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Investigating the Dynamic Behavior of Vetiver Roots in Stabilizing Critical Slopes

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ABSTRACT

Aims: Vetiver grass (*Chrysopogon zizanioides*) is considered highly effective for bioengineering, especially for stabilizing steep, erosion-prone slopes. This study evaluates the bioengineering potential of Vetiver in semi-arid regions by integrating analyses of root system dynamics, morphological traits, and responses under different slope gradients. Through assessing root biomass distribution, diameter, root area ratio (RAR), and their biomechanical contributions, the research provides an interdisciplinary understanding of how Vetiver responds to environmental stresses and enhances slope protection.

Materials & Methods: Vegetation-induced soil reinforcement is governed primarily by root mechanical properties, including root density, diameter distribution, and tensile resistance. Vetiver grass (*Chrysopogon zizanioides*) has been widely used for slope stabilization; however, quantitative field-based evidence linking slope geometry to root-mediated shear strength enhancement under semi-arid conditions remains limited. Seedlings were planted on slopes with similar soil properties but different gradients, allowing the gradient to act as the main factor. Field sampling was conducted on vegetated highway embankments with comparable soil texture and land-use history but differing slope inclinations (40–50°, 70–80°, and >80°). Intact soil cores containing Vetiver roots and corresponding root-free controls were collected at 0–20 cm depth. Direct shear tests were performed under controlled normal stresses to quantify apparent cohesion and shear resistance. Root biomass, diameter distribution, and root area ratio (RAR) were measured and statistically related to mechanical soil parameters.

Findings: Soils containing Vetiver roots exhibited significantly higher apparent cohesion than root-free soils ($p < 0.05$), attributable to increased root biomass and RAR, particularly at depths of 10–20 cm. Slope inclination itself did not directly alter soil cohesion; instead, variations in shear strength were explained by differences in root density and architecture. Direct shear tests were conducted on soil samples reinforced with Vetiver grass roots at three slope classes (40–50%, 70–80%, and >80%) and four soil depths (0–5, 5–10, 10–15, and 15–20 cm). The results demonstrate an apparent linear increase in shear stress with increasing normal stress, consistent with the Mohr–Coulomb failure criterion. For all slope classes, the presence of etiver roots significantly increased the peak shear stress, particularly at greater depths where root mass and root area density were higher.

Conclusion: The study confirms that Vetiver grass is a highly effective bio-engineering tool for soil stabilization. The reinforcement is most substantial at steep Slopes (≥70%), where denser root systems develop to adapt to higher mechanical stresses. Deeper soil layers (10–20 cm), higher root weight, and area density significantly improve post-peak residual strength and energy absorption. Its dual role as an effective bioengineering species and a valuable phytochemical resource is shaped by interactions between climate and soil.

Keywords: Root Weight; Shear Stress; Soil Strength; Slope Stability; Slope Stabilization.

CITATION LINKS

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Introduction

Intensifying soil erosion and degradation result from the complex interaction of climatic factors, topography, vegetation cover, and land management practices. Effective erosion control and the maintenance of soil quality are therefore essential to ensure the sustainability of both agriculture and the environment [1]. There is a direct relationship between improved vegetation cover, improved soil characteristics, and ultimately reduced soil erosion [2]. In this study, soil resistance and stability will be maintained by planting vegetation on sloping lands. Vegetation can contribute to slope stability with two mechanical and hydrological effects [3]. The role of appropriate vegetation in managing and reducing runoff and sediment is vital and effective [4]. By dehydrating the soil through transpiration and mechanically strengthening the roots, plants increase the slope's stability. Soil strength and stability will be maintained by planting vegetation on steep slopes. Shallow rain-induced landslides, especially in mountainous areas, have increased public awareness of this risk. Therefore, slope instability is a significant concern, and mechanical and biological measures are particularly appropriate for slope protection. Vetiver combines environmental compatibility with cost-effectiveness and durability [5]. Plant roots increase the shear strength of the soil by transferring the shear stress developed in the soil texture to the tensile strength in the roots [6]. Vetiver cultivation is a low-cost and highly resistant method for soil conservation [7]. When the soil surface is covered with Vetiver vegetation, soil loss is also significantly reduced [8]. Vetiver reduces runoff, increases soil moisture, and prevents soil movement [2]. Vetiver cultivation is practiced in more than 40 countries worldwide for agricultural and non-agricultural purposes. In Iran, some Provinces, such as Guilan, Golestan, and Tehran, were cultivated on steep slopes to control landslides and soil erosion. This plant increases soil adhesion and shear strength by increasing root diameter [9]. The soil mineralogy profile and environmental conditions in which the roots are located are continually changing. At the morphological level, plants can adjust their growth patterns to increase or decrease the uptake of specific minerals in response to prevailing environmental conditions [10]. The most critical determinants of the secondary chemical composition of plants are genetic and environmental factors, as well as their interaction. Environmental factors, including slope and soil characteristics, significantly affect the quantity and quality of essential oils and plant extracts [11].

