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An Enhanced System with Macrophytes and Polyurethane Sponge as an Eco-Technology for Restoring Eutrophic Water: A Pilot Test

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Abstract: Water eutrophication is one of the most serious environmental problems in urban lakes and ponds due to the excessive nutrients. To deal with this problem, the development of methods for supporting ecological rehabilitation has been undertaken. Meanwhile, the trophic interactions during rehabilitation also have been analyzed. In this study, a new technique was employed to solve the water eutrophication problems in an urban pond. To evaluate the water eutrophication at a pilot scale, an enhanced artificial floating-type biological treatment system (FBTS) composed of a floating bed, macrophyte, artificial biofilm carrier (polyurethane sponge) and aerator could be used as equipment for urban pond remediation. In addition, FBTS was employed to decrease the total nitrogen (TN), ammonia-nitrogen (NH_3-N), total phosphorus (TP) and chemical oxygen demand (COD) in water. Meanwhile, the changes of water qualities were monitored in the remediation process, and differences in phytoplankton functional group diversity were also registered. Cyanobacteria would decrease after the removal of P, and the diatom assemblage composition changed. The dominant species Cyanophyta were transformed to co-existed with Bacillariophyta, Pyrrophyta and Chlorophyta due to the improvement of water quality. Consequently, this new FBTS could be a promising eco-technology for the removal of nitrogen and phosphorus from eutrophic water, and even could promote the phytoplankton succession.

Keywords: floating-type biological treatment system; eutrophic water; polyurethane sponge; plant uptake; phytoplankton succession

1. Introduction

Along with the rapid urbanized development, the health of lakes and ponds in urban areas could provide recreational and touristic services, which have become an important issue of environmental sciences [1,2]. The urban lakes are final sinks of human wastes and surface runoff receives a lot of nutrients, such as nitrogen (N) and phosphorus (P). Thus, aquatic eutrophication is recognized as one of the most serious ecological problems associated with water deterioration [3]. Eutrophic lakes and ponds lack water transparency due to the bloom forming algae except macrophytes and other algae. When these phytoplankton decomposed, dissolved oxygen (DO) would be consumed by bacteria for the biomass decomposition and would drop down to an extremely low level. These reactions may lead to biodiversity reduction and invasive species development in water [4,5]. In order to improve the lakes' service values to satisfy the societal needs, the restoration of the damaged aquatic ecosystem has gradually become an essential issue in environmental sciences [6,7].

In general, phytoplankton is the first autotrophic compartment that could respond to the change of nutrient availability and other anthropogenic pressures [8]. Based on the survey of the biotic community in the water area, the evaluation of their growth and prediction of the trend in the restoration process are necessary, this can make sure of a reasonable decision in the phytoremediation engineering projects. However, the phytoplankton community has diverse characteristics, and the dominant factors of phytoplankton in different aquatic ecosystems had different situations. For example, the major driving forces shaping phytoplankton assemblages in Lake Fuxian were physical variables, particularly the light climate conditions underwater [9]. The main cause for *Microcystis* blooming was that the high concentration of nutrients might be put in a mesotrophic subtropical plateau lake, Erhai [10]. Meanwhile, environmental factors (DO, temperature, pH and redox potential) also play a significant role in the distribution of species in an artificial pond [11]. Zhang et al. [12] revealed that the biomass of the phytoplankton taxonomic groups had different responses for the environmental variables, which was based on the corresponding niches. In addition, studies on lake restoration concluded that the response trajectories during re-oligotrophication were not the same as the inverse of the previous eutrophication processes, which had the characteristics of a complex lag [13].

The first step of ecological restoration was the community structures of Phytoplankton transformation [13]. Thus, many traditional and innovative methods with physical, chemical and biological processes have been applied to alleviate eutrophication and improve water quality over the past decades [14,15]. Among those methods, eco-technologies (i.e., artificial floating islands) have been widely applied around the world due to low cost, easy maintenance, safe and high-efficiency [16,17]. An enhanced artificial floating island is a soilless planting structure that was constructed with the floating mats, aquatic plants, artificial biofilm carrier and related ecological communities (e.g., algae, biofilms, zooplankton and small invertebrates). Better performance was achieved in this system than plant and/or biofilm carriers in the conventional system [18,19]. Chang et al. [20] indicated that the enhanced artificial floating island could quickly improve water quality and inhibit the growth of algae. Besides, some algae species (i.e., *Synedra ulna* (Nitzsch.) Her. and *Spirogyra*) can be used as indicators for water quality, as can aquatic insects (i.e., *Libellulidae*, *Coenagrionidae* and *Leptophlebiidae*). Thus, artificial floating islands with above advantages can apply in the field of water landscaping and ecological engineering.

