QUALITY EVALUATION OF FROST-RESISTANT ARTIFICIAL SOIL APPLIED TO VEGETATION RESTORATION ON ROCK SLOPES IN TIBET

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Abstract. This study aimed to investigate the impact of using frost-resistant artificial soil on vegetation restoration on rock slopes in Tibet. Through field sampling and monitoring, this paper measured indicators for the stability and fertility of the artificial soil, as well as the status of vegetation restoration on slopes from 2019 to 2023. A comparison was made with natural soil under similar site conditions. Besides, the two kinds of soil quality were evaluated by calculating the soil quality index (SQI). Compared with natural soil, frost-resistant artificial soil achieved significantly higher stability and fertility, considering increases in the >0.25 mm macro-aggregate content (MAC), the mean weight diameter (MWD), organic matter (SOM), total nitrogen (TN), ammonium nitrogen (NH_4^+-N), and vegetation restoration status. During the period of 2019-2023, the average quality index (SQI) of frost-resistant artificial soil was 0.625, which is 53% higher than that of natural soil (0.408). Regression analysis shows that the SQI obtained with the above indicators was significantly correlated with indicators for vegetation restoration, so it can be used to evaluate the soil quality in cold regions. The correlation analysis and PCA revealed that the five indicators of MWD, MAC, WAC, NH_4^+-N, and TN have the strongest correlation with soil quality and contribute the most to soil quality. Therefore, it is recommended that improving aggregate and nitrogen indexes can increase SQI in the future. The quality evaluation indicated that frost-resistant artificial soil had a better effect when applied in Tibet, making it more suitable for such cold regions. This paper can provide support and reference for slope vegetation restoration technology.

Keywords: *frost-resistant artificial soil, slope vegetation restoration, soil quality, physical and chemical properties, correlation analysis, Tibet*

Introduction

Reserves of hydropower resources are abundant in Tibet, where many rivers create favorable conditions for integrated hydropower development (Suo et al., 2023). The construction of many hydropower projects in Tibet has disturbed and damaged original natural ecosystems (Li et al., 2015), resulting in the formation of many exposed rock slopes and causing a series of adverse effects such as water and soil loss and vegetation degradation (Xu et al., 2012). The Dagu Hydropower Station in Tibet is located in a cold region at a high elevation. It is characterized by freezing cold in winter, distinct temperature differences between day and night, and a low amount of precipitation. The

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area has an extremely fragile natural ecosystem (Zhang et al., 2024). When disturbed and damaged by external force, natural rock slopes can hardly recover on their own. Therefore, ecological restoration technologies for both stabilization and revegetation of rock slopes are widely applied in engineering areas in Tibet. Currently, ecological restoration technologies for rock slopes mainly include thick substrate spray-seeding (Yang et al., 2019), grid beam slope protection (Huang et al., 2023), and concrete biotechnics slope (CBS) technology, etc. The aforementioned technologies perform well in vegetation restoration in regions with superior natural conditions (Zhu et al., 2017; Cheng et al., 2020). However, in Tibet, where there are cold temperatures and frequent frost-thaw cycles, the stability and fertility of the soil are severely affected by conventional technologies (Zuo et al., 2022; Zhang et al., 2022). As a result, the above technologies are unable to achieve a successful effect in vegetation restoration. To improve the effect of vegetation restoration on rock slopes, China Three Gorges University has invented a patented product known as the frost-resistant ecological slope protection substrate (Zhou et al., 2016). The substrate is a frost-resistant artificial soil, which is a mixture of plant soil, cement, organic materials, green additives, silica fume, and palm fiber. Results of laboratory tests showed that frost-resistant artificial soil is so stable and fertile that it is suitable for the creation of vegetation habitats on rock slopes in cold regions. However, the practical effect of its field application still lacks specific data support or basis.

In recent years, there has been a significant amount of research on soil quality change and slope vegetation restoration. For example, Xu et al. (2022) and Li et al. (2018) discovered that soil fertility can not only assess the quality of soil but also reflect the restoration effect and growth status of slope vegetation. Gu et al. (2022) selected aggregate indicators to explore the adverse effects of freeze-thaw action on soil stability. Du et al. (2020) believed that the freeze-thaw process has significant effects on soil physics, chemistry and plant growth in alpine regions, and pointed out that more attention should be paid to how to reduce the loss of soil nutrients during the freeze-thaw period. Currently, there exist numerous methods for evaluating soil quality, with the most commonly utilized one being the Soil Quality Index (SQI) method (Fu et al., 2004), known for its simplicity and ease of operation (Mei et al., 2021). Research conducted by Raiesi et al. (2016) on cultivated soil land and by Shao et al. (2022) on various types of forest soil has demonstrated the accuracy of the SQI method in evaluating soil quality. Zhao et al. (2020) and Li et al. (2018) evaluated soil quality after different vegetation restoration and found that indicators such as organic matter and total phosphorus can better reflect the differences in SQI values after vegetation restoration. However, there are few studies on soil quality after slope restoration in cold areas, and long-term monitoring of soil quality in this region is also necessary.

Until now, numerous scholars have researched the impact of rock slope restoration and alterations in soil quality, primarily focusing on natural soil. However, there has been limited research on frost-resistant artificial soil in cold regions under unique environmental conditions, and no assessment of its quality has been conducted. Therefore, with previous research methods for reference, this paper explores the long-term effects of frost-resistant artificial soil used for rock slope restoration in cold regions and quantitatively evaluates the quality of frost-resistant artificial soil. In this study, rocky rock slopes were used as test areas, where frost-resistant artificial soil and natural soil were sprayed for slope vegetation restoration. By utilizing methods of field sampling and laboratory tests for nearly 5 years, we measured the stability, fertility, and effect of vegetation restoration of soil samples. We compared and analyzed the quality

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of the two soils. This paper aims to further understand the practical effect of frost-resistant artificial soil in cold regions, explore reasons for changes in soil quality, and provide a scientific basis for its extensive engineering application. It also serves as a reference for the vegetation restoration of rock slopes in cold regions.

