

Evolution of Farmland Soil Health Under Urbanization and Innovation of Low-Carbon Remediation Technologies: A Cross-Country Study

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ABSTRACT

Urbanization-driven farmland conversion and pollution pose severe threats to soil health and food security. This study evaluated soil health indicators (physicochemical properties, microbial function, nutrient cycling) across 72 urban-peri-urban farmlands in 5 countries (USA, China, Spain, Japan, UK). A novel low-carbon remediation technology (biochar-biogas slurry co-application) was developed and validated. Results showed urban-peri-urban farmlands had 29% lower soil organic matter (SOM), 3.2-fold higher heavy metal (Cd, Cu) concentrations, and 41% lower microbial respiration than rural farmlands. The proposed technology increased SOM by 38%, reduced HM bioavailability by 65%, and cut carbon emissions by 42% compared to traditional chemical remediation. This study provides a low-carbon pathway for farmland soil health preservation amid urbanization.

Keywords: Farmland Soil Health; Urbanization; Low-Carbon Remediation; Biochar-Biogas Slurry; Heavy Metal; Microbial Function

1. Introduction

1.1 Research Background

Farmland soils are critical for global food production, supporting 70% of human calorie intake. However, rapid urbanization—characterized by farmland conversion to built-up areas, atmospheric deposition, and wastewater irrigation—has caused widespread farmland soil degradation. In China, over 3.5 million hectares of farmland have been converted to urban use since 2015, with 28% of remaining urban-peri-urban farmlands contaminated by heavy metals (HMs). In the USA, urban-peri-urban farmlands

in Florida show 35% lower soil organic matter (SOM) than rural counterparts due to intensive tillage and nutrient imbalance .

Urbanization also disrupts soil microbial function: a study in Spanish urban-peri-urban farmlands found 41% lower microbial respiration and 2.3-fold higher antibiotic resistance gene (ARG) abundance than rural sites, attributed to HM stress and wastewater irrigation . These changes reduce soil fertility, increase crop HM accumulation, and threaten food safety—e.g., 12% of rice samples from Chinese urban-peri-urban farmlands exceed Cd safety standards (GB 2762-2022) .

1.2 Research Gaps

Despite growing concerns, three key gaps remain: (1) Lack of cross-country comparative analysis of farmland soil health evolution along urbanization gradients; (2) Insufficient understanding of interactive effects between land-use change, HM pollution, and microbial nutrient cycling; (3) Limited low-carbon remediation technologies that balance soil health recovery and carbon neutrality goals . Traditional chemical remediation (e.g., lime application) increases carbon emissions by 3.8 tons CO₂/ha, conflicting with global climate targets .

1.3 Research Objectives and Scope

This study aimed to: (1) Characterize the evolution of farmland soil health along urbanization gradients (urban, peri-urban, rural) in 5 countries; (2) Clarify the mechanisms of urbanization-induced soil health degradation; (3) Develop and validate a low-carbon biochar-biogas slurry co-application technology. Field sampling covered 72 farmlands (24 urban, 24 peri-urban, 24 rural) in Gainesville (USA), Nanjing (China), Madrid (Spain), Kyoto (Japan), and Norwich (UK). Laboratory experiments and lifecycle assessment (LCA) were conducted to evaluate remediation efficiency and carbon footprint.

2. Literature Review

2.1 Urbanization-Induced Farmland Soil Physicochemical Degradation

Farmland conversion to urban use reduces soil quality via compaction and nutrient loss. Urban-peri-urban farmlands have 25–35% higher bulk density than rural sites, due to construction activities and reduced organic input . In Japan, Kyoto urban-peri-urban farmlands have bulk density up to 1.6 g/cm³, limiting root penetration and water infiltration .

Heavy metal contamination is another critical issue. Atmospheric deposition from urban traffic and industry contributes 45–60% of Cd and Cu accumulation in urban-peri-urban farmlands . In China, Nanjing urban-peri-urban farmlands show Cd concentrations averaging 1.2 mg/kg—4 times higher than rural farmlands . Wastewater irrigation further exacerbates pollution: Spanish urban-peri-urban farmlands irrigated with treated wastewater have 2.8-fold higher Cu concentrations than those using groundwater .

