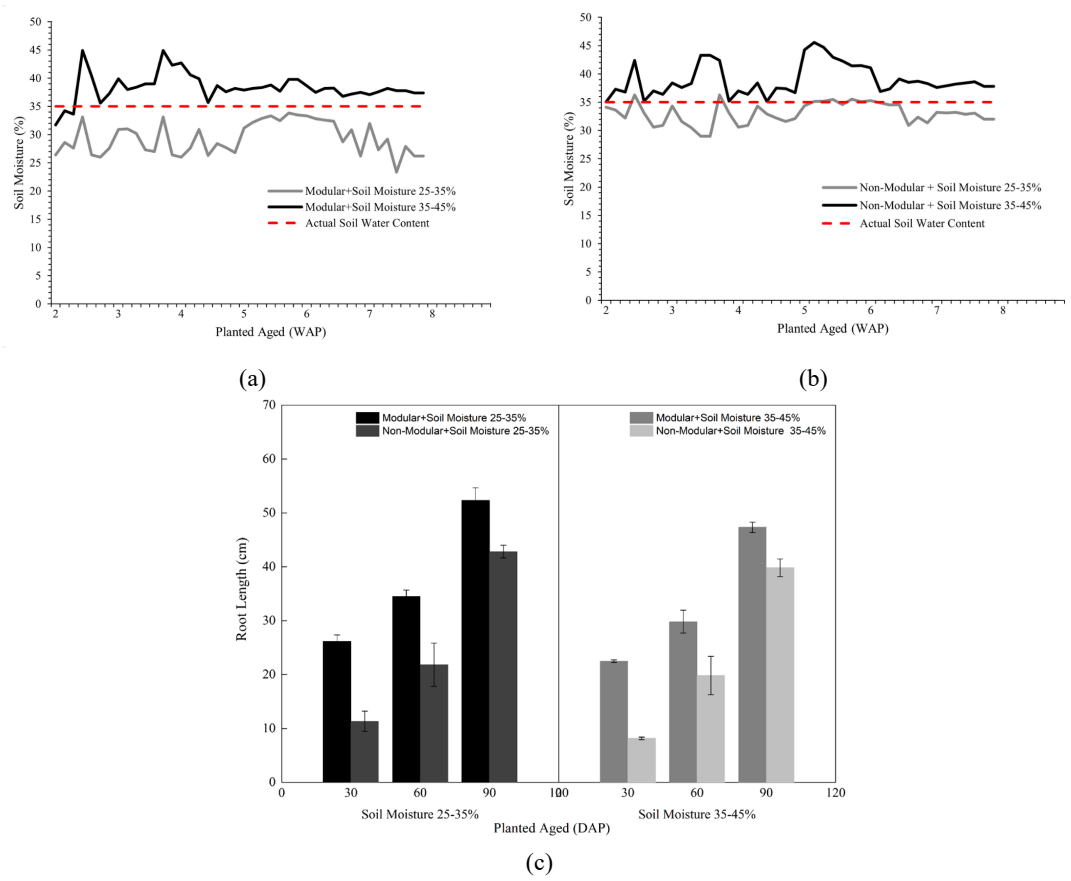


Figure 7 The effect of soil moisture on vetiver biometric traits

3.3 Measurement of the Side Root Area Ratio (RAR_{side})

This reduced energy supply inhibits cell division and elongation in the root meristem, thereby further hindering root growth. Side root area ratio (RAR_{side}) analysis was conducted to determine the fraction of soil cross-sectional area occupied by vetiver roots per unit area. This analysis was performed using image analysis methods, specifically by capturing cross-sectional images of vetiver roots in soil with ImageJ. This software calculates the image's surface area and the volume of the vetiver roots within those pixels. RAR_{side} is then calculated by dividing the total root surface area by the total soil area. The final volume and surface area values are obtained by summing the contributions from all pixels in the image (Seethepalli et al., 2021). Vetiver side root area ratio (RAR_{side}) analysis was performed on vetiver samples aged 30, 60, and 90 days after planting (DAP), and the results were compared with root length at each observation age. The relationship between side root area ratio (RAR_{side}) and root length is presented in Figure 9.

