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Research on Green Restoration Technology for Residential Areas Based on Turf-Stripped Soil and Assessment of Its Ecological Benefits

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Abstract Addressing the issue of landscape degradation in residential communities, this study proposes a synergistic technology combining "in-situ soil reconstruction from stripped turf" with "microbial remediation," and evaluates its ecological benefits. The core of the technology involves soil reconstruction based on stripped degraded turf and the enhanced application of microbial remediation techniques, including the regulation of PAH degradation by the nah gene cluster of Pseudomonas and the mediation of heavy metal sulfide fixation by the dser gene of sulfate-reducing bacteria. Using a mixture of multifunctional organic fertilizer (POM), grass sod stripping material (GS), and topsoil (TS), pot experiments showed that a POM 15% + GS 30% ratio achieved a peak effective phosphorus content of 4.48 mg/kg. Ecological benefit assessments showed that after 12 months of applying this technology in a residential community, the vegetation cover structure underwent a fundamental reversal. The proportion of high-cover areas (≥75%) increased from 4.6% to 64.61%, a 13-fold increase, while the proportion of low-cover areas (<30%) decreased from 38.15% to 3.15%, a 92% reduction. The entropy-based assessment system identified water conservation (weighting 0.218) and carbon sequestration and oxygen release (weighting 0.223) as key indicators. The ESFI value for Group A, which applied the soil reconstruction + microbial remediation technology using turf stripping, reached 0.88, an increase of 62.96% compared to pre-remediation levels, significantly higher than the 0.71 for the traditional technology Group B. Group A's soil nutrient index (SNI) increased by 123.64%, synergistically promoting vegetation productivity (+183.07%) and carbon sequestration (+171.07%).

Index Terms sod-stripped soil, residential community, green space restoration, microbial remediation, ecological benefit assessment

I. Introduction

Landscaping plays a significant role in enhancing the ecological environment of cities and improving the living conditions of residents. With the rapid development of modern cities, people's demands for the environmental quality around residential communities have also increased. Landscape design in residential communities has garnered growing attention from both urban residents and real estate developers [1], [2]. Landscape design varies significantly across different types of residential areas and exerts differing impacts on the ecological systems and human health within these regions. A well-designed landscape environment can enhance residents' health levels and sense of well-being, leading many residents to consider landscape quality as a factor in their housing purchases [3]-[5].

However, with the acceleration of urbanization, urban construction land continues to expand. Many areas of land have been damaged due to filling, mining, or misuse, leading to a reduction in soil microorganisms and a decline in physical properties, resulting in degraded soil quality and a deteriorating soil environment. This, in turn, severely impacts the destruction of existing natural vegetation and causes overall ecological damage [6]-[9]. At this point, timely implementation of greening restoration projects can promote ecological recovery of the land and improve the urban environment, providing cities with a more pleasant living environment [10], [11]. From a medium- to long-term perspective, greening restoration can also advance urban ecological civilization construction, promote ecological economic development, and establish a green and circular urban development model [12], [13].

At the same time, assessing the ecological benefits of residential greening can assist in the implementation of greening restoration efforts. Turf stripping aims to improve soil conditions and enhance soil quality, providing a better environment for plant growth. Existing turf stripping technologies are categorized into three directions: physical, chemical, and biological, such as manual methods using tools, biochar amendments, and earthworm ecological corridor systems. Exploring suitable turf stripping technologies is an important aspect of maintaining soil ecological environments and supporting greening restoration efforts.

The study proposes key technical methods for the restoration of degraded greenery in residential communities and an ecological benefit assessment system. The technical methods primarily encompass two synergistic pathways: the first is soil in-situ reconstruction technology based on the removal of degraded turf. This technology addresses the compacted and nutrient-poor soil beneath degraded turf by innovatively using a combination of multifunctional organic fertilizers, pioneer plant seeds, specific plant fibers, modified organic polymers, and reinforced mesh nets to improve soil structure and fertility. Through rigorous experimental design and data analysis, the material ratios and construction processes are optimized to rapidly restore a soil environment suitable for vegetation growth. Second, the application of microbial remediation technology. In soil remediation, the focus was on studying the genetic regulation pathways of microbial degradation of organic pollutants, as well as their adsorption, transport, intracellular accumulation, extracellular polymer (EPS) complexation of heavy metal ions, and the sulfate-reducing bacteria-mediated sulfide precipitation and fixation mechanisms. In water body remediation, the role of microorganisms in addressing eutrophication and degrading organic pollutants has been thoroughly analyzed. The Monod equation has been introduced to describe the relationship between microbial growth and environmental factors, as well as the role of EPS in pollutant flocculation. Additionally, to scientifically quantify the effectiveness of these technologies, a systematic ecological benefit assessment method has been established. This method is based on multi-source data and involves establishing a complex mathematical model, including steps such as gray correlation theory, weight standardization and conversion, forward/reverse indicator processing, correlation analysis, correlation matrix construction and combination calculation, comprehensive correlation calculation, and weight relative value calculation. Ultimately, an ecological benefit comprehensive assessment formula is derived to objectively and quantitatively evaluate core ecological benefit indicators such as soil erosion control.

