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Roles of Floating Islands in Aqueous Environment Remediation: Water Purification and Urban Aesthetics

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Abstract: Floating islands have been commonly utilized for the ecological remediation of urban waters; meanwhile, they are beneficial to landscape decoration and beauty improvement. Therefore, this work was conducted to analyze the roles of floating islands in water purification, urban aesthetics, and the potential association. Based on this, different plant-based floating islands were constructed and employed for the treatment of lake water, and biochar was utilized as fillers for the coordination and the capacity enhancement, which fulfilled the synergism of plants, biochar, and the attached microbes. Furthermore, specific effects of floating islands on the improvement of urban aesthetics were analyzed from different perspectives, and the corresponding thinking was proposed for the designing and the optimization, including plants collocation, spatial layout, cultural background, and contact with nature. This work offers a new insight into the construction of floating islands to realize the water purification and strengthen the beauty of urban landscapes, and thus improving the living environment quality of human beings on the whole.

Keywords: floating island; water purification; synergism of plants and organisms; urban aesthetics; natural harmony

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1. Introduction

The aqueous environment has an indispensable impact on human beings from the perspectives of not only survival necessity but also environmental aesthetics. Firstly, it is important to adjust the temperature of the surrounding, and the "heat-island effect" can be alleviated to a certain extent during the hot summer [1,2]. In addition, it bears the noteworthy responsibilities of storage, discharge, and flood control; at the same time, it can be also utilized as the standby source for firefighting, which is quite significant for survival and rescue [3,4]. In addition, it shows brilliant potential for air purification and provides necessary conditions for plant growth, thus further improving the living conditions of humans. However, pollution of aqueous environments has been widespread, which hinders the exertion of the intrinsic effects greatly; meanwhile, serious pollution also brings bad life experience. Consequently, much attention has been paid to the treatment of the aqueous environment, and the floating island is considered as an effective measure to take account of water purification and environmental beautification.

Floating island is one of the common methods for ecological restoration of polluted water, and the application for the treatment of urban water seems to be quite frequent. During the treatment process of floating islands, plants play the pivotal roles by virtue of the capture of the nutrients such as N and P, and the decomposition of organics will be realized through the cooperation of plants and the attached microbes; thus, plants can be considered as the direct "tools" and the indirect "medium" that provide shelters for microbes and cooperates with them [5–8]. It was reported by Brown et al. (2018) [9] that the highest removal efficiency of phosphorus by floating island can be up to 86%, and the relevant capacity for areal phosphorus removal was 16.5 $g{\cdot}m^{-2}a^{-1}$. Kong et al. (2019) [10]

employed different types of floating islands and gained the removal efficiency of total nitrogen and phosphorus with 90.3 ± 0.8% and 92.8 ± 0.6%, respectively. Except for N and P, organics can be removed with great efficiency. Zhang et al. (2018) [11] and Darajeh et al. (2016) [12] obtained the excellent removal efficiencies of organics (measured by chemical oxygen demand, COD) no matter if the initial concentration was extremely tremendous or not, verifying that floating islands showed brilliant potential in water purification. In addition, the combination of the plants and the existing water produces extra benefits about urban landscape, making the city more diverse and livelier. Therefore, it can be considered that the floating island method is an environmentally friendly revelation that displays brilliant purification capacity for water and creates ecological and beautiful scenery for the living environment. Unfortunately, related interdisciplinary research has been rarely reported, yet in-depth exploration seems to be necessary still.

Herein, floating islands with plants and biochar fillers were constructed in this study, and the removal efficiencies of ammonia nitrogen (NH_4^+-N), total nitrogen (TN), total phosphorus (TP), and COD were used to evaluate the capacity of water purification. In the meantime, analysis of the removal pathways as well as the microbial diversity was conducted for further unveiling the roles of floating islands, which provided the basis for the construction and optimization in the practical. Furthermore, advantages of floating islands in urban aesthetics were elaborated from different aspects, thus complementing the overall benefits and extending another thinking to the selection of floating islands.

2. Materials and Methods

2.1. Materials and Chemicals

The seedings of canna, water hyacinth, water spinach, and calamus were purchased from the aquatic plant base in Guangdong province, which would be further cultivated and applied for the construction of floating islands. Pine wood was purchased from Anhui province to prepare the biochar, and the skeleton of the floating island was purchased from Hebei province, with a square structure with a size of 25 cm and the raw material of high-density polyethylene.

2.2. Construction of Floating Islands and Monitoring of Treated Wastewater

Floating islands were proceeded in the glass box with a size of 800 mm × 600 mm × 600 mm, and the floating beds were arrayed as a rectangle of 3 × 2. The test water was sampled from South Lake in Wuhan, and the initial pH was 7.6 ± 0.2, which was quite suitable for the growth of plants as well as the survival and metabolism of microbes; thus, the pH would not be further adjusted. In addition, given that the growth of plants needed a sufficient area for the length extension of the roots but the oversized water space may decrease the general running of the floating islands, the experimental depth of the box was controlled at a range of 450~500 mm. In order to make a comparison of the capacity for contaminants removal, there were four kinds of floating islands applied in the test, planting with canna, water hyacinth, water spinach, and calamus, respectively. Furthermore, for better purification, biochar obtained from pine wood was utilized as the fillers for the combination, and the test groups with biochar were marked as the composite islands while the formers were named as plant islands.