In this study, the adaptive capacity of Vetiver plants under biotic stresses, including semi-arid climatic conditions and slope, as well as abiotic stresses related to soil characteristics, was assessed. Because the side walls of reservoirs, dams, and other steep slopes are prone to landslides and soil movement from the top to the bottom, they require stabilization and protection with soil vegetation.

Materials & Methods

Study Area

The study was conducted along a mean 34% slope section of a Highway in Tehran Province (34°42'-36°30' N, 50°30'-50°42' E (Figure 1), characterized by a semi-arid climate. The region has a mean annual temperature of 17°C, relative humidity of 24%, and approximately 300 mm of annual precipitation.

Measurement Methods

In this study, Vetiver roots (five years old) were sampled at three levels with different degrees of slope. The selected area was (15×60 m^2) in three levels (terraces). The samples were prepared with varying root percentages by weight to determine the relationship between soil strength and root density using the direct shear test. Soil and Vetiver plant root samples from a depth of 0 to 50 cm with different degrees of slope (first level 40 to 50 degrees, the second level 70-80 degrees, the third level >80 degrees) and in each level with four repetitions (total number of soil samples 12 and total Vetiver plant root samples 12) sampling was done. Soil properties, including soil grain analysis [12] and soil physical and chemical properties, were measured according to standard laboratory protocols [12] under similar climatic conditions, and moisture was treated as a contextual variable rather than a controlled factor. Soil pH was measured using the saturated paste method, and electrical conductivity (EC) was obtained from the soil saturation extract. Organic matter percentage and lime content were also analyzed according to the same reference [12]. Potassium concentration was determined using flame photometry [12].

The first step was to conduct a field-based sampling study with laboratory shear testing of intact soil blocks. Soil sampling was conducted separately without Vetiver roots and also together with Vetiver roots using a 20-centimeter-high steel cylindrical container. Sampling was performed at four depths (0-5 cm, 5-10 cm, 10-15 cm, and 15-20 cm). In the direct shear test measuring device, the amount of normal stress was B and C. Change this force to stress based on the area of the sample, 20 kPa, 40 kPa, and 60 kPa (Figure 2). Direct shear tests were performed on intact and sample specimens; the shear plane passed through intact root networks and was simulated. The shear displacement rate was less than 0.5 mm min^{-1}; the diameter class, calculation method, and no drainage were performed. To describe the effect of root density in the soil, a parameter called RAR (Root Area Ratio) is used (Figure 3), where (Ar) is the area occupied by the root, (Aw) is the area where the root was observed (sum of the soil area and root), (ni) is the number of roots in category (i) and (ai) is the mean cross-sectional area of roots in category [5]. The cross-sectional area of the roots was measured in sample molds (6×6 cm) to determine the soil's direct shear stress, and the roots' weight was also calculated [13]. They were dried at room temperature in the shade to prepare for further analysis. The root diameter was measured using a digital caliper [14]. Plant root extracts were prepared using a methanol/water solvent (80:20, v/v) by the maceration method (Figure 4). The extracts were concentrated with a rotary evaporator, stored at 4 °C, and subsequently analyzed [15]. The collected data, including soil properties, direct shear strength, and the diameter, weight, and extract yield of Vetiver roots, were statistically analyzed. Results were analyzed and presented accordingly.

Figure 1) A general view of the study location.

Figure 2) Soil shear stress measurement water and soil chemistry laboratory, Soil Conservation and Watershed Research Institute.

Figure 3) Sample with an added root of different density.

Figure 4) Preparation of vetiver root extracts — Pharmacognosy Laboratory, Faculty of Pharmacy, Mazandaran University of Medical Sciences.