Due to the high variability and dynamics of eco-technologies systems, the restoration trajectories will be variable and complex. There is a relative lack of studies on ecological restoration processes as it is still ascending in recent years. In this study, a kind of self-designed floating biological treatment system (FBTS) was to act as an eco-technology equipment for the remediation of water eutrophication, which is combined with the microbial carrier, macrophyte and micro-aeration system. Finally, the responses of algae to the water purification process of FBTS in a eutrophic urban pond were also evaluated.

2. Materials and Methods

2.1. Study Area

The pond S with the surface area of 5600 m^2 is located in the east of Dongguan city, Guangdong province, China (23°4′2.25″N, 113°41′12.72″E). It is a typical eutrophic pond in the Pearl River delta that was mainly polluted by domestic sewage. There was no hydraulic connection between the pond and the rivers in the city. The pollution overflow of the pipe network and non-point source pollution were the reasons for declining water quality. The water qualities of pond S were shown in Table 1.

Table 1. The water quality of pond S.

Index	Chl-a (μg/L)	COD (mg/L)	NH_3-N (mg/L)	TN (mg/L)	TP (mg/L)
Min	200	65.3	7.2	8.8	0.9
Max	305	97.8	18.8	21.0	1.7
Average	265	86.4	11.5	16.8	1.2

2.2. Description of FBTS

The cutaway of FBTS was shown in Figure 1, which was comprised of a floating bed (FB) and a microbial biofilm system (MC). The FB was constructed by a polyvinyl chloride perforated plate with a spacing of 0.20 m. *Canna* (*Canna indica* Linn.), one of the macrophytes that was most suitable for sewage treatments [21], was transplanted into perforated plate with a planting basket, respectively. The MC contained the microbial carrier and the micro-aeration systems, and the underwater part of FB were made in a stainless steel frame structure with 0.6 m high, which could combine with MC for the treatment of water. The carriers and polyurethane sponge were strung into a braided shape with the steel wires. Then, the upper and lower were fixed inside the frame to avoid blocky carrier stacking and hardening. The polyurethane sponge in the study was provided by Beijing Fengzelvyuan Environment Technology Co., Ltd., chitosan and powdered activated carbon were added in the process of material synthesis. The specific performance parameters were shown in Table 2. The aerator was fixed at the bottom of the frame to improve the redox state at the bottom of the water, and it could flush the biofilm on the surface of the carrier.

Table 2. The performance parameters of the polyurethane sponge used in this study.

Type	Appearance (mm)	Diameter (mm)	Specific Surface Area (m^2/m^3)	Material Density (g/cm^3)	Open Porosity (%)
FZ-1	50 × 50 × 50	0.2–5.0	≥15000	1.0–1.15	≥99

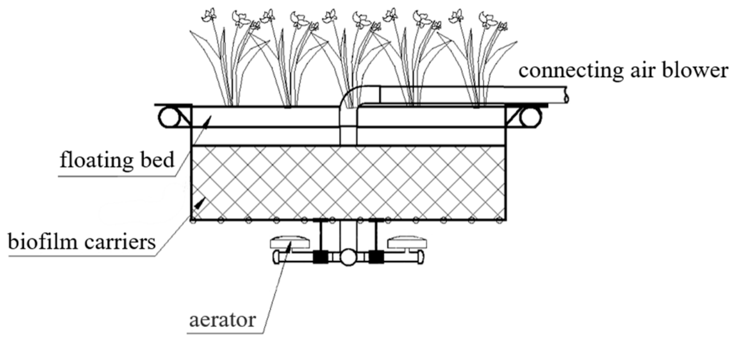


Figure 1. Cutaway of the floating-type biological treatment system (FBTS).

2.3. Experimental Design

The experiments were performed outdoors in two rectangular steel tanks with an inner dimension of 3.4 m in length, 2.0 m in width and 1.6 m in depth. The sediments from pond S (~0.5 m deep) were overlaid on the bottom of the tanks. The water from pond S was pumped into the tanks maintaining the water depth about 1 m, and marked two tanks (A and B). Meanwhile, macrophytes, biofilm carriers and an aerator were combined in tank B (Figure 1). However, tank A was the macrophytes group without biofilm carriers and an aerator. For both tank A and B, the size of the FB system was 1.8 m long × 1.0 m wide × 0.3 m high. Lastly, twenty-four clusters of the *Canna* were transplanted to each tank.

The biofilm inoculation process lasted 15 days for tank A. Firstly, aeration was carried out continuously for 72 h under static conditions. Then, the hydraulic residence time (HRT) was adjusted to be 4.5 h, and the intermittent aeration was used to maintain the concentration of DO above 2.0 mg/L in the water. Meanwhile, the indexes of chemical oxygen demand (COD) and NH_3-N in the effluent were tested regularly. The removal rates of COD and NH_3-N reached above 40%, and the microbial floc could be found on the surface of the carriers obviously, meaning that the inoculation was successful.

