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Microbial Control of Cyanobacterial Blooms in Erhai Lake

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Abstract. Erhai Lake is a plateau lake of significant ecological and socio-economic value. In recent years, continuous external inputs of nitrogen and phosphorus, together with internal factors, have intensified eutrophication, leading to a markedly increased risk of cyanobacterial blooms. Traditional physical and chemical control methods are constrained by high costs and considerable ecological risks. In response to the needs of bloom management in Erhai Lake, this paper systematically reviews its hydrological and ecological characteristics, as well as the core mechanisms and mainstream application technologies of microbial algal control, providing methodological references for the management of cyanobacterial blooms in plateau lakes.

1. Introduction

Erhai Lake is located in the Dali Bai Autonomous Prefecture of Yunnan Province and is a typical plateau lake that integrates ecological functions with socio-economic values such as water supply and tourism. Owing to its relatively large surface area and shallow depth, the lake's hydrodynamic processes and nutrient cycling are highly sensitive to external disturbances. With the growth of the watershed population and the development of industrial activities, multi-source discharges—including agricultural non-point sources, livestock and poultry breeding, and urban domestic wastewater—have led to a continuous increase in external nitrogen and phosphorus inputs. As a result, the water quality of Erhai Lake has exhibited aggravated eutrophication and an elevated risk of algal blooms[1]. Cyanobacteria are a group of photosynthetic prokaryotes that possess a strong competitive advantage in eutrophic waters. A cyanobacterial bloom refers to the phenomenon in which, under conditions of elevated nutrient levels such as nitrogen and phosphorus, cyanobacteria proliferate rapidly and accumulate on the water surface under the combined influence of suitable temperature, light, and hydrodynamic conditions. The occurrence and recurrence of cyanobacterial blooms in Erhai Lake are generally driven fundamentally by the long-term excessive input of external nitrogen and phosphorus nutrients, and are further triggered by conditions such as rising water temperatures and weakened lake hydrodynamics in the context of climate warming. At the same time, they are reinforced by feedback from internal processes, including changes in microbial community structure and function, as well as a decline in the ecosystem's self-purification capacity[2].

Cyanobacterial blooms can reduce water transparency and inhibit the growth of submerged macrophytes. Moreover, their formation and decay processes may cause significant fluctuations in dissolved oxygen, increasing the risk of localized hypoxia. At the same time, the accumulation of algal metabolites and large loads of organic matter can substantially increase the difficulty of water treatment and the risks to drinking water safety, while also adversely affecting tourism and fisheries. Therefore, it is imperative to explore bloom control strategies that are both effective and ecologically safe. However, in large plateau lakes, the vast water area, pronounced variability in meteorological and hydrological conditions, and the combined effects of external inputs and internal nutrient cycling pose significant challenges to bloom management in terms of engineering feasibility, cost constraints, and ecological risks.

At present, cyanobacterial bloom control mainly relies on physical and chemical methods. Physical measures—such as mechanical harvesting, hydrodynamic regulation, and aeration–mixing—can achieve short-term reduction to some extent, but at the scale of large lakes, they are constrained by factors such as limited coverage, high operational costs, and maintenance demands, making it difficult to sustainably suppress recurrent blooms. Chemical approaches typically involve the application of algaecides or flocculants to rapidly reduce algal biomass; however, their effects are often limited to short-term reductions in cyanobacterial density and fail to alter the underlying eutrophic conditions that promote regrowth. In addition, they may produce non-target effects, posing ecological risks and potential secondary pollution, thereby creating clear trade-offs between ecological safety and long-term management goals.The mechanisms of microbial algal control can generally be categorized into two types. The first is direct inhibition or lysis of algae, whereby relevant microorganisms interfere with cyanobacterial physiological processes through mechanisms such as cell-contact-mediated lysis, competitive inhibition, or the secretion of algicidal

