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Comparative performance assessment of ecological restoration techniques for transmission line slopes: integrating geotechnical stability and ecological indicators

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Ecological restoration of transmission line slopes is essential for infrastructure sustainability in mountainous regions, yet comparative assessments of restoration techniques are lacking. This study evaluated four restoration approaches—vegetation concrete (VC), hydroseeding (HS), ecological bags (EB), and natural restoration (NR)—over 24 months on a slope in the Three Gorges Reservoir area, China. Geotechnical indicators (shear strength, root tensile strength) and ecological indicators (vegetation coverage, Shannon diversity index, aboveground biomass, soil organic matter) were monitored throughout the experimental period. The VC treatment demonstrated superior performance, achieving the highest shear strength (45.8 kPa), root tensile strength (12.8 MPa), and vegetation coverage (82.3%), with a comprehensive evaluation score of 99.8, followed by EB (84.8), HS (72.8), and NR (42.5). Strong positive correlations were identified between ecological and geotechnical indicators (r = 0.963 for biomass–root tensile strength; r = 0.890 for coverage–shear strength), whereas a moderate correlation between Shannon diversity and geotechnical metrics (r = 0.496) suggested a trade-off between species diversity and structural stability. These findings provide quantitative guidance for selecting restoration techniques in transmission line corridor management.

KEYWORDS

comprehensive performance evaluation, ecological restoration, slope stability, transmission line slope, vegetation concrete

1 Introduction

Construction of power transmission corridors in mountainous regions destabilizes slopes through extensive excavation, resulting in shallow landslides, accelerated erosion, and structural failures that threaten both infrastructure integrity and surrounding ecosystems (Li et al., 2021; Wu et al., 2023). These geotechnical hazards compromise the stability of transmission tower foundations while simultaneously disrupting ecological corridors and causing habitat fragmentation across the landscape (Huang et al., 2024; Yin et al., 2025). The dual challenge of maintaining structural safety and ecological function has generated substantial demand for restoration strategies that address both geotechnical and environmental objectives.

Current ecological restoration practices for power transmission line areas involve diverse approaches, each with distinct operating principles and efficiency levels. Among the most promising approaches is vegetation concrete technology, which combines mechanical stabilization with vegetation establishment using engineered substrates (Cheng et al., 2023; Xiong et al., 2023). This technology has demonstrated considerable potential for slope stabilization in road construction applications (Fu et al., 2020; Wang et al., 2022). Alternative approaches include ecological retaining walls, which provide stabilization through permeable structures that support vegetation growth (Jiang et al., 2020). Spray vegetation concrete systems offer solutions for carbonaceous rock slopes with acidic soil conditions (Chang et al., 2022). Advanced formulations incorporating diatomite and zeolite additives have improved water retention and pollutant removal efficiency (Chen J. et al., 2023), while optimized planting densities enhance root reinforcement (Tan et al., 2020). Polymer-treated media have expanded the applicability of these systems (Wang et al., 2023). Hydroseeding technology, also known as spray seeding/hydraulic seed mulching, is another popular restoration technology with high construction speed and economic advantages (Xu et al.,; García-Palacios et al., 2010; De Oña et al., 2011; Li et al., 2017; Faiz et al., 2024). Recent advances have incorporated biochar into vegetation concrete to reduce carbon emissions while maintaining ecological function (Faiz et al., 2024). Root mechanical properties play an integrated role in soil improvement, where herbaceous vegetation demonstrated the highest capability in the stabilization of shallow slopes with high fiber root density (Löbmann et al., 2020; Seo et al., 2021; Gong et al., 2024).

Despite these technological advances, critical knowledge gaps persist in comparative assessments of ecological restoration methods for transmission line slopes. Existing studies predominantly focus on single techniques or short-term observations (<12 months), lacking systematic comparisons across multiple methods under identical environmental conditions (Hu et al., 2021). Long-term dynamics spanning the transition from initial establishment to mature ecosystem development remain poorly characterized. A notable deficiency exists in integrated evaluation frameworks that simultaneously incorporate geotechnical stability parameters and ecological performance indicators. These gaps limit evidence-based decision-making for restoration strategy selection in transmission corridor management.

This study provides a comprehensive comparison of four ecological restoration methods for transmission line slopes: vegetation concrete, hydroseeding, ecological bags, and natural restoration. The investigation employed comprehensive monitoring of slope displacement, soil shear strength, root tensile strength, vegetation coverage, species diversity, and soil parameters over 24 months. Principal component analysis and a multi-criteria evaluation framework were applied to systematically compare restoration effectiveness. The results advance understanding of interactions between slope stability and ecological development, providing guidance for restoration method selection in transmission corridor management.

2 Materials and methods

2.1 Study area

The research area is located in the slope within the transmission line corridor in Wanzhou District, Chongqing City, China (30° 48'N, 108°24'E), which is in the Three Gorges Reservoir area. The region is characterized by mountainous terrain with elevations ranging from 150 to 1,200 m above sea level. The area has a subtropical monsoon climate with a mean annual temperature of 18.3°C and annual precipitation of 1,200 mm, concentrated from May to September. Intense rainfall events in this region affect both slope stability and ecological restoration outcomes (Li et al., 2022).

The experimental site (S1) is located at 580 m elevation within a 500 kV transmission line corridor. As shown in Figure 1, the slope has a height of 12 m, length of 18 m, and a 45° inclination facing southeast. The soil profile comprises three layers: topsoil (0–0.3 m), weathered sandstone (0.3–2.5 m), and bedrock (>2.5 m). Prior to treatment application, the slope exhibited sparse vegetation and visible erosion, typical of disturbed areas in transmission line corridors. Site conditions are representative of slopes requiring ecological restoration in the Three Gorges Reservoir region, enabling meaningful comparison of restoration methods (Li et al., 2022).

2.2 Experimental design

The study adopted a Randomized Complete Block Design for comparing the effectiveness of four ecological restoration methods on the slope supporting the transmission line. The experimental treatments included: (1) vegetation concrete (VC), a porous cement-based substrate designed to provide mechanical stabilization while facilitating vegetation growth (Kim and Park, 2016); (2) hydroseeding (HS), where seeds, mulch, fertilizer, and water were applied for rapid surface coverage; (3) ecological bags (EB), using biodegradable geosynthetics as the growth substrate (Guo et al., 2025); and (4) natural recovery (NR), the control treatment with no human intervention. A total of 12 experimental plots were established on the slope.

