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Mechanisms of Soil Health Degradation and Optimization of Sustainable Remediation Technologies in Urban Green Spaces Under Urbanization

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ABSTRACT
Urbanization intensifies soil health degradation in urban green spaces via compaction, heavy metal (HM) accumulation, and microbial community disruption. This study assessed soil physicochemical properties, microbial diversity, and enzyme activities across 56 urban green spaces in 4 countries (USA, Japan, Belgium, China). Three sustainable remediation technologies (biochar amendment, mycorrhizal inoculation, phytoremediation) were optimized and validated. Results showed urban soils had 32% higher bulk density, 2.1-fold higher Pb/Cd concentrations, and 28% lower microbial diversity than suburban soils. The optimized biochar-mycorrhizal combined remediation increased soil organic carbon by 41% and reduced HM bioavailability by 68%. This study provides a cross-regional framework for urban soil health management.

Keywords: Urban Green Spaces; Soil Health Degradation; Heavy Metal Contamination; Microbial Diversity; Sustainable Remediation; Biochar

1. Introduction

1.1 Research Background

Urban green spaces (UGSs), including parks, gardens, and street greenbelts, play critical roles in mitigating urban heat islands, regulating hydrological cycles, and improving human well-being . However, rapid urbanization—characterized by land-use conversion, anthropogenic disturbance, and industrial/emission inputs—has caused severe soil health degradation in UGSs . Previous studies reported that urban soils exhibit distinct degradation features: soil compaction (bulk density > 1.5 g/cm^3), excessive HM accumulation (Pb, Cd, Cu exceeding regional soil quality standards), and significant declines in microbial biomass and enzyme activities .

In the USA, urban park soils in Los Angeles showed Pb concentrations up to 380 mg/kg, 7 times higher than suburban soils . In Tokyo, Japan, 62% of street greenbelt soils had bulk density > 1.6 g/cm^3, restricting

root penetration and water infiltration . Similar issues exist in European and Chinese cities: Ghent (Belgium) urban soils had 35% lower microbial diversity than rural soils , while Beijing (China) UGS soils showed 42% lower urease activity due to HM stress . These degradation phenomena threaten the ecological functions of UGSs and pose potential risks to human health via dust inhalation or direct contact.

1.2 Research Gaps

Despite extensive studies on urban soil degradation, three key gaps remain: (1) Lack of cross-regional comparative analysis of soil health degradation patterns across different urbanization levels and climatic zones; (2) Insufficient understanding of the interactive mechanisms between soil physicochemical degradation and microbial community disruption; (3) Limited optimization of sustainable remediation technologies considering both short-term efficiency and long-term soil health recovery . Addressing these gaps is essential for developing targeted management strategies for UGS soils.

1.3 Research Objectives and Scope

This study aimed to: (1) Characterize the patterns and drivers of soil health degradation in UGSs across 4 countries with different urbanization intensities; (2) Clarify the interactive mechanisms between soil compaction, HM contamination, and microbial community shifts; (3) Optimize and evaluate the sustainability of combined remediation technologies. Field sampling covered 56 UGSs (parks, street greenbelts, community gardens) in Davis (USA), Tokyo (Japan), Ghent (Belgium), and Beijing (China). Laboratory experiments and lifecycle assessment (LCA) were conducted to validate remediation efficiency and sustainability.

2. Literature Review

2.1 Urbanization-Induced Soil Physicochemical Degradation

Soil compaction is a primary physicochemical issue in UGSs, caused by foot traffic, construction activities, and heavy equipment use. A meta-analysis of 120 studies showed that urban soils have an average bulk density of 1.58 g/cm^3, 32% higher than suburban soils (1.20 g/cm^3) . Compacted soils reduce pore connectivity, leading to 45% lower water infiltration rates and 38% higher surface runoff , which exacerbates urban flooding risks.

Heavy metal contamination is another critical concern. Industrial emissions, traffic exhaust, and atmospheric deposition contribute to HM accumulation in UGS soils. In European cities, traffic-related Pb concentrations in street greenbelts range from 120–450 mg/kg , while in Chinese UGSs, Cd concentrations average 1.2 mg/kg, exceeding the national soil quality standard (0.3 mg/kg) by 3 times . These HMs not only inhibit microbial activity but also accumulate in plants, posing risks to herbivores and humans.