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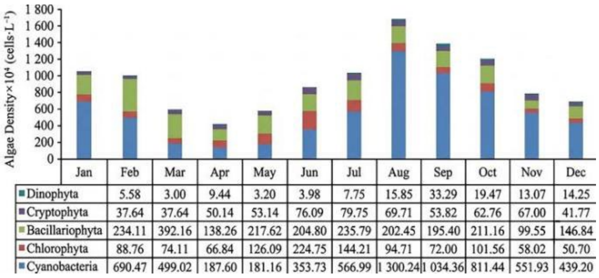
substances, thereby reducing cyanobacterial biomass. The second is indirect ecological regulation, in which microorganisms promote the assimilation, transformation, and removal of nutrients such as nitrogen and phosphorus, reducing the availability of nutrients in the water column, weakening the conditions for bloom formation, and inhibiting the dominance of cyanobacteria[3].

Therefore, this study focuses on the needs of bloom management in Erhai Lake and aims to systematically review the key mechanisms and applicable conditions of microbial algal control, analyze its potential advantages and risk boundaries under the ecological and hydrodynamic background of Erhai Lake, and, on this basis, develop a microbial regulation approach and implementation framework that can be integrated with source control and pollution reduction, ecological restoration, and emergency response. The study also seeks to provide methodological insights for the eco-friendly management of cyanobacterial blooms in similar plateau lakes.

2. Cyanobacterial Pollution and Microbial-Based Control

The occurrence of cyanobacterial blooms exhibits clear seasonal and spatial distribution patterns. Temporally, as shown in Figure 1, cyanobacterial blooms are usually concentrated between July and October each year. During this period, the water temperature is around 25°C and light conditions are sufficient, corresponding to the optimal temperature and illumination conditions for cyanobacterial growth and proliferation, thereby easily triggering large-scale bloom outbreaks[4]. Spatially, as shown in Figure 2, cyanobacterial blooms are mainly distributed in the nearshore areas of Erhai Lake, especially in the northern waters. This is because the inflow from rivers entering the lake is relatively large in this region, and the inputs of nitrogen and phosphorus account for more than 60% of the lake's total external nutrient loading. In addition, slow water movement and insufficient water exchange facilitate nutrient accumulation, thereby creating favorable conditions for cyanobacterial growth. As a result, cyanobacterial blooms in northern Erhai Lake are more severe than those in the central and southern waters[5].



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dinophyta	5.58	3.00	9.44	3.20	3.98	7.75	15.85	33.29	19.47	13.07	14.25
Cryptophyta	37.64	37.64	50.14	53.14	76.09	79.75	69.71	53.82	62.76	67.00	41.77
Bacillariophyta	234.11	392.16	138.26	217.62	204.80	235.79	202.45	195.40	211.16	99.55	146.84
Chlorophyta	88.76	74.11	66.84	126.09	224.75	144.21	94.71	72.00	101.56	58.02	50.70
Cyanobacteria	690.47	499.02	187.60	181.16	353.73	566.99	1 300.24	1 034.36	811.44	551.93	439.20

Figure 1. Monthly Variation in Average Cyanobacterial Density in Erhai Lake from 2020 to 2024 (Retrieved from: https://link. cnki.net/doi/10.16112/j.cnki.53-1223/n.2025.06.672)

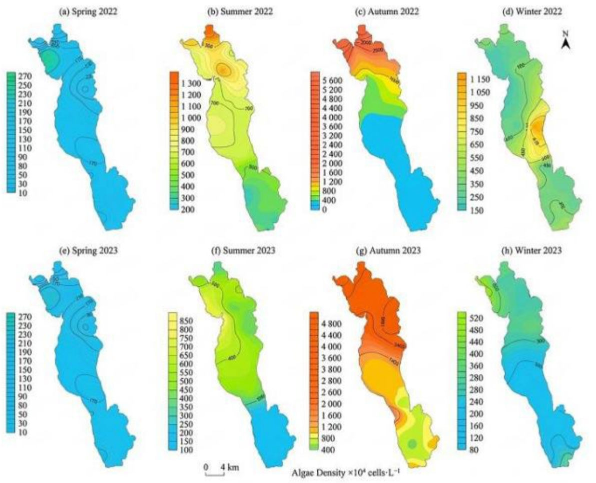


Figure 2. Spatiotemporal Distribution Characteristics of Phytoplankton Density (Retrieved from: https://link.cnki.net/doi/10.13227/j.hjkx.202406175)