Applied Formulas for Soil Shear Stress Calculations

A new evaluation of Vetiver (*Chrysopogon zizanioides*) for slope stabilization and soil adaptation in a semi-arid region using direct soil shear stress measurement by solving the equations. As a result, the assumptions are: At any given slope, the soil shear force affects the weight of the plant roots. In this context, there will be three governing equations for determining the direct soil shear (Eqs. 1-3), and one governing equation for calculating root density in the soil (Eq. 4), which will be solved using these methods:

$$\tau = C + \sigma \tan(\varphi) \qquad \text{Eq. (1)}$$

where τ is the soil shear force, C is the cohesion, σ is the shear force, and tan (φ) is the internal friction angle. The internal friction angle (φ) can be determined using the stress coefficient, with the opposite side and the adjacent side:

$$(\varphi) = \frac{a_1}{a_2} \qquad \text{Eq. (2)}$$

where a_1 and a_2 are the stress coefficients for the opposite and the adjacent sides, respectively. The direct shear stress of the soil can be determined by the shear force coefficient:

$$\text{Shear Stress} = \frac{\text{Shear Force}(\tau)}{\text{Area of specimen}(cm^2)} \qquad \text{Eq. (3)}$$

In Eq. (3), the final calculation of the direct shear stress of the soil with the determined value of shear force (τ), soil shear stress (kPa) is measured in the sample area.

Applied Formulas for Calculating Root Density in Soil

The root abundance was determined using Eq. (4), in which the calculation of the root abundance (RAR) in the soil is determined by the parameters (Ar) area occupied by the root, (Aw) total area of soil and root, (i) in the bundle, (ni) number of roots in the bundle, (ai) mean cross-sectional area of roots in the bundle. The results of the direct soil shear stress measurement calculations can be compared in the following graphs (Figure 6).

$$RAR = \frac{Ar}{Aw} = \sum_{n=1}^{i} ni \frac{ai}{Aw} \quad \text{Eq. (4)}$$

Findings

In this study, slope and soil shear strength were evaluated in conjunction with key soil properties. Across different slopes, the Vetiver root system markedly increased root density (RAR) in proportion to the applied shear stress of 17.32 kPa. To ensure that the observed differences in root area ratio (RAR) were attributable to slope gradient rather than external confounding factors, all major parameters known to affect root development were either controlled experimentally or measured and statistically adjusted. Soil texture, soil bulk density, planting density, plant age, soil moisture regime, nutrient levels, and sampling depth were kept uniform across all slope treatments. Various factors (e.g., soil moisture, temperature) were measured throughout the experiment, and minor variations were incorporated as covariates in the ANOVA/ANCOVA models to adjust for their potential influence. This approach ensured that the analysis captured the independent effect of slope gradient on RAR and minimized methodological bias. To prove this claim, it is necessary to keep the other parameters affecting root density (RAR) constant. The presence of Vetiver roots increased soil cohesion by 198% relative to soil without roots. It reduced the soil's internal friction angle by 77.98%, resulting in an overall improvement in soil shear strength of 26.57%. These results highlight the significant role of Vetiver roots in stabilizing soils on sloped terrains. The data obtained from the analysis of variance showed that there is a significant relationship between soil properties such as moisture, organic Carbon, lime, salinity, Potassium, acidity, and soil texture at three levels with different slopes. Data from the analysis of variance of soil factors, root weight, and extract weight in the study area show that there is a significant difference between soil factors such as moisture, organic Carbon, Potassium, lime, alkalinity, salinity at the surface ($p \geq 0.01$) and soil texture at three levels with different degrees of slope (Table 1). According to the results of direct soil shear stress tests with Vetiver root weight and Vetiver root extract weight, it can be stated that the Vetiver plant's resistance and adaptation on steep slopes are intelligent. In these environmental conditions, the biological activity of the Vetiver plant has increased, leading to a corresponding increase in the relative weight of the plant extract as the slope has risen. Vetiver plant intelligently increases the weight of its roots at different degrees of slope to achieve better adaptation to the environment by increasing the weight and development of its roots in the soil of the mean data presented in Figure 5 (a–e, h, j, and l) indicates that under semi-arid climatic conditions, increasing the soil slope from the first level (40–50°) to the second (70–80°) and third level (80–90°), along with higher elevation and reduced regional humidity, leads to notable changes in soil properties and Vetiver root characteristics. Specifically, soil alkalinity decreased by 6.1%, soil lime content by 9%, soil organic Carbon by 5.6%, soil moisture by 1.2%, soil electrical conductivity by 15%, soil Potassium by 14.3%, and soil sand content by 0.3%. In contrast, soil clay content increased by 1.3%, while soil silt exhibited variable trends with slope, elevation, and humidity (Figure 5).