Materials and methods

Overview of the test area

The research area is located in the engineering zone of the Dagu Hydropower Station at the middle reach of the Yarlung Zangbo River in Shannan of the Tibet autonomous region. There is a plateau temperate semi-arid monsoon climate in the engineering zone, with rainfall mainly from June to September; extreme maximum and minimum temperatures of 32.0℃ and -26.6℃, and an annual average temperature of 5.6℃; annual average precipitation of 200.0~540.5 mm, multi-year average relative humidity of 51%, and multi-year average wind velocity of 1.6 m/s; multi-year average evaporation capacity of 2075.2 mm; a frost-free period of 100~120 d a year. The ecology is fragile in the engineering zone, where there is mainly sandy loam.

Test procedures and sampling methods

Sandy loam, a natural soil collected from the Dagu Hydropower Station, is dried before use. *Table 1* shows the basic physicochemical properties of the soil. According to the mix ratio requirements in the invention patent formula (Zhou et al., 2016), sandy loam is blended evenly with cement, saw powder, green additives, silica fume, and palm fiber at a dry mass ratio of 100:10:8:5:3:1 to prepare frost-resistant artificial soil. The mixture includes ordinary Portland cement with a strength grade of 42.5, cedarwood sawdust with particles less than 2 mm in diameter, a patented green additive, silica fume with particles ranging from 0.1 to 1.0 μm and a specific surface area of 20 to 25 m^2/g, and palm fibers measuring 2.5 to 3.5 cm in length and 0.18 to 2.0 mm in diameter.

Table 1. *Basic physical and chemical properties of sandy loam soil for testing*

Soil type	Dry density/($g·cm^{-3}$)	pH value	Particle size distribution/%				
			>2 mm	2~0.5 mm	0.5~0.25 mm	0.25~0.075 mm	<0.075 mm
Sandy loam	1.43	6.7	9.01	53.82	16.79	9.47	10.91

A rocky slope at the Dagu Hydropower Station was chosen as a sample plot for vegetation restoration. The slope was divided into two test areas, where frost-resistant artificial soil and natural soil (local sandy loam) were utilized as ecological substrates to establish vegetation habitats on the rock slope. Both test areas had similar site conditions, with northward slopes measuring approximately 60° and a height of 3.4 m. The operation to restore vegetation began in September 2018. The ecological substrate is evenly sprayed onto the slope surface twice by mechanical dry spraying method, divided into base layer and surface layer. The thickness of the base layer and the surface layer were 15 cm and 2 cm respectively, and the surface layer contained a mixture of various plant seeds. After completing the operation to restore vegetation, the two test areas were then maintained and managed to the same standards.

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After maintenance and management, samples were taken, and vegetation was monitored regularly from June 2019 to August 2023, lasting for a total of 5 years. Samples were taken 4 times from June to August each year, with sampling and monitoring conducted 20 times in total. Vegetation was monitored before sampling. During each monitoring and sampling session, 6 representative quadrats measuring 1 m × 1 m were randomly selected. The vegetation in these quadrats was monitored by calculating the average value of the 6 samples. Following the vegetation monitoring, soil samples were collected from a depth of 5-10 cm using a soil sampler with a 5 cm diameter. The soil was sampled from 5 zones where vegetation was thriving using the five-point sampling method. A total of 30 samples were collected each time by parallel circular cutting, packed in sealable bags, and transported to the laboratory. The samples were put through sieves of 1 mm and 0.25 mm mesh before their physicochemical properties were tested and measured. The results of the tests were then averaged.

Selection of indicators and test methods

Based on previous studies (Bai et al., 2023; Qiu et al., 2024), we choose the following indicators as soil quality evaluation indicators in this paper, which can fully reflect the stability and fertility of soil. By monitoring the changes of these indicators, soil quality can be accurately assessed. In this paper, two categories of indicators for soil fertility and stability were used to evaluate soil quality, with the results verified through the situation of vegetation restoration. The indicators for soil fertility include organic matter (SOM), total nitrogen (TN), total phosphorus (TP), ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), available phosphorus (AP), available potassium (AK), soil bulk density (BD), and pH value. The indicators for soil stability are the >0.25 mm mechanical aggregate content (MAC) and water-stable aggregate content (WAC), the mean weight diameter of aggregates (MWD), the percentage of aggregate destruction (PAD), and the degree of aggregation (AD). Indicators for vegetation restoration include vegetation coverage (VC), aboveground biomass (AB), underground biomass (UB), and species diversity (SD).

The soil pH value was measured using a soil pH meter, while organic matter, total nitrogen, total phosphorus, bulk density, nitrate nitrogen, ammonium nitrogen, available phosphorus, and available potassium were determined using various methods such as the $K_2Cr_2O_7$-external heating method, the Kjeldahl method with an automatic nitrogen analyzer, the $HClO_4$-H_2SO_4 method, the ring-cutting method, continuous flow spectrophotometry, H_2SO4 digestion-diffusion absorption method, $NaHCO_3$ solution extraction-Mo-Sb colorimetric method, and flame photometry. The particle size distribution of mechanical- and water-stable aggregates was analyzed through dry sieving and Yoder's wet-sieving method, respectively, while micro-aggregates and mechanical composition of soil were assessed using the pipette method. Vegetation coverage was calculated by the ratio of the vertical projected area of the branches and leaves of plants on quadrats to the total surface area. Species diversity was calculated by Shannon-Wiener index (Spellerberg et al., 2003). Aboveground and underground biomass were weighed with an electronic balance.

Soil quality index SQI

Standardization of indicators

Indicators for the evaluation of soil quality are standardized using the membership function in fuzzy mathematics. Based on previous research (Guo et al., 2017), the "S-

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shaped” (*Eq. 1*) and reverse S-shaped equations (*Eq. 2*) are used to standardize soil indicators, eliminating the influence of differences in units among indicators.

$$F\left(X_{\mathrm{i}}\right)=0.9\times\frac{X-X_{\min}}{X_{\max}-X_{\min}}+0.1 \quad \text{(Eq.1)}$$

$$F\left(X_{\mathrm{i}}\right)=0.9\times\frac{X_{\max}-X}{X_{\max}-X_{\min}}+0.1 \quad \text{(Eq.2)}$$

In *Equations 1* and *2*, $F(X_i)$ represents the membership value of each indicator, where X is the measured value of this type of indicator, X_{max} is the maximum value measured for this type of indicator, and X_{min} is the minimum value measured for this type of indicator. *Equation 1* is a scoring function of “the higher, the better”, and *Equation 2* is a scoring function of “the lower, the better.”