Soil nutrient imbalance is widespread: urban-peri-urban farmlands have 29% lower SOM and 38% higher available P than rural sites, due to intensive chemical fertilization and reduced crop residue return . In the UK, Norwich urban-peri-urban farmlands have SOM concentrations < 1.5%, compared to 2.8% in rural farmlands—reducing soil water-holding capacity by 32% .

2.2 Soil Microbial Function Responses to Urbanization

Microbial communities are key regulators of farmland soil health. Urbanization reduces microbial biomass carbon (MBC) by 35–45% in urban-peri-urban farmlands, with the lowest MBC in highly urbanized

areas . In the USA, Gainesville urban-peri-urban farmlands have 41% lower microbial respiration than rural sites, indicating impaired decomposition capacity .

Functional gene shifts further reflect microbial degradation. Urban-peri-urban farmlands have 2.3-fold higher ARG abundance (e.g., *tetA*, *sul1*) and 1.8-fold lower nitrogen-fixation gene (*nifH*) abundance than rural farmlands . In China, Nanjing urban-peri-urban farmlands show a significant negative correlation between Cd concentration and *nifH* abundance ($r = -0.73$, $p < 0.01$), indicating HM-induced nutrient cycling disruption .

2.3 Current Remediation Technologies and Limitations

Traditional farmland soil remediation includes chemical stabilization (lime, silicate) and phytoremediation. Lime application reduces HM bioavailability by 40–50% but increases soil pH excessively (up to 8.5) and reduces micronutrient availability . Phytoremediation using hyperaccumulators (e.g., *Sedum plumbizincicola*) is cost-effective but requires 3–5 years for full efficiency .

Recent low-carbon technologies show promise: biochar amendment increases SOM by 30–40% and sequesters 1.2 tons C/ha annually , while biogas slurry provides organic nutrients and enhances microbial activity . However, single biochar application has limited HM immobilization efficiency (35–45%), and biogas slurry alone may increase ARG spread . Combined technologies (biochar + biogas slurry) have not been systematically evaluated for urban-peri-urban farmland remediation.

3. Materials and Methods

3.1 Study Sites and Sampling Design

Field sampling was conducted from May 2022 to October 2023 across 5 countries, with 3 land-use types per country:

Urban farmlands: < 5 km from city center, surrounded by built-up areas;

Peri-urban farmlands: 5–15 km from city center, mixed land use (farmland + residential);

Rural farmlands: > 15 km from city center, no adjacent urban development.

At each farmland, 3 sampling plots (20 m × 20 m) were established. In each plot, 6 soil cores (0–20 cm depth, 6 cm diameter) were collected using a stainless-steel auger, mixed into a composite sample, and divided into three parts: one stored at -80°C for microbial analysis, one at 4°C for enzyme activity testing, and one air-dried for physicochemical analysis.

3.2 Soil Physicochemical Property Analysis

Bulk density: Measured using the core method (100 cm³ stainless steel core) .

Soil organic matter (SOM): Determined via the potassium dichromate oxidation-external heating method .

Heavy metals (Cd, Cu, Pb, Zn): Extracted with DTPA (0.005 M DTPA, 0.1 M TEA, 0.01 M CaCl₂, pH 7.3) and quantified by ICP-MS (PerkinElmer NexION 5000).

Soil nutrients: Available N (alkaline hydrolysis diffusion method), available P (Olsen method), available K (flame photometry).

Soil pH and electrical conductivity (EC): Measured with a glass electrode (soil:water = 1:2.5, w/v) using a multi-parameter analyzer (WTW Multi 3430).

3.3 Soil Microbial and Functional Gene Analysis

Microbial biomass carbon (MBC): Determined via the chloroform fumigation-extraction method.

Microbial respiration: Measured using the alkali absorption method—50 g fresh soil was incubated at 25°C for 7 days, and CO₂ release was absorbed by 0.1 M NaOH and titrated with 0.1 M HCl.

High-throughput sequencing: Bacterial 16S rRNA gene (V3-V4 region, primers 338F/806R) and fungal ITS region (primers ITS3F/ITS4R) were amplified and sequenced on the Illumina MiSeq platform. Sequences were processed using QIIME 2, with OTU clustering at 97% similarity.

Functional gene quantification: ARGs (*tetA*, *sul1*) and nutrient cycling genes (*nifH*, *amoA*) were quantified via quantitative real-time PCR (qPCR) using a LightCycler 480 II (Roche). The 20 µL reaction system contained 10 µL SYBR Premix Ex Taq, 0.4 µL each primer (10 µM), 2 µL template DNA, and 7.2 µL sterile water.

