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Original scientific paper

Purification Effect of Ecological Floating Bed with Different Planting Density on Tailing Water

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Abstract: This study aimed to determine the optimal planting density of floating bed plants for purifying wastewater treatment plant tailwater and realizing the resourceful use of wastewater. Three commonly used floating bed plants, Iris, Zelkova, and water onion, were selected, and a self-designed and assembled floating bed frame was used as the plant carrier. Simulated wastewater treatment plant tailwater was treated for 28 days, and the pH value, chemical oxygen demand (COD), NH_4^+−N, TN, TP, and plant growth were continuously monitored. The results showed that the best water purification effect was achieved when the planting density was 67 plants/m^2. Thalia dealbata and Scirpus were found to have better TN and NH_4^+−N removal effects than Iris, while Iris had a superior TP removal effect compared to Thalia dealbata and Scirpus. Additionally, Thalia dealbata had a better COD removal effect than Iris and Scirpus. Therefore, the optimal planting density for constructing an ecological floating bed was determined to be 67 plants/m^2.

Keywords: ecological floating bed; planting density; tail water treatment

1 INTRODUCTION

The North China Plain region in China relies on a stable flow of urban rivers that are mainly recharged with sewage treatment plant tail water. However, most of the sewage treatment plants in the region discharge pollutants at concentrations higher than the Environmental Quality Standard for Surface Water (GB 3838-2002) in the IV water standards, due to the implementation of Class A pollutant concentration limits in the Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB 18918-2002). This results in a large amount of pollutants being discharged into natural water bodies, leading to water pollution. Adopting the traditional deep treatment process for upgrading these urban wastewater treatment plants would be costly and energy-intensive. To maintain the quality of the water environment and reduce pollution and carbon emissions, a greener and more efficient process is needed for the deep treatment of first-level A standard effluent from wastewater treatment plants. The plant floating bed system, a deformation of the artificial wetland system, is a promising solution that can effectively remove pollutants from sewage and promote the resourceful utilization of sewage while combining sewage treatment and utilization.

Ecological floating bed system is a common technology for purifying water quality and reducing water pollutants, featuring low cost, wide applicability and convenient management and maintenance [1-5]. García-Ávila et al. [6] used reeds and balsam fir as wetland plants and the results of their experiments showed that balsam fir had a high capacity to remove pollutants such as biochemical oxygen demand (80.69%), chemical oxygen demand (69.87%), ammoniacal nitrogen (69.69%), total phosphorus (50%), total coliforms (98.08%) and faecal coliforms (95.61%). Zhang et al. [7] used ornamental plants to purify eutrophic water and analysed and compared the growth characteristics of the plants and the effectiveness of the water treatment. The results showed that all four plants could be used as floating bed plants to treat eutrophic water bodies, and the best growth characteristics and treatment efficiency were found for the sky lake anemone. Ameri Siahouei et al. [8] investigated the potential of floating bed systems constructed by different aquatic and terrestrial plants for phytoremediation and phytodesalination of polluted water bodies. Dry Umbrella grass is a fast growing plant that can absorb pollutants. Different species of aquatic plants play different roles in purifying polluted water bodies.

Current research focuses on the comparison of pollutant removal abilities of different species of aquatic plants, in order to screen out aquatic plants suitable for constructing ecological floating beds. However, in addition to the species of aquatic plants, the planting density of floating bed plants should also be studied. In this experiment, by constructing ecological floating bed systems with different planting densities for iris, Scirpus and Thalia dealbata, the variation rules of pollutant concentrations in the water under the ecological floating bed with different planting densities were analyzed, and the appropriate planting densities of floating bed plants were determined, thus providing technical support and scientific basis for improving effluent quality of sewage treatment plants and reducing sewage treatment costs. The article includes the materials and methods required for the experiment, the results and analysis and the conclusions.

2 TEST EQUIPMENT AND MATERIALS

2.1 Test Water

Through the investigation of some sewage treatment plants in North China, it is found that the overall water quality in the tail water of sewage treatment plants in North China features extremely low organic matter content and high nitrogen and phosphorus concentration.

This test was conducted by manual water distribution, the NH_4^+−N, TN and TP of the test water used refer to the Class-A discharge standard of GB18918-2002 and Chemical oxygen demand (COD) refers to Class IV water standard in GB3838-2002 to simulate the effluent of sewage treatment plant tail water. The specific water quality parameters are shown in Tab. 1.