Based on observations at three time points (30, 60, and 90 DAP), RAR values increased with plant age. The results at 30 days after sowing showed that RAR_{side} values were still relatively low, ranging from 3–8%, while root length ranged from 10–25 cm. Furthermore, the RAR value increased at the 60-day observation period, with RAR ranging from 5–20% and root length ranging from 15–45 cm, and reached its highest value at the 90-day observation period, with RAR_{side} ranging from 10–29% and root length up to 55 cm. This pattern indicates that vetiver root concentration can increase significantly over time as the vetiver root system develops, particularly during the early stages of growth (0–3 MAP) (Jotisankasa et al., 2015).

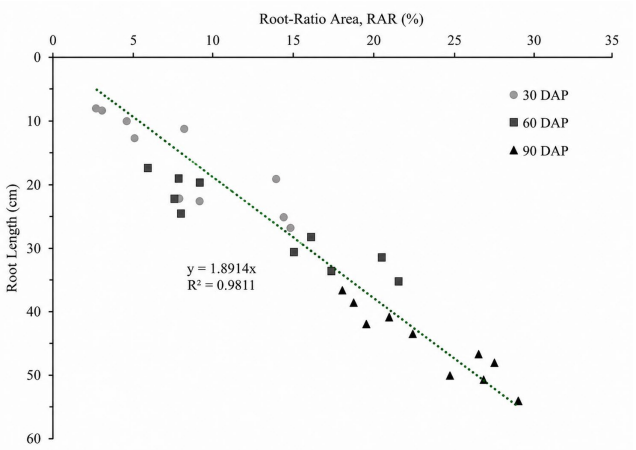


Figure 8 The correlation between root length and side root area ratio (RAR_{side})

Analysis of the relationship between RAR_{side} and total vetiver root length across three observation periods (30, 60, and 90 days after planting) revealed a strong positive correlation, with the equation $y = 1.8914x$ and an R^2 of 0.9811. This indicates that an R^2 value approaching 1 suggests that approximately 98.11% of the variation in root length can be explained by the RAR value. The observation results confirm that the RAR_{side} value is a representative root concentration index for describing the overall growth condition of the vetiver root system (Adu et al., 2025). Mechanically, the larger the root cross-sectional area in the observation plot, the higher the RAR value will be (Mahannopkul and Jotisankasa, 2019).

3.4 Tensile Root Strength Analysis

Root tensile strength (T_r) testing in this study was conducted using the uniaxial tensile test method with a Universal Testing Machine (UTM). The testing was performed on vetiver root samples subjected to various planting treatments, specifically 8 treatment combinations involving the application of jute fiber modules, the application of mycorrhizal biostimulants, and soil moisture levels (25–35% and 35–45%), resulting in eight data series: A1, A2, B1, B2, C1, C2, D1, and D2. The testing was then conducted using four root diameters (0.4, 0.6, 0.8, and 1.0 mm) for each treatment-combination sample. The selection of these diameter variations was based on the distribution of vetiver root diameters, which is dominated by roots with fine to medium diameters. Generally, vetiver roots in the 0–50 cm soil layer have an average diameter of 0.3-1.2 mm (Adu et al., 2025; Hamidifar et al., 2018). Based on the root tensile strength test results, the maximum force (F_{max}) required to break vetiver roots was determined, as shown in Figure 10.

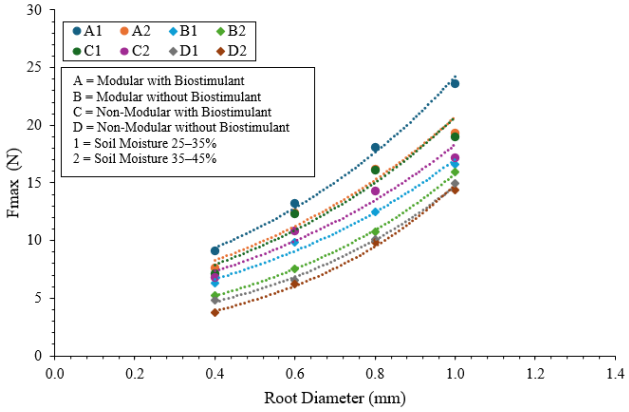


Figure 9 The correlation between root diameter and maximum force (F_{max})