Weight of index evaluation

As soil indicators have different impacts on soil quality, weights are used to denote the degree of influence of indicators (*Eq. 3*). The common factor variance obtained by principal component analysis (PCA) can reflect the contribution rate of a certain indicator to the overall variance (Jin et al., 2021), and the larger the value is, the greater the contributions the indicator will make to the overall variance.

$$W_{\mathrm{i}}=\frac{CC_{\mathrm{i}}}{\sum_{i=1}^{n}CC_{\mathrm{i}}} \quad \text{(Eq.3)}$$

In *Equation 3*, W_i represents the weight of each indicator, and CC_i represents the factor load of the i-th soil quality index.

Calculation of soil quality index

According to the unitary scores and weights of each indicator, the soil quality index (SQI) is calculated with the following formula (*Eq. 4*). The SQI value ranges from 0 to 1, and the higher the value is, the better the corresponding soil quality will be. Grading standards for SQI are determined by referring to previous research (Guo et al., 2017).

$$SQI=\sum_{\mathrm{i}=1}^{\mathrm{n}}F\left(X_{\mathrm{i}}\right)\times W_{\mathrm{i}} \quad \text{(Eq.4)}$$

In *Equation 4*, $F(X_i)$ represents the membership value of each quality indicator, while W_i denotes the weight of each quality indicator.

Data processing

SPSS 26.0 was used for statistical analysis, including one-way analysis of variance (ANOVA), Pearson correlation analysis and principal component analysis (PCA). Excel 2020 and Origin 10.0 were used for data collection and plotting.

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Results

The physical and chemical properties of soil

Measurements of samples were taken 4 times each year to obtain averages for the physicochemical properties of soil over the 5-year period from 2019 to 2023. *Table 2* shows that the changes in the indicators of the physicochemical properties of the two soils (*Table 2*). Frost-resistant artificial soil has significantly higher levels of nutrients, including organic matter, total phosphorus, total nitrogen, available phosphorus, and available potassium, compared to natural soil over a 5-year period. The differences in nutrient content between the two types of soil are mostly significant ($P < 0.05$). Specifically, the organic matter content, total phosphorus content, total nitrogen content, available phosphorus, available potassium, ammonium nitrogen, and nitrate nitrogen in frost-resistant artificial soil increase by 46.71%, 22.56%, 48.84%, 27.11%, 12.05%, 42.44%, and 11.2% respectively, when compared to natural soil.

Table 2. *Changes in two types of soil physical and chemical property indicators over the years*

Soil indicators	Two types of soil	2019	2020	2021	2022	2023
MAC (%)	Artificial soil	59.43%±4.15Ab	78.57%±6.84Aa	68.11%±6.45Aab	62.91%±5.08Ab	59.60%±5.78Ab
	Natural soil	59.98%±5.15Aab	65.97%±6.15Ba	56.35%±5.78Bab	52.21%±4.21Bb	52.20%±4.97Ab
WAC (%)	Artificial soil	30.65%±2.55Abc	42.18%±3.78Aa	37.61%±3.15Aab	34.90%±2.54Ab	29.90%±2.87Ac
	Natural soil	25.30%±2.15Bab	28.02%±2.34Ba	22.72%±2.15Bbc	19.59%±1.95Bc	19.89%±1.88Bc
MWD (mm)	Artificial soil	1.40±0.15Ac	2.04±0.17Aa	1.74±0.12Ab	1.50±0.11Ac	1.42±0.13Ac
	Natural soil	1.17±0.11Ba	1.34±0.12Ba	0.97±0.08Bb	0.90±0.09Bb	0.87±0.07Bb
PAD (%)	Artificial soil	48.45%±4.14Ba	46.27%±3.52Ba	44.71%±3.35Ba	44.55%±3.21Ba	49.85%±4.89Ba
	Natural soil	57.90%±4.28Aa	57.52%±4.34Aa	59.70%±4.81Aa	62.52%±4.12Aa	61.94%±5.82Aa
AD (%)	Artificial soil	21.26%±2.14Aab	24.41%±2.15Aa	23.51%±2.21Aab	22.68%±1.97Aab	20.61%±1.89Ab
	Natural soil	17.21%±1.45Ba	17.41%±1.61Ba	15.92%±1.54Ba	15.66%±1.48Ba	14.85%±1.38Ba
SOM ($g \cdot kg^{-1}$)	Artificial soil	60.74±6.49Aa	24.42±3.58Ac	34.10±4.21Ab	55.11±4.59Aa	62.74±6.82Aa
	Natural soil	26.20±3.15Bb	23.41±3.2Ab	32.90±4.36Aa	40.48±4.11Ba	38.63±4.06Ba
TN ($g \cdot kg^{-1}$)	Artificial soil	1.86±0.13Ab	2.53±0.21Aa	2.16±0.16Aa	2.01±0.20Aab	1.77±0.17Ab
	Natural soil	1.47±0.11Ba	1.50±0.13Ba	1.50±0.14Ba	1.23±0.11Bb	1.25±0.10Bb
TP ($g \cdot kg^{-1}$)	Artificial soil	1.20±0.11Aa	0.81±0.07Ab	0.81±0.08Ab	1.00±0.13Aa	1.19±0.09Aa
	Natural soil	0.62±0.08Bb	0.63±0.06Bb	0.84±0.09Aa	1.02±0.12Aa	0.98±0.07Ba
NH_4^+-N ($mg \cdot kg^{-1}$)	Artificial soil	10.03±1.21Ab	14.33±1.34Aa	12.02±1.12Aab	10.96±1.01Ab	9.59±0.93Ab
	Natural soil	8.59±0.84Ba	8.67±0.85Ba	8.68±0.78Ba	6.96±0.68Bb	7.07±0.73Bb
NO_3^--N ($mg \cdot kg^{-1}$)	Artificial soil	13.96±1.25Ab	19.84±1.59Aa	17.73±1.61Aab	15.80±1.41Ab	13.76±1.41Ab
	Natural soil	15.31±1.52Aab	18.08±1.68Aa	14.11±1.48Bab	12.31±1.38Bb	13.02±1.28Ab
AK ($mg \cdot kg^{-1}$)	Artificial soil	84.70±7.89Aa	101.08±9.45Aa	100.49±9.49Aa	99.71±8.94Aa	84.96±8.45Aa
	Natural soil	91.79±8.46Aa	86.86±7.54Aab	89.99±8.12Aa	75.46±6.13Bb	76.21±6.63Ab
AP ($mg \cdot kg^{-1}$)	Artificial soil	14.84±1.43Aa	9.79±1.05Ac	10.18±1.08Ac	12.42±1.15Ab	14.93±1.26Aa
	Natural soil	7.21±0.75Ba	7.43±0.69Ba	10.12±1.08Aa	12.30±1.21Aa	11.83±1.19Ba
BD ($g \cdot cm^{-3}$)	Artificial soil	1.21±0.07Bb	1.35±0.09Ba	1.29±0.06Aab	1.23±0.05Aab	1.19±0.07Ab
	Natural soil	1.36±0.08Aa	1.42±0.04Aa	1.35±0.05Aa	1.24±0.04Ab	1.26±0.03Ab
pH	Artificial soil	8.09±0.11Aa	7.43±0.09Ab	7.24±0.05Ac	7.19±0.04Ac	7.15±0.09Ac
	Natural soil	7.27±0.09Bb	7.52±0.08Aa	7.08±0.07Bc	6.92±0.05Bd	6.95±0.08Bcd