Table 1 Test water quality

Item	Concentration
COD	30 mg/L
NH_4^+–N	5 mg/L
TN	15 mg/L
TP	0.5 mg/L
pH	8.6

2.2 Testing Apparatus

A plastic water tank of 60 cm × 40 cm × 35 cm was selected to hold the test water samples, with an effective water depth of 20 cm and an effective volume of 42 L. The ecological floating bed system consists of five parts: floating bed frame, floating bed net, planting cup, planting sponge and plants. The experimental device is detailed in Fig. [1-3]. The floating bed frame is 0.5 m long and 0.3 m wide. It is formed by hot melting of PVC pipe with the diameter DN 32 and elbow, and sealed with glue at the joint. Plastic rope is selected for the floating bed mesh, which is worn on the floating bed frame in the form of a grid, with each lattice side length of 5 cm. The bottom diameter of the transplanting cup is 40.9 mm, the upper diameter is 48.5 mm, and the height is 7 mm. A plant is planted in each transplanting cup, and the space between the plant and the transplanting cup is filled with transplanting sponge, and then the transplanting cup is fixed in the floating bed net. A floating bed plant was planted in each test tank with different planting densities, and a blank control group was set up.

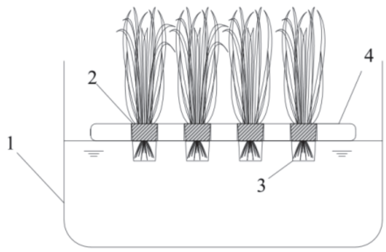

Figure 1 Ecological floating bed experimental set up
(1. plastic water tank, 2. planting sponge, 3. planting cup, 4. floating bed frame)

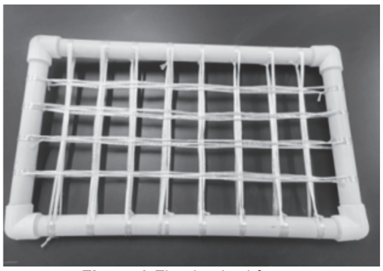

Figure 2 Floating bed frame

Figure 3 Planting cups

2.3 Test Scheme

After the test plants were pre-cultured in tap water for 7 days, the plants with good growth and uniform distribution were selected, cleaned, and transplanted into the prepared ecological floating bed and placed on the test water surface. The experiment lasted for 28 days from March 22, 2022. to April 18, 2022. The average temperature during the experiment was 17.1 ℃, the lowest temperature was 14.8 ℃, and the highest temperature was 20.1 ℃. A single kind of iris, Thalia dealbata and Scirpus were selected to construct an ecological floating bed system, and the plant density was 96 plants/m^2 in group ①, 67 plants/m^2 in group ② and 33 plants/m^2 in group ③, respectively, conduct 3 sets of parallel experiments. The control group took the blank group without plants. In the first stage of the experiment, water samples of each group were collected at 9:30 a.m. every 24 hours in the first 7 days; in the second stage, water samples were collected once a week, and water samples were collected from the upper, middle and lower parts of the box each time. After evenly mixing the water samples, they were tested to eliminate water errors. 200 ml was sampled each time, and the reduced water in the tank was supplemented with distilled water.

2.4 Determination Method

In this study, various water quality parameters were determined using different methods. The COD concentration was determined using the potassium dichromate method, NH_4^+–N was determined using Nessler's reagent photometry, TN concentration was determined using potassium persulfate oxidation ultraviolet spectrophotometry, TP concentration was determined using molybdenum-antimony resistance spectrophotometry, and the pH value was determined using PHS-2C type-pH detector. These methods were utilized to accurately measure the concentrations of each parameter in the water samples.

Methods for determination of plant samples. The growth of the plants was observed during the experiment. At the beginning and end of the experiment, the plants were removed from the floating bed, washed and dried, and the plant height, root length and fresh weight were measured.