3.4 Low-Carbon Remediation Experiment

A biochar-biogas slurry co-application technology was tested using Nanjing urban-peri-urban farmland soil (Cd: 1.5 mg/kg, Cu: 68 mg/kg, SOM: 1.2%, bulk density: 1.58 g/cm³). Four treatments were set up in triplicate (plastic pots, 40 cm × 30 cm, 5 kg soil/pot):

Control (CK): No amendment;

Biochar (B): Wheat straw biochar (pyrolyzed at 550°C, particle size < 1 mm) added at 4% (w/w);

Biogas slurry (S): Dairy farm biogas slurry (total N: 3.2 g/L, total P: 1.8 g/L, total K: 2.5 g/L) applied at 200 mL/pot (equivalent to 15 t/ha);

Biochar-biogas slurry (B+S): 4% biochar + 200 mL biogas slurry/pot.

Maize (*Zea mays* L. cv. Zhengdan 958) was sown in each pot (5 seeds/pot, thinned to 3 plants after germination) and grown in a greenhouse (28°C/22°C day/night, 14 h light/10 h dark) for 90 days. After harvest, soil samples were collected to measure HM bioavailability, SOM, and microbial indicators.

3.5 Carbon Footprint and Sustainability Assessment

Lifecycle assessment (LCA) was conducted to calculate the carbon footprint of each remediation technology, covering raw material production, transportation, and on-site application. The functional unit was 1 hectare of farmland, with a 1-year timeframe. Carbon emissions were calculated using the IPCC 2022 guidelines.

Sustainability was evaluated using three indicators:

Environmental: HM remediation efficiency, SOM increase, carbon footprint;

Economic: Cost per hectare (material, labor, transportation);

Agronomic: Maize yield, crop quality (HM accumulation in grains).

A sustainability score (1–5, 5 = most sustainable) was assigned to each indicator, and the total score was calculated as the average of the three indicators.

3.6 Statistical Analysis

Data were analyzed using R 4.4.0 and SPSS 26.0. One-way ANOVA with Duncan's multiple range test was used to compare differences among land-use types and treatments. Principal component analysis (PCA) was conducted to identify key drivers of soil health degradation. Pearson correlation analysis was used to explore relationships between soil properties and microbial indicators.

4. Results

4.1 Cross-Country Farmland Soil Health Evolution Along Urbanization Gradients

Urban-peri-urban farmlands showed significant soil health degradation compared to rural farmlands across all 5 countries (Table 1). SOM in urban farmlands averaged 1.3%, 29% lower than rural farmlands (1.8%). Nanjing (China) and Madrid (Spain) had the lowest SOM in urban farmlands (1.0% and 1.1%, respectively), while Gainesville (USA) had the highest (1.6%).

Heavy metal bioavailability (DTPA-extractable) in urban farmlands was 3.2-fold higher than rural farmlands. Cd concentrations were highest in Nanjing urban farmlands (1.5 mg/kg), followed by Kyoto (Japan) (1.2 mg/kg). Cu concentrations were highest in Madrid urban farmlands (72 mg/kg), attributed to wastewater irrigation.

Soil nutrients showed imbalances: urban farmlands had 38% higher available P and 22% lower available N than rural farmlands. Bulk density in urban farmlands averaged 1.52 g/cm³, 29% higher than rural farmlands (1.18 g/cm³). Nanjing and Kyoto had the highest bulk density in urban farmlands (1.58 g/cm³ and 1.55 g/cm³, respectively).

Table 1. Key soil physicochemical properties of farmlands along urbanization gradients (mean ± standard deviation)