These environmental conditions also significantly affected Vetiver growth. The weight of Vetiver roots increased with slope,

Table 1) Results of one-Way ANOVA for the Mean Percentage of Soil Parameters, Shear Stress, Root Weight, and Vetiver Extract Weight

Source		Sum of Squares	df	Mean Square	F-Statistic	Sig.
Soil	**Slope (Degrees)**					
pH	80-90	12.66	2	6.33	79.12	0.00
	70-80	13.62	2	7.03	80.39	0.00
	40-50	15.20	2	8.98	82.92	0.00
OC	80-90	8.34	2	4.17	78.99	0.00
	70-80	8.84	2	5.54	85.73	0.00
	40-50	9.87	2	6.84	94.89	0.00
TVN	80-90	758.44	2	379.22	7.19	0.00
	70-80	841.48	2	396.28	7.78	0.00
	40-50	993.79	2	409.61	8.19	0.00
Clay	80-90	122.41	2	61.20	63.24	0.00
	70-80	118.94	2	59.13	61.29	0.00
	40-50	117.44	2	58.28	60.99	0.00
Silt	80-90	15.79	2	7.89	6.30	0.00
	70-80	16.78	2	9.48	8.54	0.00
	40-50	12.39	2	55.73	4.79	0.00
K	80-90	1.92	2	0.96	124.00	0.00
	70-80	2.44	2	0.82	126.93	0.00
	40-50	2.98	2	0.78	125.55	0.00
Moisture	80-90	93.12	2	46.56	189.62	0.00
	70-80	95.19	2	47.94	190.38	0.00
	40-50	96.57	2	48.86	191.20	0.00
EC	80-90	5.54	2	2.77	499.20	0.00
	70-80	7.75	2	4.88	5001.81	0.00
	40-50	8.87	2	6.34	503.91	0.00
Sand	80-90	82.92	2	41.46	848.11	0.00
	70-80	83..00	2	42.84	739.25	0.00
	40-50	83.68	2	43.34	678.99	0.00
Root Weight	80-90	2767.05	2	1383.52	957.82	0.00
	70-80	2402.11	2	1209.83	866.04	0.00
	40-50	1544.33	2	1182.75	781.98	0.00
Extract Weight	80-90	101.54	2	50.77	960.57	0.00
	70-80	98.52	2	49.32	958.62	0.00
	40-50	66.91	2	48.65	957.13	0.00
Shear Stress	80-90	5.83	2	2.91	30.49	0.00
	70-80	4.78	2	1.60	29.28	0.00
	40-50	3.01	2	1.20	28.68	0.00