2.2 Soil Microbial Community Responses to Urbanization

Microbial communities are sensitive indicators of soil health. Urbanization-induced environmental stress (compaction, HM, pH changes) drives significant shifts in microbial structure and function. In the USA, urban park soils had 28% lower bacterial diversity and 35% lower fungal diversity than suburban soils, with Proteobacteria and Ascomycota becoming dominant taxa . In Japan, mycorrhizal fungal colonization rates in urban greenbelt plants were 42% lower than in suburban plants, reducing nutrient uptake efficiency .

Functional gene analysis further reveals microbial functional degradation. A study in Belgium found that urban soils had 2.3-fold lower abundance of nitrogen-fixation genes (*nifH*) and 1.8-fold lower

carbon-degradation genes (*glk*) than rural soils , indicating impaired nutrient cycling capacity. Heavy metals, especially Cd and Pb, are key drivers of these shifts: Cd concentrations show a significant negative correlation with microbial biomass carbon ($r = -0.68$, $p < 0.01$) .

2.3 Current Sustainable Remediation Technologies

Biochar amendment is widely used for urban soil remediation due to its high adsorption capacity and carbon sequestration potential. Wheat straw biochar reduced Pb bioavailability by 52% in urban soils , while wood biochar increased soil organic carbon (SOC) by 38% within 1 year . Mycorrhizal inoculation enhances plant tolerance to HM stress: *Rhizophagus irregularis* inoculation increased Pb accumulation in *Sedum alfredii* by 41% . Phytoremediation using hyperaccumulators (e.g., *Pteris vittata* for As, *Brassica juncea* for Cd) is cost-effective but has low efficiency for multi-HM contamination .

However, single remediation technologies have limitations: biochar alone cannot restore microbial diversity , mycorrhizal inoculation is ineffective in highly compacted soils , and phytoremediation requires long remediation periods . Combined technologies show promise, but their optimization and sustainability assessment across different regions remain insufficient.

3. Materials and Methods

3.1 Study Sites and Sampling Design

Field sampling was conducted from April 2022 to September 2023 in 4 cities with different urbanization levels:

Davis (USA): 14 UGSs (7 parks, 7 street greenbelts), low urbanization intensity (population density: 1,800 people/km^2);

Tokyo (Japan): 14 UGSs (5 parks, 5 street greenbelts, 4 community gardens), high urbanization intensity (population density: 6,200 people/km^2);

Ghent (Belgium): 14 UGSs (6 parks, 8 street greenbelts), moderate urbanization intensity (population density: 3,500 people/km^2);

Beijing (China): 14 UGSs (8 parks, 6 street greenbelts), high urbanization intensity (population density: 5,800 people/km^2).

At each UGS, 3 sampling plots (10 m × 10 m) were set. In each plot, 5 soil cores (0–20 cm depth, 5 cm diameter) were collected using a soil auger, mixed into a composite sample, and divided into two parts: one stored at -80°C for microbial analysis, and the other air-dried for physicochemical analysis.

3.2 Soil Physicochemical Property Analysis

Bulk density: Measured using the core method (50 cm^3 stainless steel core) .

Soil pH: Determined with a glass electrode (soil:water = 1:2.5, w/v) using a pH meter (Thermo Scientific Orion Star A211).

Heavy metals (Pb, Cd, Cu, Zn): Extracted with aqua regia ($HCl:HNO_3$ = 3:1, v/v) and quantified by inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7900).

Soil organic carbon (SOC): Analyzed via dry combustion using a LECO CNS-2000 analyzer.

Soil enzyme activities: Urease (urea hydrolysis, measured by indophenol blue colorimetry), catalase (H_2O_2 decomposition, measured by $KMnO_4$ titration), and sucrase (sucrose hydrolysis, measured by 3,5-dinitrosalicylic acid colorimetry) .

3.3 Soil Microbial Community Analysis

DNA extraction: Soil microbial DNA was extracted from 0.5 g fresh soil using the DNeasy PowerSoil Kit (Qiagen, Germany) following the manufacturer's protocol.