The running time of all the floating islands was set as approximately 48 d, and sampling was proceeded every two days. Furthermore, for the overall consideration of the feasible conditions of plants and microbes for survival, the experimental temperature was approximately 20 °C, and lighting as well as rain-proof measures were taken into consideration.

2.3. Analytical Methods

Concentrations of NH_4^+-N, TN, TP, and COD were determined according to the standards methods in triplicate [13], and the influent concentrations are shown in Table 1.

Table 1. Initial concentrations of the lake water.

Index	Concentration (mg/L)
$NH_4{}^+$-N	8.7 ± 0.5
TN	21.6 ± 0.7
TP	1.3 ± 0.2
COD	63.3 ± 1.1

2.4. High-Throughput Sequencing

Biofilm samples were obtained from the roots of different plants, which were further collected for 16s rRNA sequencing and metagenomic sequencing [14,15]. All the sequencing was fulfilled by Shanghai Majorbio Bio-pharm Technology Co., Ltd., Shanghai, China.

3. Results and Discussions

3.1. Evaluation of Floating Islands for Water Purification

3.1.1. Comparison of Contaminants Removal by Plants

As shown in Figure 1, all the plant islands displayed a satisfying capacity for water purification and the concentrations of residual contaminants were sparse. Removal of various contaminants could be attributed to the synergism of the plants and the attached microbes. Specifically, the effects could be concluded, including the following aspects, and the process could be generally concluded, as shown in Scheme 1.

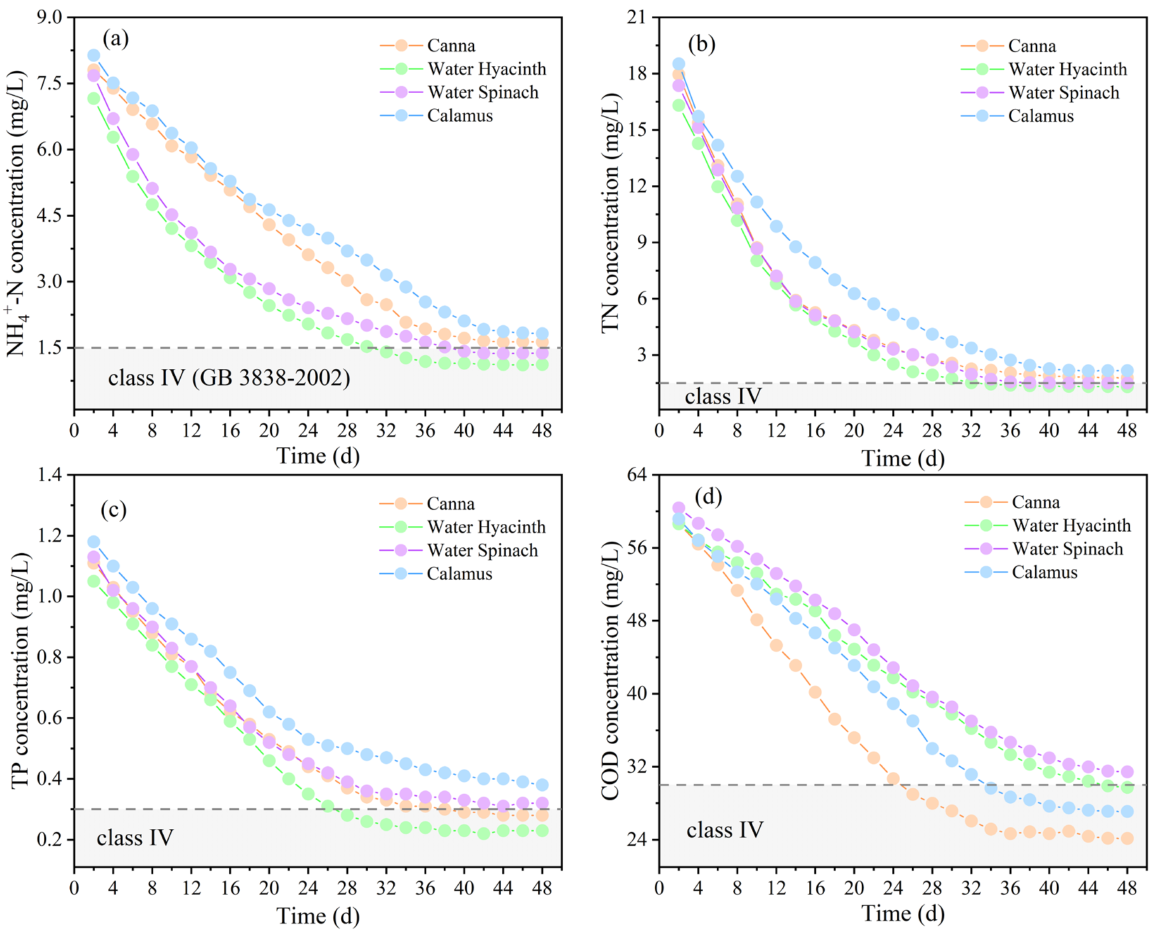
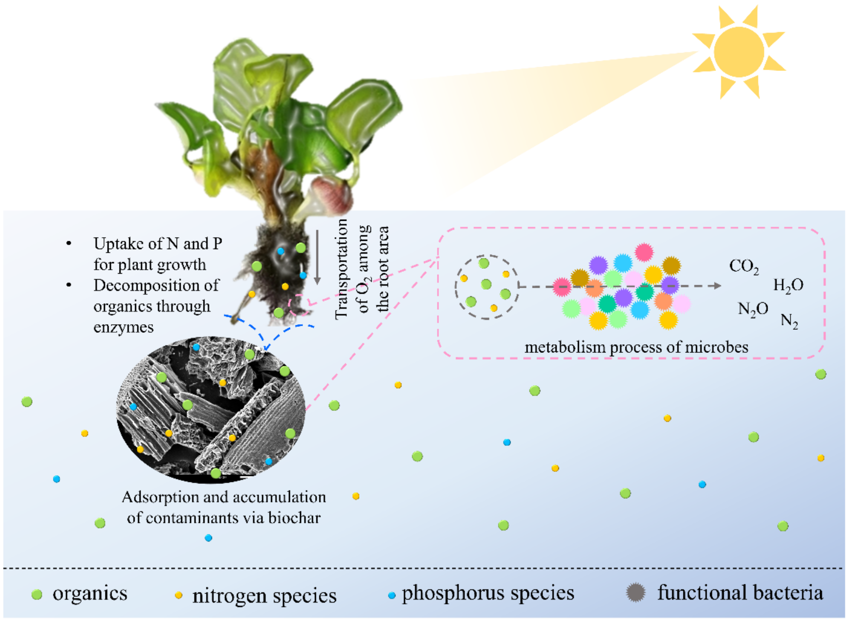


