

Engineering Evaluation of Microbe-Material Synergistic In-situ Remediation for Campus Landscape Lakes

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Abstract. Campus landscape lakes are vulnerable to combined organic and nutrient pollution because of weak hydrodynamics and limited self-purification capacity. Conventional in-situ remediation often suffers from rapid material loss and short treatment duration. This study evaluated the engineering applicability of microbe-material synergistic remediation through integrated analysis of 28 published field cases and a field investigation of a campus artificial lake in Nanning, China. The integrated results showed removal efficiencies of 82.7% for $\text{NH}_4^+\text{-N}$, 76.4% for COD, and 68.5% for TP. Dissolved oxygen (DO) was identified as a key influencing factor, and COD removal was markedly improved when DO exceeded 2 mg/L. Field monitoring indicated low-oxygen combined pollution, while historical records showed that direct material dosing led to a loss rate of over 60% and an effective treatment duration of less than three weeks. A gel microsphere encapsulation strategy based on alginate and chitosan is therefore proposed to improve material retention and treatment persistence.

1. INTRODUCTION

Campus landscape lakes are small enclosed water bodies with low flow velocity and limited self-purification capacity. They are easily affected by runoff, domestic wastewater input, and nutrient accumulation, which often results in elevated COD, ammonia nitrogen, and total phosphorus. In subtropical regions, algal growth and low dissolved oxygen frequently occur during warm seasons^[1-2].

Microbe-material synergistic in-situ remediation has been increasingly applied in landscape water treatment because it combines microbial degradation with material adsorption^[3-5]. However, its engineering performance in campus lakes remains insufficiently evaluated, especially with respect to environmental constraints, material selection, and treatment persistence^[6].

This study integrated recent field application cases and combined them with a field investigation of a campus artificial lake in Nanning, China, to evaluate remediation performance, identify major engineering constraints, and propose an optimization strategy for improving material retention.

2. MATERIALS AND METHODS

2.1 Case Collection and Screening

Field studies published from January 2020 to February 2025 were collected from Web of Science, ScienceDirect, and CNKI. The search terms included in-situ remediation,

campus pond, urban landscape water, biochar, zeolite, and microbial agent, as well as their Chinese equivalents. Eligible studies met the following criteria: (1) the study object was a small enclosed landscape water body located in a campus or park, with an area of less than 5 hm^2 ; (2) the remediation strategy involved combined material-microbe treatment; (3) water quality data before and after treatment were available for at least one of the major indicators (COD, $\text{NH}_4^+\text{-N}$, and TP); and (4) the field operation period was no less than 14 days. Indoor simulation studies and studies with incomplete or abnormal data were excluded. After screening, 28 eligible field cases were included for the integrated analysis.

2.2 Statistical Analysis of Integrated Cases

The standardized mean difference (SMD) was used as the effect size to evaluate the overall performance of the synergistic systems for COD, $\text{NH}_4^+\text{-N}$, and TP removal. For each case, SMD was calculated based on the difference between post-treatment and pre-treatment means divided by the pooled standard deviation^[7-8]. Heterogeneity was assessed using Cochran's Q test and the I^2 statistic^[9]. A random-effects model was applied. Publication bias was examined using funnel plots and Egger's test^[10-12]. In addition, subgroup analyses were performed according to material type, microbial category, climatic condition, and DO level to identify the major factors affecting remediation performance.

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2.3 Field Investigation

A campus artificial lake in Nanning, China, was selected as the study site. The lake area was about 0.8 hm² and the average depth was about 1.5 m. Three sampling sites were set in the dormitory area, lake center, and greenbelt area. Sampling was conducted once per week over four consecutive weeks from late September to mid-October 2024, yielding four sampling events in total. At each sampling event, all field and laboratory parameters were measured at the three sampling sites. DO, pH, and water temperature were measured in situ, while COD, NH₄⁺-N, and TP were analysed in the laboratory according to standard methods for water quality analysis. Historical treatment records and staff interviews were also collected to identify engineering problems in previous remediation practice.

