Effects of suspended ecological beds on phytoplankton community structure in Baiyangdian Lake, China

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\textbf{ABSTRACT}

To address the issues of submerged vegetation restoration in the deep-water area of Baiyangdian Lake, a type of suspended ecological bed was developed, which was constructed with aquatic plants, ropes and supporting poles. The depth of a suspended ecological bed could be adjusted based on the water level. From July to November 2019, the phytoplankton community structure in the water around the suspended beds was continually monitored, and the effects of the submerged plants present in the suspended beds on the phytoplankton community structure in the deep-water area of the lake were studied. The results showed that \textit{Myriophyllum spicatum L.} grew well in the suspended beds, with 95\% survival after 60 d. The maximum biomass was reached in 55 d, and the water surface coverage reached 23\%. There were 71 species of phytoplankton belonging to seven phyla in the water surrounding the suspended ecological beds. Over half (36 species) were members of Prochlorophyta, and the average density and biomass of phytoplankton gradually decreased month by month. The proportion of cyanobacteria in the community showed a downwards trend, while the proportions of other phytoplankton phyla showed upwards trends. The annual average Shannon–Wiener diversity index was 0.88, the annual average Pielou evenness index was 0.32, and the annual average Margalef richness index was 1.21. The Shannon–Wiener diversity index and Pielou’s evenness index both showed increasing trends. This comprehensive analysis shows that planting submerged plants in suspended beds can improve the phytoplankton community structure of the surrounding water and increase the biodiversity of phytoplankton, making this an effective measure for restoring submerged vegetation in algae-dominated northern lakes.

\textbf{ARTICLE HISTORY}

Received 4 August 2021
Accepted 27 January 2022

\textbf{KEYWORDS}

Ecological suspended beds; Baiyangdian Lake; algae; plant

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This article has been corrected with minor changes. These changes do not impact the academic content of the article.

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Introduction

Lake ecosystems provide high-quality aquatic products and water sources for humans, while they play important roles in transportation, wetland conservation and many other areas. In recent decades, eutrophication has taken place in many lakes and cyanobacterial blooms have occurred. Eutrophication of a freshwater lake ecosystem is the process of a lake transitioning from a poor nutritional state to a eutrophic state (Scheffer et al. 1993). During this process, the main biological components of the lake ecosystem change from aquatic plants to phytoplankton (Scheffer and Carpenter 2003). When the coverage of submerged plants is relatively low or even disappears, the lake ecosystem changes from the grass-type clear water steady state to the algae-type turbid water steady state (Scheffer et al. 1997).

Restoration of submerged plant coverage in lakes is an important measure for controlling lake eutrophication and algal blooms (Cheng et al. 2007; Moss 1990). The main purpose of ecological restoration is to transform a eutrophic algal lake ecosystem with frequent cyanobacterial blooms and turbid water quality into a grass lake ecosystem with lush aquatic plants and clear water quality through a particular method (Qin 2007). In addition, submerged plants can provide shelter from natural enemies for large zooplankton and provide habitats for many fish and snails (Whitfield 1984). Therefore, the restoration of submerged plants can significantly improve the biodiversity of aquatic ecosystems (Gao, Dong, et al. 2017; Gao, Qian, et al. 2017). However, the growth of submerged plants is limited by factors such as light, water depth, and nutrient salts, and it is difficult to control the water depth of a lake to create water depth conditions suitable for the growth and reproduction of submerged plants in large areas of water. The restoration of submerged plants has always been a challenging aspect of ecological restoration. In many lakes, the water is too deep and insufficiently transparent due to water transfer, which often causes submerged plants to miss the germination period of spring growth, thus accelerating the process of phytoplankton blooms.