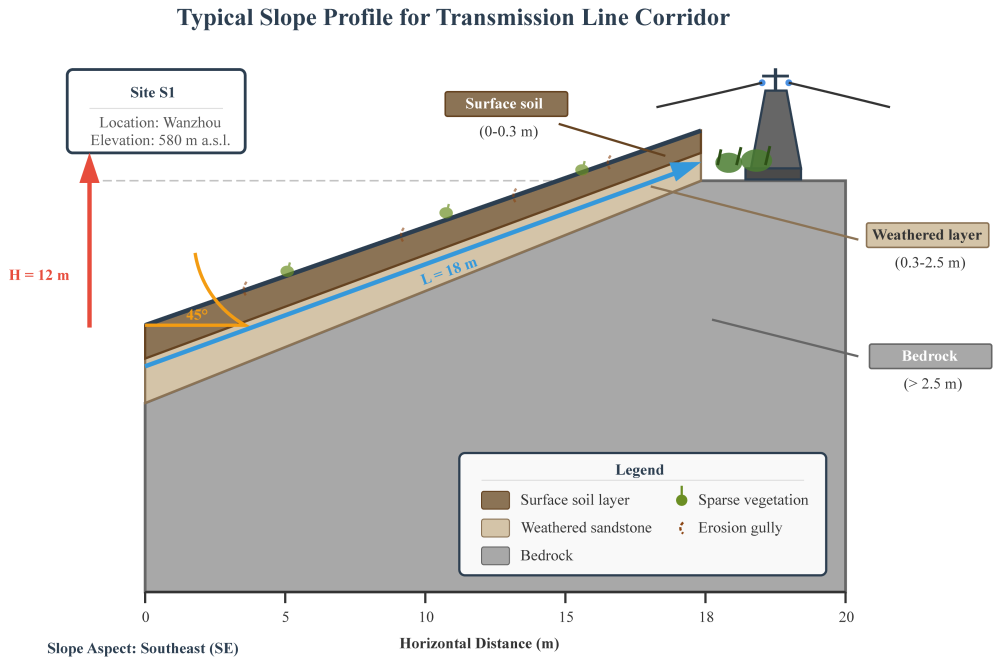

FIGURE 1
Typical slope profile for transmission line corridor showing site characteristics, soil stratification, and geometric parameters at the experimental location in Wanzhou District.

Treatment details are listed in Table 1. The vegetation-concrete mixture was made up of Portland cement, locally obtained top soil, organic compost, and water retention polymers, which were combined in relation to optimized ratios for porosity and mechanical strengths (Kim and Park, 2016). Hydroseeding involved a mixture consisting of indigenous grasses and legume seeds, with wood fiber mulch and tackifier, applied at optimized pressure. Ecological bags were made from degradable jute cloth, with soil/compost mix, vegetated with indigenous shrubs two months before their final installation in the field (Guo et al., 2025). All vegetation restoration treatments were done in May 2023 using optimized slope preparations, with surface cleaning and minor grading for similarity in starting points.

The experimental design, presented in Figure 2, reflects the random spatial distribution of treatment plots (10 m × 10 m each), which reduces the impact of topographic-Edaphic gradients on the slope area. Random number-based allocation for treatment plot identification avoids any systematic error in the experimental design. Such a well-balanced experimental design helps in making appropriate comparisons between restoration levels using statistical analyses, accounting for heterogeneity in natural settings with suitable replication levels (Eab et al., 2015). Altogether, the design enables the evaluation of geotechnical stability measures, in addition to ecological metrics, in the same settings, making it easier to mitigate any factors considered in making comparisons in other restoration research studies.

2.3 Monitoring indicators

A comprehensive monitoring system was established to evaluate geotechnical stability and ecological function throughout the 24-month study period. The monitoring system, listed in Table 2, comprises two different main sets: slope stability indicators and ecological function parameters. Slope stability was assessed using four main parameters. Surface displacement was measured monthly using a total station system to detect slope movement and provide early warning of potential instability (Bordoloi and Ng, 2020). Soil shear strength was measured using direct shear tests on intact samples extracted at 6-month intervals from the 0–30 cm depth, a

TABLE 1 Key specifications of restoration treatments applied to the transmission line slope.

Treatment	Main components	Application method	Application rate	Plot size
Vegetation Concrete (VC)	Cement:soil:compost:polymer (1:6:1:0.02)	Pneumatic spray, 5 cm	12 kg/m^2; seed 25 g/m^2	10×10 m
Hydroseeding (HS)	Seed-mulch-fertilizer slurry with tackifier	Hydraulic spray, 10 MPa	Seed 30 g/m^2, mulch 150 g/m^2	10×10 m
Ecological Bags (EB)	Jute bags (40×60×10 cm), soil:compost (3:1)	Manual installation, 20 cm spacing	25 bags/m^2, pre-vegetated	10×10 m
Natural Recovery (NR)	No intervention	Natural colonization	–	10×10 m

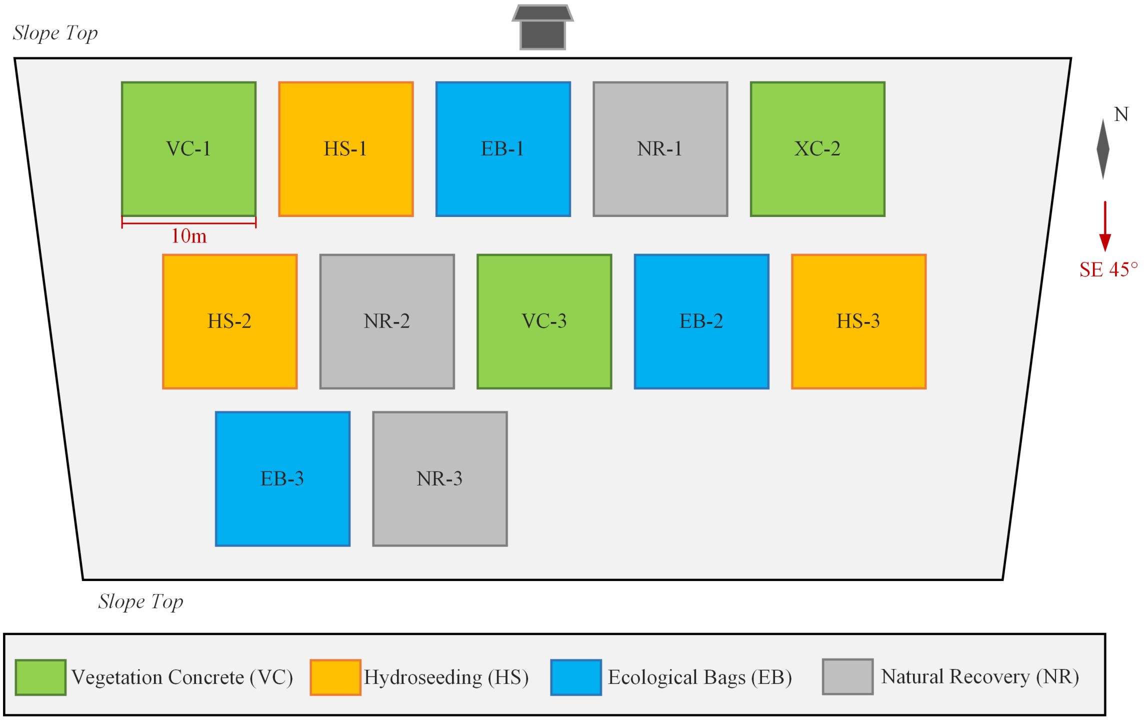

FIGURE 2
Experimental plot layout for the four restoration treatments on the transmission line slope.

key parameter for understanding root-soil mechanical integration (Jian et al., 2024). Surface erosion rates were measured using erosion pins and sediment traps at representative sites, with measurements conducted after each rainfall event to capture erosion dynamics. Root pull-out strength was measured for roots with diameters of 1–5 mm, acknowledging the heterogeneity in mechanical properties among species (Xian et al., 2025) and potential seasonal variations related to phenological cycles (Ji et al., 2025).

TABLE 2 Monitoring indicators and measurement protocols for slope stability and ecological performance assessment.