II. Greening restoration and ecological benefit assessment based on turf stripping and soil reconstruction

II. A. Soil reconstruction technology based on degraded sod removal

II. A. 1) Experimental Materials

The degraded turf was sourced from the landscaping site of a residential community. The multifunctional organic fertilizer is composed of attapulgite and $UiO-66-NH_2$. The pioneer plant seeds selected include St. Augustine grass, Bermuda grass, Kentucky bluegrass, purple fescue, sand sage, and astragalus, with a ratio of 9:4:3:2:1:1. The grass seeds were purchased from Chengdu Baihui Grass Industry Co., Ltd., with guaranteed seed germination rates. The plant fibers include hemp fiber, straw fiber, and coconut fiber, all made from 100% fiber materials that have been dried to ensure a moisture content of 15% ± 2%. The underlying mesh pad for the reconstructed turf is reinforced mesh, all purchased online. The modified organic material is a high-molecular-weight organic material with three authorized patents. It appears as a colorless solution, with the main formulation including water (360–440 weight parts), polymer monomer A solution (150–260 weight parts), polymer monomer B solution (130–170 weight parts), initiator solution (20–60 weight parts), and oxide solution (0.5–2 weight parts). The pH value is between 7.0 and 8.0, the viscosity value is between 34.0 and 42.0 mPa·s, the specific gravity is between 1.01 and 1.03, and the standard evaporation rate is $0.31kg\cdot m^{-2}\cdot h^{-1}$.

II. A. 2) Data Analysis

Processing sample data under experimental conditions, data aggregation, analysis, and graphing were performed using Excel, SPSS, and Origin. Using SPSSAU software, data results were subjected to range analysis and factor analysis to discuss the extent of the impact of added materials on turf and their interactions, and to obtain the optimal mixture configuration.

To more clearly and intuitively compare the comprehensive quality status of turf across different experimental groups, factor scores for each treatment were calculated using Formula (1).

$$Z_i = b_i X \tag{1}$$

In the formula: b_i is the i th column vector of the “component score coefficient matrix” output table of the SPSSAU software; by using the eigenvalue contribution rates of each common factor as weights for weighted summation, the comprehensive evaluation index results are obtained. The comprehensive evaluation index calculation formula is shown in Equation (2).

$$Z_{\text{Summary}} = \sum_{i=1}^{m} (V_i / p) Z_i \tag{2}$$

In the formula: $V_i P$ is the “variance explained percentage” in the “rotated variance explained percentage” column of the “variance explained table” in the output results table of the SPSSAU software.

II. B.Application of microbial remediation technology in urban garden ecological restoration

While reconstructing the structure of degraded soil and improving its basic physical and chemical properties through physical and chemical means, the ecological functions of microorganisms are introduced and enhanced. Further exploration continues into the application potential and mechanisms of microbial remediation technology in urban garden ecological restoration, particularly in the specific environment of residential communities.

II. B. 1) Application in soil remediation

In the field of urban landscape soil remediation, microbial remediation technology leverages the complex and sophisticated physiological and biochemical mechanisms of microorganisms to achieve targeted degradation and transformation of pollutants. For organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), specific microbial strains such as Pseudomonas and Bacillus play a crucial role. Their genomes contain gene clusters encoding relevant degradation enzymes. Taking naphthalene degradation as an example, the nah gene cluster encodes a dioxygenase that precisely recognizes the naphthalene ring structure, introduces oxygen molecules at specific positions, and initiates the ring-opening reaction of naphthalene. Under the action of dioxygenase, naphthalene $\left(C_{10}H_8\right)$ undergoes the following reaction:

$$C_{10}H_8 + 2O_2 \xrightarrow{\text{Double oxygenase}} C_{10}H_8O_2 \tag{3}$$

Subsequently, through a series of enzymatic reactions regulated by the nah gene cluster, naphthalene is gradually degraded into salicylic acid, which is further metabolized into intermediates of the tricarboxylic acid cycle, and ultimately mineralized into carbon dioxide and water.

In response to soil heavy metal contamination, microbial defense mechanisms involve multiple levels. At the cellular surface level, negatively charged functional groups such as phosphate and carboxyl groups on the cell wall interact with heavy metal ions through electrostatic adsorption and ion exchange adsorption, regulated by membrane transport proteins. Assuming that the transport rate of membrane transport proteins for heavy metal ions (denoted as M^{N+}) follows the Michaelis-Menten equation:

$$v = \frac{V_{\max}\left[M^{N+}\right]}{K_m + \left[M^{N+}\right]} \tag{4}$$

where $V_{\max}$ is the transport rate, $\left[M^{N+}\right]$ is the maximum transport rate, and K_m is the heavy metal ion concentration and Michaelis constant. This equation can be used to quantitatively analyze the transport capacity of membrane transport proteins for heavy metal ions. These membrane transport proteins actively transport heavy metal ions into the cell, causing them to accumulate to a certain concentration inside the cell, while simultaneously activating the cell's detoxification mechanisms. Additionally, the process by which polysaccharides, proteins, and other components in extracellular polymers (EPS) secreted by microorganisms form complexes or chelates with heavy metal ions is also regulated by microbial gene expression. Under anaerobic conditions, certain sulfate-reducing bacteria utilize enzymes encoded by the dsr gene to participate in the sulfate reduction process, producing hydrogen sulfide. Hydrogen sulfide reacts with heavy metal ions to form metal sulfide precipitates, ensuring the effective immobilization of heavy metals in soil.

