Integrating Biochar-Based Microbial Technologies with Ecosystem Regulation for Lake Organic Pollution Control

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Abstract. In recent years, lake water pollution has become increasingly serious, especially organic pollution, which has become a major problem affecting water quality and ecological security. Many physical/chemical methods used for treatment have instead caused secondary pollution to the environment. This study aims to explore the feasibility of using this multi-scale synergistic mechanism to treat organic pollutants in lakes and some future research directions, providing a sustainable and environmentally friendly approach to the treatment of organic pollutants in lakes. The combination of biochar-microbe systems with technologies such as constructed wetlands, submerged plant restoration, and food chain regulation, which utilize the ecosystem's own repair capabilities to restore the ecological environment, has formed a multi-scale synergistic system of "biochar-microbes-ecosystem regulation." Studies have shown that this system enhances the ability of microorganisms to degrade organic pollutants at the microscopic level, promotes plant-microbe interactions at the mesoscopic level, and strengthens the self-repair capacity of the ecosystem at the macroscopic level. This synergistic system can significantly improve the removal rate of organic pollution and the efficiency of ecological restoration. This method is highly sustainable and environmentally friendly and is expected to reduce reliance on traditional physical or chemical methods, avoid potential secondary pollution, and fully leverage the ecosystem's own regulatory and self-repair capabilities to achieve effective governance of lake water environments. Challenges include key bottlenecks in the mechanism of action, material stability, and ecological adaptability of this synergistic system. Future research should focus on multi-scale mechanism analysis and interdisciplinary integration to promote its advancement towards ecological engineering and large-scale application.

1 Introduction

Lakes are an important part of the Earth's ecosystem and play a key role in water resource regulation, biodiversity maintenance and climate balance. However, in recent years, lake ecosystems have been increasingly threatened, with organic pollution becoming a major

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problem affecting water quality and ecological security. Human activities such as agricultural runoff, industrial emissions and domestic sewage have introduced a large number of organic pollutants (such as pesticides, antibiotics and petrochemical residues) into lakes. These pollutants are persistent, bioaccumulate easily and are highly toxic, which not only damages aquatic ecosystems but may also harm human health through the food chain. Although various treatment methods such as physical adsorption and biodegradation have been widely studied and applied, how to achieve efficient and eco-friendly treatment of organic pollution in lakes is still an important problem to be solved in the field of environmental remediation.

Existing research mainly focuses on two types of lake pollution control pathways. The first type is material remediation technology, such as activated carbon and nano-adsorbents, which have strong adsorption performance, but have problems such as high cost, difficulty in regeneration and poor ecological compatibility. The second type is bioremediation technology, such as microbial and phytoremediation, which have environmentally friendly and sustainable characteristics, but are still limited in terms of efficiency and long-term stability. In contrast, biochar has strong adsorption capacity, adjustable structure and good ecological compatibility, and shows unique advantages in promoting pollutant removal, microbial colonization and ecosystem balance. Although existing studies have confirmed the potential of biochar-microbial systems in the adsorption and degradation of organic pollutants, related work is mostly limited to the laboratory or small-scale stage, and there is a lack of systematic research on its integration and synergistic application in actual lake ecosystems.

This review aims to build a bridge between biochar technology, microbial remediation, and ecosystem regulation, providing theoretical ideas and technical references for the sustainable governance of organic pollution in lakes in the future, and promoting the engineering transformation and practical application of "biochar-microbe-ecosystem synergy" in lake ecological restoration.

2 Biochar and its mechanism of action in microbial remediation

2.1 Physicochemical properties and environmental functions of biochar

Solid aromatic fluorocarbon complexes are produced through thermal decomposition or gasification of biomass and are a source of biochar. The value of biochar in the treatment of organic pollutants in lakes lies in its ability to fix various harmful organic substances, including tetracycline, metronidazole, antibiotics, various dyes and neonicotinic acid, and its bioavailability is reduced due to its rich porous structure and oxygen-containing functional groups.

2.2 Mechanism of action and synergistic mechanism of biochar as a microbial carrier

Biochar has two external physical properties: high porosity and rough surface, which contribute to its large surface area. The increased surface area promotes hydrophobic, hydrogen bond and electrostatic interactions between microorganisms and the biochar surface, enhances the surface adhesion of microorganisms, and promotes the attachment of free cells to the surface of biochar.

The carboxyl (-COOH), hydroxyl (-OH), quinone (=O-O=), ester (C=O-O-C), and ketone (=O) groups on the surface of biochar have a high affinity for adsorbing nutrient ions (such as nitrates and phosphates), which can increase the amount of nutrients required by microorganisms, thereby improving their added value tolerance and survival rate. At the same time, biochar provides a large number of active sites for the metabolic reactions of microorganisms, plays the role of electron acceptor or donor, and acts as a medium for redox reactions to influence the metabolic reactions of microorganisms [1].