Category	Indicator	Method	Frequency	Unit
Slope Stability	Surface displacement	Total station at fixed points	Monthly	mm
	Soil shear strength	Direct shear test (0–30 cm depth)	Every 6 months	kPa
	Surface erosion	Erosion pins and sediment traps	After rainfall events	mm, kg/m²
	Root tensile strength	Pull-out test (1–5 mm diameter)	Every 6 months	MPa
Vegetation	Vegetation coverage	UAV photography + image analysis	Monthly	%
	Species diversity	Quadrat survey (1 m × 1 m)	Every 3 months	Shannon, Simpson index
	Aboveground biomass	Harvesting and oven-drying	Every 6 months	g/m²
Soil Properties	Organic matter	Potassium dichromate oxidation	Every 6 months	g/kg
	Available nutrients	N, P, K standard methods	Every 6 months	mg/kg
	Soil pH	Potentiometric method (1:2.5)	Every 3 months	–

Ecological performance was assessed using integrated vegetation and soil measurements. Vegetation cover was measured monthly using UAV photography and image analysis, enabling rapid assessment across large areas (Li et al., 2023). The integrated UAV system helps in making an accurate assessment of vegetation establishment dynamics (Xu et al., 2022) and allows the extraction and calculation of vegetation cover in complex terrain (Chen R. et al., 2023). Species diversity was measured quarterly using quadrat sampling (1 m × 1 m), with diversity metrics calculated using the Shannon and Simpson indices. Aboveground biomass was measured semiannually using destructive sampling followed by oven-drying. Soil parameters, such as organic matter, available nutrients (nitrogen, phosphorous, potassium), and soil pH, measured according to conventional laboratory protocols on a 3- to 6-month cycle, enable a comprehensive evaluation of system performance with regard to multiple engineering stability and ecological function criteria (Yazdani et al., 2024).

2.4 Data collection

Data collection activities were done over a period of 24 months from May 2023 to April 2025, covering two entire life cycles for the observation of seasonal variations in terms of stability and ecological factors. The period for monitoring activities is quite long since it is meant to test the long-term efficiency of the restoration treatment considering that soil bioengineering systems need time for the development of root systems (Bischetti et al., 2014). The pattern for carrying out monitoring activities is dependent on the nature of parameters being measured, with monthly monitoring for dynamic factors like surface movement, vegetation cover, among others, and semi-annual monitoring for parameters like shear strength, root tensile strength, and biomass accumulation.

Standardized protocols were followed in each measurement to allow for comparison between treatments. Displacement measurements on the surfaces were carried out with a Leica TS16 total station with an accuracy of 2 mm, with control points being fixed on stable rocks away from the treated area. Soil shear strength measurements were done with a portable strain control direct shear tester (ZJ), with intact specimens being made up of soil and roots (10 cm × 10 cm × 5 cm in dimension). The root tensile strengths were measured using a digital force gauge with a resolution of 0.01 N, with mechanical clamps following a pull-out test procedure. The vegetation maps were created using a DJI Phantom 4 RTK drone at an altitude of 30 m with standardized image settings regarding pixel size and light exposure. The simultaneous observation of root systems together with soil physical properties is an essential aspect for the understanding of slope stability mechanisms (Osman and Barakbah, 2006; Ghestem et al., 2011).

Additionally, quality control measures were adopted that involved the following: (1) calibration before each sampling, (2) replicate sampling (n ≥ 3) for each destructive test, (3) sampling locations with permanent identification for replication, (4) concurrent data entry with checking, and (5) independent surveyors' double-checking for vegetation measurements. All analyses in the four labs followed national standards with certified reference standards for quality control.

2.5 Statistical analysis

All statistics were performed using the R software (Version 4.3.1), supplemented with SPSS 26.0 for some statistics. When done, the scores were then submitted to careful preprocessing for outlier tests using the inter-quartile range test, tests for normality using the Shapiro-Wilk test, and homogeneity of variance tests using Levene's test. Missing values, present in less than 3% of the total number of values, were replaced using multiple imputation approaches for integrity reasons.

The treatment differences on individual parameters were tested using one-way ANOVA with treatment as fixed factors and block as a random factor for incorporating spatial heterogeneity. In cases where the assumptions were violated in ANOVA, Kruskal Wallis tests were performed for comparison. Pairwise differences were tested using Tukey's Honestly Significant Difference test with $\alpha = 0.05$ significance level for contrasting differences among treatments. Changes over time were tested using two-way repeated measures ANOVA for treatment × time interaction.

Principal component analysis (PCA) was employed for dimensionality reduction and identification of dominant trends among monitoring indicators. PCA helps in the identification of uncorrelated principal components, which explain the maximum variation in the dataset, thus making it easy to visualize treatment performance in multiple dimensional spaces (Wu et al., 2022). The combination of PCA with weighting techniques helps in indexing complex systems effectively (Kurek et al., 2022).

A comprehensive assessment framework was developed by integrating the entropy weight method with the Analytic Hierarchy Process (AHP) for indicator weighting (Kurek et al., 2022; Pliego-Martínez et al., 2024). The entropy weight method quantifies information content based on data variability across treatments (Wu et al., 2022). For indicator j, the entropy value E_j is calculated as Equation 1:

$$E_j = -\frac{1}{\ln n}\sum_{i=1}^{n} p_{ij} \ln p_{ij} \tag{1}$$

where n represents the number of treatments, and p_{ij} denotes the normalized proportion of indicator j for treatment i. The entropy-based weight $W_j^{(E)}$ is derived as Equation 2:

$$W_j^{(E)} = \frac{1 - E_j}{\sum_{k=1}^{m}(1 - E_k)} \tag{2}$$

where m represents the total number of indicators. The AHP method incorporated expert judgment through pairwise comparison matrices, with consistency ratios (CR) maintained below 0.10 to ensure logical coherence (Kurek et al., 2022). The combined weight for each indicator was computed using the geometric mean (Equation 3) (Pliego-Martínez et al., 2024):

$$W_j = \sqrt{W_j^{(E)} \times W_j^{(A)}} \tag{3}$$

followed by normalization to ensure $\sum_{j=1}^{m} W_j = 1$. This integration strategy balances objective data-driven assessment with domain expertise, reducing potential bias from single-method approaches. Preliminary comparison revealed weight differences below 15% between entropy and AHP methods across all indicators, validating the compatibility of both weighting schemes. The comprehensive performance score S_i for each treatment was calculated as the weighted sum of normalized indicator values. Statistical significance was set at $\alpha = 0.05$ for all analyses.

3 Results

3.1 Slope stability performance

Geotechnical performance varied significantly among restoration treatments throughout the 24-month monitoring period (Figure 3). Surface displacement at 24 months was lowest in the VC treatment (3.1 ± 0.5 mm), representing an 83% reduction relative to the NR control (18.7 ± 2.1 mm; Table 3). The EB treatment exhibited intermediate displacement (4.5 ± 0.6 mm), while HS showed moderate stabilization capacity (7.2 ± 1.0 mm). Seasonal fluctuations in displacement were observed across all treatments, likely attributable to variations in soil moisture content, though restored plots consistently maintained lower displacement values than the control throughout the observation period.