II. B. 2) Application in water body restoration

Microbial remediation technology plays a critical and complex role in the ecological restoration of urban garden water bodies. In response to water eutrophication, the ammonia oxidation process of nitrifying bacteria is strictly regulated by ammonia monooxygenase (AMO) encoded by the amo gene and hydroxylamine oxidoreductase (HAO) encoded by the hao gene. AMO catalyzes the oxidation of ammonia to hydroxylamine, with the reaction equation as follows:

$$NH_3 + O_2 + 2H^+ + 2e^- \xrightarrow{AMO} NH_2OH + H_2O \tag{5}$$

HAO further oxidizes hydroxylamine to nitrite, with the reaction equation as follows:

$$2NH_2OH + O_2 \xrightarrow{HAO} 2NO_2^- + 4H^+ + 2e^- \tag{6}$$

Nitrite oxidoreductase (NXR) is encoded by gene xr and is responsible for oxidizing nitrite to nitrate, with the reaction equation as follows:

$$NO_2^- + H_2O - 2e^- \xrightarrow{NXR} NO_3^- + 2H^+ \tag{7}$$

The denitrification process carried out by denitrifying bacteria is more complex, involving genes such as napA, nirK, norB, and nosZ, which encode nitrate reductase, nitrite reductase, nitric oxide reductase, and dinitrogen oxide reductase, respectively. Through a series of enzymatic reactions, nitrate is gradually reduced to nitrogen gas. With nitrate $\left(NO_3^-\right)$ as the starting reactant, the overall reaction can be roughly represented as:

$$2NO_3^- + 10e^- + 12H^+ \xrightarrow{\text{Multiple enzymes}} N_2 \uparrow + 6H_2O \tag{8}$$

The expression of these genes is regulated by various environmental factors in the water, such as dissolved oxygen, carbon sources, and nitrogen sources. The relationship between microbial growth and substrate concentration can be described by the Monod equation, i.e., $\mu = \mu_{\max} \frac{S}{K_s + S}$, where μ is the specific growth rate of microorganisms, $\mu_{\max}$ is the maximum specific growth rate, S is the concentration of the limiting substrate (such as carbon source, nitrogen source, etc.), and K_s is the half-saturation constant. This helps us gain a deeper understanding of the interaction between gene expression regulation and environmental factors in the denitrification process.

For organic pollutants in water bodies, aerobic microorganisms utilize the tricarboxylic acid cycle (TCA cycle) and related metabolic pathways to completely oxidize and decompose them. Anaerobic microorganisms convert organic pollutants through fermentation, methane production, and other processes in an oxygen-free environment. The process by which methanogenic bacteria utilize substrates such as acetate, hydrogen, and carbon dioxide to produce methane involves multiple key enzymes, including methyl coenzyme M reductase. The activity and expression of these enzymes are strictly regulated by genes to adapt to different substrate concentrations and environmental conditions. Additionally, the interaction between extracellular polymers secreted by microorganisms and water pollutants involves not only physical-chemical processes such as electrostatic adsorption, complexation, and bridging, but also gene expression regulation of microbial secreted proteins. Through precise regulation, this process achieves the flocculation and precipitation of pollutants, thereby purifying water quality.

II. C.Assessment of ecological benefits

Whether it is the implementation of soil reconstruction technology or the application of microbial remediation strategies, the ultimate goal is to restore and enhance the ecological service functions of green spaces in residential communities. To scientifically and objectively measure the comprehensive remediation effects of these technology combinations and the resulting environmental benefits, it is crucial to establish a comprehensive, quantitative ecological benefit assessment system. Therefore, this study designed and implemented the following ecological benefit assessment process and methods.

II. C. 1) Data Collection

Data collection can be conducted through various methods, including field surveys, remote sensing technology, and ecological monitoring stations. Field surveys primarily involve direct observation, plot surveys, and biodiversity records, aiming to obtain firsthand ecological information. Remote sensing technology is used to monitor vegetation coverage and ecological changes over large areas. Long-term data collected from ecological monitoring stations can be utilized for more in-depth analysis of trends in ecosystem changes.