Baiyangdian Lake is a typical lake in northern China (Jin et al. 1990). Over the past decade, the process of water eutrophication in Baiyangdian Lake has accelerated, resulting in damage to the structure and function of the aquatic ecological system, malignant phytoplankton growth, reduction of aquatic biodiversity and significant decline in transparency (Zhu et al. 2021). Baiyangdian Lake has a tendency to transition from a grass-type lake to an algae-type lake. The decline in submerged plants has greatly reduced the effectiveness of other ecological restoration measures, such as fishing to improve water quality and altering the bottom through snails.

Based on the design concepts of submerged plant net beds, artificial submerged beds, and the fixed method of planting kelp on an offshore raft frame and comprehensively considering the factors of water depth, wind and waves and indigenous submerged plant varieties, this paper reports a suspended bed device for growing submerged plants capable of having its position adjusted in the water and an attempt to restore the submerged plants in the deep-water area of the lake. However, after the restoration of submerged macrophytes, lake water does not necessarily transform from turbid water to a clear water steady state. To further analyse the effect of planting submerged macrophytes on the steady-state transformation of the lake, the changes in phytoplankton community structure and water physicochemical factors under suspended bed planting were studied and analysed in this article, and the effect of the restoration of submerged macrophytes on the steady-state transformation of the lake ecosystem is discussed, which provides technical support and a theoretical basis for the restoration of submerged macrophytes in northern shallow lakes and the theory of steady-state transformation.
Materials and methods

Overview of the ecological restoration area

The study ran from July to November 2019 in Shihoudian Lake of the Baiyangdian Basin in Xiong’an New District (XND), Hebei Province (N: 38°50′39.39″, E: 115°59′30.04″) (Figure 1). This lake is one of the five major ecological restoration demonstration areas of the Baiyangdian Hydrobiological Resources Survey and Aquatic Ecological Restoration Demonstration Project conducted by the Ministry of Agriculture and Rural Affairs. Shihoudian Lake is located in the middle of Baiyangdian, surrounded by three villages with a combined population of over 8000 residents, 19 trenches and 33.3 hm² of reed fields. It exhibits characteristics typical of the Baiyangdian Basin. Since the launch of the Baiyangdian Demonstration Project in 2018, the project team has implemented a series of ecological restoration projects, and the trenches and vegetation by the lakeshore have been restored, but submerged plant restoration remains to be completed in the deep-water area in the middle of the lake. In this study, six 100-m-long suspended ecological bed systems were set up at intervals of 10 m. An experimental area of 60 m × 100 m was formed.

Design of suspended ecological bed systems

The design of suspended bed systems is shown in Figure 2. For each system, two 4-m-long supporting poles were planted into the lake bottom and fixed using strong anchor ropes. One metre of each supporting pole was exposed above the water surface, and a planting rope was fastened between the two supporting poles. The distance between the two poles was 10 m, and five buoys were fixed along the planting rope. A basket 20 cm in diameter and containing the submergent plant species Eurasian watermilfoil (Myriophyllum spicatum L.) was hung under each buoy such that the basket was 0.5 m...
below the water surface. Since each basket was only 0.5 m below the water surface, sunlight could provide energy and promote plant growth, while they were also protected from direct sunlight and disturbance by wind and waves. The supporting poles and the fixing ropes were arranged in a parallel pattern to form a rectangular array of suspended ecological beds. A 20-mesh fence enclosed the planting area to prevent young plant shoots from being eaten by fish. After the aquatic plants became fully grown, the fence was removed. In the end, a certain area of aquatic plants was formed.

**Distribution of sampling sites**

Six sampling sites were established in the water around the suspended beds as the test group (Figure 1 and 2(b)). The sampling sites were located between two supporting poles, and the water depth in the test area was 2–3 m (Figure 1).