Eutrophication is the primary driving factor for cyanobacterial growth, mainly characterized by excessively high concentrations of nitrogen and phosphorus in the water, exceeding the self-purification capacity of the aquatic system. Cyanobacteria possess strong uptake and adaptability to elevated nitrogen and phosphorus levels; therefore, under nutrient-rich conditions, they can undergo excessive growth and proliferation, ultimately dominating the phytoplankton community. The distribution of sampling sites is shown in Figure 3. Monitoring data indicate that when total nitrogen (TN) exceeds 1.0 mg/L and total phosphorus (TP) exceeds 0.05 mg/L, cyanobacterial blooms are more likely to occur. Consequently, increases in nitrogen and phosphorus concentrations in Erhai Lake tend to exacerbate the frequency of bloom events.Excessive application of fertilizers in agricultural production, particularly those containing nitrogen and phosphorus, can enter water bodies through surface runoff. In addition, insufficiently treated domestic wastewater from lakeside areas, carrying large amounts of ammonia nitrogen and organic matter, further intensifies the nutrient load. Some industrial wastewater discharged in excess of standards not only introduces additional nitrogen and phosphorus pollutants but may also release heavy metals. Together, these factors contribute to the worsening of eutrophication in the water body[6].Moreover, Erhai Lake is a typical semi-enclosed lake with poor water mobility and long water residence time, which prevents effective dispersion and purification of pollutants and nutrients, leading to their continuous accumulation. This hydrological characteristic makes Erhai Lake more prone to eutrophication, providing a stable environment for sustained cyanobacterial growth and further increasing the risk of bloom outbreaks.

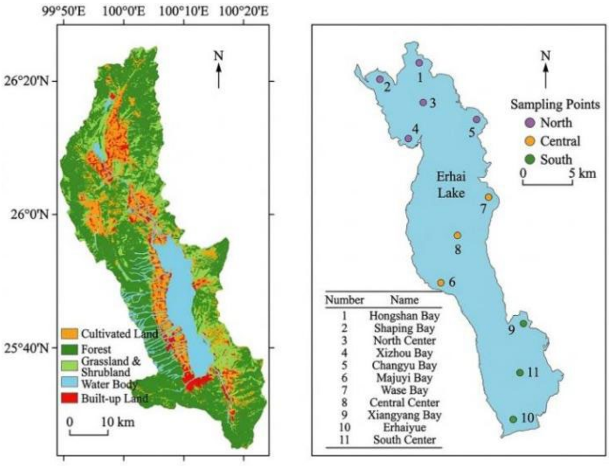


Figure 3. Land Use Types in the Erhai Lake Basin and the Distribution of Sampling Sites in This Study (Retrieved from: https://link.cnki.net/urlid/32.1331.P.20240722.1556.003)