II. C. 2) Ecological benefit assessment methods

The theoretical weights of the ecological benefit assessment indicators for soil erosion control were established using a grey correlation model, while the weighted values of the theoretical weights for ecological benefit assessment were determined based on indicator attributes. The weighted values of the theoretical weights of the indicators were calculated using the following formula:

$$Z_{ki} = \frac{V_{ki} - \min\left(V_{ki}\right)}{\max\left(V_{ki}\right) - \min\left(V_{ki}\right)} \tag{9}$$

In the formula: Z_{ki} is the standardized value of the weighting of ecological benefit assessment indicators for soil erosion in different assessment areas; V_{ki} is the standardized value of the attributes of ecological benefit indicators for soil erosion in different assessment areas; K is the number of soil erosion control units; i is the number of ecological benefit assessment indicators. A forward transformation method is used to calculate the weighting conversion of each assessment indicator:

$$Z_{ki} = \frac{V_{ki} - \min(V_{ki})}{\max(V_{ki}) - \min(V_{ki})} \times 0.9 + 0.1 \tag{10}$$

Based on the positive conversion of indicator weights, perform reverse calculations on each assessment indicator:

$$Z_{ki} = \frac{\max(V_{ki}) - V_{ki}}{\max(V_{ki}) - \min(V_{ki})} \tag{11}$$

After averaging the weights of the forward and reverse indicators, standardization calculations are performed:

$$Z_{ki} = \left\{1 - \frac{\left|\max(V_{ki}) - V_{ki}\right|}{\max\left[V_{K0} - \min(V_{ki}), \max(V_{ki} - V_{K0})\right]}\right\} \times 0.9 + 0.1 \tag{12}$$

In the formula: V_{k0} is the initial attribute value of the ecological benefit assessment index for soil erosion. An analysis of the correlation between each index is performed:

$$\gamma_{ki} = \frac{\min\left|Z_{k0} - Z_{ki}\right| + \xi \max\left|Z_{k0} - Z_{ki}\right|}{\left|Z_{k0} - Z_{ki}\right| + \xi \max\left|Z_{k0} - Z_{ki}\right|} \tag{13}$$

In the formula: $\min\left|Z_{k0} - Z_{ki}\right|$ and $\max\left|Z_{k0} - Z_{ki}\right|$ are the minimum and maximum correlations of the indicators; ξ is the correlation coefficient value. Based on the correlation analysis of ecological benefit assessment indicators, the correlation matrix for indicator assessment is calculated:

$$E(\gamma ki)_{m\times n} = \begin{bmatrix} \gamma_{11} & \gamma_{12} & L & \gamma_{1n} \\ \gamma_{21} & \gamma_{22} & L & \gamma_{2n} \\ M & M & O & M \\ \gamma_{m1} & \gamma_{m2} & L & \gamma_{mn} \end{bmatrix} \tag{14}$$

Combine calculations for each assessment indicator matrix:

$$Y = l_{i1}Z_1 + l_{i2}Z_2 + \ldots l_{in}Z_n \tag{15}$$

Based on the calculation of the indicator correlation matrix combination, the comprehensive correlation of each indicator is calculated:

$$\varepsilon_{0K} = \frac{1 + |s_0| + |s_i|}{1 + |s_0| + |s_i| + |s_i - s_0|} \tag{16}$$

In the formula: S_0 and S_i are the forward and reverse correlation coefficients, respectively; ε_{0i} is the absolute value of the correlation coefficient between indicators. Based on the analysis of the absolute value of the correlation coefficient between indicators, the relative value of the correlation coefficient is calculated as follows:

$$\eta_{0K} = \frac{1 + |s_0'| + |s_i'|}{1 + |s_0'| + |s_i'| + |s_i' - s_0'|} \tag{17}$$

In the formula: S_0' and S_i' are the relative values of forward and reverse correlation, respectively; η_{0i} is the relative value of correlation between indicators. Based on the analysis of the relative values of correlation between different indicators, the relative values of weights between different indicators are calculated:

$$\beta_j = \rho_{0i} / (\rho_{01} + \rho_{02} + \ldots + \rho_{0m}) \tag{18}$$

After determining the relative weights of different indicators, a comprehensive assessment of the ecological benefits of soil and water conservation projects is conducted:

$$R = W_T \times E = \left(r_1, r_2, r_3 ......r_n\right) \tag{19}$$

In the formula: R is the comprehensive assessment index of ecological benefits; W_T is the combination weight value; E is the indicator correlation matrix; $r_1, r_2, r_3 ... r_n$ are the relative values of indicator correlations.

III. Research on the ecological restoration benefits of community greening based on turf stripping and soil reconstruction technology

Based on the theoretical framework of the aforementioned turf stripping soil reconstruction technology and microbial remediation mechanism, this chapter verifies the regulatory effect of material ratios on soil physical and chemical properties through potted control experiments. It then monitors vegetation coverage dynamics through on-site remediation projects in residential communities, ultimately constructing an entropy-based evaluation system for quantifying the ecological benefits of ecological remediation projects.

III. A. Research on soil reconstruction through turf stripping based on microbial remediation

III. A. 1) Test Materials and Methods

High-molecular-weight organic materials (POM), grass turf strippings (GS), and topsoil (TS) were selected as raw materials. The test vegetation consisted of grass seeds from Section 2.1.1, which were mixed in different proportions to prepare reconstructed soil for grass seed pot experiments. The physical and chemical properties of POM, GS, and TS are shown in Table 1, including pH, organic matter, total nitrogen, available phosphorus, and available potassium content.