It has been confirmed that microorganisms adhere to biochar through a self-aggregation process in EPS, forming a membrane-active complex of microorganisms and their byproducts. The surface of biochar has several active regions that can promote the growth and adhesion of microorganisms, enhance their decomposition and metabolism of toxic substances [2]. Furthermore, EPS can act as a medium to enhance the electrochemical properties of biochar and promote electron transfer between microorganisms and biochar, thereby achieving a synergistic effect [3].

On the other hand, the large surface area and porous structure of biochar provide shelter for attached microorganisms [4]. The abundant carbon functional groups on biochar also provide a rich carbon source for the growth of microorganisms, while EPS, as the "carbon source transport carrier" for both, assists microorganisms in using the carbon source in biochar to grow and develop [5].

Furthermore, it has been found that EPS plays a crucial role in the biofilm between microbial cells. As an adhesive between microbial cells, it affects the growth and attachment of microorganisms on the biochar surface, thereby forming a more stable microbial community structure [6]. In one study, the main components of EPS released by microorganisms in the absence of biochar (CK) and on the biochar surface (BC) were examined using excitation matrix (EEM) spectroscopy. The results showed that the EPS content in the BC group was much higher than that in the CK group, and the fluorescence intensity of the three components, biochar (AP), soluble microbial products (SMP), and humic acid analogues (HA), was significantly higher than that in the CK group. This further indicates that biochar can increase EPS secretion, which in turn promotes the formation and stability of related biofilms [7].

2.3 Application of biochar-microbial systems in the treatment of organic pollution in water bodies

Currently, many researchers have studied the use of biochar-microbial technology for the treatment of organic pollution in water bodies. Domestic sewage contains large amounts of persistent and difficult-to-treat pollutants such as chlorophenol, nonylphenol, and nitrates. Research has been done to eliminate these pollutants, and in order to eliminate 2,4-DCP (6 mg/L) from polluted surface runoff, a highly bioreactive surface soil has been created in conjunction with microorganisms and biochar. Within 72 hours, the immobilized microbes of peanut shell biochar reached 95.03% of the 2,4-DCP destination, demonstrating strong adsorption and degrading capabilities [8].

Additionally, research has shown that biochar made from poplar and cork bark might encourage the proliferation of microbes. Naphthalic acids (NAs) and metals are eliminated from industrial water using biochar immobilization microbiological technique. It was discovered that the elimination rate of NAs (200 mg/L) was as high as 87%, whereas the sterile control group's rate was just 30% [9].

Furthermore, some scholars have studied the immobilization of Vibrio bacteria that produce biosurfactants. LQ2 was used in conjunction with corn straw biochar to treat diesel pollution in the ocean (1% (v/v)) [10]. These studies not only verified the wide applicability of the biochar-microbe synergistic system in the treatment of various complex organic pollutants, demonstrating the higher efficiency and environmental friendliness of biochar-microbe technology, but also provided strong experimental evidence and technical support for its promotion and application in actual water environments such as lakes.

3 The role of ecosystem regulation in lake restoration and its synergistic mechanism with biochar-microbe systems

3.1 Basic principles of ecosystem regulation in lake restoration

Lake ecosystems are complex socio-ecological systems composed of natural processes and human activities, and their stability depends on the dynamic balance between nutrient cycling and management feedback. Some academics have noted that the lake system maintains a temporary equilibrium between internal regulation and external disturbance rather than having a permanent balance. This feature suggests that by changing the ecological feedback loop, ecological restoration techniques like wetland restoration can move the system to a state of higher quality and lower maintenance costs [11].

3.2 Three types of ecosystem regulation mechanisms and their coupling pathways with biochar-microbe systems

3.2.1 Constructed wetland systems and biochar-microbe coupling pathway

Constructed wetlands are a type of eco-engineering that achieves the sedimentation, adsorption, and degradation of pollutants through the synergistic action of plants, microorganisms, and substrates. They are one of the most widely used ecological regulation methods in lake restoration. The core of this is that plant photosynthesis promotes dissolved oxygen release, microorganisms participate in the decomposition of organic matter, and the substrate achieves preliminary adsorption. However, traditional substrates such as sand and gravel are prone to problems such as adsorption decay and single-function. After the introduction of biochar, its porous structure and functional groups significantly enhance the adsorption capacity and microbial colonization ability of wetlands, while improving the rhizosphere redox state and nutrient exchange, and improving the synergistic efficiency of plants, microorganisms, and substrates. It performs excellently in removing organic pollution and improving system stability.