Soil shear strength increased progressively across all restoration treatments, with substantial gains observed at 12 months reflecting root system maturation. As illustrated in Figure 3b, with more specific information in Table 3, the treatment with VC resulted in higher shear strengths (45.8 ± 4.1 kPa) at 24 months, indicating an improvement of 79% over NR (32.6 ± 3.0 kPa). EB treatment showed equally good results (52.4 ± 3.8 kPa), with values from treatment HS (48.7 ± 3.6 kPa) in between. Surface erosion measurements corroborated these stability findings, with total erosion at 24 months ranging from 1.2 ± 0.3 kg/m² (VC) to 5.4 ± 0.8 kg/m² (NR), confirming the effectiveness of engineered treatments in erosion prevention.

Root tensile strength values were found to fluctuate considerably between treatments, which is reflected in Figure 3d. The VC root had an average tensile strength of 12.8 ± 1.5 MPa, which is considerably higher compared to other treatments: 8.6 ± 1.2 MPa (HS), 10.3 ± 1.3 MPa (EB), and 4.2 ± 0.8 MPa

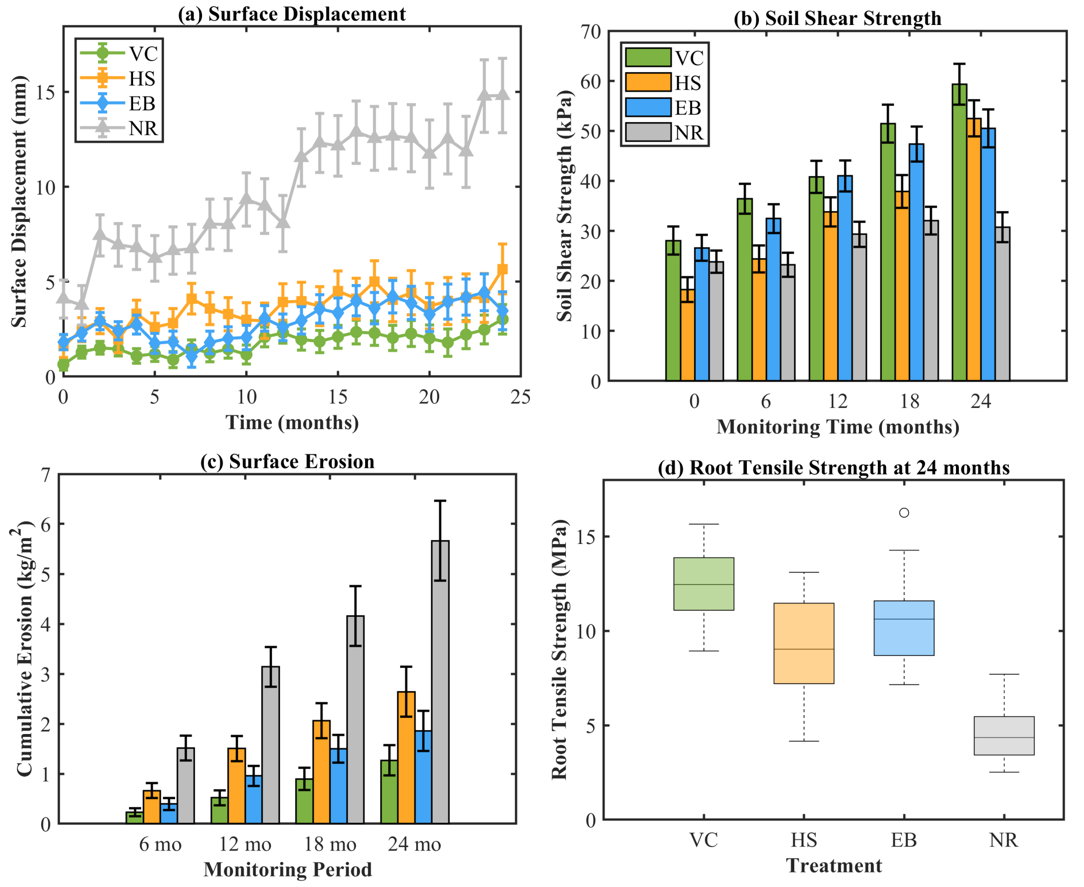

FIGURE 3
Comparison of slope stability indicators across restoration treatments. **(a)** Surface displacement over 24 months. **(b)** Soil shear strength at 6, 12, 18, and 24 months. **(c)** Cumulative surface erosion at 6, 12, 18, and 24 months. **(d)** Root tensile strength at 24 months.

TABLE 3 Statistical comparison of slope stability indicators among restoration treatments.

Indicator	Time point	VC	HS	EB	NR	F-value	P
Surface displacement (mm)	12 months	2.3 ± 0.4^{a}	5.6 ± 0.8^{b}	3.8 ± 0.5^{ab}	12.4 ± 1.2^{c}	45.6	<0.001
	24 months	3.1 ± 0.5^{a}	7.2 ± 1.0^{b}	4.5 ± 0.6^{ab}	18.7 ± 2.1^{c}	52.3	<0.001
Soil shear strength (kPa)	12 months	42.5 ± 3.2^{a}	35.8 ± 2.9^{b}	38.6 ± 3.1^{ab}	28.3 ± 2.5^{c}	18.9	<0.001
	24 months	45.8 ± 4.1^{a}	48.7 ± 3.6^{b}	52.4 ± 3.8^{ab}	32.6 ± 3.0^{c}	24.7	<0.001
Cumulative erosion (kg/m^2)	24 months	1.2 ± 0.3^{a}	2.8 ± 0.5^{b}	1.9 ± 0.4^{ab}	5.4 ± 0.8^{c}	31.2	<0.001
Root tensile strength (MPa)	24 months	12.8 ± 1.5^{a}	8.6 ± 1.2^{b}	10.3 ± 1.3^{ab}	4.2 ± 0.8^{c}	21.5	<0.001

Values are mean ± standard error (n=3 replicates). Different superscript letters indicate significant differences among treatments based on Tukey's HSD test (α=0.05). VC, Vegetation Concrete; HS, Hydroseeding; EB, Ecological Bags; NR, Natural Recovery.

(NR). There were highly significant treatment differences for each stability criterion (p< 0.001), with separate performance levels in each case distinguished by *post-hoc* tests (Table 3). The superior performance of VC across multiple indicators reflects the synergistic benefits of mechanical reinforcement from the cement-based matrix combined with biological stabilization from vegetation development. In contrast, the limited performance of NR demonstrates the inadequate self-recovery capacity of disturbed slopes without intervention.

3.2 Ecological performance indicators

Ecological performance differed significantly among restoration treatments over the 24-month period (Figure 4). Vegetation cover percentage showed varying establishment levels over time according to each restorative treatment strategy. The VC restorative treatment had better coverage consistency with 82.3 ± 3.8% at the 24th month, followed by treatment EB with 78.6 ± 3.5%, followed by treatment HS with 72.5 ± 4.2%, while treatment NR covered only 32.4 ± 4.5%, which were statistically significant (Table 4; F = 125.8, P< 0.001). There were also notable differences in vegetation cover percentage over time with marked fluctuations in the seasons, particularly in treatment HS in which winter caused drastic cover percentage decline followed by marked recoveries during the succeeding growing seasons, thereby indicating the sensitive nature of herbaceous vegetation communities in relation to different environmental factors, thus highlighting the importance of treatment in relation to the prevailing regional climatic factors.

