RESEARCH ARTICLE

Synergistic regulation of urban garden soil microbial communities and ecological remediation techniques by biochar and bioenrichment

Junjun Li[1, *], Guangwen Cheng[2]

[1]Zhengzhou College of Finance and Economics, Zhengzhou, Henan, China. [2]Henan Banhao Construction Engineering Co., Ltd., Zhengzhou, Henan, China.

Received: April 30, 2026; **accepted:** June 5, 2026.

Urban landscapes constitute a vital component of urban ecosystems. However, subject to unique disturbance factors such as frequent construction activities, improper water and nutrient management, and complex urban pollution, the quality of the soils has undergone severe degradation, which has resulted in the disruption of microbial communities and the impairment of ecological functions. Moreover, the challenges confronting these soils differ fundamentally from those associated with degraded natural soils or agricultural soils. Consequently, there is an urgent need to implement targeted remediation technologies. This study focused on urban landscaping soils to explore the synergistic regulation mechanisms of biochar and microbial reinforcement, as well as their effects on microbial communities and remediation efficiency by constructing a "biochar-functional microorganism" synergistic system. The results showed that the microbial diversity index of park soil was only 3.5, which was less than 7.0 in natural soil, with a shortage of organic matter and weak nutrient cycling, confirming its unique degradation characteristics. The synergistic treatment group demonstrated significant advantages with soil organic matter being increased by 25%, nitrogen and phosphorus fixation capacities being improved by 30% and 20%, respectively, and microbial diversity increasing to 4.8. Vegetation height and leaf area also increased by 18% and 22% compared to the control with clear remediation effects. The results indicated that biochar not only improved soil structure, moisture, and nutrient retention in urban landscaping soils but also provided a "habitat carrier" for microorganisms and reduced pollution suppression. Functional microorganisms activated the nutrient adsorption of biochar and promoted carbon-nitrogen cycling by forming a "carrier-functional" synergistic effect, addressing the core issues of "microbial survival difficulty and low nutrient utilization", which was distinctly different from the "single roles of biochar/microorganisms" mode in agricultural soils. This study confirmed that this synergistic remediation technology could be adapted to the unique degradation characteristics of urban landscaping soils, providing a basis for enhancing urban green soil and opening new pathways for urban landscaping ecological governance, contributing to the healthy ecological development of cities.

Keywords: microbial community regulation; urban garden soil; remediation; bioaccumulation; biochar.

[*]**Corresponding author:** Junjun Li, Zhengzhou College of Finance and Economics, Zhengzhou, Henan 450000, China. Email: Li.junjun@163.com.

Introduction

Globally, urbanization is advancing at an unprecedented pace, reshaping human settlement patterns and exerting a profound impact on the balance of the Earth's ecosystems [1-3]. As a vital component of the urban ecosystem, soil health directly links to the quality and sustainability of urban greening, serving as the foundation for urban ecological security and

human living environment. Urban garden soils, as a typical type of urban green space soil, bear important ecological functions such as water conservation, air purification, biodiversity conservation and are closely related to the physical and mental health of urban residents.

As the core drivers of soil biological processes, the structure and functional status of microbial communities play a decisive role in maintaining soil ecosystem health and stability. Risk assessments are essential to determine the contamination status of soils. In urban garden soils, microorganisms are not only integral to organic matter decomposition and nutrient cycling but also contribute crucially to soil structure formation, disease suppression, and pollutant degradation [4, 5]. Previous research has attempted to directly alter soil microbial composition through the introduction of specific functional microorganisms such as nitrogen-fixing and phosphorus-solubilizing bacteria to improve nutrient use efficiency and soil quality [6]. Many studies indicated that appropriate microbial inoculation could significantly enhance soil enzyme activities, increase microbial biomass carbon, improve aggregate structure, and strengthen water and nutrient retention capacities. A widely recognized approach is to utilize plant-microbe interactions for ecological remediation. Studies have demonstrated that certain native plants can stimulate the growth of beneficial microorganisms and inhibit pathogens, leading to healthier soil microbial communities, which is a promising nature-based remediation strategy. Despite the encouraging results achieved by existing research, significant challenges and research gaps remain regarding the regulation of microbial communities and the application of ecological remediation technologies within the specific context of urban garden soils. Long-term anthropogenic disturbance and cumulative pollution have led to widespread issues in urban garden soils including structural deterioration, functional degradation, and loss of biodiversity. The primary pollutants of focus are nitrogen and phosphorus. These problems not only impede normal plant growth but also pose potential risks for urban environmental pollution. Currently unresolved critical issues include how to precisely regulate microbial community structure to optimize the efficacy of ecological remediation efforts targeting nitrogen and phosphorus pollution, how to assess the long-term stability and sustainability of various remediation strategies within urban landscape soil environments, and how to achieve synergistic effects between microbial community regulation and ecological restoration to address the degradation of soil structure and function. As a critical component of the soil ecosystem, microorganisms are crucial to the biogeochemical cycle of soil, which is directly related to soil productivity and health [7, 8]. Among them, fungi, as an essential member of soil microorganisms, are rich and diverse and play a central role in ecological functions such as nutrient transformation and organic matter decomposition [9, 10]. Although previous studies primarily focused on bacteria and ignored the potential value of fungal communities in the joint remediation of rare earth tailings [11, 12], recent studies have revealed that fungi may be better adaptable to harsh soil environments than bacteria [13], indicating that it has irreplaceable importance in the ecological remediation and reclamation of rare earth mines, especially showing great potential in promoting plant diversity and productivity [14, 15].