The formal experiments were carried out under the static water condition for three times, 10 days for each time. The DO concentration was controlled by intermittent aeration in tank A. Tap water was added in each tank to compensate for the evaporation during the experimental period.

2.4. Sampling and Analysis

2.4.1. Water Qualities

Indicators of water quality, such as total nitrogen (TN), total phosphorus (TP), NH_3-N and COD, were monitored every day for evaluating the purification efficiency of water. A 500 mL mixed-water sample of surface and bottom water was taken from each tank every day. Once the sample was collected, water temperature and DO were measured immediately. Then, half of each sample was filtered (0.45 µm) to analyze NH_3-N. However, TN, TP and COD was measured by using the unfiltered subsamples. The water parameters were measured according to the protocols described in Chinese Standard Methods [22].

2.4.2. Growth Characteristics of *Canna*

At the end of the experiments, three macrophytes in one tank were selected randomly, and their root length (the length of roots penetrated into the water from the base of the stem) was determined. Plant samples were dried to a constant weight at 70 °C. The dry root biomass and above-water biomass (summation of shoots and leaves) were reported in terms of grams per square meter (g DW/m^2).

2.4.3. Measurement of Oxygen Uptake Rate (OUR)

The oxygen uptake rate measurement in the study was established by the method of Garcia-Ochoa et al. [23]. Around 250 mL of wastewater from pond S were collected in a 275 mL incubation vessel. After the wastewater was saturated with air, the polyurethane sponge and plant root were placed in the vessel, respectively. The oxygen electrode (HANNA, Kit No: HI 9143, Hanna instruments Inc., Cluj-Napoca Jud. Cluj. Romania) was then inserted into the wastewater, and the vessels were maintained as a closed system through the entire operation. In addition, the measurement of DO was taken under stirring conditions, and the concentration of it in the wastewater at a different time was measured. Thus, the oxygen uptake rate (OUR) could be estimated from the slope of the change curves.

2.4.4. Phytoplankton Community

The contents of Cyanophyta chlorophyll (blue), diatoms/Pyrrophyta chlorophyll (brown) and Chlorophyta chlorophyll (green) were tested by Phyto-PAM instrument (Heinz Walz GmbH, Eichenring 6·91090, Effeltrich, Germany) and Zeiss AxioScope A1 biological microscope (Carl Zeiss GmbH, Jena, Thuringia, Germany). The qualitative samples were collected at the end of those experiments by using the #25 plankton net (bore diameter was 0.064 µm), and samples were immediately added in the formaldehyde solution for preservation.

The dominant species of phytoplankton were determined by the species dominance index (Y), and the formula is as follows:

$$Y = \left(\frac{n_i}{N}\right) f_i$$

where N refers to the total number of individuals of all species in a sample, n_i refers to the number of individuals of the ith species in the sample and f_i refers to the percentage of the sample appearing with such species in the total samples. When $Y \geq 0.02$, this species considers the dominant species. The dominant species were classified into functional groups by referring to Padisák [24] and Reynolds [25].

2.5. Statistical Analysis

The statistical analyzing and the graphing of the experimental data were performed by using Origin 9.0 (OriginLab Corporation, Northampton, UK). An analysis of variance (ANOVA) was used to test the significance levels of difference between the treatment and control set, using $p < 0.05$ as significant. A redundancy analysis (RDA, CANOCO 4.5) was conducted to assess the phytoplankton chlorophyll and environmental variables (the concentration of wastewater chemical properties). The significance of the relationship between phytoplankton data and the environmental data was tested by Pearson correlations using SPSS 18.0 (International Business Machines Corporation, Armonk, NY, US).

3. Results

3.1. Environmental Variables

After 10 days of operation, the removal rate of COD in tank A and B were 49.8% and 69.6%, respectively (Figure 2). At the same time, the concentration of NH_3-N also decreased continuously, and the removal rates were 64.0% and 79.0% in tank A and B, respectively. That means the nitrification, caused only by radial oxygen loss of roots, was weaker than the combination of aeration and biofilm. The removal rates of TN and TP in tank B were much higher than that in tank A ($p < 0.05$). It could be explained that the denitrification rate was improved due to the existence of a biofilm carrier. In addition, the adsorption and desorption of phosphorus by plant roots was limited.