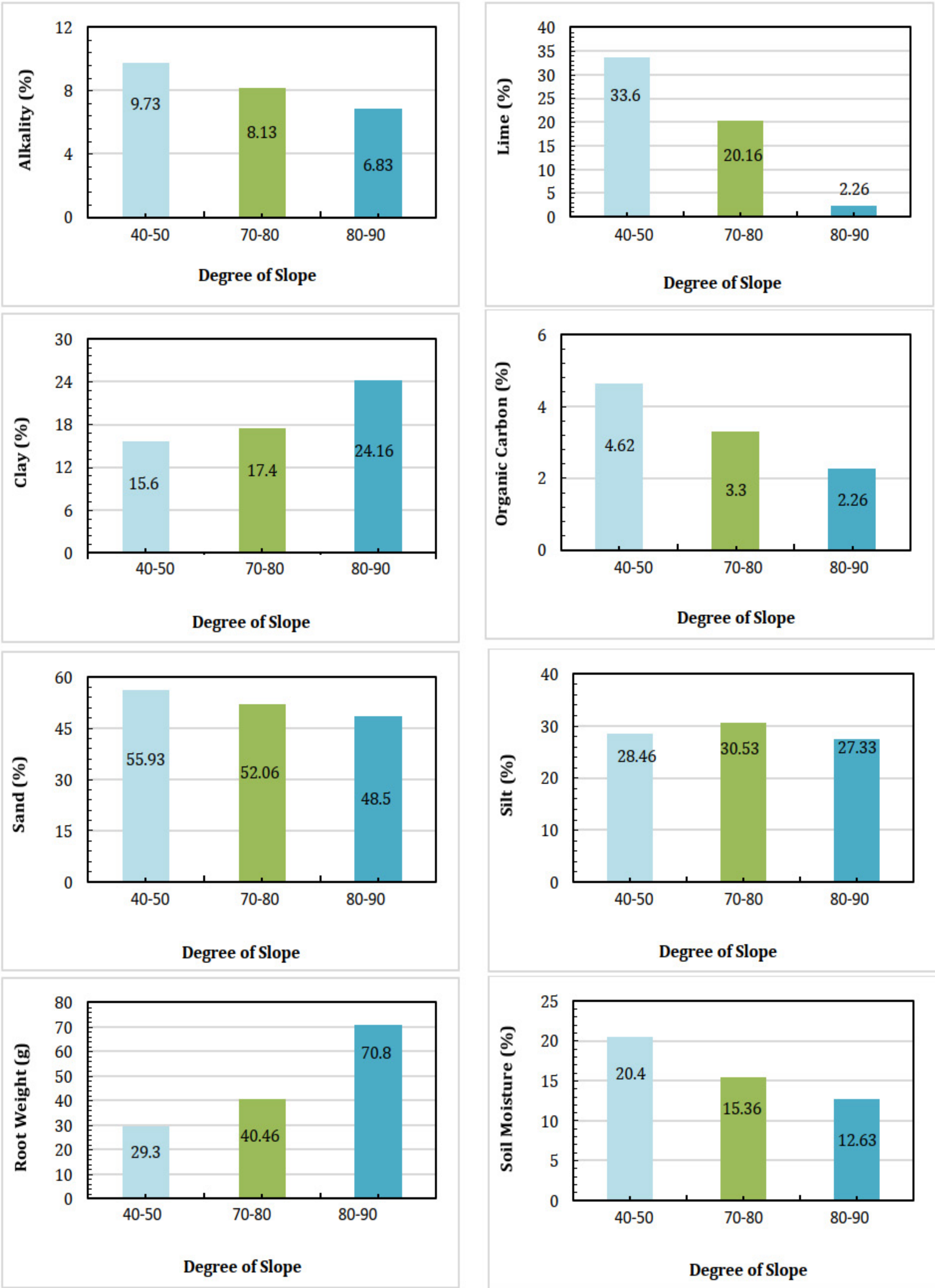

Figure 5) The values are grouped into three levels based on Duncan's multiple-range test (Tehran Province), indicating comparisons among the measured data.

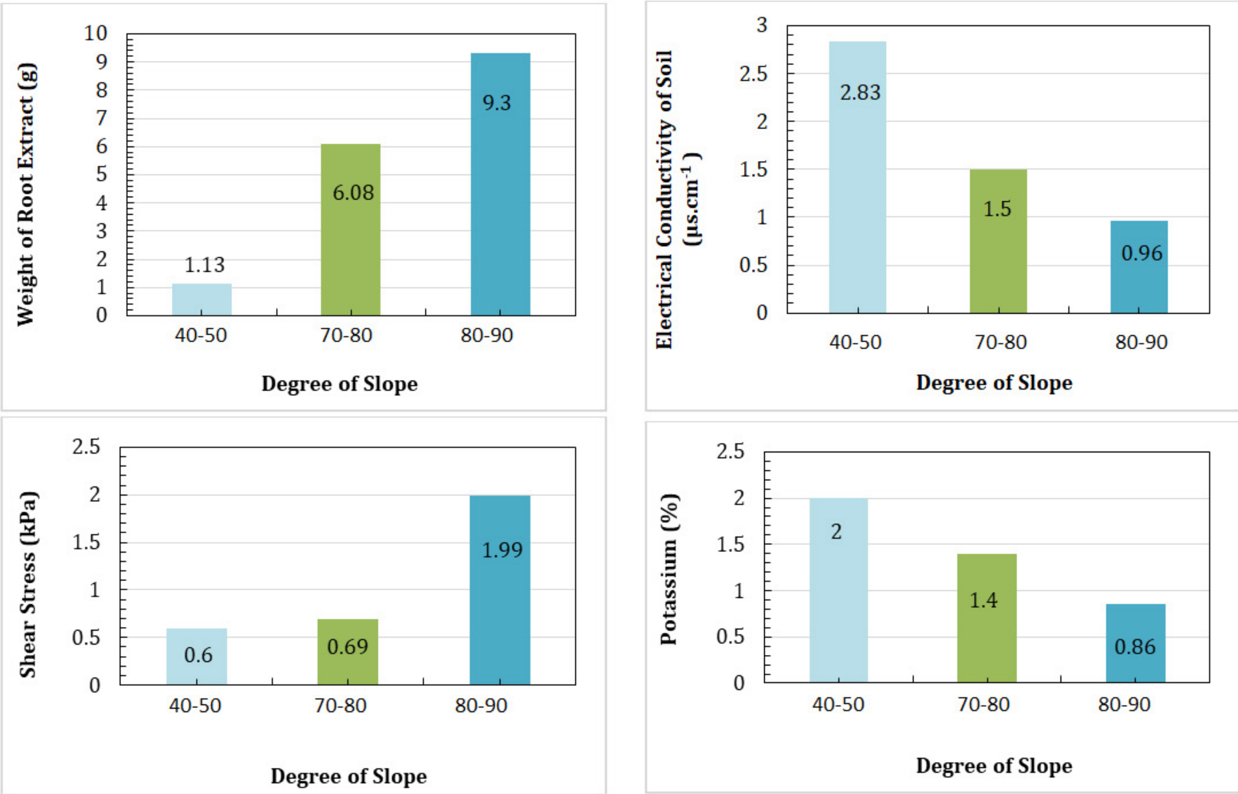

Figure 5 Continued) The values are grouped into three levels based on Duncan's multiple-range test (Tehran Province), indicating comparisons among the measured data.