Species diversity analyses yielded notable findings regarding engineered restoration systems. The HS treatment achieved the highest Shannon diversity index (2.15 ± 0.18), surpassing EB (1.84 ± 0.15) and VC (1.68 ± 0.14), despite having lower vegetation coverage. This may be attributed to the porous substrate structure in hydroseeding, which facilitates species colonization and enhances habitat-level diversity. Upon analyzing species diversity, treatment differences were significant (F = 28.5, P< 0.001), with NR treatment possessing the lowest species diversity (1.35 ± 0.12), even with seed restrictions in propagation because of exposure to harsh environments even on top surfaces.

Productivity assessment using aboveground biomass analyses showed significant hierarchical differences among treatments, with VC showing the highest accumulation (1045 ± 78 g/m^2), followed by EB (965 ± 72 g/m^2), HS (825 ± 65 g/m^2), and NR (358 ± 45 g/m^2). Soil organic matter accumulation followed similar patterns across treatments, with progressively declining rates consistent with ecological succession theory.

Simultaneously, the VC treatment showed significant improvement in soil quality (23.6 ± 2.1 g/kg), appreciated at 141% from its original status, while EB achieved 21.5 ± 1.8 g/kg, HS reached 19.4 ± 1.6 g/kg, and NR showed modest enhancement (11.5 ± 1.4 g/kg). The significant differences in soil organic matter among treatments (F = 52.3, P< 0.001) highlight the importance of active intervention to accelerate pedogenesis and achieve restoration objectives within operational timeframes.

3.3 Temporal dynamics of ecological development

Temporal patterns of ecological indicators over the 24-month period revealed distinct developmental trajectories among the four restoration treatments (Figure 5). Vegetation cover development varied by treatment; VC exhibited rapid colonization during the first six months, reaching approximately 82% coverage before entering a stabilization phase with minimal subsequent variation. The HS treatment demonstrated high levels of variation in values over the course of the seasons, fluctuating between 65-80% due to temperature and rainfall factors, eventually reaching stabilization at 72.5% values at the end of the period. The EB treatment demonstrated high levels of stability in vegetation cover development, while the NR treatment showed limited improvement, reaching only 32.4% after 24 months.

The Shannon diversity index curves were different in terms of the species accumulation pattern in each treatment group. The species enrichment pattern in the HS treatment followed an ongoing curve for the entire experimental period to reach its maximum diversity at the end (2.15), while the others followed an asymptotic curve toward their maximum diversities (1.68 for the VC treatment and 1.84 for the EB treatment) at 18 months, respectively. The NR treatment showed delayed species accumulation, reflecting the slower pace of natural colonization without intervention.

Biomass increase and the formation of soil organic matter followed the general slowing rates for each treatment, in line with traditional models for ecological successions. The VC treatment

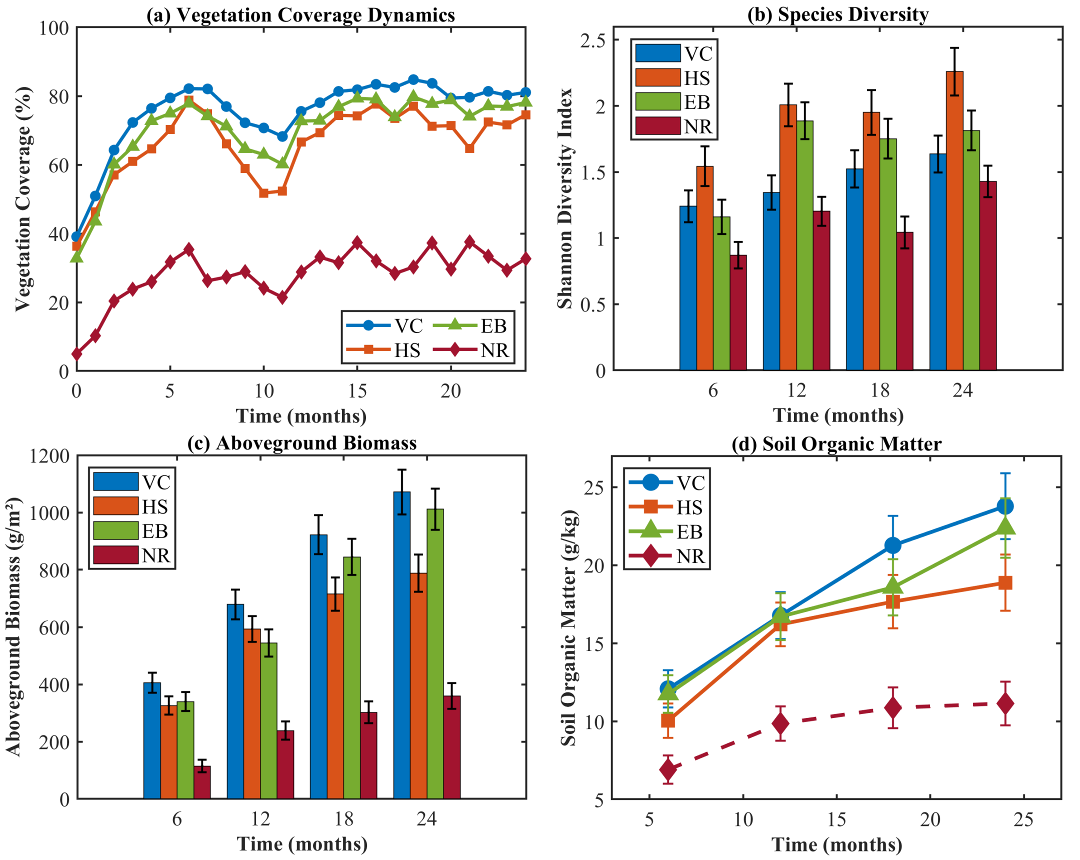

FIGURE 4
Ecological performance indicators across restoration treatments. **(a)** Vegetation coverage dynamics. **(b)** Shannon diversity index dynamics. **(c)** Aboveground biomass accumulation. **(d)** Soil organic matter development.

showed the greatest rate for the increase in biomass during the establishment phase (0–12 months), then slowing down for volume increase, eventually reaching 1045 g/m^2. Soil organic matter development offered insightful views into treatment-driven pedogenesis, with the NR method demonstrating little progress in the first six months, then continuing with only small increases (11.5 g/kg at month 24). The delayed soil organic matter development in the NR treatment underscores the importance of active restoration interventions, as natural recovery alone is insufficient to meet restoration objectives within operational timeframes on heavily degraded transmission line slopes.

3.4 Comprehensive performance evaluation and ranking

The integrated assessment using the multi-criteria evaluation method created an unequivocal hierarchical ordering with six weighted criteria (Figure 6; Table 5). The criteria weight factors were derived from the proposed assessment criteria, allocating 38% for stability criteria (shear strength and root tensile strength), while ecological criteria were allocated a combined 62% weight, accounting for engineering needs for the restoration of the transmission line on the slope sides.

TABLE 4 Statistical comparison of ecological indicators at 24 months.