The core of microbial remediation of cyanobacterial pollution lies in utilizing microbial metabolic activities to inhibit cyanobacterial growth and decompose cyanobacterial cells through multiple mechanisms[3]. First is the nutrient competition mechanism, in which microorganisms compete with cyanobacteria for available nutrients such as nitrogen and phosphorus in the water, thereby significantly reducing the nutrients required for cyanobacterial growth and achieving inhibition of their proliferation[7]. For example, Bacillus spp. and nitrifying bacteria can efficiently assimilate ammonia nitrogen and phosphate in the water, reducing the availability of nutrients necessary for cyanobacterial growth, thus suppressing their proliferation and controlling bloom occurrence.Second is the inhibitory effect of microbial metabolites. Certain microorganisms, such as Bacillus, Vibrio, and Sphingomonas, can secrete extracellular bioactive substances—including proteins, amino acids, and antibiotics—that effectively inhibit cyanobacterial growth. These secretions interfere with cyanobacterial photosynthesis by inhibiting the synthesis of photosynthetic pigments and reducing photosynthetic efficiency. They can also generate free radicals or other reactive oxygen species that damage cyanobacterial cell membranes and intracellular macromolecules, causing oxidative stress, disrupting ion metabolism, and destroying cellular homeostasis, ultimately leading to loss of cellular function and cell lysis. Finally, algicidal bacteria can directly act on cyanobacteria through contact-dependent lysis and parasitic lysis. In contact lysis, algicidal bacteria attach to cyanobacterial cells and secrete hydrolytic enzymes that degrade the cell wall, resulting in cell rupture and death. In parasitic lysis, the bacteria invade cyanobacterial cells, utilize intracellular nutrients, disrupt normal physiological metabolism, and ultimately lead to cell death[8]. In summary, based on the analysis of the spatiotemporal distribution characteristics of cyanobacterial blooms and their main driving factors, it is evident that microorganisms, as an environmentally friendly and sustainable strategy, demonstrate significant potential in cyanobacterial bloom control.

3. Applications of Microbial Approaches in Cyanobacterial Bloom Management

At present, microorganisms practically applied in algal control are mainly bacteria, such as photosynthetic bacteria, lactic acid bacteria, nitrifying bacteria, denitrifying bacteria, and Pseudomonas. Other microorganisms are generally used only as auxiliary agents to assist bacteria in algicidal processes, and there are still no reported cases in which fungi, viruses, or other microorganisms have been used independently for algal control. At present, most microbial technologies for cyanobacterial control remain at the stage of theoretical research, particularly with respect to algicidal mechanisms, and reports of practical application are relatively limited. Existing microbial technologies that have been applied in practice for cyanobacterial control can be categorized into four forms: microbial consortia for algal control, the combination of microorganisms with ecological floating island technology, in situ biofilm-based algal control, and immobilized microorganisms for algal control[9].

3.1 Microbial Consortia for Algal Control

Compared with single microbial strains, microbial consortia exhibit greater advantages in controlling cyanobacterial bloom outbreaks and improving water quality due to their synergistic effects[10]. Representative microorganisms include photosynthetic bacteria, lactic acid bacteria, yeasts, and nitrifying bacteria. Photosynthetic bacteria, among the most primitive photosynthetic organisms, can not only oxidize hydrogen sulfide to elemental sulfur but also assimilate and fix nitrogen and phosphorus in the water[11]. Lactic acid bacteria are anaerobic microorganisms that utilize the metabolic products of photosynthetic bacteria and produce organic acids such as lactic acid, thereby lowering the pH of the water and creating conditions unfavorable for cyanobacterial growth. Nitrifying bacteria convert ammonia nitrogen into nitrite and nitrate, while denitrifying bacteria further reduce nitrate and nitrite to nitrogen gas, ultimately achieving nitrogen removal[12]. Yeasts can produce physiologically active substances such as B vitamins, which promote the growth of other microorganisms within the consortium. Chen Jian [13]. introduced screened and cultivated indigenous microbial consortia into enclosed water bodies, resulting in a reduction of more than 70% in cyanobacterial biomass after 4 days. The removal rates of nitrogen and phosphorus increased by 64% and 43%, respectively, without significant rebound of these nutrients. Deng Jianming applied an enriched and screened high-efficiency algicidal microbial consortium to water bodies; noticeable algal lysis began on the fourth day, reaching peak effectiveness between days 6 and 8. Experimental results showed that after 8 days, the removal rate of chlorophyll-a exceeded 85%, indicating significant algicidal effects on both Microcystis aeruginosa and Anabaena. Therefore, microbial consortia can enhance the effectiveness of cyanobacterial bloom control, effectively suppress bloom outbreaks, improve water quality, and offer strong sustainability.