Table 1: Physicochemical properties of different materials

Material	pH	Organic matter (g/Kg)	Total nitrogen (g/Kg)	Available phosphorus (mg/Kg)	Available potassium (mg/Kg)
POM	8.36	12.57	0.51	1.65	212.01
GS	7.92	0.72	0.81	2.05	64.67
TS	6.95	0.37	0.48	1.45	114.12

POM exhibits moderate alkalinity with a pH of 8.36, and has the highest levels of organic matter and available potassium, at 12.57 g/kg and 212.01 mg/kg, respectively; grass sod strippings (GS) have the highest available phosphorus content at 2.05 mg/kg; topsoil (TS) has relatively low nutrient levels overall.

The collected POM and GS were naturally dried, impurities removed, and ground and sieved before being mixed with TS in specific proportions to form the reconstructed soil. A total of 15 treatment groups (C1 to C15) were established, with the specific material ratios detailed in Table 2. Pure POM, pure GS, and pure TS were set as experimental control groups (corresponding to CK1, CK2, and CK3, respectively). The specific procedure was as follows: 2 kg of uniformly mixed reconstituted soil was placed in a flower pot (diameter 16.2 cm, height 13.5 cm, base diameter 12.9 cm), and 50 grass seeds were planted in each pot. The experimental period was 80 days, with the room temperature maintained at approximately 25°C. Watering was performed at fixed intervals and quantities during the period. Additionally, 500 mL of rice husk charcoal was added to each group as supplementary fertilizer.

Table 2: Mass ratios of different materials in reconstructed soil

	POM/%	GS/%	TS/%
C1	5	10	85
C2	5	20	75
C3	5	30	65
C4	10	10	80
C5	10	20	70
C6	10	30	60
C7	15	10	75
C8	15	20	65
C9	15	30	55
C10	20	10	70
C11	20	20	60
C12	20	30	50
C13	25	10	65
C14	25	20	55

C15	25	30	45
CK1	100	0	0
CK2	0	100	0
CK3	0	0	100

The composition ratio range of the reconstructed soil materials in the 15 treatment groups was as follows: POM 5%-25%, GS 10%-30%, and TS 45%-85%.

After 80 days of alfalfa cultivation, the pH, organic matter, total nitrogen, available phosphorus, available potassium, and soil moisture content of the reconstructed soil were measured. This study focuses on analyzing the physicochemical properties of available phosphorus content. Available phosphorus content was determined using the molybdenum-antimony colorimetric method.

Data were processed using Excel, and a one-way analysis of variance was performed on the experimental data using SPSS 26 software. To ensure the repeatability and reliability of the data, five parallel experiments were conducted in each group, and the final results were analyzed using the average values of each group.

III. A. 2) Analysis of effective phosphorus content

The available phosphorus content in the CK1, CK2, and CK3 control groups was 1.65 mg/kg, 2.05 mg/kg, and 1.45 mg/kg, respectively. The available phosphorus content of the other 15 treatment groups with different soil composition ratios is shown in Figure 1.

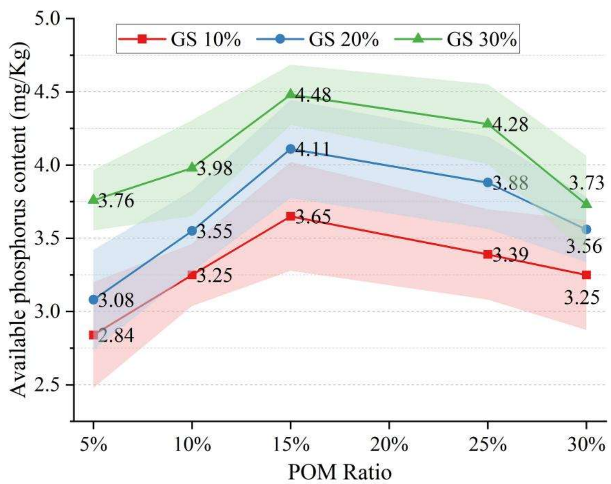

Figure 1: The effect of different ratios on the effective phosphorus content of soil

Data shows that under a fixed GS ratio, available phosphorus exhibits a trend of first increasing and then decreasing as POM increases. When GS is 10%, increasing POM from 5% to 15% results in available phosphorus rising from 2.84 to 3.65; however, when POM increases to 25% and 30%, available phosphorus decreases to 3.39 and 3.25, respectively. Excessively high levels of organic polymer materials can actually inhibit the production of organic phosphorus in vegetation. The highest available phosphorus content is observed when the POM ratio is 15%. Additionally, under a fixed POM ratio, available phosphorus increases with rising GS levels. For instance, when POM is 15%, increasing GS from 10% to 30% raises available phosphorus from 3.65 to 4.48. The highest value was observed in the POM 15% + GS 30% (C9) combination, with an effective phosphorus content of 4.48 mg/kg. Overall, this indicates that moderate to high POM levels synergistically enhance effective phosphorus when combined with high GS ratios.