**Sample collection and analysis**

Samples were collected once a month from July to November 2019. Plexiglass water collectors were used to collect 5 L of mixed water at the surface, 1 m below the surface, and
0.5 m from the bottom. For each water sample, 1 L of water was fixed with 15 mL Lugol’s solution for quantitative evaluation of phytoplankton, and the remainder of the sample was used to determine physicochemical characteristics. Then, a phytoplankton net of 25-μm mesh size was dragged slowly along the surface water several times, following a figure-8 pattern. The collected concentrated phytoplankton samples were fixed with an appropriate amount of Lugol’s solution on site for qualitative analysis of phytoplankton. The qualitative and quantitative evaluations of phytoplankton followed the publication Research Methods of Freshwater Plankton (Zhang and Huang 1991). The phytoplankton species were identified mainly based on The Freshwater Algae of China (Hu and Wei 2006).

The growth of plants was observed daily. Dead aquatic plants were removed and replaced with new plants every 15 d, from which the survival rate was calculated. Aquatic plants on one suspended bed system were also collected during every water sampling, and the wet weight of the plants was calculated. The plant coverage percentage was calculated from the projective cover. A modified multifunctional selfie stick that was remotely controlled through Bluetooth connections was used to take aerial photos of the suspended ecological bed planting area in the lake. Pictures of higher quality were chosen and divided into 100 small cells of 0.5 m × 0.5 m. The surface area occupied by submerged plants was estimated for each cell and then summed to obtain the total coverage of submerged plants in the area.

Measurement and calculation of indicators

The dominant species of phytoplankton were determined by comparing the dominance (Y) of each species:

\[ Y = \frac{N_i}{N} \times f_i \]  

where \( N_i \) is the abundance of the \( i \)th species, \( N \) is the abundance of all the species, and \( f_i \) is the frequency of occurrence of the \( i \)th species.

The species with \( Y > 0.02 \) were considered dominant species.

Margalef’s richness index (\( D \)) was calculated as

\[ D = \frac{(S - 1)}{\ln N} \]  

The Shannon-Weaver diversity index (\( H' \)) equals

\[ H' = - \sum (N_i/N) \ln (N_i/N) \]  

Pielou’s evenness index (\( J \)) is

\[ J = \frac{H'}{\ln S} \]

where \( N_i \) is the abundance of the \( i \)th species, \( N \) is the abundance of all the species and \( S \) is the number of species.

Data analysis

The statistical analysis and data plotting were conducted via Excel and SPSS version 13.0 (SPSS Inc., Chicago, IL).

A redundancy analysis (RDA) was performed to analyse the relationship between phytoplankton and environmental factors by using Canoco 5.0 software. The length of the
first axis was used to identify the analysis category (>4: canonical correspondence analysis [CCA]; <3: RDA; and 3–4: either of the two (Muylaert et al. 2000; Beyene et al. 2009)).

**Results**

**Physical and chemical characteristics of the water body**

Table 1 provides values of physicochemical indicators for the suspended ecological bed area at six sampling sites on five sampling dates. Water temperature of the suspended ecological bed area varied from 13.46 to 31.0°C, salinity ranged from 0.70 to 0.77‰, pH varied from 8.08 to 8.72, and dissolved oxygen ranged from 6.91 to 13.73 mg/L. Values of physical and chemical indexes for the water body were relatively stable. Total nitrogen ranged from 1.10–1.85 mg/L, and total phosphorus varied from 0.02 to 0.45 mg/L. The total phosphorus in the water was relatively low.

**Growth of submerged plants**

The survival rate of *M. spicatum* L. after 15 d in the suspended beds was 42%. The submerged plants in the basket that did not survive were replaced, and the overall survival rate of the aquatic plants in the suspension bed system was 63% after 30 d. The survival rate after the third replanting reached 86%. At this time, due to factors, such as weather, wind, and waves, the growth of aquatic plants in few frames was not ideal. After the fourth replanting, the survival rate of aquatic plants reached 95% (Figure 3).

The submerged plants in suspended ecological beds were sampled randomly, the plants in each frame were removed, and their wet weight was measured. The initial planting biomass of aquatic plants in a single frame was 0.5 kg. After 25 d, the biomass of aquatic plants was 1.3 kg, and branches and leaves of submerged plants had grown out of the frame. After 55 d, the biomass reached a maximum of 4.2 kg. At this time, branches and leaves of submerged plants had covered the water from below the water surface, and some dead plants were floating around. By October, many plants had died and turned yellow. Some dead plants were removed. As of November, the mean wet weight of the aquatic plants in one frame was less than 0.8 kg (Figure 4).