3. RESULTS AND DISCUSSION

3.1 Overall Remediation Performance

The integrated results showed that the microbe-material synergistic systems achieved removal efficiencies of 82.7% for NH₄⁺-N, 76.4% for COD, and 68.5% for TP (Figure 1). Compared with single-treatment approaches, NH₄⁺-N and COD removal increased by 37.2% and 43.6%^[13-14], respectively, indicating a clear synergistic effect between microbial degradation and material adsorption. Moderate heterogeneity was observed for COD and NH₄⁺-N, mainly associated with differences in water body area and hydraulic retention time^[15]. No significant publication bias was detected.

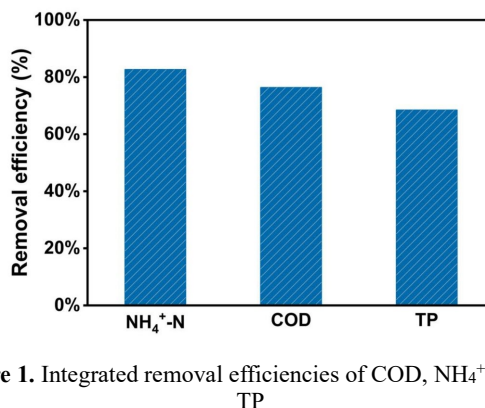


Figure 1. Integrated removal efficiencies of COD, NH₄⁺-N, and TP

3.2 Influence of Dissolved Oxygen

DO was identified as a key factor affecting remediation performance. When DO was higher than 2 mg/L, COD removal reached 83.4%; under lower DO conditions, it decreased to 61.9%. This result suggests that hypoxia can significantly reduce the effectiveness of microbe-material systems in campus lakes. In contrast, pH within 6.5-8.0 showed limited influence on system stability.

3.3 Applicability of Different Material-microbe Combinations

Different material-microbe combinations performed differently under different pollution conditions^[16]. The biochar-compound bacteria combination showed better performance for organic pollution, with COD removal of 81.4%, and maintained about 75% treatment efficiency after six weeks in subtropical regions^[13]. The zeolite-nitrifying bacteria combination was more effective for ammonia removal, reaching 86.8%^[14], and also supported regeneration of adsorption sites. The activated carbon-functional bacteria combination showed relatively better TP removal, with an efficiency of 72.5% (Table 1)^[8]. These results indicate that process selection should match the dominant pollution characteristics of the target water body^[17].

Table 1. Main material-microbe combinations and recommended application scenarios

Combination	Main target pollutant	Representative performance	Main advantage	Recommended scenario
Biochar-compound bacteria	Organic matter (COD)	COD removal: 81.4%	Strong adsorption-biodegradation synergy; relatively stable in subtropical operation	Campus lakes dominated by organic pollution
Zeolite-nitrifying bacteria	Ammonia nitrogen	NH ₄ ⁺ -N removal: 86.8%	High ammonia removal and support for adsorption-site regeneration	Water bodies with elevated ammonia nitrogen
Activated carbon-functional bacteria	Total phosphorus	TP removal: 72.5%	Better phosphorus-oriented adsorption performance	Lakes with phosphorus enrichment or eutrophication risk

3.4 Field Investigation and Engineering Constraint

The investigated artificial lake showed a typical low-oxygen combined pollution condition. The measured

COD, NH₄⁺-N, TP, and DO were 38.6 ± 4.2 mg/L, 2.41 ± 0.35 mg/L, 0.52 ± 0.08 mg/L, and 1.8 ± 0.3 mg/L, respectively. Both NH₄⁺-N and TP exceeded the Class V surface water standard in China (Figure 2 and Table 2). Historical records indicated that the lake had previously been treated twice by direct material dosing, but the

material loss rate exceeded 60%, and the effective treatment period was less than three weeks. Therefore,

rapid material loss was identified as the main engineering barrier affecting remediation persistence.