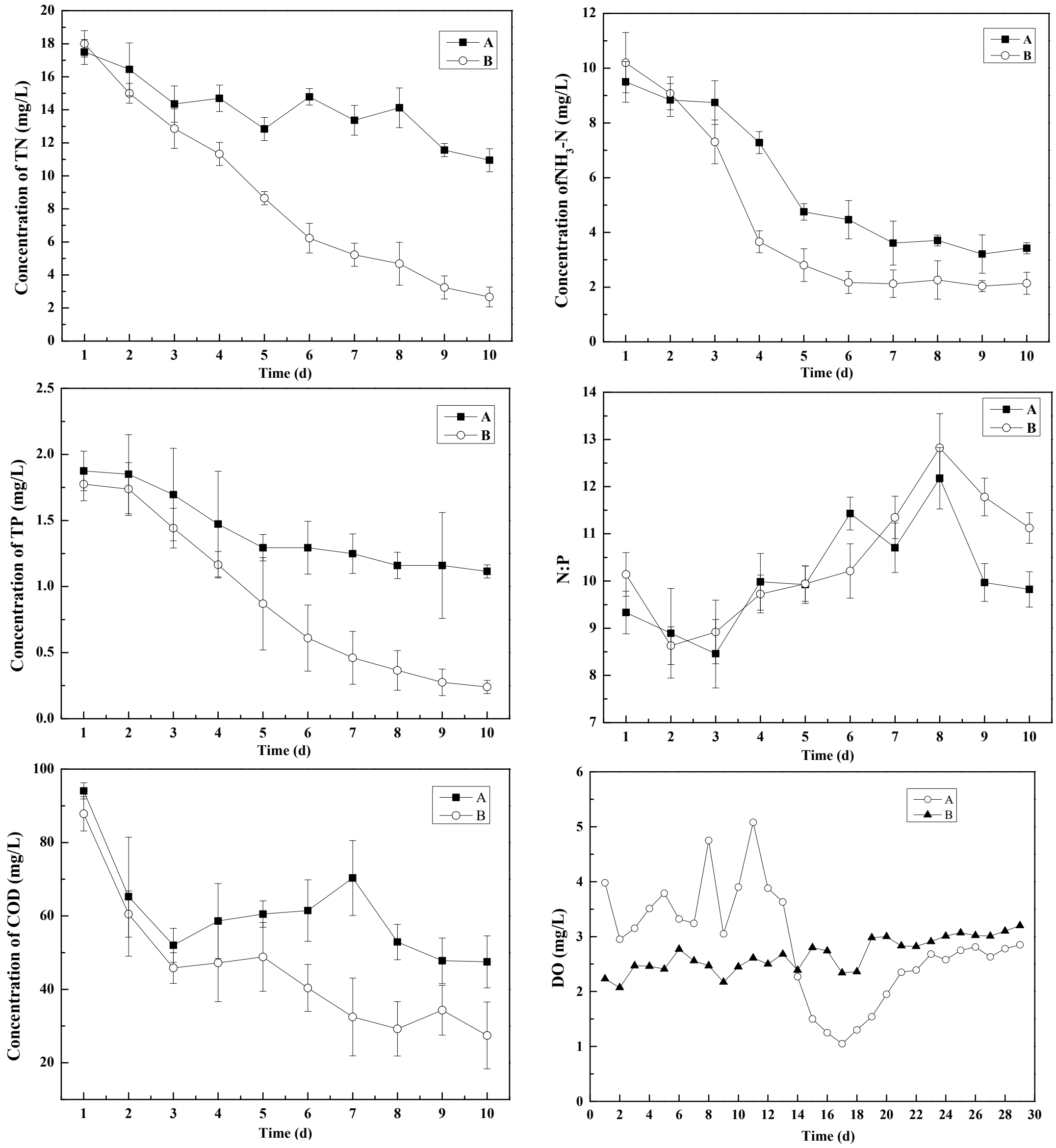


Figure 2. Changes of water parameters during experiment period (A, means tank A, which was the macrophytes group without biofilm carriers and an aerator; B, means tank B, which was the group combined with macrophytes, biofilm carriers and an aerator; means ± S.D., $n = 3$).

3.2. Plant Growth

At the end of experiments, the root lengths and root biomasses of *Canna* in tank B were higher than that in tank A (p < 0.05, Table 3) significantly. The DO concentration in tank B was maintained at 2.07–3.2 mg/L steadily (Figure 2) under the action of intermittent aeration, resulting in a more aerobic rhizosphere. On account of the oxygen diffusion through root tips influencing the root system penetrating into anaerobic substrates [26], the aerobic environment in the rhizosphere should be positively correlated to root biomass. Therefore, longer root length and larger biomass were obtained in tank B.

Table 3. Growth characteristics of *Canna* in tank B and tank C (mean ± S.D., n = 3).

Tank	Root Biomass (g DW/m^2)	Above-Water Biomass (g DW/m^2)	Root Length (cm)
Tank A	49.3 ± 3.4	279.0 ± 40.5	32.4 ± 2.9
Tank B	65.4 ± 4.6	345.6 ± 27.4	40.5 ± 3.4

3.3. Oxygen Uptake Rate

Even an aerator was not equipped in tank A, the DO concentration had never declined to <0.5 mg/L (never became anaerobic). However, the optimal dissolved oxygen level for simultaneous nitrification and denitrification (SND) was approximately 0.4–0.5 mg/L [27]. In addition, the plant roots with the organic matter also provided a large surface area for microbial growth and allowed the biofilm formation. However, the OUR of the polyurethane sponge was higher than plant roots (Figure 3), indicating that the carriers could maintain a high bioactivity and ability for N removal.