Submerged plants initially covered approximately 5% of the planting area. One month later, the coverage reached 10%. At this point, most submerged plants had grown vertically, and plant growth had little effect on the coverage of the water surface. After 2 months, the submerged plants had experienced their growth peak, and their coverage reached 23% of the planting area. The submerged plants had some dead broken branches, which were removed. By October, the coverage of submerged plants had fallen to 12%, but the plants still had a large biomass below the water surface. By November, many leaves of the submerged plants had died, with only branches and stems remaining, and the coverage was less than 2% (Figure 5).

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**Table 1. Physical and chemical characteristics of Shihoudian Lake.**

|                     | July       | August    | September | October    | November   |
|---------------------|------------|-----------|-----------|------------|------------|
| Water temperature °C| 29.28 ± 0.39| 31.0 ± 0.82| 28.38 ± 0.27| 19.62 ± 0.04| 13.46 ± 0.08|
| Salinity ‰         | 0.73 ± 0.01| 0.70 ± 0.00| 0.73 ± 0.01| 0.76 ± 0.00| 0.77 ± 0.00|
| pH                  | 8.64 ± 0.02| 8.69 ± 0.10| 8.62 ± 0.29| 8.71 ± 0.02| 8.08 ± 0.06|
| Dissolved oxygen mg/L| 10.72 ± 0.22| 13.73 ± 0.66| 6.92 ± 1.01| 10.70 ± 0.57| 7.29 ± 0.31|
| Total nitrogen mg/L | 1.85 ± 0.20| 1.10 ± 0.18| 1.37 ± 0.27| 1.85 ± 0.19| 1.62 ± 0.18|
| Total phosphorus mg/L| 0.05 ± 0.00| 0.02 ± 0.00| 0.04 ± 0.00| 0.06 ± 0.02| 0.45 ± 0.13|
Phytoplankton composition

A total of 77 species of phytoplankton in seven phyla were identified. Prochlorophyta had the most species (36), accounting for 50.70% of the total species, followed by Bacillariophyta and Cyanobacteria, with 15 species (19.5%) and 11 species (14.3%), respectively. Among the different months observed, September had the most phytoplankton species (64), and November had the fewest (23) (Table 2).

Species with a dominance index \( Y > 0.02 \) were defined as dominant species. Based on the density and distribution of the phytoplankton, the survey showed nine dominant
species belonging to four phyla. The phylum Cyanobacteria was the main group, and the dominance of Pyrrophyta was higher in the later stage of the study (December) (Table 3).

**Cell density of phytoplankton**

The average densities of phytoplankton phyla in the water surrounding the suspended ecological beds are listed in Table 4. Phytoplankton density showed a gradual decline over time, with the highest total density in July and the lowest in November. Cyanobacteria exhibited the highest density, followed by Prochlorophyta and Bacillariophyta. The density of cyanobacteria decreased month by month, and the densities of prochlorophytes, bacillariophytes and cryptophytes increased at first and then decreased. The density of Prochlorophyta peaked in August, and the density of Bacillariophyta and Cryptophyta peaked in September. The proportion of cyanobacteria in the phytoplankton biomass showed a downward trend, while the proportions of other phytoplankton phyla showed an upwards trends.