High-throughput sequencing: Bacterial 16S rRNA gene (V4-V5 region, primers 515F/907R) and fungal ITS region (primers ITS1F/ITS2R) were amplified and sequenced on the Illumina NovaSeq 6000 platform (Illumina, USA).

Data analysis: Raw reads were filtered using Trimmomatic (v0.39), merged with FLASH (v1.2.11), and clustered into operational taxonomic units (OTUs) at 97% similarity using UPARSE (v7.0). Taxonomic annotation was performed against the Silva database (bacteria) and UNITE database (fungi). Alpha diversity (Shannon index, Chao1 index) was calculated using MOTHUR (v1.44.3), and beta diversity was visualized via non-metric multidimensional scaling (NMDS) based on Bray-Curtis dissimilarity.

3.4 Remediation Experiment Design

Three remediation technologies and their combinations were tested using Beijing UGS soil (Pb: 210 mg/kg, Cd: 1.8 mg/kg, bulk density: 1.65 g/cm^3):

Biochar (B): Wheat straw biochar (pyrolyzed at 500°C, particle size < 2 mm) added at 5% (w/w);

Mycorrhizal inoculation (M): *Rhizophagus irregularis* inoculum (100 spores/g) added at 2% (w/w);

Phytoremediation (P): *Sedum alfredii* seedlings (10 cm height) transplanted at 5 plants/pot;

Combined treatments: B+M, B+P, M+P, B+M+P.

Each treatment had 3 replicates (plastic pots, 30 cm × 25 cm, 2 kg soil/pot). The experiment was conducted in a greenhouse (25°C, 16 h light/8 h dark) for 180 days. After incubation, soil samples were collected to measure HM bioavailability (DTPA extraction) and microbial diversity.

3.5 Sustainability Assessment of Remediation Technologies

Lifecycle assessment (LCA) was conducted to evaluate the sustainability of each remediation technology, covering 3 pillars:

Environmental pillar: Carbon footprint (calculated using the IPCC 2019 method), HM leaching risk (TCLP method), and microbial diversity recovery rate;

Economic pillar: Cost per hectare (material, labor, maintenance), payback period;

Social pillar: Public acceptance (questionnaire survey of 200 residents in each city), aesthetic improvement (green coverage rate).

A sustainability index (SI) was constructed: $SI = 0.4 \times E + 0.3 \times Ec + 0.3 \times S$, where E = environmental score, Ec = economic score, S = social score (1–5, 5 = most sustainable).

3.6 Statistical Analysis

All data were analyzed using SPSS 26.0 and R 4.4.0. One-way analysis of variance (ANOVA) with Tukey's HSD test was used to compare differences among groups. Pearson correlation analysis was conducted to explore relationships between soil properties and microbial diversity.

4. Results

4.1 Cross-Regional Patterns of Soil Health Degradation

Urban green space soils across all 4 cities showed significant health degradation compared to

suburban soils (Table 1). Bulk density in UGS soils averaged 1.52 g/cm^3, 32% higher than suburban soils (1.15 g/cm^3). Tokyo and Beijing (high urbanization) had the highest bulk density (1.65 g/cm^3 and 1.61 g/cm^3, respectively), while Davis (low urbanization) had the lowest (1.32 g/cm^3).

Heavy metal concentrations in UGS soils exceeded suburban levels by 2.1–3.5 times. Pb concentrations were highest in Beijing (210 mg/kg) and Tokyo (185 mg/kg), while Cd concentrations were highest in Beijing (1.8 mg/kg). SOC in UGS soils was 18% lower than in suburban soils, with the lowest SOC in Tokyo (1.2%) and highest in Ghent (2.1%).

Soil enzyme activities in UGS soils were significantly lower than in suburban soils: urease (32% lower), catalase (25% lower), sucrase (28% lower). Tokyo and Beijing had the lowest enzyme activities, while Davis had the highest.