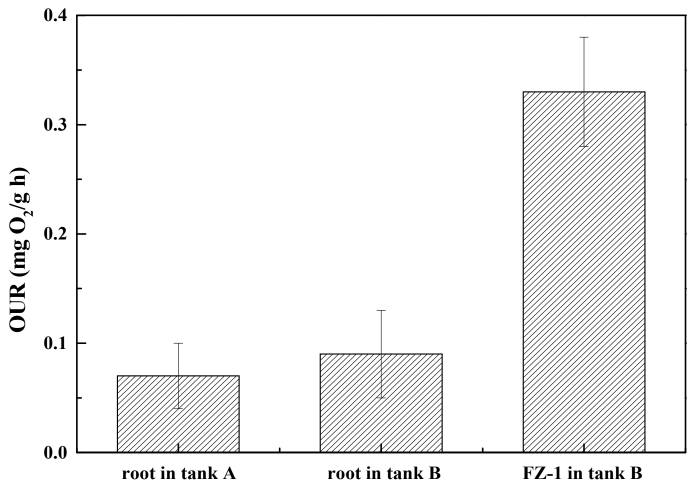


Figure 3. Oxygen uptake rate (OUR) for different tanks (means ± S.D., n = 3).

3.4. Phytoplankton Assemblages and Correlation Analysis

By comparing with pond S (p < 0.05), the removal rates of the total contents of chlorophyll in tank A and B were 49.0% and 88.7% respectively, which decreased significantly (Figure 4). The ratio of Cyanophyta chlorophyll (blue) to the total chlorophyll was cut down from 93% to 87% in tank A, and from 93% to 47% in tank B. It was indicated that Cyanobacteria would be more greatly affected by nutrients than Chlorophyta.

Overall, 46 genera belonging to six taxonomic categories (Chlorophyta, Cyanophyta, Euglenophyta, Bacillariophyta, dinophyte and cryptophytic) were observed in tank A, tank B and pound S. The dominant species were determined by the standard of dominance degree >0.02, and the dominant species were classified into eight functional groups (C, F, J, Lo, M, N, P and X_1) by referring to Padisák [24] and Reynolds [25] (Table 4). Cyanobacteria would be the dominant species in the pond S, however, the phytoplankton diversities would increase in tank B. It was indicated that the phytoplankton-dominated state could be reconstructed in the eutrophic water when the biological treatment system was embedded.

The Cyanophyta chlorophyll (blue) and Chlorophyta chlorophyll (green) were positively correlated to COD, NH_3-N, TN and TP, but were negatively correlated to TN:TP ratios (Figure 5, Table 5). Meanwhile, the TN:TP ratios were negatively correlated to concentrations of TN and TP (Figure 5, Table 5). To a certain extent, phosphorus played more important roles than nitrogen in the period of remediation.

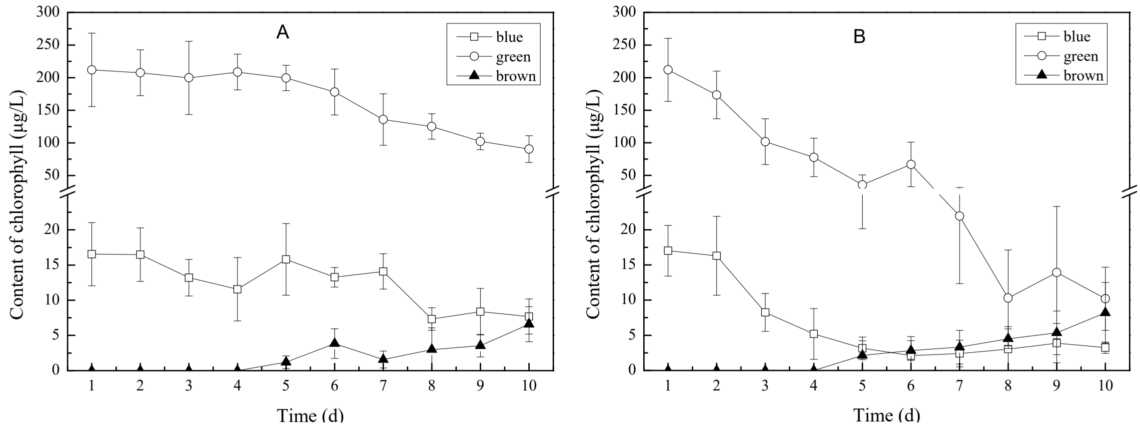
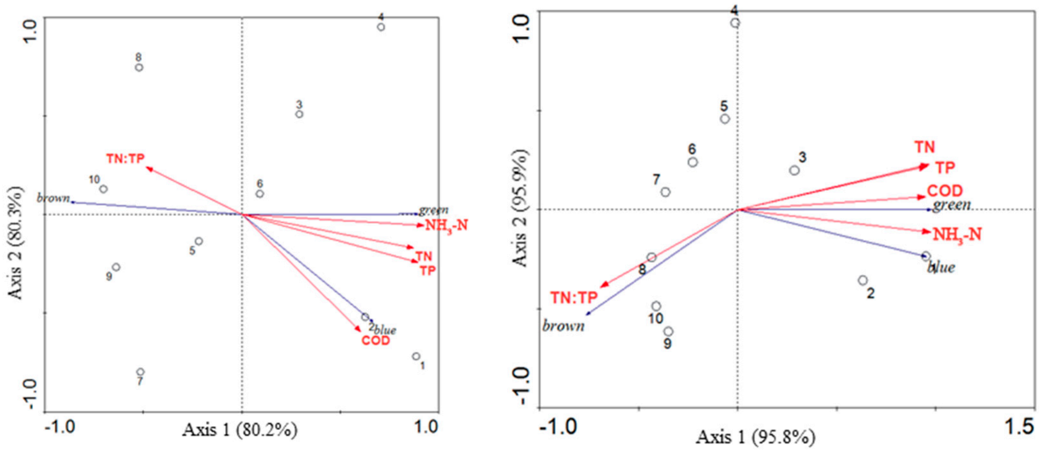