Indicator	VC	HS	EB	NR	F-value	P
Vegetation coverage (%)	82.3 ± 3.8^{a}	72.5 ± 4.2^{b}	78.6 ± 3.5^{ab}	32.4 ± 4.5^{c}	125.8	<0.001
Shannon diversity index	1.68 ± 0.14^{b}	2.15 ± 0.18^{a}	1.84 ± 0.15^{ab}	1.35 ± 0.12^{c}	28.5	<0.001
Aboveground biomass (g/m^2)	1045 ± 78^{a}	825 ± 65^{c}	965 ± 72^{b}	358 ± 45^{d}	156.2	<0.001
Soil organic matter (g/kg)	23.6 ± 2.1^{a}	19.4 ± 1.8^{b}	21.5 ± 1.9^{ab}	11.5 ± 1.4^{c}	52.3	<0.001

Values are means ± SE (n=3). Different superscript letters indicate significant differences among treatments (P< 0.05, Tukey's HSD test). VC, Vegetation Concrete; HS, Hydroseeding; EB, Ecological Bag; NR, Natural Recovery.

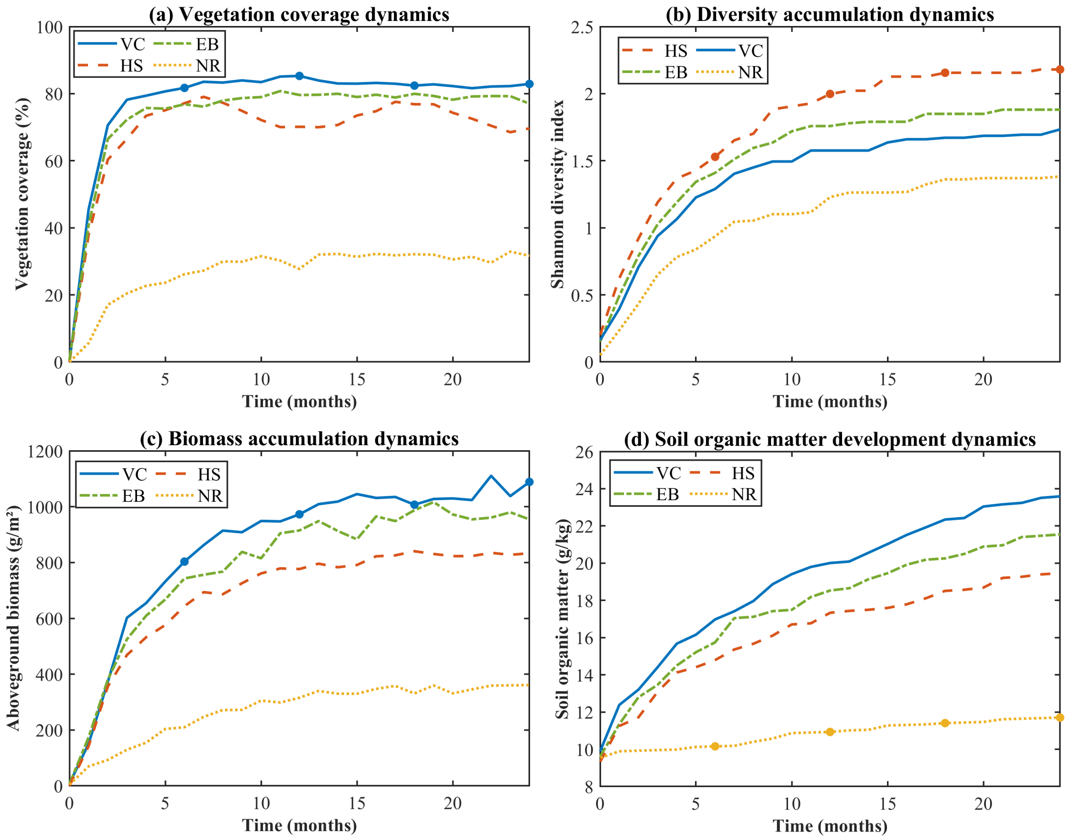

FIGURE 5
Temporal dynamics of key ecological indicators. **(a)** Vegetation coverage dynamics. **(b)** Species diversity. **(c)** Aboveground biomass. **(d)** Soil organic matter.

Performance comparison in multiple dimensions showed specific treatment responses (Figure 6a). The VC treatment performed better than other treatments in the structural engineering criteria with highly scored values (normalized scores > 98) for shear strength, root tensile strength, vegetation coverage, aboveground biomass, and soil organic matter; it also showed moderate Shannon index values (78.1 ± 0.9). In contrast, the HS treatment achieved the highest biodiversity score (100 ± 0.7) but moderate geotechnical scores (shear strength: 71.0 ± 1.5; root tensile strength: 67.2 ± 1.4). EB treatment performed moderately in

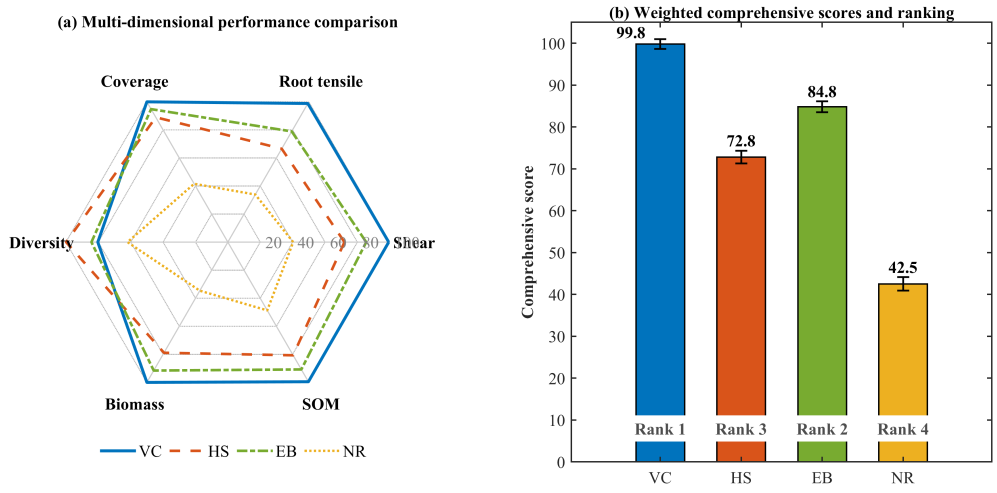

FIGURE 6
Comprehensive performance evaluation of restoration treatments. **(a)** Multi-dimensional performance comparison. **(b)** Weighted comprehensive scores and ranking.

TABLE 5 Multi-criteria evaluation scores and treatment ranking.

Indicator	Weight	VC	HS	EB	NR
Shear strength	20%	100 ± 1.2^{a}	71.0 ± 1.5^{c}	84.3 ± 1.3^{b}	40.0 ± 1.8^{d}
Root tensile strength	18%	98.5 ± 1.1^{a}	67.2 ± 1.4^{c}	80.5 ± 1.2^{b}	32.8 ± 1.6^{d}
Vegetation coverage	15%	100 ± 0.8^{a}	88.1 ± 1.2^{b}	95.5 ± 0.9^{ab}	39.4 ± 1.5^{c}
Shannon diversity	12%	78.1 ± 0.9^{b}	100 ± 0.7^{a}	85.6 ± 0.8^{b}	62.8 ± 1.2^{c}
Aboveground biomass	18%	100 ± 1.0^{a}	79.0 ± 1.3^{c}	92.4 ± 1.1^{b}	34.3 ± 1.7^{d}
Soil organic matter	17%	100 ± 0.9^{a}	82.2 ± 1.1^{c}	91.1 ± 1.0^{b}	48.7 ± 1.4^{d}
Comprehensive score	**100%**	**99.8 ± 1.2^{a}**	**72.8 ± 1.5^{c}**	**84.8 ± 1.3^{b}**	**42.5 ± 1.6^{d}**
Ranking	-	**1**	**3**	**2**	**4**

Scores normalized to 0–100 scale. Values are means ± SE (n=3). Different superscript letters indicate significant differences ($P < 0.05$, Tukey's HSD test). Weights reflect engineering priorities for transmission line slope restoration. Bold values indicate the comprehensive scores used for overall treatment ranking.

multiple criteria with no special advantage/disadvantage for any criteria.