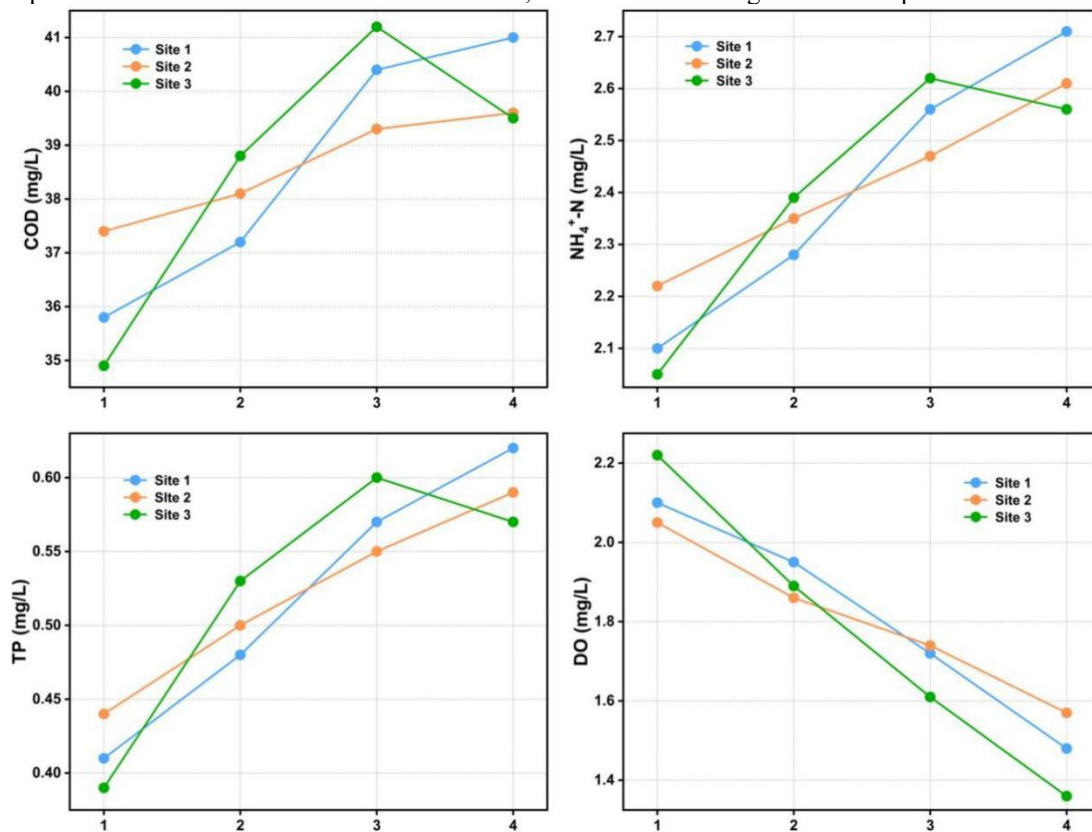


Figure 2. Temporal variations in COD, NH₄⁺-N, TP, and DO at the three sampling sites

Table 2. Water quality characteristics and engineering constraints of the investigated campus artificial lake

Indicator	Measured value	Status	Interpretation
COD	38.6 ± 4.2 mg/L	Elevated	Organic pollution present
NH ₄ ⁺ -N	2.41 ± 0.35 mg/L	Above Class V limit	Severe ammonia accumulation
TP	0.52 ± 0.08 mg/L	Above Class V limit	Obvious phosphorus enrichment
DO	1.8 ± 0.3 mg/L	Low	Hypoxic condition restricting remediation efficiency
Previous direct dosing	2 events	Implemented	Conventional engineering attempt
Material loss rate	>60%	High	Poor retention after dosing
Effective treatment period	<3 weeks	Short	Weak treatment persistence

3.5 Engineering Optimization

To reduce material loss, a gel microsphere encapsulation strategy using alginate and chitosan was proposed. Biochar and compound bacteria can be immobilized into microspheres with particle sizes of 2-5 mm. This strategy may enhance material retention, provide a more stable microenvironment for microorganisms, and prolong the treatment period. Owing to the favourable biocompatibility and biodegradability of the wall materials, the proposed approach is suitable for campus landscape lake applications. However, its practical performance still requires pilot-scale validation.

3.6 Integrated Interpretation of Case Integration and Field Investigation

The integrated cases showed that microbe-material synergistic remediation can achieve considerable pollutant removal under appropriate environmental conditions, whereas the field investigation revealed that the studied campus lake remained under low-oxygen combined pollution and suffered from serious material loss during previous direct-dosing treatments. These two findings are not contradictory. Instead, they indicate that the engineering performance of this technology depends not only on the intrinsic removal capacity of the material-microbe system, but also on environmental support and material retention in the target water body. In the present

case, the low DO condition likely restricted microbial activity, while rapid material loss shortened the effective treatment period and reduced remediation persistence. Therefore, improving material retention should be considered a priority for the practical application of in-situ remediation in campus landscape lakes.