Different lowercase letters in the same line indicate significant difference between the same soil type in different years, and different uppercase letters indicate significant difference between different soil types in the same year ($P < 0.05$)

In terms of soil stability, the mechanical and water-stable macro-aggregate content, the MWD value, and the value of aggregation of frost-resistant artificial soil are higher than those of natural soil, and their differences are significant ($P < 0.05$). Compared

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with natural soil, the mechanical- and water-stable macro-aggregate content, the MWD value, and the value of micro-aggregation increase significantly by 14.62%, 51.69%, 54.19%, and 38.76%, while the percent of loss decreases remarkably by 21.95% in frost-resistant artificial soil. The pH value of frost-resistant artificial soil is significantly higher than that of natural soil, while the bulk density of the former is lower. This suggests that frost-resistant artificial soil has been enhanced in terms of fertility, degree of aggregation, and stability compared to natural soil.

Between 2019 and 2023, various indicators exhibit different patterns of change over time. Among the fertility indicators, organic matter, and available phosphorus show an increasing trend, while others are predominantly declining. Among the stability indicators, the macro-aggregate content, degree of aggregation, and MWD values are gradually decreasing, indicating a decline in stability.

Evaluation of soil quality

Figure 1 shows that the weights assigned to indicators for evaluating the quality of frost-resistant artificial soil are evenly distributed, primarily falling within the 0.07-0.08 range (*Fig. 1*). The bulk density (BD) falls within the 0.06-0.07 range, while available potassium (AK) is as low as 0.35. In terms of weight, the indicators are ranked as follows: MAC > WAC > MWD > NH_4^+-N > TN > NO_3^--N > PAD > SOM > pH > TP > AD > AP > BD > AK. Similarly, the weight distribution of indicators for natural soil also falls within the 0.07-0.08 range, with lower weights assigned to NO_3^--N, BD, and PAD indicators, which range from 0.06-0.07. The indicators for natural soil are sequenced as MWD > WAC > SOM > TN > NH_4^+-N > MAC > AK > AD > pH = TP > AP > NO_3^--N > BD > PAD in descending order. In the two soils, MAC, MWD, WAC, TN, and NH_4^+-N have higher weights, and they all contribute more to soil quality.

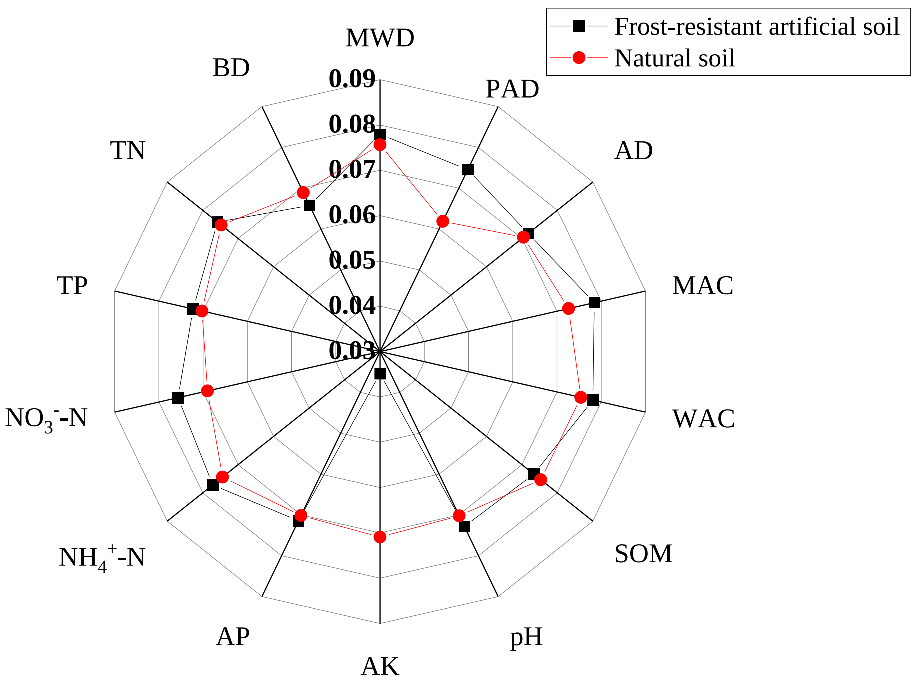

***Figure 1.** Weights of two types of soil quality indicators*

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The results of soil quality evaluation are depicted in *Figure 2*. The soil quality index (SQI) clearly varied as the years increased. In the five years from 2019 to 2023, the SQI values of the two soils showed an inverse V-shaped trend of first increasing and then decreasing over time, reaching their peaks in 2020 (*Fig. 2*). In 2019, the average SQI of frost-resistant artificial soil was 0.587, and that of natural soil was 0.404. However, their average SQIs were 0.729 and 0.459 in 2020, increasing by 24.13% and 13.40% respectively. Thereafter, from 2021 to 2023, the average SQI of frost-resistant artificial soil and natural soil both decreased gradually to a minimum of 0.579 and 0.376 respectively in 2023.