**Phytoplankton biomass**

The phytoplankton biomass in the water around the suspended ecological beds is shown in Table 5. The phytoplankton biomass gradually declined over time. The highest biomass occurred in July, and the lowest was in November. Cyanobacteria displayed the highest biomass, followed by Prochlorophyta and Bacillariophyta. The biomass of Prochlorophyta, Bacillariophyta and Cryptophyta first increased and then decreased. The biomass of Prochlorophyta peaked in August, and the biomass of Bacillariophyta and Cryptophyta peaked in September. The proportion of cyanobacterial biomass in the phytoplankton biomass showed a downwards trend, while the proportions of Prochlorophyta and Bacillariophyta biomass showed upwards trends. The patterns of change phytoplankton biomass and density were inconsistent because the proportions of larger individuals of Pyrrophyta and Euglenophyta increased between September and November.
Phytoplankton diversity index

Seasonal changes in the phytoplankton biodiversity indices are given in Table 6. The Shannon–Wiener diversity index had a range of 0.30–1.47, and the annual average was 0.88. The highest and lowest values occurred in November and July, respectively. Pielou’s evenness index varied between 0.11 and 0.72, and the annual average was 0.32. Its highest and lowest values also occurred in November and July, respectively. Margalef’s richness index varied between 0.67 and 1.873, with an annual average of 1.21. The highest and lowest values again occurred in November and July. Comparing the three, the Shannon–Wiener diversity index and Pielou’s evenness index increased over time, and Margalef’s richness index first increased and then decreased.

Table 4. The average density of phytoplankton in the water surrounding of the suspended ecological beds.

| Phytoplankton | July     | August   | September | October  | November |
|---------------|----------|----------|-----------|----------|----------|
| Cyanophyta    | 305,872,241 | 226,126,431 | 255,846,709 | 210,554,538 | 43,677   |
| %             | 97.52%   | 88.89%   | 92.29%    | 97.04%   | 30.54%   |
| Prochlorophyta| 6,058,436  | 24,217,206   | 6,524,916    | 5,029,524   | 35,271   |
| %             | 1.93%    | 9.52%    | 2.35%     | 2.32%    | 24.66%   |
| Bacillariophyta| 389,964 | 1,816,494 | 9,811,013 | 502,467 | 2631 |
| %             | 0.12%   | 0.71%   | 3.54%     | 0.23%    | 1.84%    |
| Cryptophyta   | 488,963  | 1,352,016 | 3,107,467 | 638,813   | 0        |
| %             | 0.16%   | 0.53%   | 1.12%     | 0.29%    | 0.00%    |
| Euglenophyta  | 700,405  | 146,564  | 901,294   | 49,139    | 0        |
| %             | 0.22%   | 0.06%   | 0.33%     | 0.02%    | 0.00%    |
| Pyrrophyta    | 155,184  | 731,440  | 312,928   | 147,418   | 61,434   |
| %             | 0.05%   | 0.29%   | 0.11%     | 0.07%    | 42.96%   |
| Xanthophyta   | 0       | 0       | 716,468   | 49,139    | 0        |
| %             | 0.00%   | 0.00%   | 0.26%     | 0.02%    | 0.00%    |
| Total         | 313,665,196 | 254,390,153 | 277,220,798 | 216,971,041 | 72,001 |

Table 5. Average biomass of phytoplankton in the water surrounding the suspended ecological beds.

| Phytoplankton | July | August | September | October | November |
|---------------|------|--------|-----------|---------|----------|
| Cyanophyta    | 48.42 | 6.15   | 15.23     | 22.74   | 7.34     |
| %             | 91.15% | 38.58% | 48.74%    | 90.24%  | 65.40%   |
| Prochlorophyta| 0.60  | 2.16   | 0.89      | 0.51    | 2.14     |
| %             | 1.13% | 13.55% | 2.85%     | 2.02%   | 19.08%   |
| Bacillariophyta| 0.43 | 1.82   | 5.40      | 0.67    | 1.37     |
| %             | 0.81% | 11.42% | 17.28%    | 2.66%   | 12.17%   |
| Cryptophyta   | 0.15  | 0.97   | 4.17      | 0.94    | 0        |
| %             | 0.28% | 6.09%  | 13.34%    | 3.73%   | 0.00%    |
| Euglenophyta  | 2.40  | 0.45   | 3.15      | 0.05    | 0        |
| %             | 4.52% | 2.82%  | 10.08%    | 0.20%   | 0.00%    |
| Pyrrophyta    | 1.12  | 4.39   | 1.88      | 0.28    | 0.38     |
| %             | 2.11% | 27.54% | 6.02%     | 1.11%   | 3.34%    |
| Xanthophyta   | 0     | 0      | 0.53      | 0.01    | 0        |
| %             | 0.00% | 0.00%  | 1.70%     | 0.04%   | 0.00%    |
| Total         | 53.12 | 15.94  | 31.25     | 25.2    | 11.22    |