The scoring values resulted in the following rank: VC (99.8 ± 1.2) > EB (84.8 ± 1.3) > HS (72.8 ± 1.5) > NR (42.5 ± 1.6), with highly significant differences between treatments ($F = 428.5$, $P < 0.001$). The excellent performance in VC resulted from the integrated efforts in mechanical strengthening and biological stabilization. The EB treatment gave good scores because of its stable average scores in medium to high levels, indicating its viability in areas where well-balanced geotechnical-ecological performance is required. The average position in rank for the HS treatment resulted from its basic restrictions in structural reinforcement capabilities despite its high diversity levels. The much lower score in NR (42.5 ± 1.6) validated the unsuitability of passive restoration principles in meeting operational stability criteria in acceptable periods on heavily altered transmission line slopes.

3.5 Correlation analysis figures

Pearson's Correlation analyses showed there were significant relationships between geotechnical stability parameters and ecological performance indicators for each treatment level in the time sequences (Figure 7, $n = 48$). The investigation pointed to mostly positive significant relationships between each pair of indicators, although the nature and significance of these relationships ranged considerably depending on the pair of parameters investigated.

Root tensile strength had the highest positive correlation with aboveground biomass accumulation ($r = 0.963$, $R^2 = 0.927$, $P < 0.001$), demonstrating that biomass accumulation is a good predictor for the mechanical reinforcement capability of roots (Figure 7b). This is in line with the direct positive relation between photosynthesis and resource allocation to roots, where higher aboveground biomass accumulation is directly associated with higher levels of root system development with higher tensile strengths. This relationship has practical implications for slope management, as vegetation biomass can serve as a non-destructive field indicator for estimating root mechanical reinforcement capacity. Similarly high positive correlations were also obtained between shear strengths and aboveground biomass ($r = 0.951$, $R^2 = 0.904$, $P < 0.001$), as well as between root tensile strength and vegetation cover ($r = 0.907$, $R^2 = 0.822$, $P < 0.001$), indicating the coupled processes within vegetation establishment and slope stabilization.

Organic matter content in the soil had a positive significant relationship with shear strength ($r = 0.903$, $R^2 = 0.815$, $P = 0.001$), indicating that soil pedogenesis is an equally important mechanism for improving geotechnical stability in addition to root reinforcement (Figure 7c). This highlights the importance of soil development as a mechanism linking ecological restoration to slope stability, potentially through aggregate formation, enhanced water retention, and improved soil cohesion. The relationship between vegetation cover percentage and shear strength ($r = 0.890$, $R^2 = 0.792$, $P = 0.001$) provided additional evidence concerning the pivotal mechanism provided by vegetation establishment. From an engineering perspective, this correlation enables UAV-based vegetation monitoring to serve as an indirect indicator for soil shear resistance changes, supporting cost-effective slope stability assessment.

Conversely, although Shannon diversity index is generally characterized by strong positive correlations with the other ecological performance metrics, it generally displayed moderate positive associations with shear strength ($r = 0.496$, $R^2 = 0.246$, $P < 0.001$), indicating a much weaker level of associations compared with other ecological metrics (Figure 7f). This pattern reflects a trade-off between species diversity and functional homogeneity in engineered restoration systems, where the treatments with maximum geotechnical capacity (primarily VC) supported high levels of system stability with rather homogeneous vegetation communities, thereby outperforming treatments with higher levels of spontaneous species immigration (primarily HS), which supported high levels of diversity at the expense of structural reinforcement capabilities. Collectively, these results thus show that while the majority of ecological stability performance metrics generally associated closely with stability improvement, diversity is a partially independent criterion requiring separate treatment in

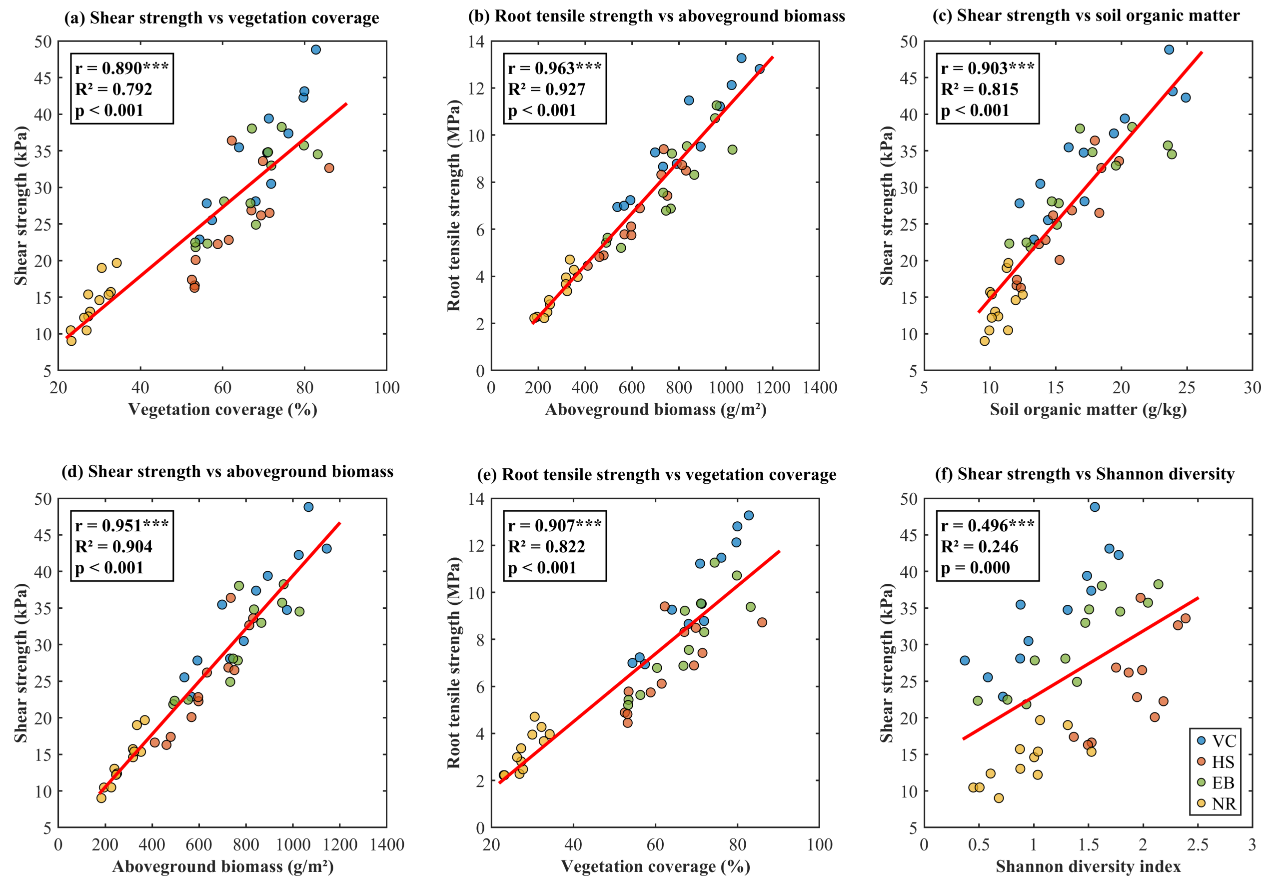

FIGURE 7
Relationships between geotechnical stability and ecological performance indicators. **(a)** Shear strength vs. vegetation coverage. **(b)** Root tensile strength vs. aboveground biomass. **(c)** Shear strength vs. soil organic matter. **(d)** Shear strength vs. aboveground biomass. **(e)** Root tensile strength vs. vegetation coverage. **(f)** Shear strength vs. Shannon diversity index. ***p < 0.001.

ecological restorative strategies targeting geotechnical and ecological performance objectives.