3.2 Combined Application of Microorganisms and Ecological Floating Island Technology for Algal Control

Ecological floating island technology utilizes buoyant materials as carriers to transplant terrestrial or higher aquatic plants into eutrophic water bodies. At the same time, microbial consortia are inoculated onto plant roots to form a rhizosphere microbial system, thereby achieving water purification. On the one hand, microorganisms remove harmful substances in the water through ingestion and degradation, while plant roots absorb and transform nutrients such as nitrogen and phosphorus, resulting in a significant reduction in nutrient concentrations and improvement in water quality.

Yang Faming selected Myriophyllum aquaticum (with root lengths greater than 30 cm) and vetiver grass as pioneer species, combined with native aquatic plants such as Scirpus and Typha, to construct ecological floating islands covering 5%–15% of the water surface. Meanwhile, composite microbial consortia—including photosynthetic bacteria, actinomycetes, Bacillus, and Pseudomonas—were inoculated onto the roots to form stable biofilms. Experimental results showed that the selected aquatic plants achieved average removal rates of 36.0% for nitrogen and 32.4% for phosphorus. Through multiple synergistic effects—including efficient nutrient uptake and release of algal-inhibiting substances by plants, organic matter degradation and nitrogen/phosphorus removal by microorganisms, activation of indigenous self-purifying microbial communities, and grazing of algae by zooplankton around the root zone—the material basis for cyanobacterial growth was effectively reduced, cyanobacterial proliferation was directly inhibited, water transparency and dissolved oxygen were improved, and the aquatic ecosystem cycle was enhanced, ultimately achieving effective control of bloom outbreaks.

On the other hand, floating island vegetation can reduce light penetration into the water column, thereby inhibiting algal photosynthesis, lowering phytoplankton biomass, and alleviating bloom occurrence. Zhao [14] using a eutrophic river in Jiaxing, Zhejiang as a study case, constructed an integrated floating island system composed of riparian vegetation and embedded biofilm adsorption units. Their results showed significant seasonal variation in purification performance. During summer and autumn, the average removal rates of total nitrogen (TN), ammonia nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), nitrite nitrogen (NO_2^--N), total phosphorus (TP), and chlorophyll-a reached 36.9%, 44.8%, 25.6%, 53.2%, 43.3%, and 64.5%, respectively—higher than those in winter and spring by 16.2%, 18.4%, 12.8%, 25.8%, 26.3%, and 58.7%. The system also achieved over 40% removal of total suspended solids (TSS), more than 60% removal of Escherichia coli, and over 30% removal of heavy metals such as copper and arsenic, demonstrating significant purification efficiency. Ecological floating islands provide both ecological and economic benefits, including efficient purification of eutrophic waters (through nitrogen and phosphorus removal, algal inhibition, and removal of heavy metals and suspended solids), as well as the potential for resource utilization of plant biomass (e.g., as animal feed). Additionally, they require minimal land area, are adaptable to various open water bodies, are easy to construct, and can improve aquatic ecological structure, thereby promoting a positive ecological cycle.