Figure 1. Comparison of contaminants removal of plant islands with different plants: (**a**) $NH_4{}^+$-N, (**b**) TN, (**c**) TP, (**d**) COD.



Scheme 1. General roles of components in floating islands for the removal of contaminants.

(1) The well-grown roots exhibited a great network structure and acted as the filter to realize the preliminary immobilization of contaminants; (2) N and P could act as the essential components for the growth of plants, and the attached microbes could also realize the transformation through metabolism, such as NH_4^+-N, NO_3^--N, P, etc., thus finally decreasing the concentration of N and P moieties in the aqueous environment; (3) organics could be decomposed with the effects of enzymes produced by roots; meanwhile, microbes could take advantages of organics as the carbon source for the growth, thus facilitating the degradation during the metabolism process; (4) oxygen could be secreted by roots to form the anaerobic/anoxic/aerobic micro-areas, which provided the microbes with suitable conditions for the removal of N and P [16–20].

Therefore, it can be observed in Figure 1 that different plants displayed quite diverse performances in NH_4^+-N, TN, TP, and COD removal, which may be owing to the capacity discrepancy of root filtration, plant growth, oxygen production, etc. Furthermore, it can be seen that removal efficiencies were quite remarkable in the first few days (e.g., 0~8 d) while the decreasing of contaminants was so negligible during the final stage (e.g., 40~48 d), since the immobilization and utilization effects of roots for plant growth as well as the metabolism of microbes could be proceeded quickly; thus, the macroscopic phenomena showed the significant decreasing of various contaminants at first. However, the immobilization capacity would be saturated, and the rate of growth or metabolism would be flat or even stagnant during the process. Consequently, variation of the general removal efficiency would be more and more gradual, and it could be seen that the removal obtained the equilibrium in the last few days. Moreover, it can be seen that indexes of treated water can meet or nearly accord with the class IV of the quality standards for surface water (GB 3838-2002), showing that the four plants used in the floating islands showed great potential for the removal of contaminants. In general, water hyacinth displayed a relatively superlative performance among them since all the indexes of the related plant island met the standard of class IV.