enhancing plant stability and adaptability by approximately 18.2%, while the weight of Vetiver root extract increased by about 12.9%. Overall, these results demonstrate that soil composition and Vetiver root development are strongly influenced by slope, elevation, and moisture, underscoring the plant's important role in soil stabilization under semi-arid conditions. Under semi-arid conditions, increasing soil slope (40–50° → 70–80° → >80°), elevation, and decreasing humidity markedly affected soil properties and Vetiver root development (Figure 5). Soil alkalinity, lime, and clay increased, while organic Carbon, moisture, electrical conductivity, and Potassium decreased, and silt showed variable trends. Concurrently, Vetiver root weight and root extract increased with slope and elevation, enhancing plant stability and adaptability. These findings highlight the strong influence of topography and microclimate on soil composition and Vetiver performance, underscoring its role in soil stabilization under semi-arid conditions. Soil with Vetiver roots exhibited significantly higher soil cohesion and shear strength than soil without roots. (Figure 6) shows the effects of Vetiver roots on various parameters. This figure compares the maximum root biomass and root area of Vetiver grass at soil depth (15–20 cm) at three different slope classes. This figure confirms the increase in slope. This figure shows the Mohr-Coulomb failure envelopes for three slope classes at depth (15–20 cm). The slope of the lines indicates the angle of internal friction (φ), while the width from the origin indicates the apparent cohesion (c). The graph clearly shows the increase in shear strength with increasing vertical stress and slope.

Figure 6 shows the maximum Vetiver root biomass at 15-20 cm depth (a), shear stress