This study aimed to elucidate the response mechanisms of urban garden soil microbial communities to nitrogen and phosphorus pollution, formulate targeted strategies for regulating these microbial communities based on the specific characteristics of urban garden soils, and validate the efficacy of these strategies, thereby providing effective technical support for the ecological restoration of urban garden soils and, in turn, enhancing overall soil health. The study integrated molecular biology, ecology, and soil science to comprehensively analyze microbial communities in urban garden soils to fill the research gap in microbial community regulation and ecological restoration for urban garden soils contaminated by nitrogen and

phosphorus and enrich the theoretical system of urban soil ecology and microbial ecology. By developing feasible microbial community modulation strategies, this research provided scientific guidance for ecological restoration in urban gardens, supported the sustainable development of urban landscaping, and also provided a reference for the ecological remediation of other types of urban contaminated soils, promoting the healthy development of urban ecosystems and the construction of livable cities.

Materials and methods

Urban garden soil ecological restoration

This study investigated the remediation effect of biochar combined with enriched plants and different types of organic fertilizers on urban park soil through a 12 week *in situ* pot experiment, which included one blank control group (CK) with no remediation material and five remediation treatment groups with six biological replicates in each group. All experimental groups were treated with 1.75 kg/m² calcium magnesium phosphate fertilizer + 0.7 kg/m² fly ash and then additionally divided into TBD group with tall fescue cover + 2 kg/m² biochar + commercial organic fertilizer, PBD group with wide leaved barnyard grass cover + 2 kg/m² biochar + commercial organic fertilizer, BD group with 2 kg/m² biochar + commercial organic fertilizer, BG group with 2 kg/m² biochar + livestock manure organic fertilizer, and BF group with 2 kg/m² biochar + decomposed straw organic fertilizer. Biochar was plowed to a soil layer of 0 - 20 cm. CK was only applied with equal amounts of calcium magnesium phosphate fertilizer and fly ash as the base. Specialized organic fertilizers, calcium magnesium phosphate fertilizers, and fly ash were provided by Zhongnong Fertilizer Co., Ltd (Lianyungang, Jiangsu, China). Corn stover pyrolysis biochar with a specific surface area of 189.6 m²/g and pH of 8.2 was purchased from Shangqiu Jinhe Biotechnology Co., Ltd (Shangqiu, Henan, China). The 5 L pot was selected for the experiment with 6 biological replicates for each treatment. Specific microbial strains of nitrogen-fixing bacteria and phosphate-solubilizing bacteria were introduced into the soils to regulate the soil microbial community. The cultivation environment was an artificial climate chamber with a day/night temperature of 25℃/18℃, 14 hours of light per day, a relative humidity of 60%, and a soil field water holding capacity of 60% maintained by weighing method. There was no additional input of fertilizers or pesticides. The soil in the pot was regularly analyzed and monitored from the beginning of the introduction of strains, which included the changes in the structure of microbial communities in the soil such as the number and proportion of different types of microorganisms, the dynamic changes of nitrogen, phosphorus, and other nutrients in soil, and the effects of nitrogen-fixing bacteria and phosphorus-solubilizing bacteria on soil nutrient transformation. Soil and plant samples were collected at the end of the experiment for the determination of soil physicochemical properties, high-throughput sequencing of fungi, and detection of plant growth indicators. 0 - 20 cm surface soil was collected using a five-point sampling method with 6 replicates per group. 10 g of fresh soil was frozen at -80℃ for microbial sequencing, and the remaining samples were naturally air dried and sieved through a 2 mm sieve for physical and chemical analysis. The microbial species covered the main groups such as bacteria, fungi, actinomycetes, and their community structure and diversity were analyzed. Standard procedures were employed to assess soil chemical properties. The soil pH was measured using the potentiometric method with water to soil ratio of 2.5:1 and parallel measurement 3 times. Total nitrogen (TN) was determined using the Kjeldahl method by boiling sample at 380℃ for 60 minutes, while total phosphorus (TP) and total potassium (TK) were measured using $HClO_4$-H_2SO_4 digestion molybdenum antimony colorimetric method by measuring absorbance at 880 nm. Available phosphorus (AP) was extracted using 0.03 mol/L NH_4F - 0.025 mol/L HCl, shaking at 200 rpm for 30

min. Organic carbon (SOC) was determined by $K_2Cr_2O_7$ oxidation method heating at 175 - 180℃ for 5 minutes. The total amount of heavy metals was determined by microwave digestion with HNO-$HClO_4$-HF and atomic absorption spectrometry (AAS) or Agilent 7800 Inductively coupled plasma mass spectrometer (ICP-MS) (Agilent Technologies, Santa Clara, CA, USA). Fungal DNAs from total fungi and *Arbuscular mycorrhizal* (AM) fungi were extracted and purified from collected soil samples using TIANamp Soil Microbial Genomic DNA Kit (TianGen Biotech Co., Ltd, Beijing, China) following manufacturer's instructions. Polymerase chain reaction (PCR) was then performed using Phusion® High-Fidelity PCR Master Mix (Thermo Fisher Scientific, Waltham, MA, USA) and specific primers targeting the fungal ITS region (ITS1F: 5'- CTT GGT CAT TTA GAG GAA GTA A -3'. ITS2R: 5'- GCT GCG TTC TTC ATC GAT GC -3') and the AM fungal 18S rRNA gene (AML1: 5'- ATC AAC TTT CGA TGG TAG GAT AGA -3'. AML2: 5'- GAA CCC AAA CAC TTT GGT TTC C -3'). PCR reaction consisted of 4 µL 5× Phusion HF buffer, 2 µL 2.5 mmol/L dNTPs, 0.8 µL each 10 µmol/L primers, 0.4 µL Phusion DNA polymerase, 10 ng template DNA, and sterile ddH_2O supplemented to 20 µL. The PCR amplification was performed at 98℃ for 3 minutes followed by 35 cycles of 98℃ for 30 seconds, 55℃ for 30 seconds, 72℃ for 30 seconds, and then 72℃ for 10 minutes using Bio-Rad T100 Thermal Cycler (Bio-Rad, Hercules, CA, USA). PCR products were inspected by 2% agarose gel electrophoresis. The sequencing library was constructed after the purification of PCR product from gel using AxyPrep gel recovery kit (Axygen, Union City, CA, USA). The PCR products were then sequenced using Illumina MiSeq PE250 platform (Illumina, San Diego, CA, USA). Sequencing data quality control was performed using Trimmomatic v0.39 (http://www.usadellab.org/cms/?page=trimmomatic), while sequence splicing was performed by using FLASH v1.2.11 (https://github.com/ebiggers/flash). Operational taxonomic unit (OUT) clustering was performed by using UPARSE v7.0 (https://drive5.com/uparse/) with 97% similarity threshold. Species annotation was performed by using UNITE v8.3 fungal database (https://unite.ut.ee/), diversity analysis, principal coordinates analysis (PCoA) sorting, and Adonis analysis in the R v4.2.1 vegan package (https://vegandevs.github.io/vegan/) with a significance level set to $P < 0.05$. QIIME (https://qiime.org/) and Mothur (https://mothur.org/) were employed to assess the impact of remediation treatments on fungal community structure, diversity, and the abundance of specific fungal groups.