III. B. Assessment of the ecological restoration effects of greening based on turf-stripped soil

Based on the determination of the optimal ratio, the soil reconstruction technology was further applied to the restoration project of degraded green spaces in a residential community. Through 12 months of continuous remote sensing monitoring of vegetation coverage, the transformation characteristics of the ecological structure during the restoration process were analyzed.

III. B. 1) Spatio-temporal characteristics of vegetation coverage in residential communities

Taking a residential community as the study subject, the application of soil reconstruction and microbial remediation technology based on turf removal was initiated in July 2023, with the aim of investigating changes in vegetation coverage over the next 12 months. The vegetation coverage in the study area was categorized into the following grades: high coverage (≥75%), medium-high coverage (60%-75%), medium coverage (45%-60%), medium-low coverage (30%-45%), and low coverage (<30%). The spatiotemporal distribution changes in vegetation coverage in the study area from 2020 to 2024 were also investigated. The proportion of different types of vegetation coverage in the greened areas after ecological restoration is shown in Figure 2.

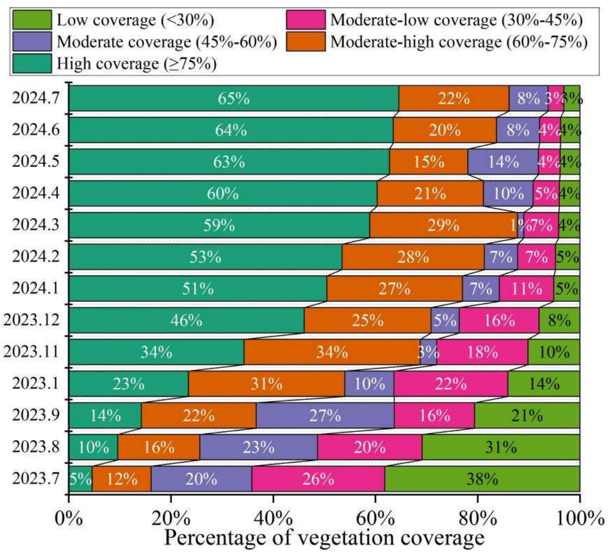

Figure 2: The proportion of different types of vegetation coverage in the community

It can be seen that, in the initial state, the community was primarily characterized by low coverage and medium-low coverage, accounting for a combined 64.19%, while high coverage accounted for only 4.6%. After the repair was initiated, the low coverage area decreased by 7.31% in the first month, from 38.15% to 30.84%, while the high coverage area doubled (from 4.6% to 9.62%). By the third month, medium-coverage areas saw a significant increase, rising from 11.54% to 22.44%, while low-coverage areas further decreased to 20.59%. A key turning point occurred in November 2023, when the proportion of high-coverage areas exceeded 30% for the first time, surpassing the 10.16% of low-coverage areas, while medium-coverage areas sharply decreased to 3.2%. During the winter (December 2023–February 2024), high coverage continued to grow to 53.47%, but the growth rate slowed, with an average monthly increase of approximately 3.5%. By the end of the restoration period, high coverage reached 64.61%, a 13-fold increase from the initial level, medium-high coverage remained at 21.54%, and low coverage areas dropped to 3.15%, a 92% decrease. Following the implementation of restoration techniques, the vegetation coverage structure reversed from a "pyramid-shaped" structure (dominated by low coverage) to an "inverted pyramid-shaped" structure (dominated by high coverage). The first four months constituted a rapid response phase, with an average monthly growth rate of 7.4% for high coverage. Subsequently, the process entered a stable maintenance phase, with an average monthly growth rate of ≤2.1% in 2024.

III. B. 2) Analysis of potential driving factors for the quality of greenery in residential communities

We analyzed the potential driving factors of housing community greening quality and selected eight factors for correlation analysis: soil retention quality, carbon storage quality, soil quality (i.e., physical and chemical properties such as organic matter content, pH value, and organic phosphorus content), community topography and microclimate, vegetation coverage, water conditions and maintenance management, underground obstacles, and weed and pest pressure. The Pearson correlation analysis of community greening quality is shown in Figure 3.

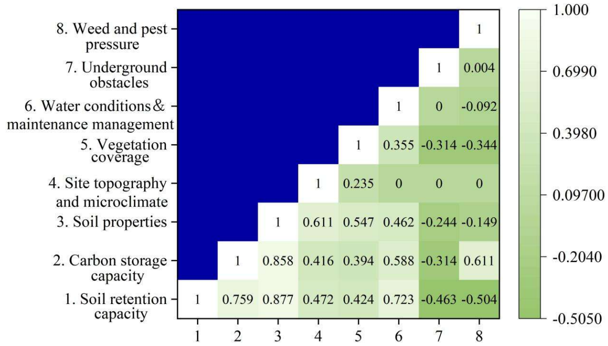

Figure 3: Pearson correlation analysis of the quantity of greenery in the community