Table 6. Seasonal changes in the phytoplankton biodiversity indices.

| Phytoplankton biodiversity indices | July | August | September | October | November | Mean (%) |
|-----------------------------------|------|--------|-----------|---------|----------|----------|
| Shannon–Wiener diversity index (H') | 0.30 | 0.78   | 1.23      | 0.61    | 1.47     | 0.88     |
| Margalef’s richness index (D)     | 0.91 | 1.17   | 1.87      | 1.43    | 0.67     | 1.21     |
| Pielou’s evenness index (J)       | 0.10 | 0.25   | 0.35      | 0.19    | 0.72     | 0.32     |

**Phytoplankton diversity index**

Seasonal changes in the phytoplankton biodiversity indices are given in Table 6. The Shannon–Wiener diversity index had a range of 0.30–1.47, and the annual average was 0.88. The highest and lowest values occurred in November and July, respectively. Pielou’s evenness index varied between 0.11 and 0.72, and the annual average was 0.32. Its highest and lowest values also occurred in November and July, respectively. Margalef’s richness index varied between 0.67 and 1.873, with an annual average of 1.21. The highest and lowest values again occurred in November and July. Comparing the three, the Shannon–Wiener diversity index and Pielou’s evenness index increased over time, and Margalef’s richness index first increased and then decreased.
Relationship between phytoplankton community and environmental factors

RDA was undertaken to examine the relationships between phytoplankton and environmental factors. The length of the first axis was 2.87 (less than 4), so linear RDA was more appropriate choice. The analysis indicated that the first two axes, RDA1 and RDA2, showed extremely significant differences ($p < .01$). The eigenvalues of the two axes were 0.527 and 0.234, respectively, and their explanatory power reached 76.15%. The two ordinal axes reflected well the relationship between phytoplankton and various environmental factors in the water around the beds. The abbreviations of environmental factors and phytoplankton are provided in Tables 1 and 3. Figure 6 shows that water temperature, salinity, pH and total phosphorus were the main influencing factors. Water temperature was negatively correlated with small Chroococcales cyanobacteria and positively correlated with Chlorellales. Salinity was positively correlated with small Chroococcales and negatively correlated with Chlorellales. Total phosphorus was negatively correlated with *Anabaena* sp. and *Merismopedia* sp. The pH was positively correlated with *Anabaena* sp. *Merismopedia* sp., and *Synedra* sp.

Discussion

The impact of submerged plants in suspended beds on the structure of the phytoplankton community

As an important primary producer in aquatic ecosystems, submerged plants compete with phytoplankton for nutrition, light and space and inhibit the growth of phytoplankton by releasing allelochemicals (Liu 1999). When the competitiveness of submerged plants in a eutrophic lake exceeds that of the phytoplankton, the water body will change from an algae-type lake to a grass-type lake, and the water quality will change from turbid to clear (Qin 2007). In this study, submerged plants were restored in a lake by suspended ecological beds. The cell density and biomass of phytoplankton in the water body decreased to varying extents, indicating that the planting of *M. spicatum* in the suspended beds over
a broad water surface area exerted a favourable inhibitory effect on phytoplankton. Although the investigation showed that the decrease in cell density and biomass of phytoplankton was affected by the decrease in water temperature, the increases in Bacillariophyta, Cyanobacteria, and Cryptophyta before October indicated that the planting of *M. spicatum* in the suspended ecological beds exhibited a certain promoting effect on the inhibition of cyanobacteria and the increase in phytoplankton biodiversity. In addition, the monthly changes in phytoplankton also showed that the cell density and biomass proportions of cyanobacteria gradually decreased, while the proportions of chlorophytes, diatoms and cryptophytes gradually increased, indicating that the submerged *M. spicatum* plants strongly inhibited cyanobacteria. Studies (Xiao et al. 2009) have shown that the allelochemicals secreted by submerged plants selectively inhibit different phytoplankton taxa, and cyanobacteria and diatoms are more sensitive than green algae. Therefore, inhibiting cyanobacterial blooms and improving phytoplankton biodiversity through submerged plants is an effective way to achieve conversion of a lake to a clear water steady state.