Figure 4. Contents of the chlorophyll. (A, means tank A, which was the macrophytes group without biofilm carriers and an aerator; B, means tank B, which was the group combined with macrophytes, biofilm carriers and an aerator).



(**a**) (**b**)

Figure 5. Redundancy analysis (RDA) diagram of phytoplankton groups (chlorophyll contents for blue, green and blown) and environmental parameters (total nitrogen (TN), NH_3-N, total phosphorus (TP), chemical oxygen demand (COD) and N:P ratio) for tank A (**a**) and tank B (**b**).

Table 4. Predominant species and predominant functional groups (FG) in three tanks [10,25].

Phylum	Species	Abundance ($\times 10^4$ ind./L)	Biomass (mg/L)	Dominance Degree (Y)	FG	Habitat Characteristics
			Pond S			
Cyanophyta	*Microcystis flosaquae*	3456	1.73	0.860	M	Eutrophic to hypertrophic, small to medium-sized lakes
Cyanophyta	*Microcystis marginata*	307	0.15	0.076	M	

Table 4. *Cont.*

Phylum	Species	Abundance ($\times 10^4$ ind./L)	Biomass (mg/L)	Dominance Degree (Y)	FG	Habitat Characteristics
			Tank A			
Chlorophyta	*Staurastrum pingue*	630	3.15	0.509	P	Similar to that of codon N (continuous or semi-continuous mixed layer) but at higher trophic states
Cyanophyta	*Microcystis marginata*	499	0.25	0.403	M	Eutrophic to hypertrophic, small to medium-sized lakes
Chlorophyta	*Tetraedron tumidulum*	29	0.06	0.023	J	Shallow, mixed, highly enriched systems
			Tank B			
Cyanophyta	*Microcystis marginata*	77	0.04	0.325	M	Eutrophic to hypertrophic, small to medium-sized lakes
Cyanophyta	*Microcystis flosaquae*	38	0.02	0.162	M	
Bacillariophyta	*Cyclotella meneghiniana*	12	0.96	0.065	C	Eutrophic small- and medium-sized lakes with species sensitive to the onset of stratification
Bacillariophyta	*Melosira granulata*	7	0.22	0.030	P	Similar to that of codon N (continuous or semi-continuous mixed layer) but at higher trophic states
Pyrrophyta	*Peridinium bipes*	11	0.12	0.046	L_O	Deep and shallow, oligo to eutrophic, medium to large lakes
Chlorophyta	*Staurastrum pingue*	24	0.12	0.102	N	Continuous or semi-continuous mixed layer
Chlorophyta	*Oocystis elliptica*	10	0.10	0.041	F	Clear, deeply mixed mesotrophic-eutrophic lakes
Chlorophyta	*Chlorella pyrenoidosa*	7	0.01	0.030	X_1	Shallow, eutrophic-hypertrophic environments

Table 5. Coefficients of the Pearson correlation between phytoplankton chlorophyll and environmental indicators (n = 90).