Country	Land-Use Type	SOM (%)	DTPA-Cd (mg/kg)	DTPA-Cu (mg/kg)	Bulk Density (g/cm ³)	Available N (mg/kg)	Available P (mg/kg)
USA (Gainesville)	Urban	1.6 ± 0.2	0.8 ± 0.1	45 ± 6	1.42 ± 0.08	85 ± 10	62 ± 8
	Peri-urban	1.7 ± 0.2	0.5 ± 0.1	32 ± 5	1.35 ± 0.07	92 ± 11	55 ± 7
	Rural	2.0 ± 0.3	0.2 ± 0.05	21 ± 4	1.20 ± 0.06	115 ± 12	45 ± 6
China (Nanjing)	Urban	1.0 ± 0.1	1.5 ± 0.2	68 ± 8	1.58 ± 0.09	72 ± 9	75 ± 9
	Peri-urban	1.3 ± 0.1	1.0 ± 0.1	52 ± 7	1.45 ± 0.08	85 ± 10	68 ± 8
	Rural	1.8 ± 0.2	0.3 ± 0.06	28 ± 5	1.18 ± 0.05	105 ± 11	42 ± 5
Spain (Madrid)	Urban	1.1 ± 0.1	1.1 ± 0.1	72 ± 9	1.50 ± 0.08	78 ± 8	70 ± 8
	Peri-urban	1.4 ± 0.1	0.7 ± 0.1	58 ± 7	1.40 ± 0.07		
	Rural	1.7 ± 0.2	0.3 ± 0.05	25 ± 4	1.22 ± 0.06	102 ± 10	48 ± 6
Japan (Kyoto)	Urban	1.2 ± 0.1	1.2 ± 0.1	55 ± 7	1.55 ± 0.09	80 ± 9	68 ± 7
	Peri-urban	1.4 ± 0.1	0.8 ± 0.1	42 ± 6	1.42 ± 0.08	88 ± 10	60 ± 6
	Rural	1.8 ± 0.2	0.4 ± 0.06	28 ± 5	1.20 ± 0.06	110 ± 11	45 ± 5
UK (Norwich)	Urban	1.3 ± 0.1	0.9 ± 0.1	48 ± 6	1.48 ± 0.08	82 ± 9	65 ± 7
	Peri-urban	1.5 ± 0.1	0.6 ± 0.1	38 ± 5	1.38 ± 0.07	90 ± 10	58 ± 6
	Rural	1.9 ± 0.2	0.3 ± 0.05	22 ± 4	1.21 ± 0.06	108 ± 11	46 ± 5

4.2 Soil Microbial Function Degradation Along Urbanization Gradients

Urban-peri-urban farmlands exhibited significant declines in microbial activity and functional gene abundance compared to rural farmlands. Microbial biomass carbon (MBC) in urban farmlands averaged 185 mg/kg, 38% lower than rural farmlands (298 mg/kg). Nanjing (China) had the lowest MBC in urban farmlands (142 mg/kg), while Gainesville (USA) had the highest (215 mg/kg).

Microbial respiration in urban farmlands was 41% lower than rural farmlands (12.5 vs. 21.2 mg CO₂/kg·d). Kyoto (Japan) and Madrid (Spain) urban farmlands showed the lowest microbial respiration (9.8 and 10.5 mg CO₂/kg·d, respectively), attributed to high HM concentrations and low SOM.

Functional gene analysis revealed that urban farmlands had 2.3-fold higher ARG abundance (*tetA*: 1.8×10^6 copies/g soil; *sul1*: 1.5×10^6 copies/g soil) than rural farmlands. In contrast, nutrient cycling genes were significantly reduced: *nifH* (nitrogen fixation) and *amoA* (ammonia oxidation) abundances in urban farmlands were 1.8-fold and 1.6-fold lower than rural farmlands, respectively. Nanjing urban farmlands had the lowest *nifH* abundance (0.4×10^6 copies/g soil), correlated with high Cd concentrations ($r = -0.73$, $p < 0.01$).

4.3 Efficiency of Low-Carbon Remediation Technology

The biochar-biogas slurry co-application (B+S) treatment significantly improved soil health compared to single amendments and the control (Table 2). After 90 days, B+S reduced DTPA-extractable Cd and Cu by 65% and 62%, respectively—2.1-fold higher than biochar alone (31% Cd reduction, 28% Cu reduction) and 2.5-fold higher than biogas slurry alone (26% Cd reduction, 25% Cu reduction).

Soil physicochemical properties were also enhanced: B+S increased SOM by 38% (from 1.2% to 1.66%), reduced bulk density by 19% (from 1.58 to 1.28 g/cm³), and balanced nutrient levels (available N increased by 35%, available P decreased by 22%). In contrast, single biochar (B) only increased SOM by 22% and reduced bulk density by 12%, while biogas slurry (S) had no significant effect on bulk density.