3.1.2. Enhancement of Water Purification Combined with Filler

Based on the result above, biochar was utilized as fillers for strengthening the capacity of floating islands and increasing the removal efficiencies on the whole. As shown in Figure 2, all the composite islands displayed better performance and various indexes of treated water met class IV of the standard (GB 3838-2002), and some of them could even accorded with class III, demonstrating the significant effectiveness for water purification with the additional fillers. Furthermore, it can be found that the fast removal process was remarkably enhanced, especially at the first stage of 0~8 d, and the final equilibrium reached in advance, which could be attributed to the brilliant properties of biochar. Briefly, biochar displayed brilliant performance in the porous structure and functional groups, which provided abundant active sites for the rapid adsorption process, and the generally negative charged properties were also conducive to the removal of contaminants such as NH_4^+-N [21–23]. In order to eliminate the effects of biochar on the removal efficiencies, exploration for the removal of various contaminants with biochar alone was conducted; the results are shown in Figure 3. It can be observed that the rapid adsorption proceeded within the first 2 h, since active sites on biochar were relatively abundant and the contaminants could be adsorbed quickly. However, the adsorption was quite ponderous as the reaction proceeded, and it reached equilibrium in the later dozens of hours, yet the overall removal efficiencies were not very significant, showing that the enhancement above did not originate from the direct adsorption by biochar. Accordingly, water purification in composite island systems can be actually reckoned on the synergism among plants, biochar, and the attached microbes. Apart from the effects analyzed in Section 3.1.1, biochar participated in the direct and indirect pathways during the removal process, and Scheme 1 exhibits the figurative effects. Firstly, pores and functional groups always served as active sites for the physical and chemical removal, such as pore filling and surface complexation, and the effects were especially notable during the initially rapid adsorption process [24–26]. Additionally, concentrations of N and P around the roots would be higher owing to the enrichment of biochar, thus realizing the better utilization by plants and further boosting the removal of contaminants by plants and the attached microbes. In addition, biofilms can be gradually formed on biochar particles and the extra biological metabolism would further promote the removal of NH_4^+-N, P, COD, etc. In general, adding biochar could not only stimulate the initial adsorption with obvious effects but also continuously affect the subsequent process. Hence, the performance, including the rate of rapid adsorption, the final efficiencies, and the equilibrium during the whole running, was much better than plant islands.

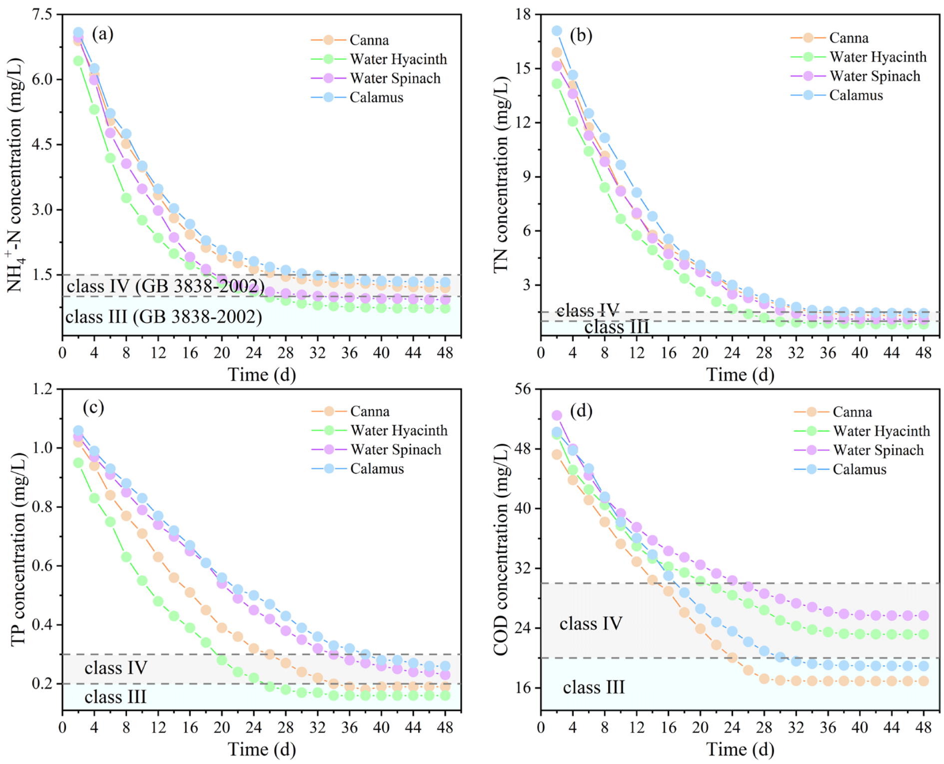


Figure 2. Removal enhancement via combining with biochar: (**a**) NH_4^+-N, (**b**) TN, (**c**) TP, (**d**) COD.