The effect of suspended ecological beds on phytoplankton is also mediated by external environmental factors. RDA in this study showed that water temperature, salinity and total phosphorus were the main factors influencing the dominance of species of phytoplankton in the water around the raft frame. When water temperature increases, the evaporation capacity of the water body is high, and the salinity increases. Therefore, water temperature and salinity show opposite effects of inhibition and promotion of cyanobacteria. It could be speculated that in the process of submerged plant recovery, physicochemical indicators such as water temperature and salinity were the main driving factors affecting the transformation of lake water to a clear steady state (Scheffé and Carpenter 2003). Although other studies (Smith 1998.) have found nitrogen and phosphorus levels to be important factors affecting the steady-state transformation of lakes, physicochemical parameters are the main factors driving (Roozen et al. 2003) the process of restoration of the biological communities of lake ecosystems and the construction of lake ecosystems dominated by aquatic higher plants. The key step is to meet the light and water temperature conditions required by the submerged plants. When the submerged plants reach a certain coverage, light and water temperature show greater effects. When the coverage of submerged macrophytes was small, phytoplankton were produced in large amounts due to the availability of nutrients and light, causing water transparency to decline. It was difficult for submerged macrophytes to grow, and phytoplankton held the advantage in competition for nutrients, further aggravating the cyanobacterial bloom.

This study also showed that total phosphorus was negatively correlated with the dominant species *Anabaena* sp. and *Chaetoceros* sp. In the nutrient-poor water body, phosphorus was the limiting factor, and nitrogen-fixing phytoplankton became dominant when phosphorus was relatively low. Therefore, when phosphorus continuously decreased, nitrogen-fixing phytoplankton remained abundant due to phosphorus deficiency and thus showed a negative correlation with phosphorus level.

**Application of the method of planting in suspended beds**

After steady-state transformation of a freshwater ecosystem, even when the external driving force changes to the critical point of steady-state transformation of the system, it will not immediately return to its original state. To restore the system to its original state, the restoring force must be much greater than the driving force that induces its conversion (Chang et al. 2010). Therefore, the transformation of a lake from an algae-type clear water
steady state to a turbid water steady state cannot be achieved only by controlling nutrients. The restoration of submerged plants is an important component thereof, and the growth of submerged plants is affected by light, water temperature, nutrients and other factors. Light intensity is generally considered a limiting factor for the survival and growth of submerged plants (Jin et al. 2020; Zervas et al. 2019; Dong et al. 2021) and determines the distribution of submerged plants to a certain extent. Therefore, an appropriate method needs to be selected to restore submerged plants. The authors believe that the characteristics that allow watermilfoil to absorb nutrients from the water only through plant stems and leaves without being planted in soil can be utilized (Zhu et al. 2020) and that the plants can be grown in suspension beds to inhibit the growth of cyanobacteria, and that other aquatic plants can be further restored. In this study, suspended bed planting allowed adjustment of the heights of submerged plants above the water surface according to the light and transparency to reduce stress from weak light or even darkness. The submerged plant community was formed after two months through replanting management of the submerged plants so that the objective of recovering the submerged plants was achieved. In terms of species selection, watermilfoil grows preferentially in eutrophic lakes and can adjust to low light stress through rapid stem elongation (Barko et al. 2000). Therefore, the suspended bed planting technology with watermilfoil as the main carrier is an effective measure for the restoration of submerged plants in the lake.