Based on the test results, the maximum force (F_{max}) showed a consistent positive correlation with root diameter across all treatments. The test results show that treatment sample A1 consistently produced the highest F_{max} value, reaching 23.63 N at a diameter of 1.0 mm, while sample D2 produced the lowest value, 14.41 N at the same diameter. In general, the F_{max} values obtained increased from a diameter of 0.4 mm onward, ranging from 3.78 to 12.42 N, and remained consistent at subsequent diameters up to a root diameter of 1.0 mm, yielding F_{max} values of 14.41–23.63 N. This study aligns with that of Fata et al. (2022), which found that F_{max} increased with root diameter. The increase in F_{max} values with increasing root diameter occurs because roots with larger diameters have a larger cross-sectional area, enabling them to distribute tensile stress over a wider area before failure occurs (Adu et al., 2025). Subsequently, the F_{max} value was used to calculate the root tensile strength (T_r) as a function of root diameter, using Equation 4. The results of the root tensile strength testing are presented in Figure 11.

The results of the root tensile strength (T_r) tests showed that tensile strength decreased as root diameter increased. The highest root tensile strength (T_r) was obtained at the smallest diameter (0.4 mm) under treatment A1, reaching 72.5 MPa, and then decreased at larger diameters, with T_r reaching 30 MPa at 1.0 mm. Meanwhile, the lowest T_r values were obtained in treatment D2 at 0.4 mm (30 MPa) and at 1.0 mm (18.35 MPa). These findings are consistent with the results of a study conducted by Adu et al. (2025), which reported root tensile strength values ranging from 23.4 to 33.1 MPa at 70 days after planting, and a study by D'Souza et al. (2019), which reported root tensile strength values ranging from 40 to 180 MPa. The relationship between root diameter and tensile strength (T_r) exhibits a negative exponential relationship, such that as root diameter increases, tensile strength decreases (Fata et al., 2022). Generally, finer-textured roots and thinner root structures have higher cellulose content, resulting in higher mechanical strength than coarse roots (Machado et al., 2015; Yang et al., 2016).

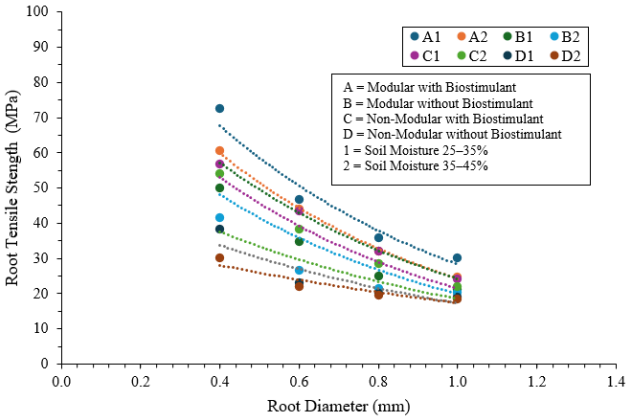


Figure 10 The correlation between root diameter and root tensile strength (T_r)

In general, samples treated with the modular and biostimulant treatments yielded higher root tensile strength (Tr) values than samples treated with other treatments. This indicates that the modular and biostimulant treatments can significantly affect vetiver root development. Modular treatment provides a more structured root growth space, thereby producing a stronger root tissue structure (Susilawati & Veronika, 2016). Furthermore, biostimulants stimulate plant metabolic activity, enhance nutrient uptake efficiency, and strengthen the plant's response to abiotic stress (Chen et al., 2022). Regarding soil moisture, samples with 25–35% moisture content yielded higher Fmax values than those with 35–45% moisture content. This occurs because reduced water content causes cell wall compaction, thereby increasing the stiffness and mechanical strength of root tissues (Boldrin et al., 2021; Yang et al., 2016). Therefore, growth environmental conditions, including nutrient availability and soil moisture content, influence root chemical composition, which ultimately impacts root mechanical properties (Zhang et al., 2019).