Table 1. Soil physicochemical properties of urban green spaces (UGSs) and suburban soils across 4 cities

City	Land Type	Bulk Density (g/cm³)	Pb (mg/kg)	Cd (mg/kg)	SOC (%)	Urease (mg NH-N/ g·d)
Davis (USA)	UGS	1.32 ± 0.08	95 ± 12	0.6 ± 0.1	1.8 ± 0.2	1.25 ± 0.11
	Suburban	1.10 ± 0.06	35 ± 8	0.2 ± 0.05	2.3 ± 0.3	1.82 ± 0.15
Tokyo (Japan)	UGS	1.65 ± 0.10	185 ± 25	1.2 ± 0.2	1.2 ± 0.1	0.85 ± 0.07
	Suburban	1.20 ± 0.07	65 ± 10	0.3 ± 0.08	1.8 ± 0.2	1.32 ± 0.10
Ghent (Belgium)	UGS	1.48 ± 0.09	120 ± 18	0.8 ± 0.1	2.1 ± 0.2	1.05 ± 0.09
	Suburban	1.18 ± 0.06	45 ± 9	0.2 ± 0.06	2.6 ± 0.3	1.58 ± 0.12
Beijing (China)	UGS	1.61 ± 0.09	210 ± 30	1.8 ± 0.3	1.5 ± 0.2	0.78 ± 0.06
	Suburban	1.12 ± 0.05	75 ± 11	0.4 ± 0.1	2.0 ± 0.2	1.28 ± 0.11

4.2 Soil Microbial Community Degradation

Urban green space soils had significantly lower microbial diversity than suburban soils. Bacterial Shannon index in UGS soils averaged 5.8, 28% lower than suburban soils (8.1). Fungal Shannon index in UGS soils averaged 4.2, 35% lower than suburban soils (6.5). Tokyo and Beijing had the lowest microbial diversity, while Davis had

the highest (Figure 1A). Beta diversity analysis via NMDS showed clear separation between UGS and suburban soil microbial communities (stress = 0.18 for bacteria, 0.21 for fungi), with UGS samples clustering closely across cities—indicating urbanization-induced microbial homogenization (Figure 1B).

Taxonomic composition of microbial communities also differed significantly between UGS and suburban soils. For bacteria, Proteobacteria dominated UGS soils (38% of total taxa), 12% higher than in suburban soils (26%). In contrast, Acidobacteria were more abundant in suburban soils (22% vs. 13% in UGS soils). For fungi, Ascomycota accounted for 45% of taxa in UGS soils, compared to 32% in suburban

soils, while Basidiomycota were less abundant in UGS soils (18% vs. 29% in suburban soils). Notably, mycorrhizal fungal taxa (e.g., *Rhizophagus*, *Lactarius*) were 52% less abundant in UGS soils than in suburban soils, with the lowest abundance in Tokyo (8% of fungal taxa) and Beijing (10%).

(A) Alpha diversity (Shannon index) of bacterial and fungal communities; Error bars represent standard deviations; Different letters indicate significant differences ($p < 0.05$) between UGS and suburban soils within each city. (B) NMDS ordination of bacterial communities based on Bray-Curtis dissimilarity; Red dots = UGS soils, Blue dots = suburban soils; Ellipses represent 95% confidence intervals for each group.

Pearson correlation analysis revealed that soil bulk density and HM concentrations were the key drivers of microbial diversity loss (Table 2). Bacterial Shannon index showed a significant negative correlation with bulk density ($r = -0.72$, $p < 0.01$) and Cd concentration ($r = -0.68$, $p < 0.01$), while fungal Shannon index was negatively correlated with Pb concentration ($r = -0.65$, $p < 0.01$) and positively correlated with SOC ($r = 0.59$, $p < 0.01$). This suggests that compaction and HM contamination directly suppress microbial diversity, while higher SOC mitigates these negative effects.

Table 2. Pearson correlation coefficients between soil properties and microbial diversity indices

Soil Property	Bacterial Shannon Index	Fungal Shannon Index	Bacterial Chao1 Index	Fungal Chao1 Index
Bulk Density	-0.72**	-0.58**	-0.69**	-0.55**
Cd Concentration	-0.68**	-0.49*	-0.65**	-0.47*
Pb Concentration	-0.61**	-0.65**	-0.58**	-0.62**
SOC	0.54*	0.59**	0.51*	0.56**
pH	-0.32	-0.28	-0.29	-0.25

*(Note: *$p < 0.05$, *$p < 0.01$; $n = 56$ for UGS soils, $n = 28$ for suburban soils)*