Risk assessment of ecological restoration of urban garden soil

A comprehensive site survey of the target urban garden was conducted including information about soil texture, vegetation cover, and surrounding pollution sources. According to the results of the survey, representative soil samples were collected in different areas to ensure the diversity and representativeness of the samples. Based on common soil contaminant types such as heavy metals, organic pollutants, nutrients, *etc*., a preliminary list of contaminants tests was established focusing on the content of nutrients such as nitrogen (N) and phosphorus (P), as well as the possible presence of heavy metals and organic pollutants. The U.S. Environmental Protection Agency (USEPA)'s Risk-Based Corrective Action (RBCA) model was used to process and analyze the detection data to assess the risk level of soil pollution.

Data processing

AutoCAD 2014 (https://web.autocad.com) and ArcGIS 10.8 (https://www.arcgis.com/) were employed for data processing. The data from field surveys such as terrain, rivers, roads, and more were imported into ArcGIS to build a detailed terrain and geomorphology model. Contour data was converted into a triangulated irregular network (TIN) to generate a mesh digital elevation model (DEM) to accurately analyze key information such as elevation, slope, aspect, and rainwater catchment [16]. By comparing the data before and after the construction of mountains,

rivers, and confluence areas around the city, the impact of urban construction on the ecological environment could be scientifically evaluated and provide strong data support and theoretical basis for formulating effective environmental restoration plans and help the application of biochar and bioaccumulation in urban garden ecological restoration.

Remediation treatment for fungal community analysis

Two representative sites in Dingnan and Xinfeng counties within Ganzhou, Jiangxi, China were selected as experimental areas, which covered different soil types and vegetation coverage with 10 of 50 m^2 sites as the small experimental plot mainly for basic research on soil microbial communities and 3 of 5,000 m^2 sites as the larger garden area to simulate practical application scenarios. Remediation technology adopted a synergistic method of precise application of biochar and reasonable introduction of plants and microorganisms with bioaccumulation function. The application rate of biochar was 2 kg/m^2 of soil. By uniformly spreading it in layers, the biochar was evenly distributed throughout the soil and effectively fulfilled its intended function. Meanwhile, alfalfa, ryegrass, and other plant varieties suitable for the local soil and climate conditions and having bioaccumulation capacity were selected for planting with a planting density of 100 plants/m^2. In addition, specific microbial flora such as *Bacillus* and nitrogen-fixing bacteria were inoculated into the soil with a soil inoculation rate of 1×10^8/g to promote the optimization of soil microbial community structure and the restoration of ecological functions. A variety of representative garden plant species were selected. Tall trees such as the French plane tree with the height up to tens of meters, straight trunks, large canopies, and lush foliage were selected in this study, which helped to dominate the urban garden ecosystem, provide shade and habitat for other organisms, while absorbing a large amount of carbon dioxide and releasing oxygen in photosynthesis, and played a key role in regulating the local climate of the city. The shrub crape myrtle, a relatively low plant with a height of generally 2 - 5 meters, more branches, small leaf area, and thin texture, could adapt to the relatively arid environment. Its characteristic of the leaf made an advantage in water use efficiency, reduced water evaporation, and was conducive to the survival of relatively water-scarce areas in urban gardens. Its rich flower color and long flowering period characteristics increased the ornamental nature of the garden landscape. Herbaceous plants such as *Ophiopogon vulgaris* with the height usually 10 - 30 cm, slender, clumped, small area, numerous leaves, shallow and dense root system made it to quickly cover the ground, effectively prevent soil erosion, and also provide rich organic carbon sources for soil microorganisms, promote the growth and reproduction of soil microorganisms, maintain the stability of soil structure, and enhance soil fertility in the process of urban garden soil ecological restoration, which played a fundamental role in the balance and stability of the entire garden ecosystem. Two years after the joint remediation, soil samples were systematically collected. The topsoil and litter were cleared, and then samples were taken at 0 - 20 cm depth in four directions 30 cm outside the trunk. The soil samples collected in each treatment area were mixed to ensure representativeness with one bag of samples being collected in each region (n = 15). The sample was then divided into two parts with one being quickly cooled and transported to the laboratory for fungal DNA extraction and sequencing and the other being naturally dried under indoor ventilation and dark conditions and sieved to determine soil environmental factors including physical and chemical analysis, nutrient determination, pollution detection, and microbial community structure analysis.