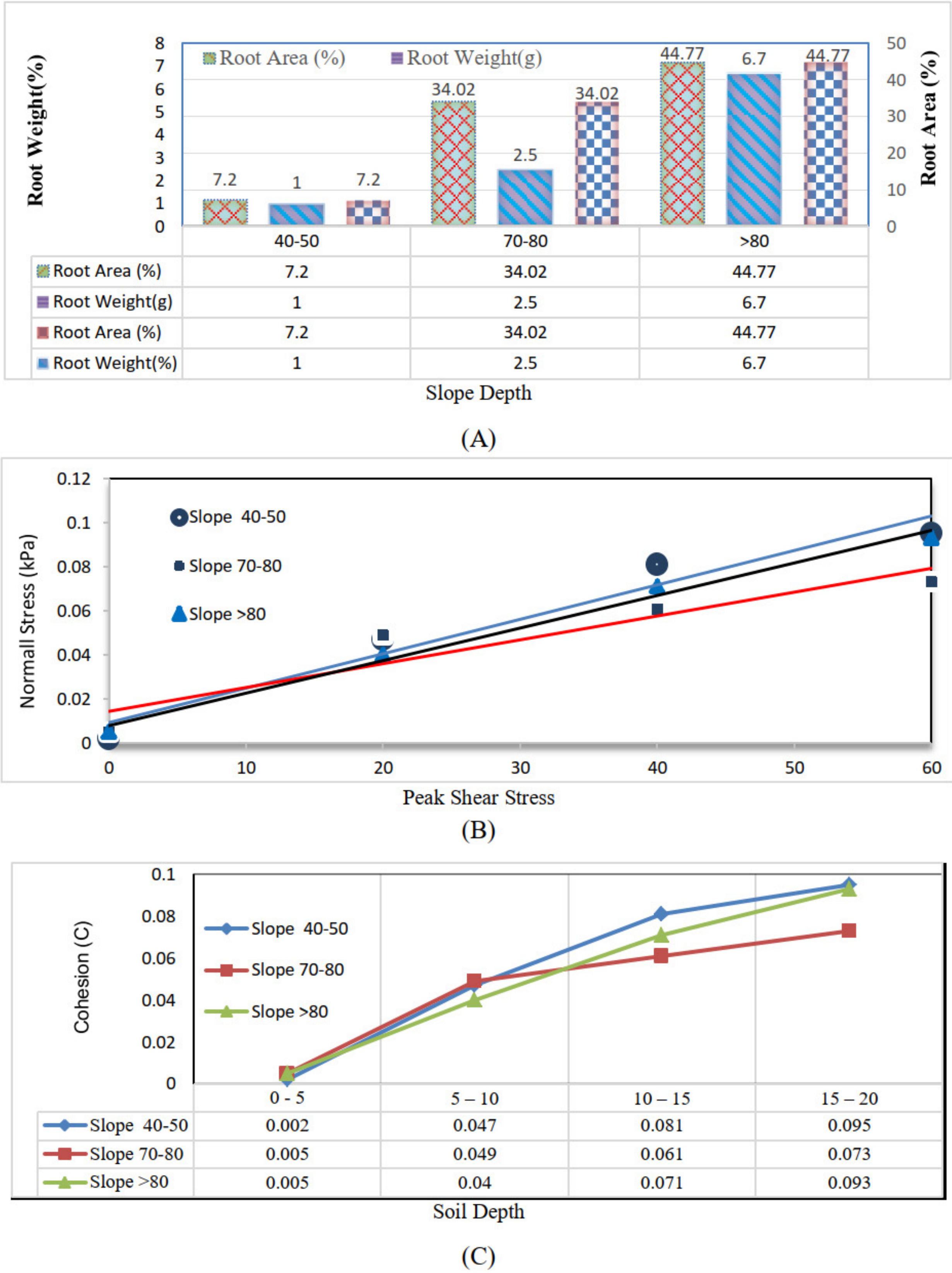

Figure 6) Results of the study on the performance of vetiver plant roots in slope stabilization.

Maximum Vetiver root biomass at 15-20 cm depth (A), shear stress vs. normal stress (Mohr-Coulomb failure envelope) (B), and the effect of depth and slope on cohesion at different slopes, illustrate the increasing trend of apparent cohesion (C) vs. normal stress (b), and the effect of depth and slope on cohesion at different slopes, illustrating the increasing trend of apparent cohesion (c) with increasing soil depth and slope in Tehran. It directly supports the textual conclusions regarding the effects of soil depth and slope on cohesion enhancement.

Data from Table 2 indicate the types of plant performance and growth in response to environmental stresses. At the first level, the weight of the plant root is lower than at the second and third levels, and the results of soil shear stress measurements show that the soil shear force at the first level is lower than at the second and third levels. In fact, the plant changes its weight to create the necessary shear resistance in response to soil shear force. Therefore, the results of measuring the weight of Vetiver plant roots are directly related to the amount of soil shear force (Table 2).

The correlation between soil properties, root weight, and Vetiver plant extract weight in Table 3 shows that soil properties (alkalinity, organic Carbon, lime, clay, sand, silt, and soil moisture) are correlated with root weight and Vetiver root extract weight. In the Tehran region, there is a significant relationship ($p \leq 0.01$) between the soil silt factor and the root weight and the weight of Vetiver root extract in the same location (Table 3).

Table 2) the Result of Shear Stress and Vetiver Plant Weight (Tehran Province)**.**

Source of Variation	First Level (Slope 40-50 °)	Second Level (Slope 70-80 °)	The Third Level (Slope >80°)
Root Weight (g)	6.1±0.8	9±0.4	10.2±0.9
	4±0.1	7±0.7	7.5±1.2
	2±0.9	5.2±0.6	5.5±0.3
Shear Stress (kPa)	3.36±1.1	3.45±0.8	3.50±0.9
	1.89±0.7	2.94±1.3	2.92±0.6
	1.14±0.9	1.72±0.5	2±0.7

Table 3) the Result of Pearson's Bivariate Correlation Between Soil Factors, Shear Stress with Root Weight and Extract Weight of Vetiver Plant (Tehran Province).

Source		pH	OC	TVN	Clay	Silt	K	Moisture	EC	Sand	T
Root Weight(g)	Pearson Correlation	-0.93*	-0.92**	-0.80**	0.98**	-0.50	-0.94*	-0.89**	-0.87*	-0.95*	0.95**
	Sig. (2-tailed)	0.00	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00
	N	9	9	9	9	9	9	9	9	9	9
Extract Weight (g)	Pearson Correlation	-0.97**	-0.98**	-0.86**	0.88**	-0.19	-0.98**	-0**	-0.99**	-0.99**	0.90**
	Sig. (2-tailed)	0.00	0.00	0.03	0.02	0.62	0.00	0.00	0.00	0.00	0.00
	N	9	9	9	9	9	9	9	9	9	9
Root × Slope	Pearson Correlation	-0.88**	-0.75**	-0.97**	-0.57	-0.90**	-0.83**	-0.81**	-0.87*	-0.91**	0.98**
	Sig. (2-tailed)	0.00	0.00	0.01	0.00	0.10	0.00	0.00	.007	0.00	0.00
	N	9	9	9	9	9	9	9	9	9	9

*Correlation is significant at the 0.05 level (2-tailed). **Correlation is significant at the 0.01 level (2-tailed).