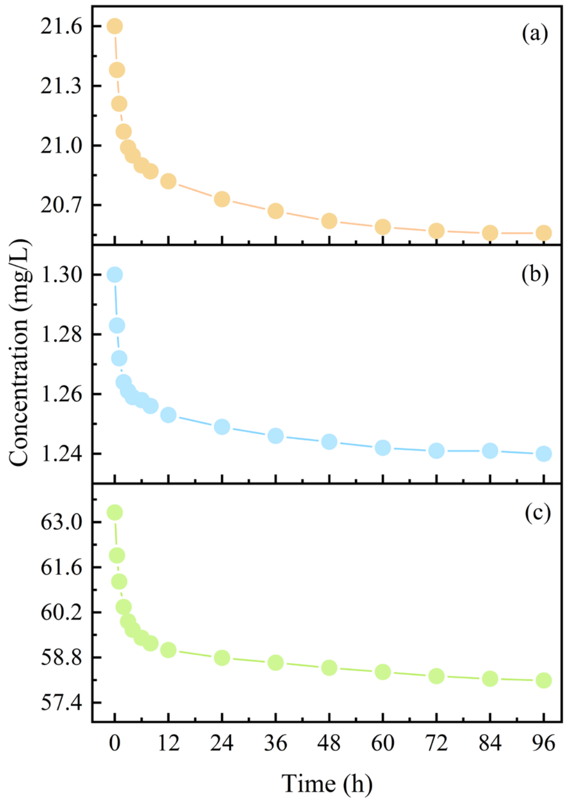


Figure 3. Removal of the contaminants with biochar alone: (**a**) TN, (**b**) TP, and (**c**) COD.

3.2. Analysis of Bio-Diversity and the Corresponding Contribution

In order to verify the existence and the contribution of microbes, high-throughput sequencing was employed for the determination of the biodiversity, and Table 2 shows the microbial Alpha diversity indexes of the different plant islands above. For a more concise expression of the subsequent paragraphs, A1~A4 are applied for representing the plant islands of canna, water hyacinth, water spinach, and calamus, respectively.

Table 2. Alpha diversity index analysis.

Sample	Sobs	Shannon	Simpson	Ace	Chao	Coverage
A1	1409	5.73	0.00714	1713.80	1712.85	0.98
A2	1093	5.12	0.016275	1426.93	1392.06	0.99
A3	1090	5.14	0.016104	1416.24	1391.00	0.99
A4	1448	5.74	0.007236	1717.44	1684.49	0.99

As shown in Table 2, it can be observed that A1 and A4 exhibited the higher indices of Shannon, Ace, and Chao, indicating that plant islands of canna and calamus showed better microbial richness; meanwhile, ecosystems of them may be more tolerant to pollutants and more conducive to microbial activity. Consequently, it can be explained why canna and calamus islands displayed the better performance of organics removal in Section 3.1.1. Furthermore, Venn diagram analysis was performed on the samples, and the results are shown in Figure 4. The number of OTUs shared among all the islands reached 586, implying that the community structures of the plant islands above were quite similar. Notably, unique microbes of A1 (167) and A4 (187) were much higher than A2 and A3, which may be another reason why they possessed the higher removal efficiency of organics.

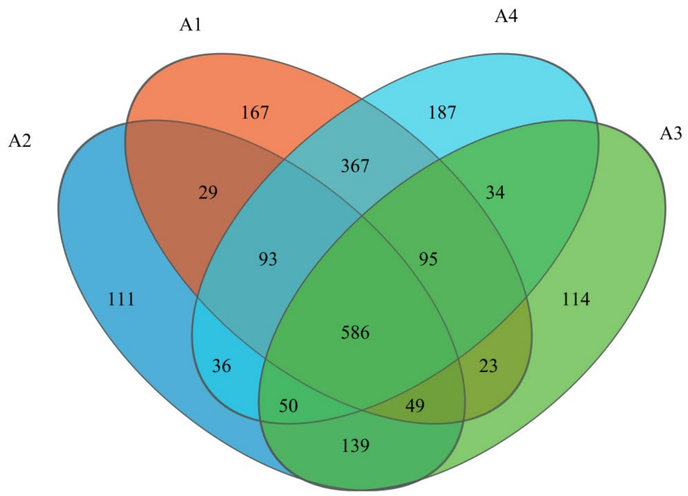


Figure 4. Venn diagram of different salinity concentrations.

For more specific comparison, the evolution of microbial community structure at phylum or genus level was proceeded for further exploration. As shown in Figure 5, it can be observed that *Proteobacteria* [27], *Bacteroidota* [28], *Actinobacterio* [29], *Chloroflexi* [30], and *Acidobacteriota* [31] were the dominant phylum in the plant islands, and it was interesting that all of them were capable of removing nitrogen and organics, which accounted for a proportion over 87.48% in the islands above. The phenomena above could be explained by the comprehensive results of the strong survival ability of microorganisms and the excellent living conditions provided by plant islands. Consequently, it seemed that the resistance to the growth and reproduction for functional bacteria was quite negligible; thus, the removal of nitrogen and organics could be conducted with great efficiency. Moreover, it can be found that *Proteobacteria* (A1: 39.75%; A2: 30.55%; A3: 29.50%; A4: 39.74%) and *Bacteroidota* (A1: 28.18%; A2: 22.04%; A3: 20.50%; A4: 29.92%) were much more significant in canna and calamus islands, while water hyacinth and water spinach depended more on the other advantageous gates, which may explain why water hyacinth and water spinach displayed a better performance in NH_4^+-N removal. In summary, functions of dominant flora tended to be the same, although there were some differences in the abundance of dominant phylum in the plant islands above, and the microorganisms with higher abundance played the key roles in the better performance in the removal.