The variation in root tensile strength should be considered in relation to plant development. During the early growth stage, increasing root growth and biomass can enhance the mechanical contribution of roots to soil reinforcement. In this study, root development increased progressively from 30 to 90 DAP, indicating an increasing reinforcement contribution during the observation period. However, as vegetation ages and enters senescence or withering, root tissues may gradually lose their mechanical integrity and decompose, potentially reducing their long-term contribution to soil reinforcement. Therefore, sustainable slope stabilization should consider continuous vegetation growth and regeneration. Since this study was limited to 90 DAP and did not cover the withering or death stage, the long-term changes in root tensile strength and reinforcement capacity were not directly quantified.

3.5 Shear Strength Analysis

Soil shear strength is one of the most important parameters in slope stability studies. Soil shear strength tests were conducted to determine the effect of vetiver planting with various treatment variations on soil shear strength, thereby obtaining the cohesion (c) and internal friction angle (φ) parameters. In this study, tests were conducted on a laboratory scale using soil planted with vetiver (*Chrysopogon zizanioides*) with a combination of treatments including planting patterns (modular and non-modular), application of biostimulants, and moisture content (25–35% and 35–45%), at observation ages of 60 and 90 days after planting (DAP). Shear strength analysis was performed by interpreting the stress-displacement curve. Testing continued until the sample failed or until the sample reached a

maximum displacement of 20% of the soil sample's diameter during testing. The results of the direct shear test are shown in Figure 12.

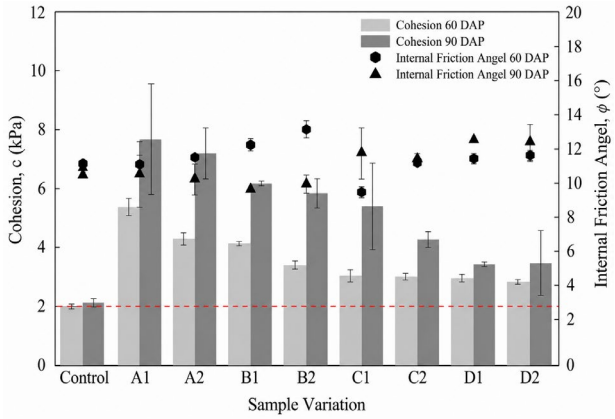


Figure 11 Vetiver root contribution to soil shear strength parameters

Based on direct shear strength tests, all soil samples with vegetation reinforcement yielded higher soil strength than those without vegetation (controls). At a planting age of 60 days after planting (DAP), the A1 combination sample yielded a cohesion (c) value of 5.45±0.28 kPa with an internal friction angle (φ) of 11.41°±0.52°. Meanwhile, the sample with the lowest shear strength parameters was obtained from sample D2, with a cohesion (c) value of 2.99±0.07 kPa and an internal friction angle (φ) of 11.93°±0.29°.

Then, at a planting age of 90 days after plant (DAP), the highest shear strength parameters were also obtained in sample A1, with a cohesion value (c) of 7.70 ± 0.32 kPa and an internal friction angle (φ) of 10.89° ± 1.83°, while the lowest values were found in samples D1 and D2, with a cohesion value (c) of 3.60 ± 0.10 kPa and an internal friction angle (φ) of 12.64° ± 1.64°. Compared with the control (c) 2.13 ± 0.10 kPa, A1 increased cohesion by approximately 156% at 60 DAP and 262% at 90 DAP. In contrast, the internal friction angle showed relatively limited variation among treatments, indicating that the improvement in shear strength was primarily associated with increased apparent cohesion resulting from root reinforcement.