4.3 Efficiency of Remediation Technologies

All remediation treatments reduced HM bioavailability and improved soil microbial diversity compared to the control (untreated UGS soil), but combined treatments outperformed single technologies (Table 3). The **B+M (biochar + mycorrhizal) treatment** showed the highest remediation efficiency: DTPA-extractable Pb and Cd concentrations decreased by 68% and 72%, respectively—significantly higher than single biochar (42% Pb reduction, 48% Cd reduction) or mycorrhizal (35% Pb reduction, 39% Cd reduction) treatments. The B+M+P (biochar + mycorrhizal + phytoremediation) treatment had slightly lower HM reduction efficiency (62% Pb, 65% Cd) than B+M, likely due to competition for nutrients between *Sedum alfredii* and mycorrhizal fungi.

Soil physicochemical properties also improved with remediation. The B+M treatment increased SOC by 41% (from 1.5% to 2.1%) and reduced bulk density by 18% (from 1.65 g/cm^3 to 1.35 g/cm^3), while soil enzyme activities (urease, catalase, sucrase) increased by 58%, 45%, and 52%, respectively, compared to

the control. Single phytoremediation had the weakest effect on physicochemical properties, only increasing SOC by 12% and reducing bulk density by 8%.

Microbial diversity recovery was most pronounced in the B+M treatment: bacterial Shannon index increased from 5.2 to 7.1 (37% improvement), and fungal Shannon index increased from 3.8 to 5.9 (55% improvement) . Mycorrhizal fungal abundance in the B+M treatment reached 22% of total fungal taxa—3.1 times higher than the control (7%). In contrast, single biochar treatment only increased bacterial and fungal diversity by 18% and 23%, respectively, indicating that mycorrhizal inoculation enhances microbial community restoration.

Table 3. Heavy metal (HM) bioavailability and soil property changes after 180 days of remediation

Treatment	DTPA-Pb (mg/kg)	DTPA-Cd (mg/kg)	SOC (%)	Bulk Density (g/cm³)	Urease (mg NH-N/g·d)
Control	45.2 ± 3.8	0.92 ± 0.08	1.5 ± 0.2	1.65 ± 0.09	0.78 ± 0.06
B (Biochar)	26.2 ± 2.1**	0.48 ± 0.05**	1.9 ± 0.2**	1.42 ± 0.07**	1.05 ± 0.08**
M (Mycorrhizal)	29.4 ± 2.5**	0.56 ± 0.06**	1.6 ± 0.1	1.51 ± 0.08*	0.92 ± 0.07*
P (Phytoremediation)	31.8 ± 2.7**	0.61 ± 0.07**	1.7 ± 0.1*	1.52 ± 0.08*	0.89 ± 0.07*
B+M	14.5 ± 1.3**	0.26 ± 0.03**	2.1 ± 0.2**	1.35 ± 0.06**	1.23 ± 0.10**
B+P	18.3 ± 1.6**	0.32 ± 0.04**	2.0 ± 0.2**	1.38 ± 0.07**	1.18 ± 0.09**
M+P	22.6 ± 1.9**	0.38 ± 0.05**	1.8 ± 0.1*	1.45 ± 0.08**	1.01 ± 0.08**
B+M+P	17.2 ± 1.5**	0.32 ± 0.04**	2.0 ± 0.2**	1.37 ± 0.07**	1.15 ± 0.09**

*(Note: *p < 0.05, *p < 0.01 compared to control; Values are means ± standard deviations of 3 replicates)*

4.4 Sustainability Assessment of Remediation Technologies

The sustainability index (SI) ranked the treatments as: B+M (4.3) > B+P (3.8) > B+M+P (3.6) > M (2.9) > P (2.7) > B (2.5) > Control (1.0) (Table 4). The B+M treatment achieved the highest environmental score (4.5) due to low carbon footprint (0.8 tons CO_2/ha), 68% HM leaching risk reduction, and 37% microbial diversity recovery. Its economic score (4.1) was also high, with a cost of ¥110,000/ha and payback period of 3.2 years—lower than B+M+P (¥150,000/ha, 4.5 years). Socially, B+M had high public acceptance (82% of residents supported it) and improved green coverage by 25%, contributing to a social score of 4.3.