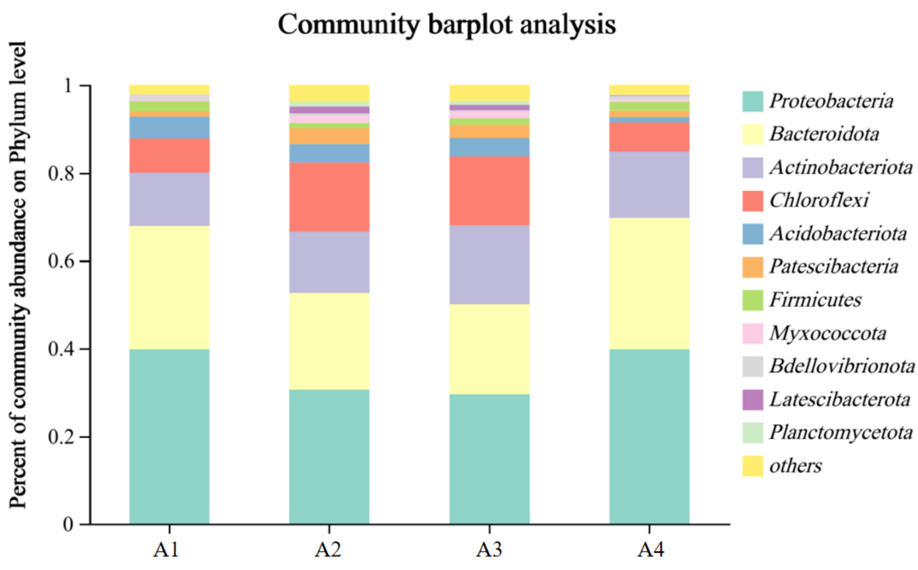


Figure 5. Evolution of microbial community structure at phylum level.

In order to further explore the influences of different plants on the microbial community structure, species with the top 50 abundance were selected for microbial analysis at the genus level, and the results are shown in Figure 6 and Table 3. According to hierarchical clustering analysis, it could be observed that A1 and A4 were quite similar, while A2 and A3 showed significant similarity, which may further prove the corresponding similitude in capacities for the removal of N and P as well as the bio-degradation of organics. In addition, it was shown in Figure 6 that the microorganism distribution of all islands was relatively uniform, and there was no excessive proportion of bacteria on the whole. The common dominant bacteria in the islands were *Saprospiraceae* and *Ferruginibacter*, and both of them displayed remarkable effects on organics degradation; however, the former had been reported to capture other bacteria as feeds by cell aggregation [32,33]. Therefore, A1 and A4 performed much better in COD removal owing to the much higher proportion of *Saprospiraceae* and *Ferruginibacter*. Moreover, the commonly reported bacteria for organics degradation, *Leucobacter* and *Flavobacterium*, occupied a certain abundance in A1 and A4 but were almost absent in A2 and A3 [34,35], thus further expounding why COD removal efficiencies of A1 and A4 were greater than that of A2 and A3.