Effects of fertilization on plant dry weight, fresh weight, soluble sugar, organic acid, sugar-acid ratio and soil enzyme activities, microbial diversity distribution

Plant fresh weight was measured immediately after harvest, while the dry weight was determined after oven drying at 75℃ to constant

weight. Soluble sugar content was determined by using anthrone colorimetry method, while organic acid content was determined by using acid-base titration. Sugar-acid ratio was then calculated accordingly. Soil urease activity was determined by measuring the logarithm value of amino nitrogen released per unit of soil after 24 hours of culture. Soil sucrase activity was indirectly reflected by the content of remaining sugars after sodium hypochlorite treatment. Acid phosphatase activity was determined by measuring the amount of p-nitrophenol produced per unit hour according to the p-nitrophenyl phosphate method. Polyphenol oxidase and peroxidase activities were measured by using pyrogallol colorimetric method. Glucose oxidase activity was determined by the 3, 5-dinitrosalicylic acid colorimetric method. Microbial diversity distribution was evaluated based on OTU clustering using UParse software version 7.0 (https://www.drive5.com/uparse/) versus species classification studies on Effective Tags of all samples [17, 18]. By establishing a 97% identity threshold, sequences were classified as OTUs. The sequence with the highest frequency of occurrence among OTUs was selected as the representative sequence. The species annotation was performed by using Mothur method (https://mothur.org/) combined with SILVA's SSUrRNA database (https://www.arb-silva.de/) [19, 20], setting a threshold for acquiring taxonomic information ranging from 0.8 to 1. The detailed taxonomic data collected were then counted and resolved to reveal the community composition of the samples at different taxonomic levels of Kingdom, Phylum, Class, Order, Family, and Genus [21, 22].

Determination of the microbial phosphorus content

5 g of fresh drying soil sample was placed in a 6 cm Petri dish and fumigated before mixing with 100 mL of 0.5 mol/L $NaHCO_3$ solution (pH 8.5) and shaking at room temperature for 30 minutes. The phosphorus content in the filtrate was determined by the molybdenum antimony anti-colorimetric method. Meanwhile, six other soil samples were prepared, three of which were added with 0.5 mL of 250 μg/mL KH_2PO_4 followed by extracting and filtering with $NaHCO_3$ solution. The phosphorus concentration in the filtrate was measured. The microbial phosphorus content (SMBP) was calculated as follows.

$$SMBP\ (mg/kg) = (FU - Fy) \times (Kp \times R)$$

where FU and Fy were the phosphorus contents in fumigated and unfumigated soil extracts, respectively. Kp was the proportion of microbial extraction determination with the value being set to 0.4. R was the recovery rate after adding inorganic phosphorus.

Statistical analysis

SPSS 26.0 software (IBM, Armonk, NY, USA) was employed for statistical analysis of this research. One-way ANOVA followed by Duncan's multiple range test was used to determine significant differences among treatments with *P* value less than 0.05 defined as statistically significant. Visual graphs were generated by using Origin 2022 (OriginLab Corporation, Northampton, MA, USA).

Results and discussion

Soil physicochemical properties and fungal community under different remediation treatments

The effects of plant mulch-biochar-organic fertilizer remediation on soil chemical properties demonstrated that there were certain differences in the effects of different combination remediation treatments on soil chemical properties. The pH value of BF reached 6.85 due to the stronger alkaline buffering capacity of decomposed straw organic fertilizer to neutralize the acidity of degraded soil and provide a suitable environment for microbial growth, which was significantly higher than that of BD and BG treatments ($P < 0.05$). However, there were no significant differences among the pH values of PBD, TBD, and BD. The BD treatment had a significant effect on soil organic carbon content, increasing it to 42.05 g/kg, which was

Table 1. Differences in fungal community structure distribution after remediation treatment.

Between groups	Sum of squares of deviations	F	R^2	*P*
TBD-BD	0.2052	1.1616	0.234	0.6
BD-PBD	0.204	1.728	0.318	0.1212
TBD-PBD	0.3204	1.722	0.3168	0.24
BG-BD	0.4344	3.7764	0.528	0.0012
BF-BG	0.2268	1.6464	0.306	0.1212
BF-BD	0.5184	3.9396	0.5412	0.0012

higher than that of BF and BG treatments ($P < 0.05$), indicating that the organic fertilizer source had a significant effect on soil chemical properties, especially the organic carbon content. The results reflected the subtle differences in the regulation of soil chemical properties between different combinations of remediation treatments. The fungal diversity showed that the Shannon index of BD was lower than that of the non-grass mulching treatment after different plant mulching-biochar-organic fertilizer remediation ($P < 0.05$). The fungal diversity of organic fertilizer (BD) treatment was higher than that of livestock manure organic fertilizer (BG and BF) ($P < 0.05$), and Shannon and Simpson indexes of BF treatment were the lowest. The combined treatment of biochar-organic fertilizer had no significant effect on fungal diversity and richness. The fungal community coverage was > 0.9950 after all treatments, indicating that the sequencing results could accurately reflect the soil microbial community structure. A total of 385 soil-specific OTUs were found under *Paspalum latifolia* mulch (PBD) treatment, while 371 were found under biochar-organic fertilizer (BD) treatment. PBD and BD treatments significantly improved the species richness of soil fungal communities, confirming the effectiveness of these two remediation methods. The effects of various remediation treatments on fungal community structure in urban park soil showed that Adonis analysis revealed a significant difference in fungal community structure among BG, BF, and BD treatments ($P < 0.01$), indicating that different organic materials could shape fungal community composition by changing soil carbon nitrogen ratios and nutrient availability. Organic fertilizer sources were the core factor driving soil fungal community differentiation in urban gardens. The results confirmed the significance of remediation measures on differences in fungal community distribution (Table 1). Compared with single biochar organic fertilizer (BD), biochar combined with livestock and poultry manure organic fertilizer (BG and BF) significantly changed the structure of soil fungal communities, indicating that different sources of organic fertilizers had a significant impact on the composition of soil microbial ecosystem. However, under plant cover-biochar-organic fertilizer treatment, the soil fungal community structure showed a specific segregation trend but without statistically significant difference. This result revealed that plant cover combined with biochar-organic fertilizer remediation significantly affected the potential impact of soil fungal community structure. The application of biochar combined with commercial organic fertilizer could enhance soil carbon storage through external carbon input and native organic matter stimulation effects, while the carbon mineralization rate of livestock manure and straw organic fertilizer was faster, and the short-term organic carbon accumulation effect was weaker. Plant cover treatment did not show a significant effect on fungal diversity, which might be due to the fact that, during the short-term cultivation period of 12 weeks, the input of plant root exudates had not significantly regulated the formation of fungal communities, while the application of biochar organic fertilizer could directly improve the soil nutrient environment and rapidly enhance fungal diversity.