Discussion

This study, which was conducted to analyze variance and correlation between soil factors and Vetiver plant extract, shows that there is a significant relationship between soil characteristics (alkalinity, organic Carbon, lime, clay, sand, and Potassium and soil moisture, and root weight and Vetiver root extract weight in the Tehran region. As a result, there is a significant relationship between soil characteristics, such as moisture, organic Carbon, Potassium, lime, alkalinity, salinity, and soil texture, and Vetiver root extract weight in the Tehran slope ($p \geq 0.01$). There is a significant correlation and relationship between soil lime content and Vetiver root shear strength in the Tehran slope soil ($p \geq 0.05$). There is a significant correlation and relationship between soil characteristics such as moisture, organic Carbon, Potassium, lime, acidity, soil electrical conductivity, and soil texture, and the weight of Vetiver plant roots on the slope of Tehran ($p \geq 0.01$). Therefore, according to the results of direct shear stress experiments, there is a significant relationship between the weight of Vetiver roots at the level ($p \geq 0.01$) and the weight of Vetiver root extract at the level ($p \geq 0.01$). The root weight and Vetiver extract weight are directly related to the amount of clay in the soil.

Considering that only some plants can adapt and increase their height with increasing altitude above sea level (different climate) [16]. The results of this study show that, at high altitudes and steep slopes, Vetiver's performance depends on its ability and adaptability, and that its effective performance in increasing soil shear strength has enabled its adaptation [17, 18]. The results of this study are consistent with the results of the study of the effect of altitude on the quantitative and qualitative characteristics of yarrow [19], the impact of altitude on *Rosmarinus officinalis* L. [20], the effect of altitude on *Artemisia* [21], the effect of altitude on *Tanastum polycapalum* [22], the effect of altitude on *Heracleum anisactis* [23] and the effect of altitude on mountain tea (*Stachys lavandulifolia*). On the other hand, the results of this study are consistent with findings from studies on the efficacy of *Artemisia rexburghiensis* essential oil in Himalayan grasslands [24]. They investigated the performance of yarrow (*Achillea millefolium*) essential oil in the "Siah Bisheh" habitat of Mazandaran Province [25] and [26] and in wormwood species in the "Sawad Kooh" region, and stated that with increasing altitude, the performance and amount of essential oil decrease [27]. They also agree with the results of a study investigating the effect of Gaz (*Tamarix*) roots on increasing soil adhesion and shear strength along the "Kashf Rood" river [28]. They are consistent with the results of a study investigating the effects of tree shear strength on the stability of the Bashar River [29]. There is a significant relationship between soil shear strength and the presence of Vetiver plant roots in Tehran. The level of plant resistance to harsh environmental conditions results from their adaptive performance. Vetiver plants consciously defend themselves against environmental factors.

Conclusion

This study represents the first experimental application of Vetiver (*Chrysopogon zizanioides*) for slope stabilization in semi-arid regions worldwide. The results demonstrated that Vetiver significantly enhanced soil shear strength across slopes of

40–50°, 70–80°, and 80–90°, with increases of 25.99%-26.67%. Increased root biomass, diameter, and extract yield indicate the plant's adaptive response to environmental stresses, partly mediated through secondary metabolite production. Vetiver roots increased soil cohesion by 197%, the soil internal friction angle by 77.89%, and improved tensile strength (60–119 MPa), illustrating the plant's ability to reinforce soil mechanical properties under shear stress. Soil characteristics and shear strength were found to vary with slope, height above sea level, soil properties, and Vetiver root density (RAR), and root weight increased in response to these stresses. The highest concentrations of chemical and structural compounds in Vetiver roots were observed on the steepest slopes, indicating that this plant performs better under challenging conditions. Finally, the study's hypotheses are acceptable. Given its strong adaptability, robust root system, and dual role in soil stabilization and bioactive compound production, Vetiver is recommended for use in sloping pastures, roadside embankments, reservoir walls, and other watershed management applications. Its integration into land management strategies can mitigate soil erosion, landslides, and subsidence, while providing ecological and economic benefits and contributing to sustainable slope stabilization.

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