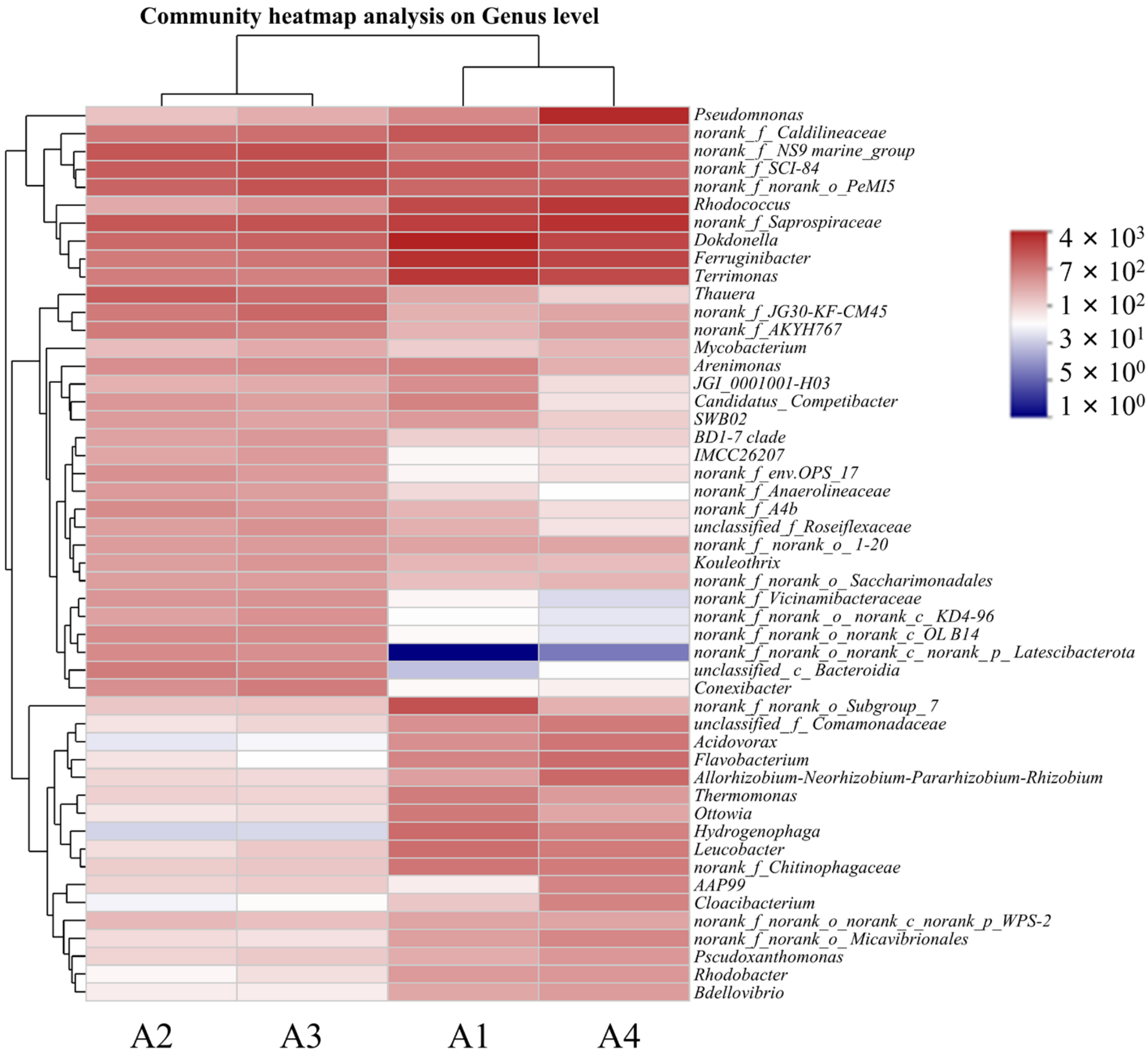


Figure 6. Evolution of microbial community structure in genus level (only the top 50 genera are shown, and the data are displayed by log 10 number. The phyla corresponding to the different genera are marked by different colors).

Table 3. Proportion of functional bacteria in different floating islands.

Sample	Proportion (%)			
	A1	A2	A3	A4
Caldilineaceae	2.12	3.13	2.28	2.01
NS9_marine_group	1.74	3.99	4.16	2.41
SC-I-84	2.92	3.55	3.77	2.16
Saprospiraceae	4.94	3.93	3.90	6.29
Dokdonella	4.28	5.82	5.95	4.38
Ferruginibacter	6.22	2.02	2.04	4.47
Thauera	0.69	3.62	2.51	0.32
Flavobacterium	1.36	0.30	0.16	2.23
Leucobacter	2.01	0.33	0.44	1.63

However, results concerning both water purification in Section 3.1.1 and microbial community determination in Figure 6 showed that A2 and A3 were more effective for nitrogen removal. It could be observed that the typical denitrifying bacteria, such as *Dokdonella*, *Caldilineaceae*, and *Thauera*, occupied the higher abundance in A2 and A3, indicating that conditions of A2 and A3 were more suitable for the survival of denitrification bacteria and more conducive to the process of nitrogen removal [36–38]. Furthermore, *SC-I-84* showed strong tolerance to highly polluting environments; thus, the notable abundance indicated that the composition of plant islands and biochar fillers were conducive to the survival of microorganisms [39]. Furthermore, it has been revealed that *NS9_marine_group* displayed the brilliant function of nitrification, and the significant abundance in A2 and A3 verified the advantages of NH_4^+-N removal efficiency in Section 3.1.1 [36]. In conclusion, differences among the removal of various contaminants, such as nitrogen and organics, were more likely to depend on the interactions among the key functional microorganisms, and the suitable conditions provided by plant islands played pivotal roles in the distribution of dominant bacteria.

3.3. Appreciation from the Views of Urban Aesthetics

Except for the effects on water purification, floating islands displayed important influences on the urban aesthetics, and this part was proceeded for analyzing the specific roles and proposing some comments on the construction of floating islands.

3.3.1. Effects of Overall Landscapes

Though the modern buildings, roads, and cars exhibited the city pulchritude of science and technology, the designs above lacked the beauty of natural scenery; meanwhile, intimate contact between human being and nature was hindered to some extent. Therefore, the critical approach was adding some embellishments belonging to nature for the improving of the diversified beauties of cities, and the application of floating islands in urban water, such as lakes, would play an indispensable role in aesthetic enhancement through direct and indirect pathways.

Firstly, floating islands showed intuitive beautification effects owing to their existence, since the lake itself was relatively empty and lacked the beauties of color and flexibility. Hence, the decoration of floating islands on the lake made it more beauteous in spatial hierarchy; at the same time, the application of plants endowed it with more color, such as the green branches and leaves, and purple and yellow flowers of water hyacinth and canna, respectively, etc., which better displayed the vitality of the lake.