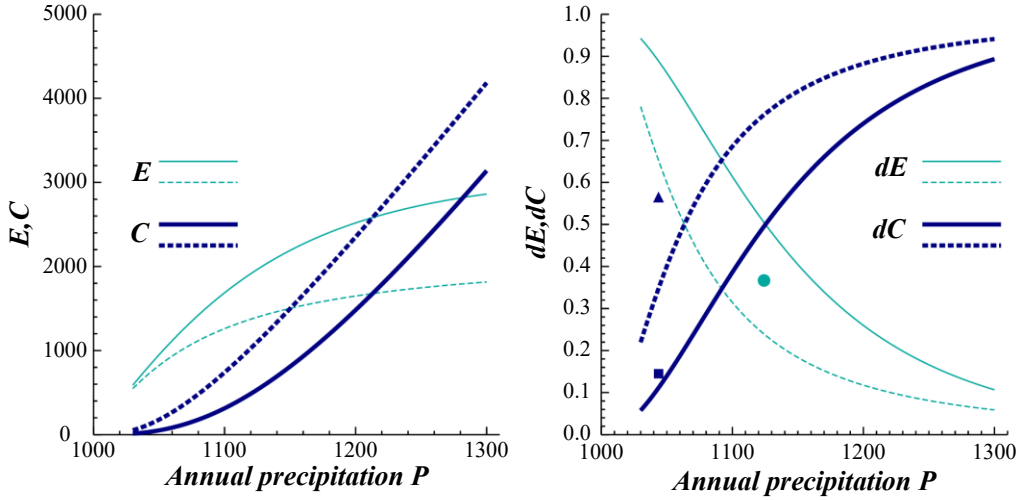

Figure 1. Total phosphorus accumulation.

Effects of fertilization on plant dry weight and fresh weight

The application of soil fertilization significantly promoted the growth of soil. The soil's fresh and dry weight after fertilization increased considerably. In eight test sites, compared with the control group (CK), the application of soil fertilization increased the soil fresh weight in the range of 3.01 - 8.1% with an average increase of 4.00% ($P < 0.01$). The dry weight increase range was 2.37 - 7.71% with an average increase of 5.07% ($P < 0.01$). The results indicated that balanced fertilization could effectively alleviate nitrogen and phosphorus nutrient limitations, promote the accumulation of plant photosynthetic products, and increase biomass in response to the nutrient limitation characteristics of degraded soil in urban gardens. Meanwhile, the increase in plant biomass could be achieved through the input of root exudates and residues, providing more carbon sources for soil microorganisms and forming a positive interaction between plants and microorganisms, which was also the core mechanism for fertilization to simultaneously enhance soil microbial activity and plant growth. The result strongly proved the positive effect of soil fertilization in improving the soil environment, promoting soil nutrient uptake, and crop growth and development.

Effects of biochar on soil nitrogen, phosphorus and potassium accumulation

The effect of soil fertilization on total phosphorus accumulation demonstrated that, compared to the control group (CK), applying soil fertilization increased the accumulation of total phosphorus in the eight test sites by 17.64% to 50.17%, respectively ($P < 0.01$), and the difference reached a very significant level. Except for soil sample 8, the phosphorus contents of other soil samples were at high levels. As the annual precipitation increased from 1,050 mm to 1,300 mm, the total phosphorus accumulation in the soil rapidly increased for an increase of more than 10 times (Figure 1). The results indicated that precipitation conditions and biochar enrichment jointly promoted the migration and fixation of phosphorus elements and improved the nutrient storage capacity in urban garden ecosystems. Applying soil fertilization could promote the accumulation of soil phosphorus not only in high-phosphorus soil but also in low-phosphorus soil. More importantly, with the increase of soil nutrient content, the accumulation of phosphorus in plants showed an upward trend, which indicated that soil fertilization could effectively promote plant phosphorus absorption in soils with different nutrient levels. Soil fertilization treatment significantly increased the potassium

Table 2. Comparison of microbial community regulation and ecological restoration technologies in urban landscape soil.

Comparison aspect	Microbial community regulation	Ecological restoration
Technique core	Regulation of microbial structure	Utilization of microbial degradation
Primary method	Introduction of beneficial microbes	*In-situ*/*ex-situ* restoration
Degradation effectiveness	15 - 20% increase	25 - 30% increase
Cost estimation	Low to moderate	Moderate to high
Time duration	Longer (6 - 8 months)	Variable (4 - 6 months)
Environmental impact	Minor	Minor (prevent secondary pollution)