Index	TN	TP	NH_3-N	COD	Total Chlorophyll	Green	Blue	Brown
N:P ratio	−0.558 *	−0.718 **	−0.681 **	−0.426	−0.543 *	−0.522 *	−0.554 *	0.624 **
TN		0.972 **	0.826 **	0.877 **	0.926 **	0.879 **	0.927 **	−0.795 **
TP			0.898 **	0.836 **	0.920 **	0.884 **	0.919 **	−0.828 **
NH_3-N				0.751 **	0.835 **	0.826 **	0.837 **	−0.764 **
COD					0.843 **	0.860 **	0.839 **	−0.671 **
Total chlorophyll						0.954 **	0.994 **	−0.712 **
Green							0.935 **	−0.640 **
Blue								−0.729 **

Notes: * and ** indicate significance of Pearson correlation at $p \leq 0.05$ and 0.01, respectively.

4. Discussion

Floating islands systems had been tested in stormwater ponds, lakes, rivers, water supply reservoirs, aquaculture environment, etc. [27]. The mesocosm and pilot studies on the removal of organic matter, suspended solids, nutrients and metals showed that the systems could improve the quality of a wide variety of the polluted waters. Van de Moortel [28] implemented floating macrophyte mats in a mesocosm for the sewer overflow treatment. It was shown that the presence of floating mats contributed to a lower pH and NH_3-N (from 1.4% to 34%), TN (from 19% to 44%), TP (from 4% to

31%) and COD (from 30% to 49%) were significantly removed, the similar removal efficiencies were obtained in previous studies for the macrophytes in tank A. As shown in Figure 2, the removal rates of NH_3-N, TN, TP and COD were 7.0%–66.2%, 6.0%–37.4%, 1.3%–40.5% and 30.6%–49.5%, respectively. However, exploring the performance of plant species and microorganisms was conducive to identify the combination of those for optimizing the remediation efficiencies [29]. Sun et al. [30] confirmed that the removal efficiency of nitrogen was greatly enhanced by adding the immobilized denitrifies in the water of floating islands. One of the key elements of the floating islands was the biofilm carriers (Figure 1). The polyurethane sponge, with a high mechanical strength, large specific surface area, rough surface and good adhesion to microorganisms, could be considered as an ideal growth medium [31]. Another advantage of the polyurethane sponge was that it could achieve simultaneous nitrification and denitrification (SND) due to the high dissolved oxygen (DO) gradient in the cubic biofilm [32]. Results from Song et al. [33], TN removal efficiency in a moving bed biofilm reactor with polyurethane sponges as biocarriers was 84.2% ± 4.8%, which would achieve nearly 10% higher removal efficiency than those with conventional sponges as biocarriers. Similarly, the TN removal efficiency in Tank B with polyurethane sponges as biocarriers was 85.2% after reaction, which could be nearly 50% higher than the removal efficiency in Tank A without biocarriers (Figure 2).

Traditionally, N:P ratios were proposed as an index to classify lakes into N- or P- limited categories. Takamura et al. [34] indicated that most of the N:P ratios were less than 10 during the *Microcystis* blooms in Kasumigaura Lake. In this study, high biomass of *M. marginata* and *M. flosaquae* were obtained in pond S (Table 4), while the N:P ratios were lower than 10 at the beginning (Figure 2). However, some studies had noted that the N:P ratio was not a suitable indicator, which was limiting in urban shallow eutrophic lakes, because the adding of N and P had exceeded the assimilative capacity of the phytoplankton [35]. The low N:P ratios were presumably the result, but not the cause of the *Microcystis* bloom [36]. However, phosphorus was considered as the primary limiting factor for the algal growth with the increasing ratios of N:P in lakes and streams [37,38]. The shallow lakes required a special consideration because they could accomplish the transform between two stable states: (1) An abundance of submerged vegetation provides a high-quality wildlife habitat that would be usually achieved in the clear-water condition, and (2) the frequent algal blooms and the poor habitat quality would occur in the turbid-water condition. The lake was in a highly resilient clear state, a highly resilient turbid state or a dynamic region would be determined by the shallow lake's TP level with related critical TP tipping points [39]. Adsorption and sedimentation were the key factors for the geochemical removal mechanisms of P in wetlands [40]. Polyurethane sponge with a large porosity and a large specific surface area used as a biofilm carrier, which could exhibit good adsorption performance in treatment processes [33,41]. The adsorption efficiency of P by a biological treatment system in tank B was obviously higher than that in tank A, by the sedimentation processes and plant roots (Figure 2).

It was hypothesized that the phosphorus-sensitive cyanobacteria were significantly affected by low phosphorus pressure [42]. Lang et al. [43] and Su et al. [44] reported that the number of cyanobacteria decreased due to the less competitive advantage of cyanobacteria under reduced phosphorus conditions after the removal of phosphorus in shallow water. In this study, the reduction of cyanobacteria was also more sensitive than Chlorophyta (Figure 4). However, some authors stated that the cyanobacteria were dominant in both low and high P conditions [45]. The results of this study indicated that the Cyanophyta chlorophyll (blue) was positively correlated to TP (Figure 5, Table 5). This might also be related to the fact that cyanobacteria store P in their cells [46,47]. In addition to the nutrients, the type of habitat also had a significant impact on the development of cyanobacteria in small water bodies. The macrophytes could restrict wind-induced water movement to produce a calm habitat as Cyanobacteria prefer in quiet water without turbulence [48]. Especially the Cyanobacteria in ponds that preferred the macrophyte-dominated sites compared with open water [47]. Even in some cases, the development of cyanobacteria was resistant to the allelopathic secreted substances from the macrophytes [49]. A long-term and stable partial nitrification could be achieved in the intermittent aeration [50,51]. Besides, the suitable relatively calm state for cyanobacteria was disturbed by the aeration, resulting in the higher removal rate obtained in tank B with aeration than that in tank A without aeration (Figure 4).