The observed increase in cohesion is consistent with previous studies on vetiver-based soil reinforcement. (Eab et al., 2015), (Hamidifar et al., 2018), and (Badhon, 2021) reported increases in soil cohesion or shear strength of approximately 100%, 119.6%, and 88.2%, respectively, following vetiver planting. The increase observed in A1 in the present study was therefore higher than those reported in these studies. Furthermore, (Nurmansyah et al., 2026) reported a maximum cohesion of 19.55 kPa and a root cohesion contribution of 8.57 kPa in a vetiver–modular system. The differences in magnitude among studies may be attributed to differences in soil properties, plant age, root development, moisture conditions, and experimental configuration. Unlike (Nurmansyah et al., 2026), the present study further evaluates the combined effects of modular and non-modular planting patterns, biostimulant application, and soil moisture conditions.

Mechanically, vetiver roots contribute to soil shear strength through physical interaction and interlocking within the soil matrix. When the soil undergoes shear deformation, roots crossing the shear plane are mobilized and generate additional resistance against soil displacement (Wu et al., 1979). The root network therefore, acts as a reinforcing component that limits soil-particle displacement and increases the resistance of the root–soil matrix (Resqiyanto et al., 2025). The higher cohesion observed in A1 compared with D1, D2, and the control suggests that differences in treatment conditions led to varying levels of root development and, consequently, different reinforcement effects.

The relationship between root development and soil cohesion was further evaluated using root weight, as shown in Figure 13. An increasing relationship between root weight and cohesion indicates that greater root biomass contributes to higher soil cohesion through enhanced root–soil interaction. This observation is consistent with previous studies reporting that vetiver root development and density are important factors controlling the mechanical reinforcement of soil (Badhon, 2021; Hamidifar et al., 2018; Wang et al., 2020).

Mechanically, higher root biomass can generate greater shear strength, with cohesion being the parameter most responsive to changes in root density. This is evident from the increase in root weight, which correlates with increased soil cohesion; the greater the root weight in the shear strength test samples, the higher the resulting cohesion. This mechanism directly increases soil shear strength through root reinforcement, thereby enhancing soil stability, particularly on slopes prone to failure (Gao et al., 2023).

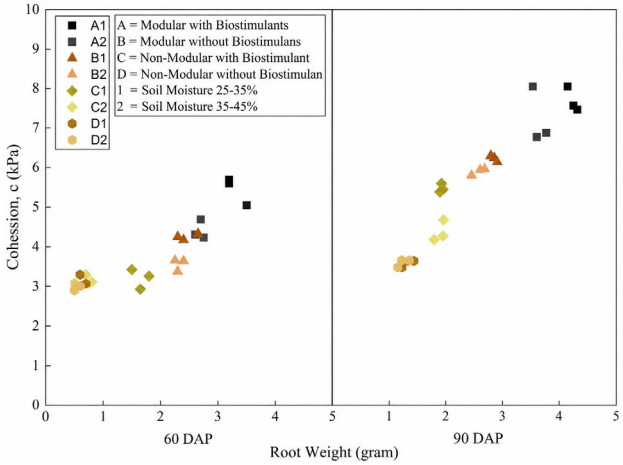


Figure 12 Relationship between cohesion and root weight

Based on the direct shear test results, the differences in soil shear strength parameters among the three treatments were not statistically significant. Sample A1, which received a combination of modular treatment, biostimulant, and 25–35% moisture content, exhibited the highest cohesion and root weight values compared to samples receiving other treatment combinations. During this phase, the modular system created a more controlled root growth environment, leading plant roots to grow vertically. In contrast, in non-modular samples, roots tended to grow in all directions without clear boundaries, meaning not all shear planes were reinforced by plant roots, which could affect the resulting soil shear strength values. Additionally, the application of Arbuscular Mycorrhizal Fungi (AMF) helps plants absorb nutrients optimally, thereby enhancing root growth through increased root diameter and expanded root networks, and improving root biomechanical properties (Chen et al., 2018; Song et al., 2012). A structured spatial distribution of roots can influence the effectiveness of soil reinforcement, with a more structured root system producing more consistent shear strength values (Phan et al., 2021).