A comparison of the two soils reveals that the Soil Quality Index (SQI) of frost-resistant artificial soil surpassed that of natural soil in the 5 years from 2019 to 2023. During this period, the former exceeded the latter by 45.26% (2019), 59.02% (2020), 47.22% (2021), 59.16% (2022), and 54.21% (2023) respectively. In the 5 years, the average SQI of frost-resistant artificial soil was 0.625, which was 53% higher than that of natural soil (0.408).

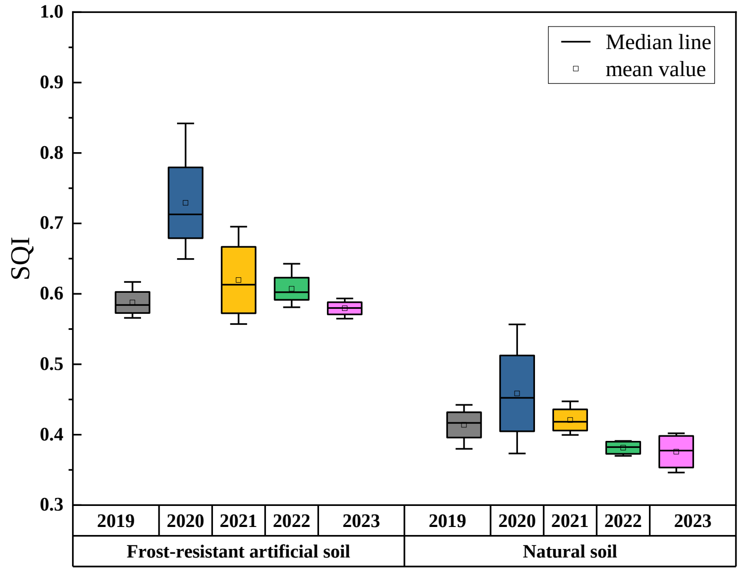

Figure 2. *Two types of soil quality index (SQI) in different years*

Changes of vegetation indicators

Figure 3 shows the vegetation restoration situations after slope restoration. The changes in vegetation coverage, species diversity, and aboveground and underground biomass on the slope after two types of soil restoration are relatively similar, with the highest in 2020 and the lowest in 2023 (*Fig. 3*). When comparing the two types of soil, it is evident that the vegetation coverage, species diversity, aboveground and underground biomass of frost-resistant artificial soil are significantly higher than those of natural soil in different years. Among these differences, the highest values of vegetation coverage, species diversity, aboveground and underground biomass of frost-resistant artificial soil can reach 85%, 2.0, 55.48 g, and 13.06 g, respectively. In contrast, the highest values of the four indicators of natural soil are only 61%, 1.23, 33.42 g, and 7.97 g, respectively. The four indicators of natural soil are only 60% to 70% as effective as the freeze-resistant artificial soil. This suggests that using frost-

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resistant artificial soil for slope restoration yields better vegetation restoration results compared to natural soil, and the vegetation coverage on slopes restored with natural soil is relatively low.

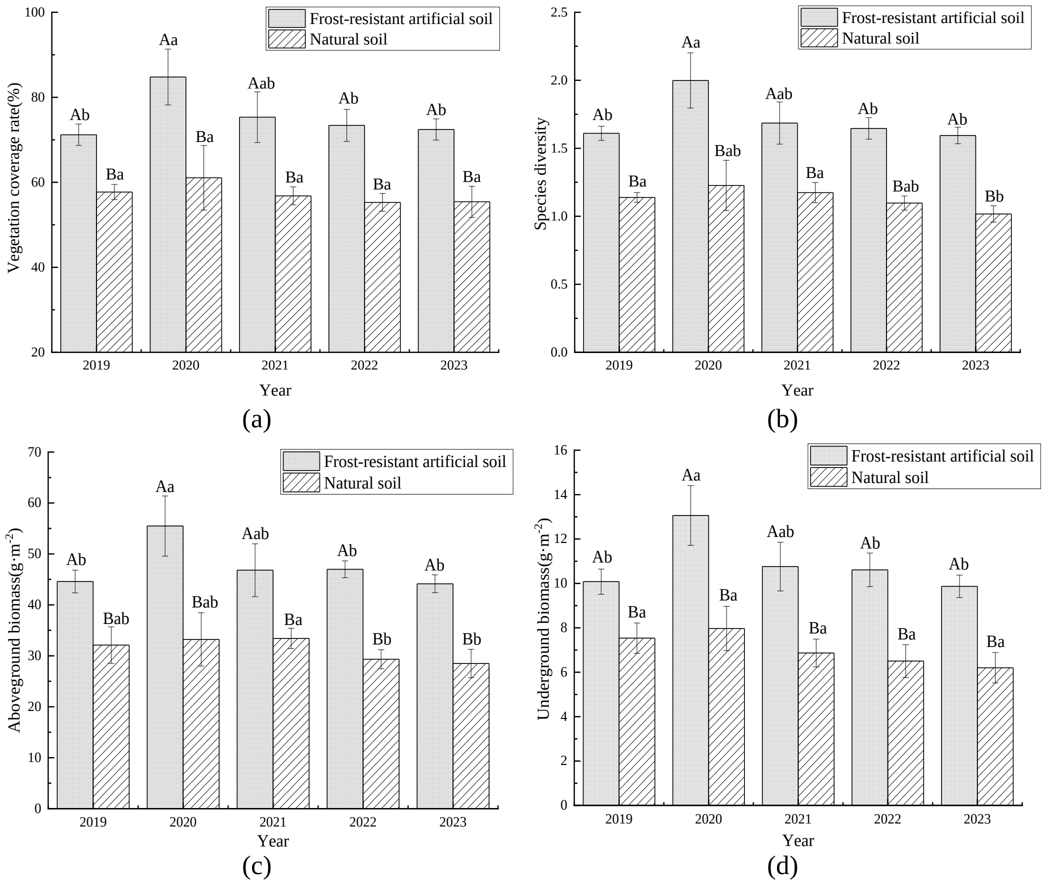

Figure 3. *Vegetation restoration of two types of soils. (a) Vegetation coverage rate. (b) Species diversity. (c) Aboveground biomass. (d) Underground biomass*

Correlation between SQI and vegetation indicators

Figure 4 shows the results of regression analysis between four vegetation indicators (coverage, aboveground and underground biomass, and species diversity) and the Soil Quality Index (SQI) of two soils (*Fig. 4*). This analysis was conducted to validate the SQI values calculated using the aforementioned indicator data. The SQI values of the two soils showed significant positive correlations with the four vegetation indicators over a period of 5 years. The regression coefficients between frost-resistant artificial soil and vegetation coverage rate, species diversity, aboveground biomass and underground biomass are 0.852, 0.850, 0.858 and 0.856, and those between natural soil and these four vegetation indicators are 0.783, 0.751, 0.775 and 0.802. The high linear fitting relationship between vegetation indicators and soil quality SQI values proves the strong positive mutual influence between vegetation and soil quality. The SQI values obtained from the indicator data accurately reflect and predict the effectiveness of slope vegetation restoration. Therefore, the SQI can be utilized to evaluate the soil quality and vegetation status of rock slopes on the plateau of Tibet with high accuracy.