3 RESULTS AND ANALYSIS

3.1 Effects of Different Planting Densities on Plant Growth

During the experiment, the growth of the three plants was good, the leaves gradually grew bigger, the plant height increased, and the new roots germinated and developed well. The plant growth was shown in Tab. 2. In the experiment, the survival rate of plants was higher. The survival rate of plants in the Thalia dealbata group and the Scirpus group was 100%. In the iris group, the survival rate of iris ① in the iris group was 86.96%, and the survival rate of plants of iris ② and iris ③ was 87.5%. The fastest growing plant in iris group was iris ②, and the increase of average plant height, root length and fresh weight before and after the experiment were 9.60 cm, 8.08 cm and

4.47 g, respectively. Iris ③ grew the slowest, with an average increase of 15.72 cm, 6.30 cm and 2.38 g, respectively. In Thalia dealbata group, the fastest growing plant was Thalia dealbata ②, and the increase of average plant height, root length and fresh weight before and after the experiment were 11.85 cm, 0.92 cm and 1.39 g, respectively. The slowest growing plant was Thalia dealbata ③, and the increases of average value were 6.97 cm, 0.22 cm and 0.51 g, respectively. In the Scirpus group, the fastest growth was scallion ②, and the increase of average plant height, root length and fresh weight before and after the experiment was 23.03 cm, 7.45 cm and 5.18 g, respectively; Scallion ③grows the slowest, and the increase was 20.49 cm, 4.21 cm and 4.12 g, respectively.

Table 2 Comparison of plant growth

Plant	Experimental group	Average value of plant height / cm		Mean value of maximum root length / cm		Average fresh weight of plants / g	
		Beginning	End	Beginning	End	Beginning	End
Iris	①	26.89 ± 13.79	44.83 ± 14.92	5.86 ± 2.61	13.78 ± 1.98	17.08 ± 8.72	21.39 ± 4.85
	②	29.09 ± 13.32	48.69 ± 12.33	5.91 ± 2.12	13.99 ± 2.05	18.09 ± 3.49	22.56 ± 5.66
	③	24.42 ± 6.43	40.14 ± 11.89	5.76 ± 2.98	12.06 ± 2.54	17.94 ± 6.57	20.32 ± 5.21
Thalia dealbata	①	16.16 ± 8.51	24.27 ± 10.25	4.18 ± 1.13	4.98 ± 1.07	12.94 ± 5.66	13.96 ± 5.10
	②	16.34 ± 8.38	28.19 ± 9.33	4.76 ± 2.60	5.68 ± 2.86	13.44 ± 5.09	14.83 ± 7.31
	③	16.73 ± 10.62	23.70 ± 10.23	4.33 ± 3.69	4.55 ± 1.87	13.20 ± 7.60	13.71 ± 6.13
Scirpus	①	25.78 ± 9.87	47.89 ± 17.04	5.54 ± 2.97	9.79 ± 4.09	13.48 ± 7.06	17.67 ± 7.43
	②	23.70 ± 10.23	46.73 ± 9.47	4.75 ± 1.87	12.20 ± 4.11	13.71 ± 6.13	18.89 ± 4.88
	③	24.27 ± 10.25	44.76 ± 14.68	4.28 ± 1.07	8.49 ± 2.50	12.96 ± 5.10	17.08 ± 5.82

3.2 Removal Effect of Single Water Quality Index

(1) Change of pH value in water. The change of pH value in water will affect the photosynthetic efficiency of plants by changing the existence form of dissolved inorganic carbon in water, and finally change the removal efficiency of pollutants in water [9]. The initial pH value of the experiment was 8.6. As can be seen from Fig. 4, in the first stage of the experiment, the plant roots continuously released organic acids such as sugars and amino acids into the test water, and the plant respiration produced carbon dioxide, which resulted in the continuous accumulation of carbon dioxide [10], so that the pH value in the test water began to decline rapidly. On the 5th day, the pH value of all test groups decreased to the lowest, and the lowest was iris ③ (pH value was 7.83). With the experiment going on, the pH value of the test water showed a slow rise until it reached a relatively stable state. During the experiment, the pH value of the water body ranged from 7.83 to 8.76, and the average pH value of the blank control group was 8.63 ± 0.07.