In contrast, single treatments had lower SI: biochar alone had a low social score (2.8) due to limited aesthetic improvement, while phytoremediation had a low environmental score (2.6) because of slow HM reduction (requiring 2+ years for full efficiency). The B+M+P treatment's lower SI than B+M was attributed to higher costs (due to *Sedum alfredii* transplantation and maintenance) and lower public acceptance (68% vs. 82% for B+M), as residents expressed concerns about plant establishment delays.

Regional differences in sustainability were minor but notable: in Davis (low urbanization), B+M had a slightly higher SI (4.5) due to lower initial HM concentrations, while in Tokyo (high urbanization), the SI was 4.1—still the highest among all treatments. This indicates the B+M treatment's adaptability across different urbanization levels.

Table 4. Sustainability assessment of remediation technologies (mean ± standard deviation across 4 cities)

Treatment	Environmental Score (E)	Economic Score (Ec)	Social Score (S)	Sustainability Index (SI)
B+M	4.5 ± 0.3**	4.1 ± 0.2**	4.3 ± 0.2**	4.3 ± 0.2**
B+P	4.0 ± 0.3**	3.7 ± 0.2**	3.8 ± 0.3**	3.8 ± 0.2**
B+M+P	4.2 ± 0.2**	3.2 ± 0.3*	3.6 ± 0.2**	3.6 ± 0.2**
M	3.1 ± 0.2*	2.8 ± 0.2*	3.0 ± 0.2*	2.9 ± 0.2*
P	2.6 ± 0.2*	2.9 ± 0.2*	2.7 ± 0.2*	2.7 ± 0.2*
B	2.8 ± 0.2*	2.4 ± 0.2*	2.8 ± 0.2*	2.5 ± 0.2*
Control	1.0 ± 0.1	1.0 ± 0.1	1.0 ± 0.1	1.0 ± 0.1

*(Note: *p < 0.05, *p < 0.01 compared to control; Scores are on a 1–5 scale, with 5 = most sustainable)*

5. Discussion

5.1 Drivers of Cross-Regional Soil Health Degradation in UGSs

This study confirms that urbanization intensity is the primary driver of UGS soil degradation, with high-urbanization cities (Tokyo, Beijing) showing more severe compaction, HM accumulation, and microbial loss than low-urbanization cities (Davis). Two key mechanisms explain these patterns:

5.1.1 Anthropogenic disturbance intensity

High-urbanization cities have higher foot traffic (e.g., 120–180 people/m^2/day in Tokyo parks vs. 30–50 in Davis) and more frequent construction activities, leading to 25–30% higher bulk density . Compaction reduces soil pore space, limiting oxygen and water availability for microbes—consistent with the negative correlation between bulk density and microbial diversity ($r = -0.72$, $p < 0.01$).

5.1.2 Pollution source accumulation

Traffic exhaust (a major Pb/Cd source) is more intense in high-urbanization cities (e.g., 800,000 vehicles/day in Beijing vs. 120,000 in Davis), contributing to 2.1–3.5 times higher HM concentrations . These HMs bind to microbial cell membranes, inhibiting enzyme activity and reducing taxonomic diversity—evident in the 52% lower mycorrhizal fungal abundance in UGS soils.

Notably, Ghent (moderate urbanization) showed milder degradation due to strict urban planning policies (e.g., 30% green space protection, low-emission vehicle zones), which reduced compaction

and pollution inputs. This suggests that policy interventions can mitigate UGS soil degradation, even in urbanized regions.

5.2 Synergistic Mechanisms of B+M Remediation

The B+M treatment's superior performance stems from three synergistic effects:

5.2.1 Physical-chemical stabilization by biochar

Wheat straw biochar (pyrolyzed at 500°C) has a high specific surface area (185 m^2/g) and cation exchange capacity (28 cmol/kg), which adsorbs HMs via electrostatic attraction and complexation . This reduces HM bioavailability by 68–72%, alleviating toxic stress on microbes.

5.2.2 Microbial symbiosis by mycorrhizae

Rhizophagus irregularis forms symbiotic relationships with plant roots (even in UGS soils), increasing root exudate secretion (e.g., organic acids, amino acids) by 45% . These exudates serve as carbon sources for microbes, promoting the recovery of beneficial taxa (e.g., Acidobacteria, Basidiomycota) and increasing enzyme activities by 45–58%.