4 Discussion

The comparative study shows that vegetation concrete performed best for transmission line slope restoration, achieving 45.8 kPa shear strength and 82.3% vegetation coverage at 24 months. This shear strength exceeded values reported by Kim and Park (2016) for porous vegetation concrete (30–35 kPa at comparable timeframes), likely due to optimized cement-soil ratios and polymer formulations. Root tensile strength (VC: 12.8 MPa) fell within the upper range documented by Xiong et al. (2023) for herbaceous species in similar systems (8–14 MPa), confirming the effectiveness of the species selection strategy. The improved performance is also attributed to optimized formulation practices and specific material selection (Cheng et al., 2023), consistent with laboratory-scale tests for porous vegetation-concrete systems (Kim and Park, 2016).

The highly stable results emerge from the complementing effects associated with simultaneous structural stabilization and biological reinforcement processes. The cement-stabilized matrix provides essential early-stage protection, enabling vegetation establishment under the harsh microenvironmental conditions typical of transmission line corridors. Subsequent root development contributes to long-term stabilization through mechanical anchorage (Bordoloi and Ng, 2020). The strong correlation between root tensile strength and aboveground biomass (r = 0.963) indicates that biomass accumulation could serve as a practical indicator for assessing stabilization performance (Jian et al., 2024; Xian et al., 2025). Root development substantially improved shear resistance, with measured tensile strengths (VC: 12.8 MPa) approaching values reported for woody vegetation in established bioengineering systems (Tan et al., 2020).

The moderate correlation between Shannon diversity and geotechnical properties (r = 0.496) reveals a potential trade-off between species diversity and functional homogeneity. This pattern may be interpreted through ecological theory: the niche complementarity hypothesis predicts that diverse communities enhance function through resource partitioning, while the selection effect suggests that dominant species drive performance. In the present engineered system, the selection effect appears predominant, as VC treatment favored fast-establishing, mechanically robust grasses that maximized geotechnical performance but limited species colonization. The superior diversity in HS treatment reflects the positive influence of porous microhabitat heterogeneity on species establishment

(García-Palacios et al., 2010). This finding aligns with observations from semi-arid motorway restoration projects, where habitat heterogeneity promoted spontaneous colonization and species coexistence (Löbmann et al., 2020; Gong et al., 2024), though such diversity gains may come at the cost of reduced root biomass concentration.

The stability improvements observed in root-reinforced systems are consistent with results from controlled laboratory studies (Eab et al., 2015); however, field conditions introduced additional variability due to temporal fluctuations and environmental stochasticity.

In terms of the perspectives of implementing these systems, vegetation concrete is well suited to high-priority slopes where immediate stabilization is required, even if it entails high upfront costs in comparison to hydroseeding options (Fu et al., 2020). Recent carbon footprint analyses imply that formulations with biochar additions could improve their ecological sustainability with no compromise in engineering performance (Faiz et al., 2024). The performance criteria hierarchies discussed in this work correlate well with other investigations in Alpine regions for similar applications (Hu et al., 2021), although comprehensive economic studies considering life cycle costs would be beneficial in arriving at informed choices (Yazdani et al., 2024).

The 24-month observation period may not fully capture long-term system dynamics, especially with regard to possible degradation of synthetic polymer additives (Wang et al., 2023) and seasonal variation in root mechanical properties (Ji et al., 2025). Future studies need to investigate treatment long-term performance in terms of different time scales and geological factors (Li et al., 2022) for comprehensive design criteria development for transmission line corridors' restoration.

Several limitations warrant consideration when interpreting these findings. The single-site experimental design, while enabling controlled comparisons, constrains the generalizability of results to other geological formations, climatic zones, and slope configurations. The 24-month monitoring period captured establishment and early development phases but may not reflect long-term successional trajectories or the durability of synthetic components beyond initial stabilization. Sample size limitations (n = 3 replicates per treatment) may reduce statistical power for detecting subtle performance differences, particularly for indicators with high spatial variability. The 45° slope gradient represents moderate steepness; performance patterns on steeper or gentler slopes require separate investigation. Economic cost-benefit analyses, though beyond the current scope, would strengthen practical decision-making frameworks for corridor managers.

5 Conclusions

This comparative study establishes a clear performance hierarchy among ecological restoration methods for transmission line slopes, with vegetation concrete achieving the highest overall performance in both geotechnical stability and ecological indicators. The VC system performed impressively with respect to shear strength (45.8 kPa), root tensile strength (12.8 MPa), and vegetation cover (82.3% at 24 months), thereby acquiring comprehensive evaluation scores of 99.8, which were markedly higher than other variants. Ecological bags systems ranked in the medium range with respect to comprehensive scoring (84.8), while hydroseeding systems showed diminished stability factors with better biodiversity function (Shannon Index: 2.15). Natural recovery systems were too poor for operational stabilization within acceptable time scales, acquiring only 42.5 comprehensive scores. Correlation analyses confirmed strong positive associations between ecological and geotechnical factors (r > 0.89 for biomass-stability combinations), with a moderate correlation between diversity and structural factors (r = 0.496), indicating a trade-off between ecological diversity and structural performance.

The results offer quantitative criteria for choosing treatments during transmission line corridor restoration projects. Vegetation-concrete is the superior alternative for high-prioritized structure slopes where immediate stabilization with long-term durability is required; in such circumstances, the combined beneficial effects of mechanical stabilization with biologic stabilization outweigh high costs during implementation. Ecological bags systems present alternatives where the criteria for stabilization concern moderate levels with improved ecological objectives, while hydroseeding schemes could be appropriate where biodiversity preservation takes precedence over optimal structural performance. The multi-criteria evaluation method discussed in this investigation assists in considering geotechnical-ecologic criteria in a comprehensive manner, thereby covering significant knowledge gaps in performance comparison among different stabilization schemes.

This research advances understanding of vegetation-based slope stabilization and provides quantitative benchmarks for sustainable restoration of transmission line infrastructure in mountainous environments. Future long-term studies are warranted to further validate these findings across diverse site conditions.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

QZ: Methodology, Supervision, Writing – original draft, Writing – review & editing. Y-FZ: Conceptualization, Data curation, Writing – original draft. OZ: Formal analysis, Investigation, Writing – original draft. W-MX: Software, Validation, Writing – original draft. XJ: Data curation, Visualization, Writing – original draft.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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