Soil quality is strongly positively correlated with soil conservation material quality, with a correlation coefficient (r) of 0.877, indicating that soil physical and chemical properties are critical for soil and water conservation. It is also highly correlated with carbon storage material quality, with an r of 0.858, confirming the contribution of healthy soil to carbon sequestration capacity. Water conditions and maintenance management are significantly positively correlated with soil conservation material quality, with an r of 0.723, highlighting the importance of scientific irrigation and maintenance in maintaining soil structure. Vegetation cover is moderately positively correlated with soil quality, with a correlation coefficient of 0.547, indicating that increased vegetation cover can improve soil properties. Additionally, soil conservation and carbon storage are highly synergistic, with a correlation coefficient of 0.759, indicating that soil erosion control directly promotes carbon sink functions. Topography and microclimate are positively correlated with soil quality, with a correlation coefficient of 0.611, as topography indirectly regulates soil health by influencing water and heat distribution. Weed and pest pressure are negatively correlated with soil conservation quality (r = -0.504), reflecting their disruptive impact on vegetation stability. Underground obstacles are significantly negatively correlated with soil conservation quality (r = -0.463) and carbon storage (r = -0.314), indicating that underground obstacles severely constrain ecological functions.

As shown in the correlation analysis in Figure 3, soil quality is the core hub of greening restoration, and its improvement can simultaneously optimize soil and water conservation and carbon sink functions. Water management and vegetation cover are important auxiliary drivers, while underground obstacles and weed pressure are the main limiting factors. It is necessary to prioritize soil improvement and remove underground obstacles to maximize ecological benefits.

III. C. Research on the ecological benefits of greening restoration in residential communities

Given the significant correlation between increased vegetation coverage and soil quality, further quantitative assessments are needed through multiple control experiments to evaluate the synergistic enhancement effects of soil reconstruction technology on core ecological functions such as carbon sequestration and water conservation.

This study selected a residential community as the research subject, randomly dividing the community area into 12 regions. Five regions were selected as the experimental Group A, applying the soil reconstruction technology based on turf removal and microbial remediation technology proposed in this paper. Another five regions were selected as the experimental Group B, applying traditional greening restoration technology. The remaining two undisturbed natural regions served as the control group, and quantitative evaluations were conducted on them. The experiment lasted for three months. Before the experiment began, indicators were measured in each area, and another round of measurements was conducted after the experiment concluded. The results for each group represent the average values across all areas.

III. C. 1) Evaluation system for ecological restoration project performance indicators

To evaluate the ESFI values of different ecological restoration projects, the entropy weight method was used to process five indicators: vegetation productivity, soil conservation, water conservation, carbon sequestration and oxygen release, and atmospheric regulation. The corresponding weight values for each indicator were obtained, and the ESFI values for residential ecological restoration projects were calculated by weighting and summing the indicators. The entropy weight method benefit indicator weights for ecological restoration projects are shown in Table 3.

Table 3: Weight of benefit indicators for ecological restoration projects

	Information entropy	Information utility	Weight
B1: Vegetation productivity (gC/m2)	1.473	-0.473	0.201
B2: Soil retention (t/hm2)	1.471	-0.471	0.174
B3: Water conservation (mm)	1.39	-0.39	0.218
B4: Carbon sequestration and oxygen release (g/m2)	1.461	-0.461	0.223
B5: Regulation of the atmosphere	1.445	-0.445	0.184

The weighting distribution of the five major benefit indicators of ecological restoration projects shows that water conservation has the highest weighting at 0.218, indicating that this indicator has the most significant impact on comprehensive ecological benefits (ESFI). Carbon sequestration and oxygen release has the second highest weighting at 0.223. Vegetation productivity has a weighting of 0.201, slightly higher than soil conservation at 0.174 and atmospheric regulation at 0.184. The five indicators are relatively evenly distributed.

III. C. 2) Comparative analysis of different ecological restoration projects

The pre- and post-experiment soil nutrient levels (SNI is the soil nutrient index) and green engineering benefit evaluation indicators for Experiment Group A (soil reconstruction based on turf stripping + microbial remediation technology), Experiment Group B (traditional greening remediation technology), and the control group are shown in Tables 4 and 5, respectively.

Table 4: Soil nutrient indicators of the green areas in the experimental area

	Experimental Group A			Experimental Group B			Control group		
	Pre	Post	Change range	Pre	Post	Change range	Pre	Post	Change range
Organic matter (g/Kg)	2.97	10.28	246.13%	3.03	6.21	104.95%	3.49	3.75	7.45%
Total nitrogen (g/Kg)	10.89	19.38	77.96%	11.32	13.12	15.90%	11.67	9.30	-20.31%
Available phosphorus (mg/Kg)	0.84	1.82	116.67%	0.82	1.28	56.10%	0.85	0.91	7.06%
Available potassium (mg/Kg)	62.03	98.27	58.42%	62.21	70.64	13.55%	62.04	57.53	-7.27%
SNI	0.55	1.23	123.64%	0.56	0.87	55.36%	0.52	0.56	7.69%