3.2.2 Submerged plant restoration and biochar-microbe synergistic pathway

Submerged plant ecological restoration is one of the most widely used technologies in eutrophic water bodies. It mainly removes nutrients such as nitrogen and phosphorus from the water body through the absorption of roots, stems and leaves of plants and the biotransformation function of attached microorganisms. At the same time, it increases dissolved oxygen, stabilizes bottom sediment and provides a habitat for aquatic organisms, thereby enhancing the self-purification capacity of the lake ecosystem [12]. However, this system is susceptible to water quality deterioration, bottom sediment pollution and light conditions, and plants are prone to degradation and the activity of microbial communities is unstable [13]. Introducing biochar-microbe systems into the plant root zone or bottom sediment can buffer the toxicity of pollutants, fix rhizosphere pollutants and provide a stable attachment substrate for degrading bacteria. Organic pollutants adsorbed by biochar can be used as carbon sources for microorganisms, and its conductivity promotes rhizosphere electron transfer and improves co-metabolic efficiency. In addition, biochar can regulate rhizosphere physicochemical conditions such as pH and conductivity, effectively alleviate pollution stress, improve plant tolerance, and enhance the overall interaction efficiency between plants and microorganisms, thereby improving the stability and resilience of the ecosystem.

3.2.3 Food chain regulation mechanisms and carbon–fungus embedding pathways

Food chain regulation achieves indirect control over algae, water quality, and pollutants in water bodies through artificial intervention in the food web structure (such as stocking filter-feeding fish or managing benthic animals) and serves as an important supplement to the regulation of lake ecosystems. Its advantages include low maintenance and high adaptability, but the regulation effect can be unstable due to disturbances such as climate and hydrological fluctuations. Integrating a biochar–microorganism system into this can achieve synergistic effects through the following pathways: on one hand, biochar can adsorb organic pollutants, stabilizing water quality and reducing toxic substrate loads, providing a safer habitat for primary producers and benthic animals; on the other hand, microbial degradation can reduce the accumulation of harmful metabolites and mitigate the risk of excessive algal growth. In addition, biochar can also serve as a nutrient and energy buffering platform, balancing energy flow within the food chain, helping to stabilize key trophic levels, and overall enhancing the regulatory resilience of the ecosystem.

4 Challenges and future prospects of biochar-microorganism-ecosystem synergistic systems

4.1 Existing challenges

Despite the promising application results of the biochar-microbe-ecosystem synergistic system, a series of key challenges remain in its transition from experimental validation to practical implementation. First, the long-term survival and activity maintenance of microbial communities in the natural environment are unstable, and biochar materials may experience aging, clogging, and saturation, affecting the sustainability of remediation. Second, the molecular-level understanding of the synergistic mechanism is still limited, and the fate and ecological safety of some intermediate metabolites require further evaluation. Furthermore, the system faces practical difficulties in its application from the laboratory to the entire lake scale, particularly regarding uniform dosing, recovery mechanisms, compatibility with the original ecosystem, and adaptation to seasonal changes. Finally, the economic costs of large-scale preparation, transportation, and storage of biochar are not yet clear, and a systematic analysis of its life-cycle benefits is needed.

4.2 Future outlook

With the continuous evolution of the concept of lake ecological pollution control, the multi-scale synergistic system of "biochar-microbe-ecosystem regulation" has shown good environmental friendliness and application potential. Future research should focus on the following three directions: First, the development of customized materials. Functional biochar with high specific surface area and specific active sites should be designed for different pollutants and lake types to achieve stronger adsorption and catalytic synergistic effects. Second, the construction of efficient microbial agents. Through strain screening and community optimization, composite degradation bacteria with strong environmental adaptability and complementary functions should be cultivated to break through the bottleneck of long-term stability and stress resistance and build a truly meaningful "living material". Third, the optimization and integration of synergistic governance schemes. Under different lake ecological backgrounds, phased and regional application strategy research should be carried out to optimize the addition parameters and operation process, promote the transition from single-point experiments to system governance, and help the engineering implementation of lake ecological restoration. Future research can also draw on the social-ecosystem modeling idea to incorporate the biochar-microbe-ecosystem synergistic system into a broader lake management framework, comprehensively consider the interaction between ecological processes, management feedback and policy decisions, and thus promote the development of lake restoration towards systematization and dynamism.

5 Conclusion

This paper studies a biochar-microbe-ecosystem synergistic system. This system, through a three-dimensional coupling of physical, chemical, and biological processes, enhances microbial degradation and pollutant transformation, plant-microbe interactions and nutrient cycling, and ecosystem stability and self-repair capabilities at multiple levels, constructing a highly environmentally friendly and sustainable governance model. Research shows that this system can significantly improve the efficiency of organic pollution removal and ecological restoration, demonstrating good application potential and promotional value.

However, its large-scale engineering application still faces practical challenges such as insufficient material stability, imbalanced microbial community structure, insufficient ecological safety assessment, and unclear economic feasibility. Future research should focus on material development, microbial screening, and optimization of synergistic governance schemes to systematically improve the stability and adaptability of the biochar-microbe-ecosystem, promoting its development from laboratory theory to engineering applications.

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