3.6 Simple Linear Regression Modeling of Root Biometric Factors and Soil Mechanical Properties

Simple and multiple linear regression modeling was performed on several combinations of root characteristics to examine their effects stepwise, ranging from the effect of treatment on root length to the effect of root characteristics on soil cohesion (c), a proxy for soil shear strength. The parameters used included modular (M) and biostimulant (B) treatments, as well as root length (L_r), leaf length (L_l), side root area ratio (RAR_{side}), and root weight (W_r). This modeling aims to evaluate the contribution of each parameter, both individually and in combination, while identifying the mathematical relationships between variables and the most dominant parameters at each stage of

the analysis. The modeling results are presented as the coefficient of determination (R^2) and regression equations that represent the functional relationships between variables, where an R^2 value approaching 1 indicates the model's increasing ability to explain variation in the data.

Based on the regression analysis results, it was found that the morphological characteristics of vetiver roots (*Chrysopogon zizanioides*) are strongly associated with increased soil cohesion, both individually and in combination with variables that incorporate root length (L_r), side root area ratio (RAR_{side}), and root weight (W_r). The results of the regression modeling of the influence of vetiver root morphological characteristics on soil cohesion are presented in Table 2.

Table 2 Regression modeling of the influence of vetiver root morphological characteristics on soil cohesion

Characteristic Combination	R^2	Function
(L_r)	0.72	$c = 0.11(L_r) + 0.52$
(RAR_{side})	0.79	$c = 17.8(RAR_{side}) + 1.22$
(W_r)	0.6	$c = 0.94(W_r) + 2.78$
(L_r) + (RAR_{side})	0.78	$c = 0.05(L_r) + 17.82(RAR_{side}) + 0.63$
(L_r) + (W_r)	0.85	$c = 0.08(L_r) + 0.54(W_r) + 0.66$
(RAR_{side}) + (W_r)	0.84	$c = 13.42(RAR_{side}) + 0.40(W_r) + 1.3$
(L_r) + (RAR) + (W_r)	0.86	$c = 0.06(L_r) + 3.26(RAR_{side}) + 0.50(W_r) + 0.78$

Note: L_r = Root length; RAR = Root area ratio; W_r = Root weight

In the single-variable model, the root area ratio (RAR_{side}) parameter had the greatest influence, with a coefficient of determination (R^2) of 0.79. This value is slightly higher than that of the root length (L_r) variable, which yielded an R^2 of 0.72, and the root weight (W_r) variable, which yielded an R^2 of 0.6. In the two-variable model, the combination length (L_r + W_r) yielded the highest coefficient of determination (R^2), reaching 0.85. This value is slightly higher than the (RAR_{side} + Wr) combination, which yields an R^2 of 0.84. The results of the two-variable analysis indicate that combining multiple root morphological parameters consistently improves estimates of soil cohesion. This is demonstrated in a three-variable regression model that combines the parameters (L_r), (RAR_{side}), and (W_r), yielding the highest coefficient of determination (R^2) of 0.86. In general, root morphological growth can be influenced by optimal growing conditions. Therefore, a further analysis was conducted to assess the effects of the treatments on vetiver plants, particularly root growth parameters. Furthermore, the regression results for the effect of treatment on the root length parameter (L_r) are presented in Table 3.

Table 3 Regression modeling of the effect of treatment on the root length parameter

Characteristic Combination	R^2	Function
Modular + Biostimulant	0.87	$L_r = 0.41(DAP) + 11.78$
Modular	0.88	$L_r = 0.41(DAP) + 9.67$
Biostimulant	0.97	$L_r = 0.53(DAP) – 6.39$
-	0.92	$L_r = 0.52(DAP) – 8.83$

Note: DAP = Days after planting

In the regression model examining the effect of treatments on root length, biostimulant application yielded the highest R^2 of 0.97, surpassing both the modular treatment (R^2 = 0.88) and the combination of the two (R^2 = 0.87). This indicates that the application of mycorrhizal biostimulants (AMF) has a more consistent, linear effect on root length growth as plants age. The relatively uniform planting-age coefficients, ranging from 0.41 to 0.53 across all models, indicate that root growth is linear and continuous regardless of the treatment applied. Next, a further analysis was conducted to determine the effect of other biometric parameters on root length (L_r), such as leaf length (L_l) and side root area ratio (RAR_{side}). The results of the regression modeling of the effects of other biometric parameters on root length (L_r) are presented in Table 4.