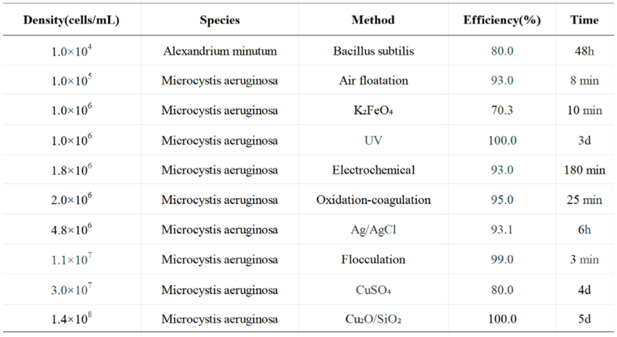
3.3 In Situ Biofilm-Based Algal Control

In situ biofilm-based algal control technology involves introducing biofilm carriers into water bodies, allowing microorganisms and small zooplankton to accumulate on the carrier surfaces and gradually form biofilms with high biological density. These biofilms can not only rapidly adsorb and precipitate phosphate in the water, but also release natural allelochemicals that inhibit algal growth. Wu [15] found that attached biofilms not only reduced the rate of phosphorus release from sediments, but also secreted water-soluble allelochemicals, such as indole and 3-oxo-α-ionone, which significantly inhibited cyanobacterial growth by damaging thylakoid membranes and blocking electron transport in photosystem II, thereby completely disrupting photosynthesis. Through pilot-scale and field experiments, the study confirmed that attached biofilms dominated by diatoms, bacilli, and cocci could synergistically inhibit Microcystis aeruginosa through nutrient competition and allelopathic effects. Pilot-scale data showed that the concentrations of ammonia nitrogen, nitrate nitrogen, and total dissolved phosphorus in the biofilm-treated group were 0.54, 0.67, and 0.12 mg/L, respectively, significantly lower than those in the control group (1.40, 2.46, and 0.41 mg/L). In field experiments, the concentrations of ammonia nitrogen, nitrate nitrogen, and total dissolved phosphorus within the biofilm enclosures were maintained at 0.12–1.42, 0.06–0.22, and 0.07–0.54 mg/L, respectively, remaining below the nutrient threshold required for cyanobacterial bloom development. As the core inhibitory mechanism against cyanobacteria, allelopathy played a dominant role. Indole and 3-oxo-α-ionone secreted by microbial communities on the biofilm exhibited significant algal inhibition at a concentration of 25 μg/L, and completely suppressed cyanobacterial growth at 100 μg/L. Experimental results showed that after day 17 of the pilot experiment, chlorophyll-a was no longer detectable in the biofilm-treated group, indicating the absence of cyanobacterial blooms. In coculture experiments, cyanobacterial cell density decreased from 0.54 × 10^6 cells/mL to 0.01 × 10^6 cells/mL, whereas in the pure culture group it increased to 2.8 × 10^6 cells/mL. The inhibitory effect of attached biofilms on cyanobacteria did not rely solely on nutrient limitation, but was mainly achieved through the release of allelochemicals. In addition, during the field experiment, biofilm biomass increased from 1882 g/m^3 to 2740 g/m^3, further enhancing both the release of allelochemicals and the capacity for nutrient competition. As a result, no cyanobacterial bloom occurred during the experiment, and chlorophyll-a concentrations remained consistently lower than those in the control group. In situ biofilm-based algal control is environmentally friendly and does not cause secondary pollution. It can efficiently inhibit cyanobacterial growth through allelopathic effects, degrade microcystins, and create favorable transitional conditions for the restoration of aquatic ecosystems, making it suitable for a variety of eutrophic water bodies.