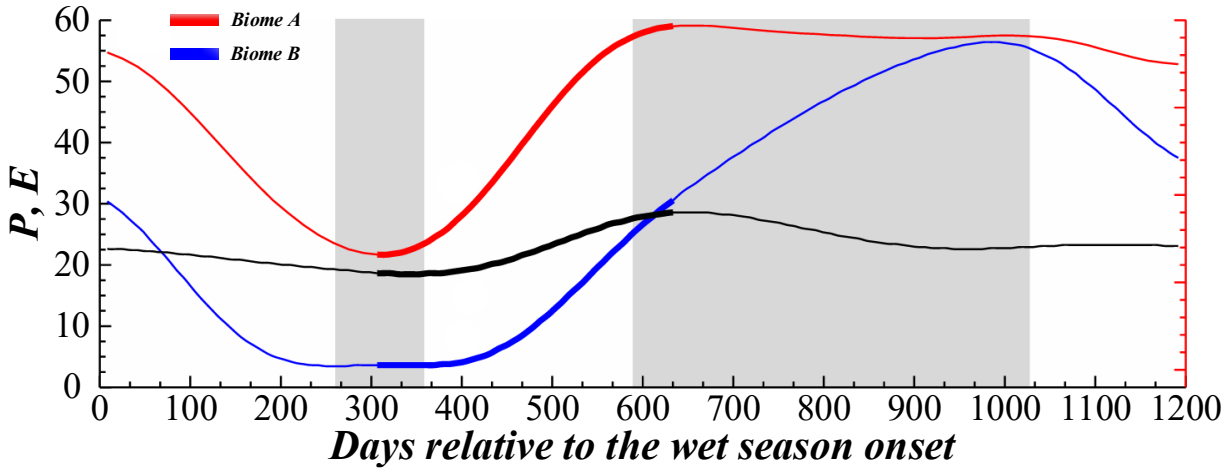

Figure 2. Effects of balanced fertilization on soluble sugar, organic acid, and sugar-acid ratio.

accumulation in the soil. Compared with the control group, the potassium accumulation in the soil in the eight soil samples increased by 9.70% to 28.39%, respectively ($P < 0.01$). Fertilization significantly enhanced the ability of soil to absorb potassium, which might be achieved by improving the soil environment and enhancing plant nutrient absorption capacity, thus considerably increasing the potassium content in crops. The results confirmed that the biochar organic fertilizer synergistic system could reduce nitrogen, phosphorus, and potassium leaching losses through the pore adsorption effect of biochar, while the activation of functional microorganisms enhanced nutrient bioavailability and expanded soil nutrient pools. Unlike agricultural soils, urban garden soils suffered from frequent human disturbance leading to the destruction of aggregate structure and severe nutrient leaching. This collaborative system could simultaneously achieve nutrient retention and activation, accurately match the degradation characteristics of urban garden soils, and mutually confirm the "carrier function" synergistic effect proposed in this study. The core characteristics, degradation efficiency, cost estimation, period, and environmental impact of microbial community regulation technology and ecological restoration technology in urban garden soil were compared. From the perspective of degradation efficiency, ecological restoration technology was relatively superior, but microbial community regulation technology might have a cost advantage. In practical applications, suitable technical solutions needed to be selected based on specific needs and conditions (Table 2).

Effects of balanced fertilization on plant soluble sugar, organic acid and sugar-acid ratio

The effects of balanced fertilization on soluble sugar, organic acid, and sugar-acid ratio in soil

showed that the balanced fertilization could significantly increase soil soluble sugar and optimize the sugar-acid ratio, but it had little effect on organic acid content. Overall, it reduced acidity. In soil fertilization treatment, sample 8 had the highest soluble sugar content, significantly higher than sample 7 and sample 2, which indicated that soil fertilization and application of trace elements such as boron and zinc could effectively increase soil sugar content. The increase in the sugar-acid ratio was especially significant in the treatment group with soil fertilization. The sugar-acid ratios of samples 8, 6, 7, and 2 were higher than those of the groups without soil fertilization. The combined application of trace elements and park soil (sample 8) significantly increased the sugar-acid ratio compared to the single application of soil fertilization (sample 2) with increases of 45.6%, 3.8%, and 27.2%, respectively. Among the treatments without soil fertilization, the sugar-acid ratio of treatment 9 was the highest, which was significantly different from that of sample 5. Compared with the treatment without soil fertilization, the sugar-acid ratio of the treatment with soil fertilization increased significantly with an increase of 17.7% to 84.9% (Figure 2). The results indicated that soil fertilization with trace elements boron and zinc could effectively promote crop sugar accumulation, significantly increase the sugar-acid ratio, and optimize crop quality. Especially, when trace elements were combined with soil fertilization, their positive effects on the sugar-acid ratio were more prominent. Balanced fertilization combined with boron, zinc, and trace elements could significantly increase soluble sugars in plants, which indicated that the synergistic supply of nitrogen, phosphorus, potassium, and trace elements could effectively promote plant photosynthetic carbon metabolism and enhance carbohydrate accumulation. Meanwhile, increasing the sugar acid ratio could improve the composition of plant root exudates, promote the colonization of beneficial microorganisms in the rhizosphere, strengthen the ability of rhizosphere nutrient activation, and form a virtuous cycle of "nutrient supply plant metabolism microbial activation", providing a stable biological basis for the long-term health maintenance of urban garden soil.

Soil enzyme activities under different fertilization treatments

The association analysis of environmental factors showed that, compared to the control group, livestock manure organic fertilizer (LF), green manure fertilizer (GM), and nitrogen fertilizer (NF) treatments significantly increased the urease activity of the inter-vegetation soil in the park ($P < 0.05$) with LF treatment having the best effect followed by NF and GM. LF and GM treatments also significantly increased soil invertase activity ($P < 0.05$), especially LF treatment. Similarly, LF and GM treatments significantly increased acid phosphatase activity in park inter-vegetation soils ($P < 0.05$). LF treatment was superior to GM, while NF treatment significantly decreased this enzyme activity. In addition, LF and GM treatments could dramatically enhance the activities of soil polyphenol oxidase and peroxidase ($P < 0.05$), among which LF treatment had the most significant improvement effect. In contrast, NF treatment had no noticeable change. These results indicated that LF and GM treatments significantly promoted soil enzyme activities across park vegetation, whereas the effects of NF treatments were relatively limited, which were consistent with previous research findings that the application of chemical fertilizers alone could significantly reduce soil phosphatase activity by lowering soil pH and inhibiting microbial growth, while the combination of organic fertilizers could improve soil physicochemical environment, enhance microbial metabolic activity, and promote extracellular enzyme secretion. Soil enzymes were a direct reflection of microbial metabolic functions, and their increased activity directly reflected the restoration effect of remediation treatment on the carbon, nitrogen, and phosphorus cycling function of urban garden soil.