Table 4 Regression modeling of the effects of other biometric parameters on root length

Characteristic Combination	R^2	Function
(L_l) + (RAR)	0.95	$L_r = 0.16(L_l) + 105.96(RAR_{side}) + 3.4$
(L_l)	0.87	$L_r = 0.4(L_l) + 4.44$
(RAR)	0.92	$L_r = 162.56(RAR_{side}) + 5.07$

Note: L_l = Leaf length; RAR_{side} = Side root area ratio

In the regression model of other biometric parameters against root length, the combination of leaf length (L_l) and RAR produced the strongest model (R^2 = 0.95), with an RAR coefficient of 105.96 that far outweighed the (L_l) coefficient of 0.16. The magnitude of this RAR_{side} coefficient further reinforces the previous finding that RAR_{side} is a key variable in the vetiver root system. Mechanically, the RAR represents the fraction of the soil cross-sectional area occupied by roots; thus, the higher the RAR_{side} value, the greater the potential of vetiver roots to cut through the slip plane and convert soil shear stress into root tensile stress (Wu et al., 1979). It is this mechanism that makes RAR the most representative index for describing the contribution of roots to increased cohesion (Adu et al., 2025; Mahannopkul and Jotisankasa, 2019).

Overall, the three regression model tables indicate an interrelated chain of effects. The combination of the three root morphological parameters (L_r), (RAR_{side}), and (W_r) serves as the primary representation of soil strength, with root length (L_r) as the main parameter. Furthermore, the application of biostimulants (B) had the greatest effect on root length, while the combination of leaf length (L_l) and side root area ratio (RAR_{side}) was among the other biometric parameters influencing root length. Consequently, a series of interconnected mathematical relationships was derived to establish the final predictive equation for cohesion. The final results of the cohesion prediction equation are presented in Table 5.

The results of the modeling analysis show that cohesion prediction equations can be developed based on data availability, ranging from models that use root morphology parameters separately to those that use a combination of parameters simultaneously. These differences allow flexibility in applying the models based on data availability. Although all models were developed through the same process, different levels of simplification can affect each model's predictive ability. Therefore, further evaluation is needed to determine the degree of agreement between the prediction results and the laboratory test data. The results of the agreement validation between the prediction and laboratory test data are presented in Figure 14.

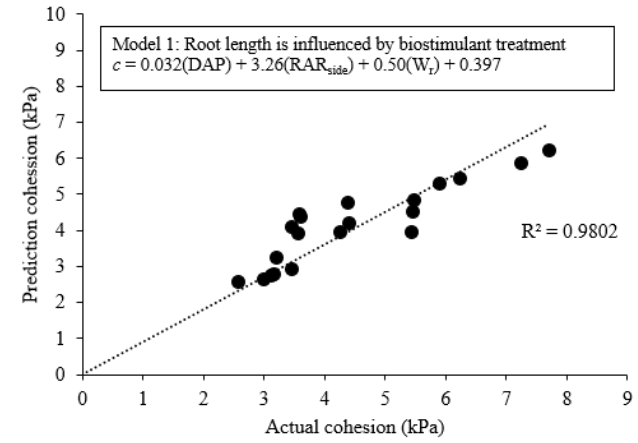
Based on validation results comparing predicted data with laboratory test data, it was found that both developed models demonstrated good predictive ability. Both models used a combination of the three root morphological parameters; however, the difference lies in the root length parameter (L_r), which is influenced by the application of the treatment, and the root length parameter (L_r), which is influenced by other biometric parameters. Model 1, which uses the (L_r) parameter influenced by the application of biostimulants, yields an R^2 value of 0.979, whereas Model 2, which uses the (L_r) parameter influenced by other biometric parameters, including leaf length (L_l) and root area ratio (RAR), yields an R^2 value of 0.985. These modeling results indicate that the variability in cohesion values can be consistently explained by these three root

morphological components; therefore, cohesion estimates will be more representative when multiple parameters are considered simultaneously.