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Correlations among physicochemical properties of soil

Figure 5a, b shows a correlation analysis was conducted on the above fourteen evaluation indicators of the two soils. It can be seen that the MWD value, the pH value, MAC, NO_3^--N, and NH_4^+-N content all significantly correlate with multiple other indicators (*Fig. 5a*). Behind them are the BD and TN content, which also show significant correlations with multiple other indicators. *Figure 5b* reveals significant correlations between MAC, the pH value, and the NO_3^--N content, as well as multiple other indicators. It also shows significant correlations between the MWD value, WAC, NH_4^+-N, and TN content, along with multiple other indicators (*Fig. 5b*). This suggests that indicators such as MWD, MAC, WAC, NH_4^+-N, BD, and TN content are the six major indicators that influence the stability and fertility of soil after the restoration of rock slopes. Zhang et al. (2019) and Maurya et al. (2020) also argue that the aforementioned indicators show a strong correlation with factors like soil stability and nutrient content. Therefore, the findings of this study align closely with previous research results.

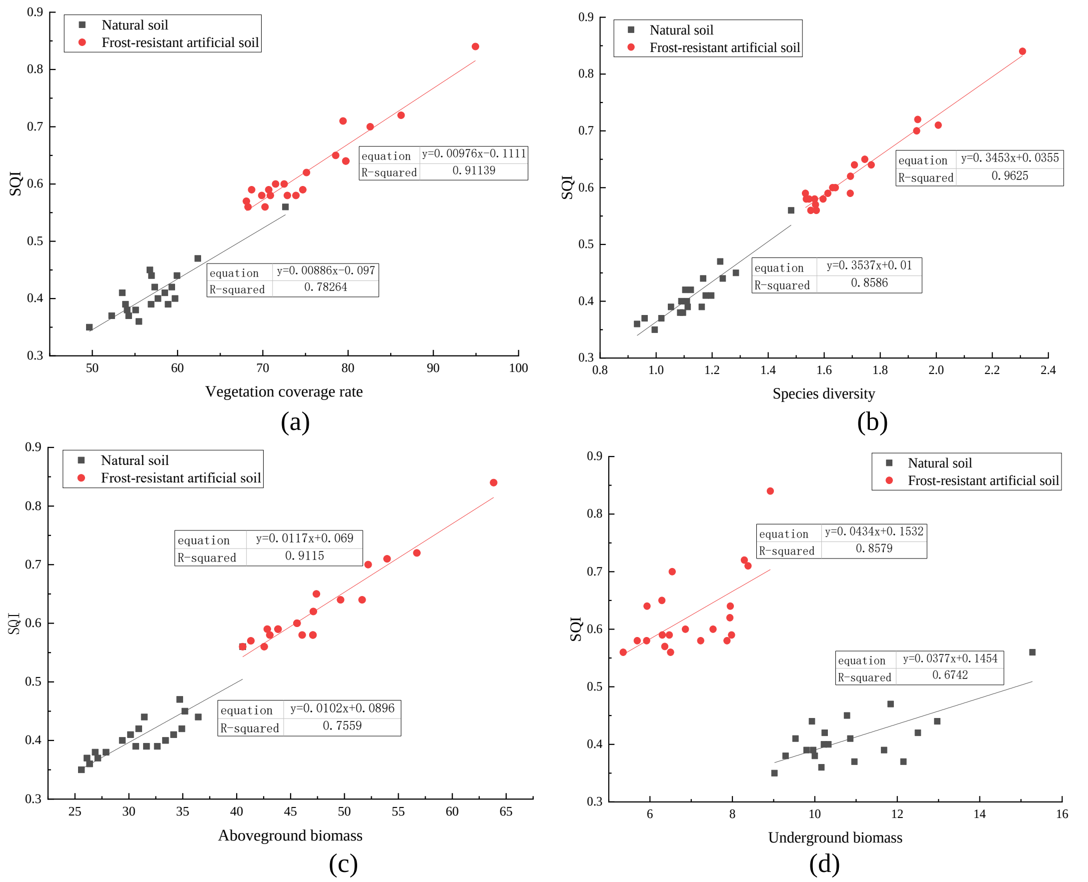

Figure 4. *(a) Correlation between vegetation coverage rate and SQI values. (b) Correlation between species diversity and SQI values. (c) Correlation between aboveground biomass and SQI values; (d) Correlation between underground biomass and SQI values*

Figure 5c shows the correlation analysis between the above indicators and vegetation indicators. It can be found that MWD, MAC, WAC, TN, and NH_4^+-N are significantly correlated with the four vegetation indicators of VC, SD, AB, and SB, indicating that these indicators significantly affect vegetation growth (*Fig. 5c*). MWD, MAC, and

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WAC are important indicators of soil aggregate stability, which significantly affect soil erosion resistance, water retention, and aeration ability. Good macro-aggregates can provide a more suitable growth environment for plant roots. TN and NH_4^+-N are key indicators of soil fertility, and their content is positively correlated with plant growth rate. Adequate nitrogen is an important guarantee for plant growth. The above PCA also shows that these indexes have a high contribution rate to soil quality, so these five indexes can be used to assess the ecological restoration effect of slope in future studies.