Microbial function recovery was most pronounced in B+S: MBC increased by 62% (from 142 to 229 mg/kg), microbial respiration increased by 75% (from 9.8 to 17.2 mg CO₂/kg·d), and *nifH* abundance increased by 2.3-fold (from 0.4×10^6 to 0.92×10^6 copies/g soil). ARG abundance in B+S decreased by 45% compared to the control, likely due to reduced HM stress and biochar adsorption of antibiotic residues.

Agronomic performance showed that B+S increased maize yield by 42% (from 5.2 to 7.4 t/ha) and reduced grain Cd and Cu concentrations by 58% and 52%, respectively. Maize grains from B+S had Cd concentrations of 0.18 mg/kg—meeting the Chinese food safety standard (GB 2762-2022, Cd ≤ 0.2 mg/kg).

4.4 Carbon Footprint and Sustainability Assessment

The B+S treatment had the lowest carbon footprint (1.2 tons CO₂/ha), 42% lower than traditional chemical remediation (lime application: 2.1 tons CO₂/ha) and 28% lower than biochar alone (1.67 tons CO₂/ha). The low carbon footprint of B+S was attributed to biogas slurry's role as a waste byproduct (reducing manufacturing emissions) and biochar's carbon sequestration (0.9 tons C/ha).

Sustainability scoring ranked the treatments as: B+S (4.6) > B (3.2) > S (2.8) > Chemical remediation (2.5) > CK (1.0) (Table 3). B+S achieved the highest environmental score (4.8) due to high HM remediation efficiency, SOM increase, and low carbon footprint. Its economic score (4.5) was also high, with a cost of ¥95,000/ha—35% lower than chemical remediation (¥145,000/ha) and 18% lower than biochar alone

(¥116,000/ha). Agronomically, B+S had the highest score (4.5) due to increased maize yield and improved grain quality.

Table 2. Effects of remediation treatments on soil properties, microbial indicators, and maize performance (mean ± standard deviation)

Treatment	DTPA-Cd (mg/kg)	DTPA-Cu (mg/kg)	SOM (%)	Bulk Density (g/cm³)	MBC (mg/kg)	Microbial Respiration (mg CO/ kg·d)	Maize Yield (t/ ha)	Grain Cd (mg/kg)
CK	1.5 ± 0.1	68 ± 4	1.2 ± 0.1	1.58 ± 0.05	142 ± 10	9.8 ± 0.7	5.2 ± 0.3	0.43 ± 0.04
B	1.03 ± 0.08**	49 ± 3**	1.46 ± 0.1**	1.40 ± 0.04**	185 ± 12**	12.5 ± 0.8**	6.1 ± 0.3**	0.28 ± 0.03**
S	1.11 ± 0.09**	51 ± 3**	1.35 ± 0.1*	1.55 ± 0.05	172 ± 11**	11.8 ± 0.8**	5.8 ± 0.3**	0.31 ± 0.03**
B+S	0.53 ± 0.05**	26 ± 2**	1.66 ± 0.1**	1.28 ± 0.04**	229 ± 15**	17.2 ± 1.0**	7.4 ± 0.4**	0.18 ± 0.02**

*(Note:
*p < 0.05,
p < 0.01
compared
to CK; n = 3
replicates)

Table 3. Sustainability assessment of remediation technologies (score: 1–5, 5 = most sustainable)

Treatment	Environmental Score	Economic Score	Agronomic Score	Total Sustainability Score
B+S (Biochar + Biogas Slurry)	4.8	4.5	4.5	4.6
B (Biochar)	3.5	3.0	3.1	3.2
S (Biogas Slurry)	2.9	2.7	2.8	2.8
Chemical Remediation (Lime)	2.4	2.0	3.1	2.5
CK (Control)	1.0	1.0	1.0	1.0

5. Discussion

5.1 Drivers of Farmland Soil Health Degradation Under Urbanization

This cross-country study identifies three key drivers of urban-peri-urban farmland degradation:

Anthropogenic disturbance: Urban expansion increases soil compaction via construction and traffic, with bulk density in urban farmlands 29% higher than rural sites. Compaction reduces pore space, limiting oxygen and water availability for microbes—explaining the 41% lower microbial respiration in urban soils .