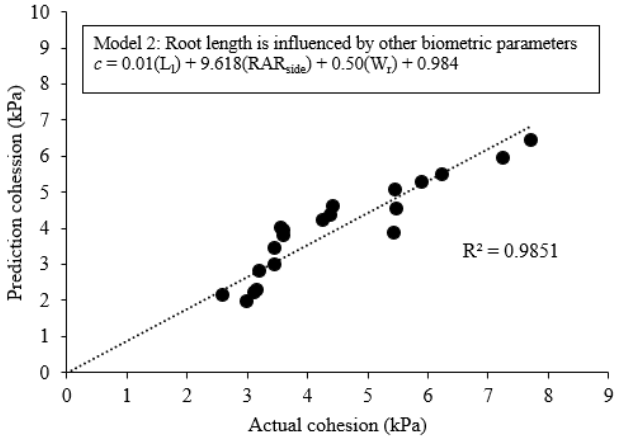
Table 5 Cohesion prediction equation

Model	Input Parameters	Equation
1	(L_r) + (RAR_{side}) + (W_r)	Initial equation: $c = 0.06(L_r) + 3.26(RAR_{side}) + 0.50(W_r) + 0.78$ Final equation: $c = 0.032(DAP) + 3.26(RAR_{side}) + 0.50(W_r) + 0.397$
	Root length is influenced by biostimulant treatment With: (L_r) = (0.53 (DAP) – 6.39)	
2	(L_r) + (RAR_{side}) + (W_r)	Initial equation: $c = 0.06(L_r) + 3.26(RAR_{side}) + 0.50(W_r) + 0.78$ Final equation: $c = 0.01(L_l) + 9.618(RAR_{side}) + 0.50(W_r) + 0.984$
	Root length is influenced by other biometric parameters With: (L_r) = $0.16(L_l) + 105.96(RAR_{side}) + 3.4$	

Note: L_r = Root length; RAR = Root area ratio; W_r = Root weight



(a)



(b)

Figure 13 Results of the validation of the agreement between the predicted data and the laboratory test data

4. CONCLUSIONS

Based on the results of the study, it can be concluded that the combination of modular jute treatment and AMF biostimulant (treatment A1) consistently produced the highest vetiver root growth response in every observation period, with root length reaching approximately 54 cm and RAR values up to 29% at 90 days after planting (DAP), as well as root tensile strength reaching 72.5 MPa at a root diameter of 0.4 mm. These results indicate a synergistic effect between the modular geotextile and the mycorrhizal biostimulant in accelerating vetiver root development during the early growth stage for slope stabilization. Additionally, soil moisture control within the 25–35% range consistently promoted deeper and longer root growth compared to the 35–45% moisture content treatment across all observation periods (30, 60, and 90 DAP). Under mild water-deficit conditions (25–35%), vetiver exhibited adaptive root elongation, with root lengths reaching 47–54 cm at 90 days after planting, whereas the 35–45% treatment yielded root lengths of only 38–44 cm. This occurred because higher moisture content reduced soil aeration and inhibited root aerobic respiration, thereby limiting root elongation. Furthermore, all vegetated soil samples yielded higher cohesion values than the vegetated control (c = 2.13 ± 0.10 kPa). At 90 days after planting, treatment A1 had the highest cohesion value of 7.70 ± 0.32 kPa, a root weight of 4.24 ± 0.07 grams, and an internal friction angle of 10.89° ± 1.83°, representing an increase of about 3.6 times compared to the control. Meanwhile, the lowest cohesion value in the vegetated samples was recorded in treatment D2 at 3.60 ± 0.10 kPa, which was still 69% higher than the control. These findings demonstrate the consistent effectiveness of vetiver root reinforcement across all tested treatment combinations.

5. ACKNOWLEDGMENTS

This work was supported by PT Hutama Karya (Persero). The authors sincerely appreciate their support.

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