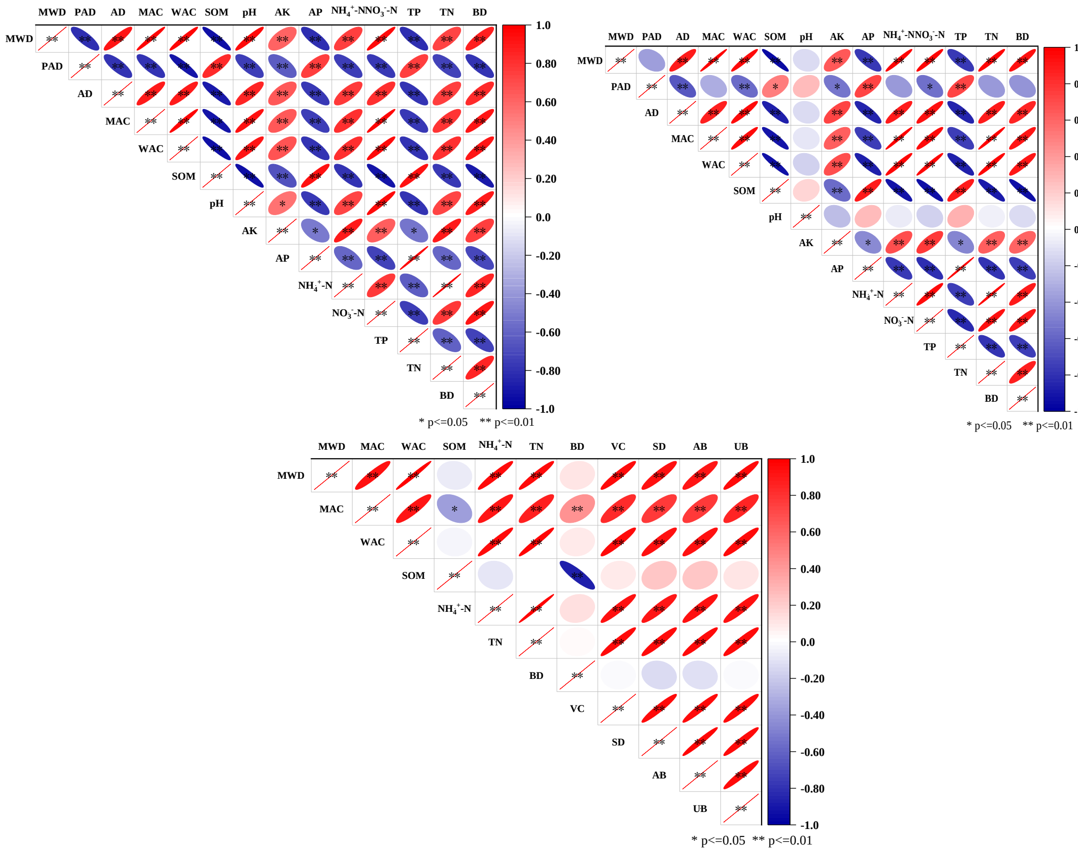

***Figure 5.** (a) Correlation between different indicators of natural soil. (b) Correlation between different indicators frost-resistant artificial soil. (c) Correlation between soil indicators and vegetation indicators*

Discussion

Advantages of frost-resistant artificial soil in slope restoration

Existing studies by many scholars suggest that the success of rock slope restoration primarily depends on the stability and fertility of the substrate soil and the growth of vegetation (Du et al., 2023). The use of two types of soil in this study indicates that the aggregate stability and fertility of frost-resistant artificial soil improved significantly within a 5-year period. Frost-resistant artificial soil significantly enhances fertility by increasing the content of SOM, TP, and TN by 46.71%, 22.56%, and 48.84% respectively compared to natural soil. This richer nutrient base supports vegetation growth, leading to high vegetation coverage and species diversity even in harsh environmental conditions. The higher organic matter content in frost-resistant artificial

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soil compared to natural soil is mainly due to the transformation of organic saw powder blended with soil over time, resulting in the formation of organic matter (Mohamed et al., 2023). Additionally, the organic gels present in organic matter act as cementation and conglomeration agents, increasing the macro-aggregate content in soil and enhancing soil stability (Yu et al., 2020). The rich microbial agents in green additives will also facilitate the growth of various microorganisms and nutrients in the soil, which will significantly enhance soil fertility.

In terms of soil stability, the WAC, MWD value, and agglomeration degree of frost-resistant artificial soil increased by 51.69%, 54.19%, and 38.76%, respectively, compared to natural soil. The improvement in these indicators means that the soil structure is more stable and can effectively resist natural erosion such as wind and water erosion, thus protecting the stability of the slope. First, when cement added meets water in the soil, hydration will occur to generate a large quantity of compounds such as gels and crystals. These compounds can conglomerate micro-aggregates, which are cemented to form crystal nets and solid and dense macro-aggregate structures (Suksiripattanapong et al., 2022), thus improving soil strength and reducing the percentage of aggregate destruction. Second, the addition of silica fume can increase the porosity of the soil (Türköz et al., 2021), thus relieving the negative impact of frost heaving and thaw collapse on soil structure and improving soil stability. Additionally, palm fiber added can enhance connectivity among soil particles as well as the shear strength of soil (Bouaricha et al., 2020). In addition, a suitable pH value and low bulk density of frost-resistant artificial soil also provide a suitable environment for microorganisms, increasing water retention and facilitating root growth and expansion. Consequently, frost-resistant artificial soils also have better water retention and erosion resistance, which helps reduce soil erosion and promote vegetation growth.

Changes and evaluation in SQI of frost-resistant artificial soil over time

In the five-year period from 2019 to 2023, the inverse V-shaped fluctuation of SQI values of the two soils reflects the dynamic nature of the soil ecosystem. Bai et al. (2023) calculated soil SQI values of various natural zones on the Qinghai Tibet Plateau with eight nutrient indexes including organic matter, and found that SQI showed a downward trend. This study aligns with the findings of Bai and other previous researchers (Ferreira et al., 2022), suggesting that soil nutrients in cold regions generally exhibit a decreasing trend, leading to a decline in soil quality. An analysis of the reasons for this phenomenon reveals that soil aggregates have the ability to aggregate and disperse in response to changes in environmental and vegetation conditions. Due to the frequent freeze-thaw action in cold regions every year, soil aggregates gradually disperse (Liang et al., 2021). Additionally, plant roots that grow annually insert soil particles, breaking up clods and resulting in fewer macro-aggregates and higher porosity (Liu et al., 2020). The dispersion of aggregates in soil significantly influences soil stability, as evidenced by a gradual decrease in stability over time. In cold regions of Tibet, soil erosion is more prevalent, and the nutrients in the soil also decrease as plants grow (Yu et al., 2019). Meanwhile, a reduction in the number of macro aggregates in the soil results in a decreased ability of the soil to retain nutrients. Consequently, the quality of the soil is declining over time. But in the second year following slope restoration, the nutrients originally in the soil substrate remained adequate, and the soil aggregate structure was not greatly impacted by freeze-thaw cycles, so the highest SQI values were attained during this year.