Environmental factors affected microbial diversity distribution

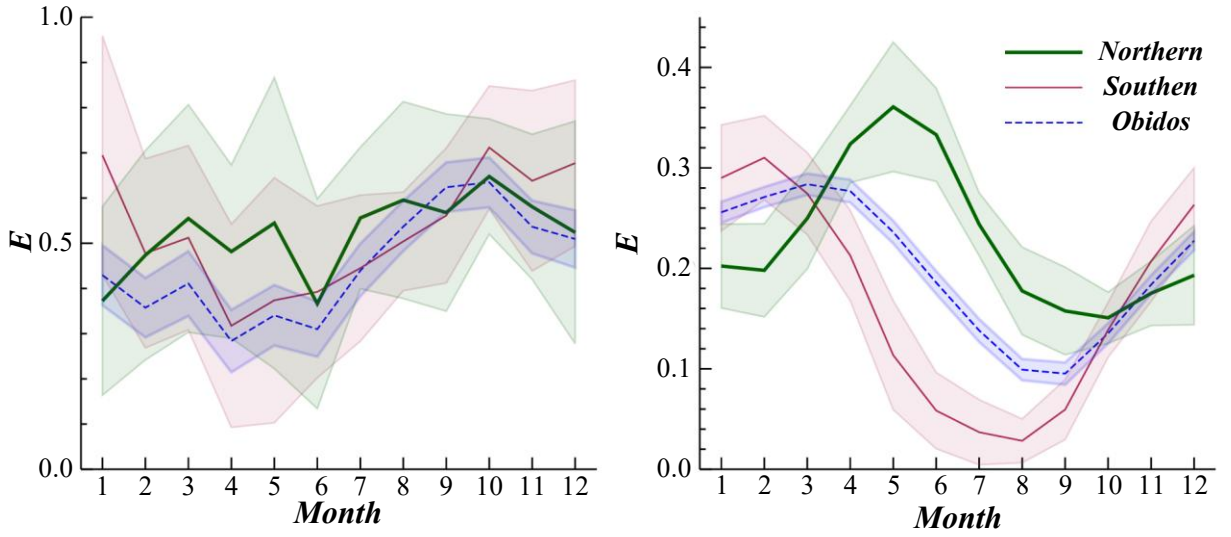

Figure 3. Correlation response of environmental factors and microbial activity.

There was a significant seasonal correlation between environmental factors and microbial diversity in different regions. The Northern region reached a peak of 0.33 in the 5th month, then gradually declined and stabilized around 0.16 in the 12th month. The Southern region experienced the most significant fluctuations with the lowest of only 0.03 in the 7th month but rebounded to 0.26 in the 12th month. The Obidos curve showed a relatively gentle overall change, maintaining a range of 0.09 to 0.28 throughout the year. The results indicated that precipitation, temperature, and nutrient changes collectively affected the activity of soil microbial communities in urban gardens, while the synergistic effect of biochar and bioaccumulation could alleviate ecological pressure caused by environmental fluctuations and improve soil system stability and recovery capacity (Figure 3).

Microbial diversity distribution under different fertilization treatments

Under CK, GM, and LF treatments, the hierarchical clustering was greater than that of NF treatment, indicating that nitrogen fertilizer treatment reduced species richness of inter-vegetation soil in the park. Meanwhile, NF, GM, and LF treatments were gentler than CK, indicating that these treatments improved the uniformity of species with GM treatment showing the highest smoothness and the largest uniformity of species. These results revealed the effects of different treatments on soil microbial diversity and uniformity across park vegetation. NF treatment reduced soil microbial species richness, while GM and LF treatments improved species evenness, indicating that organic fertilizer input could effectively alleviate the selection pressure of single chemical fertilizer on microorganisms, maintain community stability, and provide core guarantees for the sustainable development of soil ecological functions in urban flower gardens.

Conclusions

Microbial communities play an irreplaceable role in the ecological restoration of urban garden soils. Different forms of plant mulching combined with biochar and organic fertilizer or biochar combined with different organic fertilizers had different effects on soil chemical properties, fungal diversity and richness, and community structure. Among them, PBD and BD treatments significantly increased the species richness of soil fungi, and different organic fertilizer sources had a significant effect on soil chemical properties,

especially organic carbon content. Fertilization increased soil fresh and dry weights, significantly increased the accumulation of total phosphorus and potassium. Balanced fertilization could increase soil soluble sugar and optimize sugar-acid ratio. In terms of soil microbial metabolic activity and community structure, LF and GM treatments significantly promoted the activities of various soil enzymes, and different treatments had different effects on soil microbial diversity and uniformity. The preliminary pot-based findings further indicated the potential of microbial community regulation technology combined with biochar addition in improving urban garden soil environments. The field application case further demonstrated the practical value of microbial-based remediation technologies in urban garden soil improvement. However, to verify and expand these initial results under real-world conditions, multi-season field experiments should be carried out in future, which would help clarify the adaptability of this synergistic technology to different urban garden soil types, seasonal climate variations, and complex on-site disturbance factors, thereby providing more reliable support for practical applications. Future research should further integrate basic pot investigations, multi-scale field experiments, and practical application cases to form a complete technical system suitable for urban garden soil restoration.

Acknowledgements

This research was funded by 2023 Henan Province's Undergraduate University Research Teaching Project "Landscape Design" (Grant No. teaching high [180]).