In terms of soil nutrients, the experimental group A showed significant increases in all indicators. Organic matter increased from 2.97 g/kg to 10.28 g/kg, representing a 246.13% increase; nitrogen content increased from 10.89 g/kg to 19.38 g/kg, representing a +77.96% increase; available phosphorus increased from 0.84 mg/kg to 1.82 mg/kg, a +116.67% increase; available potassium increased from 62.03 mg/kg to 98.27 mg/kg, an increase of 58.42%, and the soil nutrient index (SNI) increased from 0.55 to 1.23, an increase of 123.64%. The increase in Group B was significantly lower than that in Group A, with organic matter increasing from 3.03 to 6.21 (104.95%), available phosphorus increasing from 0.82 to 1.28 (56.10%), and the SNI value increasing by only 55.36%. The control group showed minimal changes, with the SNI value increasing by only 7.69%, while nitrogen content and available potassium even decreased (-20.31% and -7.27%, respectively).

Table 5: Evaluation indicators of the benefits of the greening project

	Experimental Group A			Experimental Group B			Control group		
	Pre	Post	Change range	Pre	Post	Change range	Pre	Post	Change range
Vegetation productivity (gC/m2)	57.52	162.82	183.07%	58.69	100.73	71.63%	57.64	61.30	6.35%
Soil retention (t/hm2)	26.98	51.28	90.07%	23.19	35.69	53.90%	30.57	31.95	4.51%
Water conservation (mm)	100.85	127.33	26.26%	101.54	111.42	9.73%	98.82	101.84	3.06%
Carbon sequestration (g/m2)	24.99	67.74	171.07%	25.02	46.12	84.33%	24.67	25.94	5.15%
Oxygen release (g/m2)	65.88	163.40	148.03%	67.53	89.27	32.19%	69.66	68.44	-1.75%
Aerobic regulation of the atmosphere	0.75	0.87	16.00%	0.75	0.78	4.00%	0.76	0.75	-1.32%
ESFI	0.54	0.88	62.96%	0.53	0.71	33.96%	0.54	0.55	1.85%
Vegetation coverage (%)	26.21%	62.39%	138.04%	23.87%	38.92%	63.05%	24.90%	26.87%	7.91%

In terms of vegetation coverage and ecological benefits, the vegetation coverage in Experiment Group A increased from 26.21% to 62.39%, representing a 138.04% increase. Key ecological benefit indicators such as vegetation productivity saw a significant increase in Experimental Group A, rising from 57.52 gC/m² to 162.82 gC/m², an increase of 183.07%. Carbon sequestration capacity (24.99 → 67.74 g/m², +171.07%), and oxygen release (65.88→163.40 g/m², +148.03%) all doubled. In Experiment B, the vegetation coverage rate reached only 38.92% (+63.05%), with vegetation productivity of 100.73 gC/m² and carbon sequestration of 46.12 g/m², both of which were less than 62% of those in Group A. In the control group, the changes in all ecological benefit indicators were less than 8%, with vegetation coverage increasing by only 2 percentage points.

Overall, the grass sod removal soil reconstruction + microbial remediation technology used in Experimental Group A demonstrated overwhelming advantages in soil improvement, vegetation restoration, and ecological function enhancement. In terms of soil nutrients, the increase in SNI values was 2.2 times that of traditional technologies; carbon sequestration increased by 2 times that of traditional technologies; carbon fixation per unit area reached 1.6 times that of traditional technologies; and the increase in comprehensive ecological benefit ESFI values was nearly 2 times that of traditional technologies. The stability of the control group data further validates the necessity of the restoration technology, highlighting the core value of the new technology in the ecological restoration of degraded green spaces.

IV. Conclusion

This study significantly improved the ecological restoration efficiency of degraded green spaces in residential communities by integrating the “turf stripping soil reconstruction-microbial remediation” technology system.

Potted plant experiments determined that the optimal soil amendment combination is (POM 15% + GS 30%), with available phosphorus content reaching 4.48 mg/kg, a 208% increase compared to the topsoil control group. An increased proportion of turf stripping material (GS) directly drives the growth of available phosphorus, while excessive POM (>25%) inhibits phosphorus conversion by 7.3%.

After 12 months of restoration, high vegetation coverage (≥75%) surged from 4.6% to 64.61%, while low coverage (<30%) decreased from 38.15% to 3.15%, with the structure reversing from a “pyramid-shaped” to an “inverted pyramid-shaped” distribution.

Soil quality serves as a pivotal variable, exhibiting a strong correlation with carbon storage ($r = 0.858$), directly determining soil and water conservation ($r = 0.877$) and vegetation coverage ($r = 0.547$).

In Experiment A, which applied the greening restoration technology described in this paper, the soil nutrient index (SNI) increased to 1.23, representing a 123.64% increase, which is 2.23 times that of traditional technology. Vegetation productivity increased by 183.07% (from 57.52 to 162.82 gC/m²). Carbon sequestration and oxygen release efficiency reached 2.1 times that of traditional techniques. The entropy weight method confirmed water conservation (weight 0.218) and carbon sequestration and oxygen release (weight 0.223) as key contributing factors, with Group A's ESFI value at 0.88, a 24% increase over Group B's 0.71.

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