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In the process of slope restoration, soil stability can ensure the basic stability and safety of rock slopes (Liu et al., 2021); soil fertility can guarantee the fast growth of plants. The growth of vegetation is the most intuitive indicator for observing the quality of rock slopes restored. Moreover, vegetation roots can reinforce soil, and leaves can reduce surface runoff and relieve splash erosion by rain, which will effectively reduce soil erosion (Wen et al., 2023), and vegetation litter can also increase soil humus and nutrients (Liu et al., 2022b). According to current standards (Technical code for eco-restoration of vegetation concrete on steep slope of hydropower projects) for the energy industry of the People's Republic of China (Xu et al., 2016), reasonable soil quality is a key index in the benefit evaluation of vegetation restoration, as well as a prerequisite for the healthy growth of plants. The standards stipulate requirements for indicators such as the nitrogen, phosphorus and potassium content in soil. To comprehensively assess the soil quality of frost-resistant artificial soil, we conducted a comparison with other soil types. As indicated by previous research (Bai et al., 2023), the SQI level of the frost-resistant artificial soil was notably high. In fact, the SQI value of the frost-resistant artificial soil surpassed that of most soils in cold regions, highlighting its superior soil stability and fertility. However, this artificial soil still shows deficiencies in certain indicators, indicating that improvements are necessary. The principal component and correlation analysis above reveals that MWD, MAC, WAC, TN, and NH_4^+-N play a significant role in determining the SQI value and vegetation growth. Soil quality should be improved by increasing soil aggregates and nitrogen content in the long term.

Improvement suggestions and prospects of frost-resistant artificial soil

Based on this research result, we propose suggestions for optimizing the soil quality of frost-resistant artificial soil, aiming to guide slope restoration. In the early stage of slope restoration (1-2 years), the soil has high density, strength, and alkaline pH value, which are not conducive to the rapid growth of vegetation. Therefore, it is recommended to increase the proportion of green additives by 2%-4% in the early stage, using their rich microbial agents to reduce pH value and increase nutrient and microbial content (Li et al., 2018). Meanwhile, sulfur fertilizer can be considered to further regulate soil pH and improve fertility (Sönmez et al., 2016). About 2-3 years after slope restoration, soil quality and vegetation may deteriorate. At this time, attention should be paid to improving soil nutrients and aggregate structure, especially nitrogen and macro-aggregate content. It is recommended to apply nitrogen fertilizer to supplement nitrogen and add biochar to improve soil aggregate structure, reduce freeze-thaw effects, and provide long-term stable nutrient supply for vegetation (Liu et al., 2022a). In addition, it is necessary to closely monitor the risk of slope instability caused by the decline of soil strength, and take corresponding protective measures. In summary, for the use of freeze-resistant artificial soil, the soil composition should be appropriately adjusted according to the actual situation. During the early stage, the emphasis was on regulating pH value and nutrients, with a focus on increasing the content of soil nutrients and macro-aggregates in the middle and late stages. This approach ensures that the frost-resistant artificial soil maintains good stability and fertility levels during long-term freeze-thaw cycles conditions, ultimately guaranteeing the sustainability of slope restoration.

The application of frost-resistant artificial soil in Tibet finds that it has wide application potential in cold regions. However, climate conditions vary in different regions, and further research and optimization of regional adaptability are needed. In the promotion process, it will face challenges such as high transportation costs and

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environmental adaptability, and the cost of frost-resistant artificial soil materials is 20%-25% higher than that of natural soil. However, its SQI average is 53% higher than that of natural soil, indicating its economic feasibility. To balance costs and benefits, it is suggested to adjust the proportion of admixtures according to the frequency of freeze-thaw cycles. According to the findings of this study, in high-frequency regions (>40 times/year), the use of admixtures can be finely adjusted accordingly or remain unchanged. In low-frequency regions (<20 times/year), it is recommended to decrease the proportion of admixtures appropriately in order to reduce costs. In summary, the application prospects of frost-resistant artificial soil in cold regions are broad, and its application needs to be further refined and optimized. The monitoring period and application area should be extended in the future to gain a more comprehensive understanding of the dynamic situation of long-term soil quality and vegetation restoration.

Conclusions

(1) The fertility and stability of frost-resistant artificial soil were higher than those of natural soil in different years within the five-year period, and the vegetation restoration effect was also better. The average SQI of frost-resistant artificial soil was 0.625 in the five years, exceeding that of natural soil (0.408) by 53%. It indicates that frost-resistant artificial soil is more suitable for the creation of vegetation habitats with better soil quality on rock slopes.

(2) In regression analysis, the Soil Quality Index (SQI) demonstrated a significant positive linear correlation with the four vegetation indicators, suggesting a strong interdependence between vegetation and soil quality. This implies that the SQI value can effectively assess both soil quality and vegetation restoration outcomes following slope restoration, with a high level of precision.

(3) Correlation and principal component analysis indicated that MWD, MAC, NH_4^+-N and TN could be used to reflect and evaluate soil quality in future studies. Since soil aggregates and nitrogen content indexes have a greater impact on soil quality, improving these two aspects can enhance soil quality.

(4) From 2019 to 2023, the average SQI values and vegetation restoration of the two soils showed a gradually deteriorating trend with increasing years. To improve the long-term restoration effect, it is recommended to increase the proportion of green additives and add sulfur fertilizer or biochar to reduce soil pH and increase nutrients.

(5) The cement, silica fume, and palm fiber added to frost-resistant artificial soil can remarkably improve its stability, while saw powder and green additives can enhance its fertility. According to existing industrial standards, frost-resistant artificial soil is more suitable for rock slopes in cold regions. Long-term tests and promotion can be carried out in more regions in the future.

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