3.4 Immobilized Microorganisms for Algal Control

Immobilized microbial algal control is a method in which algicidal microorganisms are fixed onto carriers made of biomass-based materials or polymer materials. This approach can effectively minimize the influence of factors such as hydrological and climatic variation and dilution within the water body, while also enabling the recovery and reuse of microorganisms, thereby reducing the overall cost of algal control. Seung Won Jung [16] verified the effectiveness of activated carbon–polyvinyl alcohol sponge (APVAS)-immobilized Pseudomonas fluorescens (SK09) for controlling blooms of Heterocapsa circularisquama. In the experiment, the initial algal density was 2.04 × 10^4 cells/mL. After the addition of 4,000 APVAS carriers of 1 cm^3 each (each carrier loaded with 1 × 10^8 cells/cm^3 of SK09, corresponding to a total inoculation density of approximately 5 × 10^6 cells/mL), the density of H. circularisquama in the APVAS+SK09 treatment group decreased from 1.8 × 10^4 cells/mL to 0.8 × 10^4 cells/mL, with a maximum algicidal effect of 72%, while chlorophyll-a concentration declined by 75.9%. In contrast, in the APVAS-only carrier group and the blank control group, algal density increased to 2.8 × 10^4 cells/mL and 2.38 × 10^4 cells/mL, respectively, and chlorophyll-a concentration increased by 337.3% and 436.0%, respectively. In terms of nutrients, the dissolved nitrogen concentration in the APVAS+SK09 group was 1.13 ± 0.20 mg/L, compared with 1.25 ± 0.21 mg/L in the control group, while dissolved inorganic phosphorus remained at approximately 67.8 ± 9.1 μg/L in all three groups, with no significant difference. The abundance of other phytoplankton showed no obvious fluctuation, confirming that this immobilized system could achieve species-specific control of H. circularisquama through efficient algal lysis and nutrient adsorption, without causing ecological disturbance.

In view of the relevant algal control technologies and the spatiotemporal distribution characteristics of cyanobacterial blooms in Erhai Lake, this study constructs an integrated prevention and control strategy with a full-chain connection from source control, process regulation to emergency disposal centered on functional composite microbial consortia, and defines a three-level implementation framework. First, a coupled "in situ biofilm-composite microbial consortium" measure is established at the lake inlet estuaries. The in situ biofilm carrier provides a stable colonization environment for the composite functional microbial consortium, while the metabolic functions of the consortium enable the deep purification of pollutants entering the lake, thereby reducing the nitrogen and phosphorus load into the lake at the source and inhibiting cyanobacterial proliferation. Meanwhile, the deployment of in situ biofilm carriers such as porous biomass fillers at the lake inlet estuaries can also retain particulate pollutants entering the lake; Second, a long-term regulation measure for synergistic purification based on the "ecological floating island-immobilized microorganisms" system is targeted constructed in waters with a high incidence of blooms, to build a full-space ecological regulation network for the lake water body; Finally, emergency disposal of local sudden bloom events and regular microbial supplementation measures are dynamically implemented on demand. Ultimately, a microbial prevention and control system for cyanobacterial blooms adapted to plateau lakes is established, providing technical support for the long-term management of blooms in Erhai Lake and similar plateau lakes. The control performance of different methods on algal blooms with different algal densities is shown in Figure 4.



Density(cells/mL)	Species	Method	Efficiency(%)	Time
1.0×10^4	Alexandrium minutum	Bacillus subtilis	80.0	48h
1.0×10^5	Microcystis aeruginosa	Air floatation	93.0	8 min
1.0×10^6	Microcystis aeruginosa	K_2FeO_4	70.3	10 min
1.0×10^6	Microcystis aeruginosa	UV	100.0	3d
1.8×10^6	Microcystis aeruginosa	Electrochemical	93.0	180 min
2.0×10^6	Microcystis aeruginosa	Oxidation-coagulation	95.0	25 min
4.8×10^6	Microcystis aeruginosa	Ag/AgCl	93.1	6h
1.1×10^7	Microcystis aeruginosa	Flocculation	99.0	3 min
3.0×10^7	Microcystis aeruginosa	$CuSO_4$	80.0	4d
1.4×10^8	Microcystis aeruginosa	Cu_2O/SiO_2	100.0	5d

Figure 4. The control performance of different methods on algal blooms with the different algal densities. (Retrieved from: https://www.mdpi.com/2192416)