Secondly, the existence of plants in floating islands could optimize the urban environment and enhance the biodiversity because floating islands could be considered as continents to provide the temporary landing sites for aquatic birds (e.g., hydrophasianus chirurgus and egret), insects (e.g., dragonfly and butterfly), and other organisms, which facilitate the food chain and nutrient cycling. In addition, owing to the daily activities of the creatures on the lake, urban landscapes were more vibrant since the combination of dynamic and static elements made the lake as well as the whole city full of vigor.

Moreover, as the main part of the landscapes, the ornamental nature of lakes seemed to be quite important; thus, the quality of water would determine the overall scenery. As shown in Section 3.1, it could be observed that contaminants such as N and P could be fully removed, and the water quality would be significantly enhanced after the purification effects of floating islands. Accordingly, owing to the brilliant quality of the lake water, survival and reproduction of aquatic organisms could be guaranteed, and the aquatic ecological environment would be well maintained; meanwhile, the swimming of creatures such as fish and frog could be observed through the clear water, thus building up the lively landscapes with static lake and dynamic creatures.

In addition, lake water would not give off an unpleasant smell after purification, and the plants in floating islands may emit the fragrance of flowers and leaves, which further promotes the views and experiences near the lakes.

In general, application of floating islands in urban water could not only realize the in situ ecological remediation but also add to the multidimensional natural beauties, which improve the life quality of human beings and fulfill the better contact between humans and nature.

3.3.2. Conception of Optimized Designing

According to the analysis above, floating islands played remarkable roles in water purification and enhancement in urban aesthetics. Therefore, ideas about the construction of floating islands were proposed based on this, and the designing principles established the islands from the aesthetic point of view as much as possible if the water purification effects could be satisfied. Specific comments were exhibited as follows:

Firstly, as for the selection and collocation of plants, growth periods should be fully considered in order to avoid the obstruction and suspension of the effects of purification and landscapes, since the survival and growth of plants would be obstructed under the cold conditions, especially in winter. Additionally, local plants should be preferentially taken into consideration, which could not only prevent the invasion of alien organisms but also ensure the satisfying growth in floating islands and adaption to the local climate and cultural landscapes [40,41].

Secondly, arrangement of floating islands should be proceeded from the perspectives of the overall spatial layout, and the proportion of floating islands in the lake was quite important. That is, an extremely large area of floating islands would lead to the visual error that the surface of the lake was narrow and crowded, thus bringing humans to depressed and distressed moods; however, it was not appropriate when the proportion was too small, since the plants landscapes were sparse and the lake lacked the beauty of hierarchy, thus whittling down the general ornamentals. In addition, attention should also be paid to the details of plant collocation, such as the suitable arrangement of the height, profile, color, etc., of plants, which could better display the natural scenery; at the same time, florescence could be considered as another determination for the collocation; thus, the visual beauty could be maintained as much as possible even in cold conditions.

In addition to the visual appreciation, the designing of floating islands is supposed to focus on reflecting cultures. Based on this, the artistic conception of poetries could be integrated for the creation of landscapes, and the relevant culture backgrounds of histories or geographies could be also combined accordingly, which endow the scenery with profounder meanings [42,43]. Therefore, the construction of floating islands could be conducted through the ways of not only choosing plants with specific cultures but also creating a certain aesthetic perception in the lake, which may bring human beings into the immersive sense and make a sufficient understanding of the connotations of plant cultures.

Furthermore, in the medium of contacting human beings with nature, the designing of floating islands should emphasize the contacting and harmony with human beings. For example, trestle bridges could be built and extended into the lake; thus, humans could better come into contact with the water and the plants in floating islands, which reflects the friendly interaction between human and nature as well as the harmonious scene of "Landscapes were picturesque and humans were in the picture".

4. Conclusions

In this work, roles of floating islands were analyzed from the perspectives of water purification and urban aesthetics. Firstly, floating islands with different plants were constructed for the treatment of lake water and the evaluation of purification capacity, and the water hyacinth island exhibited the satisfying uptake of N and P as well as the removal of organics. Based on this, biochar was utilized as fillers for the coordination with plants and the enhancement of purification, and the results showed that the treated water of all groups met class IV or even III of the standards (GB 3838-2002), which was attributed to the synergism among plants, biochar, and the attached microbes. Accordingly, biodiversity of all groups was analyzed, and the results verified the notable effects of various microbes. Except for the roles above, the application of floating islands was quite significant for the beautifying of surroundings and the optimization of urban aesthetics. The arrangement of floating islands improved the hierarchical beauty of the landscapes; meanwhile, plants and flowers added the natural colors, which further optimized the scenery on the lake. In addition, habitat creatures on floating islands as well as those in the water increased the dynamic beauty of the landscapes, and the fragrance of the plants elevated the overall comfort. Furthermore, ideas about construction and optimization of floating islands were proposed from the perspectives of plant collocation, spatial layout, cultural background, and contact with nature. In general, floating islands exhibited notable effects on water purification and natural decoration; thus, the application in urban water demonstrated great advantages and potential.

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