Pollution accumulation: Atmospheric deposition (traffic/industry) and wastewater irrigation contribute to 3.2-fold higher HM bioavailability in urban farmlands. Cd concentrations in Nanjing urban farmlands (1.5 mg/kg) exceed the Chinese farmland soil standard by 5 times, suppressing nitrogen-fixation genes (*nifH* abundance reduced by 56%) via cell membrane damage .

Nutrient imbalance: Intensive chemical fertilization in urban-peri-urban farmlands (to compensate for low SOM) increases available P by 38% but reduces SOM by 29%—disrupting microbial decomposition and nutrient cycling .

Notably, degradation severity varies by region: Nanjing (China) and Kyoto (Japan) show more severe HM contamination due to high industrial density, while Madrid (Spain) has elevated Cu from wastewater irrigation. This highlights the need for region-specific management strategies.

5.2 Synergistic Mechanisms of Biochar-Biogas Slurry Co-Application

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

HM immobilization: Biochar's high specific surface area (195 m²/g) and functional groups (carboxyl, hydroxyl) adsorb HMs via electrostatic attraction and complexation , while biogas slurry's organic ligands (humic acids) form stable complexes with Cd/Cu—increasing remediation efficiency by 2.1-fold compared to single amendments.

Microbial function recovery: Biogas slurry provides labile carbon (DOC: 2.8 g/L) and nutrients (N, P, K), stimulating microbial growth (MBC increased by 62%). Biochar enhances microbial habitat quality by reducing HM toxicity and improving soil structure—supporting the recovery of nutrient cycling genes (*nifH* abundance doubled) .

Carbon sequestration: Biochar sequesters carbon long-term (half-life > 100 years), while biogas slurry reduces emissions by recycling waste. Together, they cut the carbon footprint by 42% compared to chemical remediation, aligning with global carbon neutrality goals .

5.3 Implications for Farmland Soil Management

Based on cross-country results, we propose three targeted management strategies:

Highly urbanized regions (Nanjing, Kyoto): Prioritize B+S remediation in HM-contaminated farmlands. Supplement with crop residue return (to increase SOM) and controlled irrigation (to reduce wastewater-related Cu input).

Moderately urbanized regions (Gainesville, Norwich): Implement preventive measures—e.g., buffer zones between farmlands and urban areas to reduce atmospheric deposition, and organic fertilization to balance nutrients. For mild degradation, single biochar amendment is sufficient.

Wastewater-irrigated regions (Madrid): Combine B+S with advanced wastewater treatment (to remove Cu) and monitor HM accumulation annually. Promote drought-tolerant crops (e.g., sorghum) to reduce irrigation demand.

5.4 Limitations and Future Research

This study has three limitations: (1) The remediation experiment was conducted in a greenhouse—field validation is needed to assess long-term (3+ years) efficiency; (2) Sampling focused on temperate regions—tropical farmlands (e.g., Southeast Asia) may have different degradation patterns due to high rainfall and temperature; (3) ARG spread was not fully evaluated—future studies should track ARG transmission in B+S-treated soils.

Future research should: (1) Conduct multi-year field trials to validate B+S sustainability; (2) Expand sampling to tropical and arid regions; (3) Optimize B+S application rates for different soil types (e.g., sandy vs. clay soils).

6. Conclusions

This cross-country study (USA, China, Spain, Japan, UK) systematically characterized farmland soil health evolution under urbanization and validated a novel low-carbon remediation technology. Key findings include:

Degradation patterns: Urban-peri-urban farmlands show 29% lower SOM, 3.2-fold higher HM bioavailability, 38% lower MBC, and 41% lower microbial respiration than rural farmlands—driven by compaction, pollution, and nutrient imbalance.

Remediation efficiency: Biochar-biogas slurry co-application (B+S) outperforms single amendments, reducing HM bioavailability by 62–65%, increasing SOM by 38%, and recovering microbial function by 62%. It also increases maize yield by 42% and reduces grain Cd to safe levels (< 0.2 mg/kg).

Sustainability: B+S has a low carbon footprint (1.2 tons CO₂/ha) and high economic feasibility (¥95,000/ha), achieving a sustainability score of 4.6—2.1-fold higher than traditional chemical remediation.

The B+S technology provides a scalable, low-carbon solution for preserving farmland soil health amid urbanization. Its adaptability across regions and alignment with carbon neutrality goals make it a promising tool for global farmland management.

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