References

1. Gao Y, Wang W, Jiang S, Jin Z, Guo M, Wang M *et al*. 2024. Response characteristics of the community structure and metabolic genes of oil-recovery bacteria after targeted activation of petroleum hydrocarbon-degrading bacteria in low-permeability oil reservoirs. ACS Omega. 9(31):33448-33458.
2. Zhou J, Zhang RQ, Wang P, Gao YP, Zhang J. 2024. Responses of soil and rhizosphere microbial communities to Cd-hyperaccumulating willows and Cd contamination. BMC Plant Biol. 24:398.
3. Zhou W, Hao J, Guo Y, Zhao C, Zhang M, Zhang S, *et al*. 2024. Revealing bioresponses of biofilm and flocs to salinity gradient in halophilic biofilm reactor. Bioresour Technol. 401:130727.
4. Zhou M, Wang J, Wang H, Ran X, Xue H, Liu C, *et al*. 2024. Revealing the comprehensive impact of organic compounds on the partial nitrification-anammox system during incineration leachate treatment: Metabolic hierarchy and adaptation. Water Res. 255:121534.
5. Wang SZ, Yan J, Heal KV, Li HY, Yu YC, Zhou CF. 2024. Rhizosphere microbial roles in phosphorus cycling during successive plantings of Chinese fir plantations. For Ecol Manag. 570:122227.
6. Zhao N, Huang Y, Lai H, Wang Y, Mei Y, Zeng X, *et al*. 2024. The role of abiotic and biotic factors of aged brine in directing microbial assembly and volatile profiles of Paocai during fermentation. Food Biosci. 57:103592.
7. Li C, Ding Y, Zhang S, Chen M, Wang Y, Jia Z, *et al*. 2024. The short-term effect of simulated acid rain and nitrogen deposition on the soil microbial functional profile targeting C, N, and P cycling. Appl Soil Ecol. 197:105327.
8. Ducci A, Abán C, Huidobro J, Vargas-Gil S, Acreche M, Pérez-Brandan C. 2024. Short-term service crops affect the spatial organization of soil aggregates, microbial C-N biomass, and microbial activities in a degraded monoculture system. Appl Soil Ecol. 199:105419.
9. Liu Y, Li JW, Su JF, Li X, Li X. 2024. Simultaneous removal of ammonia nitrogen, calcium and cadmium in a biofilm reactor based on microbial-induced calcium precipitation: optimization of conditions, mechanism and community biological response. J Environ Manage. 358:120912.
10. Boixel AL, Rouxel T, Andrivon D, Affichard M, Le May C. 2024. Slipping through the cracks: challenges and prospects for investigating fungal plant disease complexes. Crop Prot. 184:106826.
11. Shaghaleh H, Hamoud YA, Sun Q, Sheteiwy MS, AbdElgawad H. 2025. Soil flushing coupled with aminated-nanocellulose/MOF hydrogel nanocomposites adsorbents: a novel sustainable remediation strategy for Cr (VI)-contaminated agricultural soils. Sep Purif Technol. 353(Part B):128440.
12. Zhong H, Tang W, Li Z, Sonne C, Lam SS, Zhang X, *et al*. 2024. Soil Geobacteraceae are the key predictors of neurotoxic methylmercury bioaccumulation in rice. Nat Food. 5(4):301–311.
13. Wu Y, Wang Z, Yan Y, Zhou Y, Huma B, Tan Z, *et al*. 2024. Recovery and regeneration of water-hardened magnetic composite biochar sphere for the removal of multiple heavy metals in contaminated soils. J Clean Prod. 450:141906.
14. Zhang XR, Gong ZQ, Zhuang J, Ludlow RA, Chen X, Guo SH. 2024. Remediation of field agricultural soil contaminated with both heavy metals and veterinary antibiotics by a degrading strain-biochar composite at different temperatures and combinative conditions. Water Air Soil Pollut. 235(11):685.

15. Huang Q, Wang B, Shen J, Xu F, Li N, Jia P, *et al*. 2024. Shifts in C-degradation genes and microbial metabolic activity with vegetation types affected the surface soil organic carbon pool. Soil Biol Biochem. 192:109371.
16. Boualam O, El Alami S, Ibaghlin H, Chadli C, Tanji K, El Gaidoumi A, *et al*. 2024. Resourceful exploitation of sedimentary clay: Designing a dual-chambered borosilicate glass reactor system for the efficient treatment of malachite green and phenol through SCRT adsorption and 5%Fe@SRCT catalysis via CWPO, with evaluation of seed germination and fish survival. Water Environ Res. 96(8):e11090.
17. Chao CX, Chen XR, Wang J, Xie YH. 2024. Response of submerged macrophytes of different growth forms to multiple sediment remediation measures for hardened sediment. Front Plant Sci. 15:1450404.
18. Sharuddin SSN, Abdullah SRS, Abu Hasan H, Othman AR, Ismail NI. 2024. Rhizobacterial-assisted phytoremediation for accelerated petroleum-hydrocarbon removal in crude-oil sludge. Sci Total Environ. 954:176189.
19. Wang Y, Zhao Z, Jiao M, Li T, Wei Y, Li R, *et al*. 2024. Rhizospheric bacterial communities against microplastics (MPs): Novel ecological strategies based on the niche differentiation. J Hazard Mater. 480:135806.
20. Tang Y, Zhang D, Xu H, Dai L, Xu Q, Zhang Z, *et al*. 2024. The role of topography feedbacks in enrichment of heavy metal elements in terrace type region. Front Environ Sci. 12:1291917.
21. Tang L, Mei JT, Hua ZL, Fu J. 2024. Self-assembled sodium alginate/graphene hydrogel enhances sulfamethoxazole removal: impacts of hydrogel properties on the microbial community. Surf Interfaces. 51:104751.
22. Cui X, Sun W, Wang Z, Zhu X, Song X, Liu J, *et al*. 2024. Simulated study on electrochemical regeneration of ammonium persulfate for naphthalene degradation in soil. Int J Environ Sci Technol. 21(13):8553-8564.