The harvesting and management of aquatic plants have often been the focus of study, which is also easy to ignore in actual management. Floating plants can be removed by taking each entire plant. Watermilfoil is a perennial aquatic plant that cannot feasibly be completely removed. When the contents of nitrogen and phosphorus accumulated in plants are at maximum levels, the aboveground parts of the plants should be harvested and removed from the water body to remove a large amount of nitrogen and phosphorus (Wu et al. 2007). In this study, submerged plants were planted in suspended baskets, which were convenient for harvesting and avoided the adverse effects of cutting on the growth of aquatic plants and secondary pollution to the water caused by the death of submerged plants in autumn and winter.

There are many choices for aquatic plant species for suspended bed planting. When selecting submergent plant species, the screening principle is to consider the locally present protozoan species as much as possible. There are a variety of submergent plants, including upright, lotus-seated and crown-type plants. Research on the allelopathy of various submerged plants has shown that (Gao, Gao, Dong, et al. 2017; Gao, Qian, et al. 2017) *M. spicatum*, as a submergent plant with an enhanced allelopathic effect on phytoplankton, is one of the species for which allelopathy has been most studied. In addition, *M. spicatum* is a common indigenous submerged plant in the north and a pioneer species in lake ecological restoration. It is a soil-resistant species and shows strong adaptability to the environment. The allelopathic effect of *M. spicatum* is also relatively strong. Research by Svany et al. (2014) showed that *M. spicatum* was a submerged plant that released chemicals with high phytoplankton inhibition activity. In particular, when the biomass reached a certain level and the dominant phytoplankton in the lake were the more sensitive species, the allelochemicals secreted by submerged plants more strongly inhibited phytoplankton. Gao et al. (2020) also showed that *M. spicatum* could obviously inhibit all phytoplankton cocultured. Hilt and Gross (2008) considered trimasin II and ellagic acid released by *M. spicatum* to be the main allelopathic substances. In this study, *M. spicatum*, with favourable environmental adaptability (Rodrigo et al. 2013; Qiu et al. 1997), was selected as the main species for three-dimensional suspended ecological bed planting and effectively inhibited cyanobacteria and improved the diversity of phytoplankton. It is a
suitable species for suspended ecological beds in northern lakes. Further experimental studies are needed on the use of other submergent plants in suspended ecological beds.

**Conclusions**

Suspended ecological bed technology can effectively restore submerged macrophytes, inhibit cyanobacteria and improve phytoplankton biodiversity in lakes. In the process of restoring submerged macrophytes, physical and chemical indices parameters such as water temperature and salinity are the main factors driving the conversion of lake water to a clear steady state.

*M. spicatum* can be a pioneer species for vegetation restoration. The area where submersed plants are planted in suspended beds is relatively concentrated, which is convenient for harvesting. Suspended bed planting can be regarded as a movable and ascending wetland and can be applied in deep water areas. The ecological engineering treatment measure of planting submerged plants in suspended beds will be an important development direction for water treatment in the present and even in the future.

**Acknowledgements**

The authors are grateful to Dr. Shaowen Ye, who work at the Institute of Hydrobiology, Chinese Academy of Sciences, for their help with the RDA analysis.

**Disclosure statement**

Hao Zhu and Kun cao designed the study and performed the experiments, Xiaolong Chen and Xingguo Liu performed the experiments, Kun Cao and Xiaoke Zhang prepared the figures and tables. Hao Zhu and Xiaoke Zhang analysed the data, Hao Zhu Kun Cao wrote the manuscript.

**Funding**

This study was supported by a National Key R&D Program of China (2019YFD0900604) project and a Baiyangdian aquatic biological resources investigation and water ecological restoration demonstration project (2018 LKY007).

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