5.2.3 Soil structure improvement

Biochar reduces bulk density by creating macro-pores (50–100 μm), while mycorrhizal hyphae (10–20 μm diameter) stabilize soil aggregates. Together, they increase soil porosity by 22%, improving oxygen diffusion and microbial habitat quality .

This synergy addresses the limitations of single technologies: biochar alone cannot restore microbial symbionts, and mycorrhizae alone cannot immobilize HMs—highlighting the need for combined remediation to achieve both short-term pollution control and long-term soil health recovery.

5.3 Implications for UGS Soil Management

Based on cross-regional results and remediation efficiency, we propose three targeted management strategies for UGS soils:

5.3.1. High-urbanization cities (Tokyo, Beijing)

Prioritize B+M remediation in high-traffic parks and street greenbelts. Supplement with periodic soil aeration (e.g., core aeration twice/year) to reduce compaction, and restrict heavy construction near green spaces to limit HM inputs.

5.3.2 Moderate-urbanization cities (Ghent)

Maintain existing green space protection policies, and apply B+M remediation selectively in pollution hotspots (e.g., near highways). Promote native plant-mycorrhizal combinations (e.g., *Quercus robur* + *Rhizophagus irregularis*) to enhance ecological resilience.

5.3.3 Low-urbanization cities (Davis)

Preventive measures are key—implement permeable pavement in green space buffers to reduce compaction, and use low-emission maintenance equipment to minimize HM deposition. For mild degradation, single biochar amendment is sufficient to restore soil health, avoiding the higher costs of combined treatments.

5.4 Limitations and Future Research Directions

This study has three key limitations:

Temporal scope: The field sampling and remediation experiment were conducted over 18–24 months,

which may not capture long-term (5+ years) soil health dynamics—such as biochar aging effects on HM adsorption or mycorrhizal community persistence.

Climatic representation: The 4 study cities (temperate: Davis, Tokyo, Ghent; semi-arid: Beijing) do not include tropical or arid regions, where UGS soil degradation (e.g., salinization in arid zones) and remediation efficiency may differ.

Plant-microbe interactions: The study focused on mycorrhizal fungi but did not explore other beneficial microbes (e.g., rhizobia, PGPR—plant growth-promoting rhizobacteria) that could enhance remediation synergy.

Future research should address these gaps by:

Establishing long-term monitoring plots (5–10 years) to track soil health recovery and remediation longevity;

Expanding sampling to tropical (e.g., Singapore, Rio de Janeiro) and arid (e.g., Phoenix, Dubai) cities to validate the B+M treatment's adaptability;

Investigating tripartite interactions (plant + mycorrhizae + PGPR) to optimize microbial consortia for multi-stress (compaction, HM, drought) resistance.

6. Conclusions

This cross-regional study (USA, Japan, Belgium, China) systematically characterized soil health degradation in urban green spaces (UGSs) and optimized sustainable remediation technologies. Key findings include:

Degradation patterns: Urbanization intensity drives UGS soil degradation—high-urbanization cities (Tokyo, Beijing) had 32% higher bulk density, 2.1–3.5 times higher Pb/Cd concentrations, and 28–35% lower microbial diversity than low-urbanization cities (Davis). Soil compaction and HM contamination were the primary drivers of microbial diversity loss ($r = -0.72$ to -0.61, $p < 0.01$).

Remediation efficiency: The biochar-mycorrhizal (B+M) combined treatment outperformed single technologies, reducing DTPA-extractable Pb/Cd by 68–72%, increasing SOC by 41%, and restoring bacterial/fungal diversity by 37–55%. This synergy arises from biochar's HM adsorption, mycorrhizal symbiosis, and joint soil structure improvement.

Sustainability: The B+M treatment achieved the highest sustainability index (4.3) across all regions, balancing low carbon footprint (0.8 tons CO_2/ha), economic feasibility (¥110,000/ha, 3.2-year payback), and high public acceptance (82%).

The B+M treatment provides a scalable, climate-adaptable solution for UGS soil management. Targeted strategies—prioritizing remediation in high-urbanization cities and prevention in low-urbanization regions—can reconcile urbanization with soil health sustainability.

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