4. Challenges in the Process of Microbial Remediation

The challenges in microbial remediation are mainly reflected in factors such as water temperature fluctuations, dissolved oxygen variation, interspecific competition, and hydrodynamic conditions. Fluctuations in water temperature have a significant influence on microbial metabolic activity. Most algicidal microorganisms perform best at 20–30°C, whereas excessively low temperatures reduce their metabolic efficiency. Erhai Lake exhibits considerable seasonal variation in water temperature, and the low temperatures in winter in particular can weaken the effectiveness of microbial remediation[17]. To improve treatment performance, microorganisms may be introduced during suitable seasons, and cold-tolerant strains may also be screened. At the same time, the diurnal temperature range and depth-related temperature differences in Erhai Lake[18] further increase the complexity of the microbial living environment, which may lead to fluctuations in consortium activity. [19]

Changes in dissolved oxygen also have an important effect on microbial activity. Dissolved oxygen levels in Erhai Lake are influenced by water depth, season, and day–night cycles, while different microorganisms vary considerably in their oxygen requirements[20]. To improve dissolved oxygen conditions in the water body, ecological restoration measures are recommended, such as planting aquatic vegetation and creating artificial water circulation to increase oxygen supply and reduce internal oxygen consumption.

In addition, once exogenous microorganisms are introduced into Erhai Lake, they must compete with indigenous microorganisms for resources. Since native microbial communities have already formed relatively stable ecological networks, exogenous consortia often find it difficult to maintain a long-term dominant position. As a result, exogenous microorganisms may show significant effects in the initial stage, but their effectiveness tends to decline over time. To enhance treatment performance, repeated inoculation or the design of more stable microbial consortia may be considered in order to strengthen the competitiveness of exogenous microorganisms. Hydrodynamic conditions are also an important factor affecting the effectiveness of microbial remediation. In the northern part of Erhai Lake, water flow is relatively strong, which can easily wash away microorganisms and shorten their effective action time. To address this issue, embedding techniques may be used to immobilize microorganisms in polymer gels or magnetic materials, thereby reducing the negative effects of flow-induced scouring[21].

Cost control is another major challenge in microbial remediation. For large lakes, both the initial investment and long-term operation and maintenance costs are relatively high. In particular, when microbial community activity declines rapidly, periodic reinoculation is required, increasing management difficulty. At the same time, if external pollution is not effectively controlled, nitrogen and phosphorus pollution in the water may promote cyanobacterial proliferation at a rate far exceeding the inhibitory capacity of microorganisms, making it difficult to effectively curb the repeated outbreak of blooms. Therefore, in addition to microbial remediation, it is essential to strengthen pollution source control and reduce the input of nitrogen and phosphorus pollutants in order to ensure the long-term stability of treatment outcomes.

5. Conclusion and Prospects

The occurrence of cyanobacterial blooms in Erhai Lake is primarily caused by external nitrogen and phosphorus pollution and water eutrophication, while environmental factors such as water temperature and dissolved oxygen fluctuations further exacerbate the problem. To address this issue, microbial remediation technology has gradually become an important approach for the control of cyanobacterial blooms in Erhai Lake. The core mechanisms of microbial remediation include nutrient competition, inhibition by metabolic products, direct algal lysis, and indirect ecological regulation, all of which effectively suppress cyanobacterial growth. However, although microbial remediation has demonstrated strong eco-friendly potential in bloom control, it is still constrained by multiple factors such as hydrological conditions and interspecific competition. Therefore, microbial remediation alone is unlikely to completely resolve the problem of cyanobacterial blooms. In the future, further development of microbial remediation technology should continue to focus on strain optimization and technological innovation. Genetic engineering may be employed to enhance the adaptability of algal-control microorganisms, and multifunctional strains with both algicidal activity and nitrogen/phosphorus transformation capacity may be screened to improve treatment efficiency. Meanwhile, integrating hydrodynamic models to simulate microbial dispersal pathways, thereby enabling demand-based inoculation and precise regulation, will also be an important direction for reducing costs and improving remediation efficiency. Ultimately, through integrated management and technological innovation, microbial remediation is expected to become a core technology for the long-term control of cyanobacterial blooms in Erhai Lake and similar plateau lakes, providing strong support for lake ecological restoration and sustainable utilization.

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