4. CONCLUSIONS

Microbe-material synergistic in-situ remediation showed good potential for treating combined pollution in campus landscape lakes, especially for ammonia nitrogen and COD removal. Dissolved oxygen was identified as a key limiting factor, and maintaining DO above 2 mg/L is important for stable treatment performance. The field investigation in Nanning showed that rapid material loss after direct dosing was the principal engineering constraint. A gel microsphere immobilization strategy was therefore proposed as a potential approach to improve material retention and treatment persistence, although its actual engineering effect still requires further validation.

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REFERENCES

1. Chen H, Ma L, Guo X, et al. Biochar immobilized bacteria for in-situ remediation of eutrophic landscape water: A field study in southern China. *Journal of Environmental Sciences*, 2024, **136**: 245-256.
2. Wang T, Li Y, Zhang J, et al. Performance comparison of different porous materials in purifying urban polluted ponds. *Environmental Pollution*, 2023, **320**: 121089.
3. Liu X, Zhao K, Xu L, et al. Meta-analysis of microbial remediation efficiency in urban water bodies: Influencing factors and uncertainty. *Water Research*, 2023, **235**: 119876.
4. Zhou Q, Ding Y, Wu F, et al. Zeolite combined with nitrifying bacteria for ammonia removal in campus scenic ponds. *Chemosphere*, 2022, **303**: 135012.
5. Yang B, Xu H, Liu Y, et al. Long-term performance of slow-release bioremediation materials in landscape water: A two-year observation. *Science of the Total Environment*, 2022, **835**: 155433.
6. Zhang Wei, Li Na, Wang Lei. Field experimental study on remediation of campus landscape water by biochar combined with microorganism. *Journal of Environmental Engineering*, 2023, **17**(5): 1523-1532.
7. Kim J, Park S, Lee H, et al. Alginate-encapsulated biochar for sustained release of nutrients and microbial agents in water treatment. *Journal of Hazardous Materials*, 2024, **465**: 133124.
8. Park H, Kim Y, Lee S, et al. In-situ remediation of urban ponds using functional materials: A multi-year field study in Seoul. *Water Research*, 2023, **241**: 120089.
9. Wang Xiaodong, Zheng Hong, Ma Jun. Application progress of microcapsule technology in environmental pollution control. *Chemical Industry and Engineering Progress*, 2023, **42**(3): 1456-1468.
10. Xu J, Wang Q, Li Z, et al. Field application of functional bacteria combined with zeolite for rapid ammonia removal in eutrophic ponds. *Journal of Water Process Engineering*, 2023, **53**: 103678.
11. Liu M, Zhang Y, Wang H, et al. Lanthanum-modified activated carbon for enhanced phosphate removal in urban landscape water. *Journal of Cleaner Production*, 2024, **435**: 140023.
12. Chen W, Lin Z, He Y, et al. Biofilm formation on biochar surfaces in subtropical climate: Implications for long-term water remediation. *Bioresource Technology*, 2024, **395**: 130245.
13. Luo Y, Chen S, Huang L, et al. Effects of dissolved oxygen on microbial community structure during biochar-assisted remediation. *Frontiers in Microbiology*, 2022, **13**: 892345.
14. Liu Wei, Gao Ning, Zhang Min. Water quality status and eutrophication evaluation of typical landscape water bodies in Nanning. *Environmental Science Survey*, 2023, **42**(4): 45-51.
15. Zhao Feng, Huang Li, Sun Tao. Effect of aging process of biochar on its adsorption performance and its mechanism. *Environmental Chemistry*, 2022, **41**(7): 2234-2243.
16. Li Hua, Wang Fang, Zhang Qiang. Application effect and microbial response of compound microbial agents in landscape water remediation. *Environmental Science*, 2023, **44**(9): 5012-5021.
17. Sun Peng, Zhou Tao, Zheng Yang. Characteristics and Source Analysis of Campus Landscape Water Pollution in Nanning City. *Environmental Science Survey*, 2024, **43**(1): 32-38.