In general, cultures with low N:P ratios (<10) could benefit the growth of diatoms [52], and more than 90% of publications showed the hypothesis that the diatom assemblage composition change was caused by TP in lakes [53]. The diatoms/Pyrrophyta chlorophyll (brown) was detected, and showed an upward trend (Figure 4) after the fifth day, which was positively correlated to the N:P ratio (Figure 5, Table 5). Especially in tank B, the diatoms would become one of the dominant species after the experiments (Table 4). Most diatom-TP transfer functions were based on all taxa in sedimentary diatom assemblages including planktonic, epiphytic and benthic taxa. However, some benthic taxa would likely be more sensitive to the changes of habitat than to nutrient concentrations, indicating that TP correlated well with geochemical proxies in the lake [53]. The bio-carrier with the reduction of nitrogen and phosphorus concentration could provide suitable habitat for phytoplankton such as epiphytic diatoms, which would play an important role in improving the biological diversity.

Ecologists ascribed that phytoplankton species had an identical or a similar life style, and a living strategy into a basic unit "functional group" for the response analysis of the environmental changes [24]. Group M (*Microcystis*) could grow in the eutrophic to hypertrophic conditions in small to medium-sized lakes, which would occur as the colonies of different sizes under natural conditions. It would cause serious environmental and ecological problems in temperate and tropical freshwater ecosystems [54]. Group P (*Staurastrum, Peridinium*) were able to live in eutrophic waters with mild light, and they favored the high transparency [25,55]. A succession of group M (pond S) to group P (tank A and tank B) was observed as the shading effect by macrophytes and the transparency would increase with the continuous improvement of the water quality. Meanwhile, a succession group of M (pond S) to group C (tank B) was observed. The population development of group C (*Cyclotella*) was often subject to the availability of silicon, and they were dependent upon turbulence for the suspension [25]. Therefore, the disturbance of the water body and the release of trace elements in sediment would be conducive to the growth of diatoms due to the intermittent aeration. In addition, although other functional groups occupied a small proportion of the total biomass, their roles in aquatic ecosystems could not be ignored. Overall, a shift from severe eutrophication to lightly eutrophication would be indicated by the successions of phytoplankton.

The changes of the phytoplankton communities were strongly related to the concentrations of nutrient and the fluctuations of water level, as well as the water temperatures and the rainfall. The sustainable treatment technologies would be necessary as the extreme weather events and the human disturbances were more frequent and severe. In addition, the scale of sampling and measurements should be enlarged to guarantee more solid data and test results in future experiments.

5. Conclusions

An enhanced artificial floating-type biological treatment system (FBTS) was constructed by the floating bed, the macrophytes, the artificial biofilm carriers (polyurethane sponge) and aerator. The removal efficiency of TN in FBTS was nearly 50% higher than that in the only macrophyte system after 10 days of treatment, and the responses of algae to the water purification process had also been observed. The results showed that the low N:P ratio was presumably due to the result of a *Microcystis* bloom, which was the dominant photoplankton species in pound S. Meanwhile, the total chlorophyll, Cyanophyta and Chlorophyta chlorophyll were positively correlated to COD, NH_3-N, TN and TP, but negatively correlated to the N:P ratio. The adsorption efficiency of P by FBTS was obviously higher than by sedimentation and by the root adsorption of macrophytes. On the one hand, the removal of P resulted in the reduction of the phosphorus-sensitive Cyanobacteria, and the relatively suitable state of Cyanobacteria would be disturbed by the aeration process. On the other hand, the diatoms/Pyrrophyta chlorophyll (brown) positively correlated to the N:P ratio showed an upward trend, which supported the hypothesis that the composition of diatom would be changed by TP. The successions of the phytoplankton functional groups were from group M (*Microcystis*) to group

P (*Staurastrum*, *Peridinium*) and group C (*Cyclotella*). The dominant species of Cyanophyta would be transformed to the co-existed with Bacillariophyta, Pyrrophyta and Chlorophyta in FBTS. Consequently, this new FBTS could be a promising eco-technology with a high removal efficiency of nitrogen and phosphorus in the eutrophic water system, and even would promote the succession of phytoplankton.

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