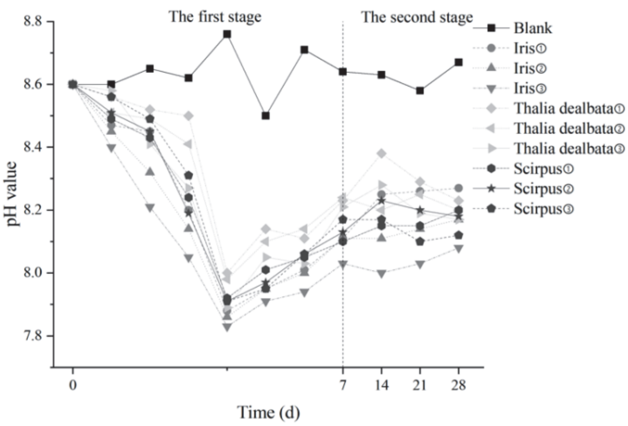

Figure 4 Influence of floating bed plants on pH water

(2) Change in nitrogen in water the initial concentration of TN and NH_4^+−N in the test water was 15 mg/L and 5 mg/L, respectively. As can be seen from Fig. 5 and Fig. 6, the concentration of nitrogen in the water of the experimental group with plants showed an overall downward trend, and was far lower than that of the blank control group.

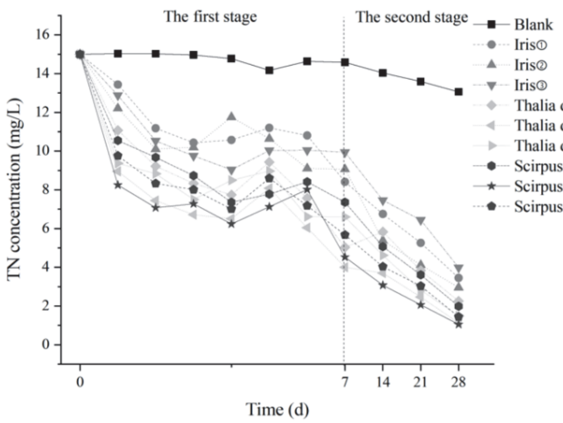

Figure 5 Comparison of TN removal by floating bed plants

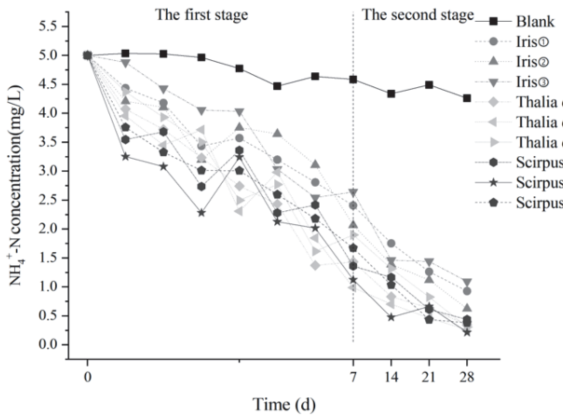

Figure 6 Comparison of NH_4^+−N removal by floating bed plants

On the 4th to 5th day, TN and NH_4^+−N concentrations of each experimental group briefly increased, which was due to the existence of various forms of nitrogen nutrition in the test water, among which organic nitrogen rapidly decreased due to sedimentation [11]. With the progress of the test, sedimentation gradually took a disadvantageous position. At this time, under the action of microorganisms, organic nitrogen in the form of particles in the sediment is continuously dissolved into the water.

Since the 6th day, under the influence of plant root exudates, a large number of nitrifying and denitrifying bacteria gathered in the plant root microbial community, resulting in a gradual decline in nitrogen content in the test water. However, with the decrease of nitrogen concentration in the test water under static conditions, the nitrification and denitrification effect gradually weakened and the nitrogen concentration curve tended to be gentle [12]. At the end of the experiment, the removal rates of TN and NH_4^+−N in the blank control group were 12.93% and 14.80%, respectively, and the best removal efficiency was in the test group of Scirpus ②. TN and NH_4^+−N decreased to 1.985 mg/L and 0.213 mg/L, respectively, and the removal rates were 92.99% and 95.74%, respectively. On the whole, the nitrogen removal effects of scallion and Thalia dealbata with different planting densities were similar, and both were better than that of iris.

(3) Change of TP in water the removal methods of TP by ecological floating bed system include plant root absorption, plant assimilation and microbial decomposition. The initial concentration of TP in the test water was 0.5 mg/L. As can be seen from Fig. 7, the nitrogen content in the water of the blank control group was much higher than that of the experimental group with plants.

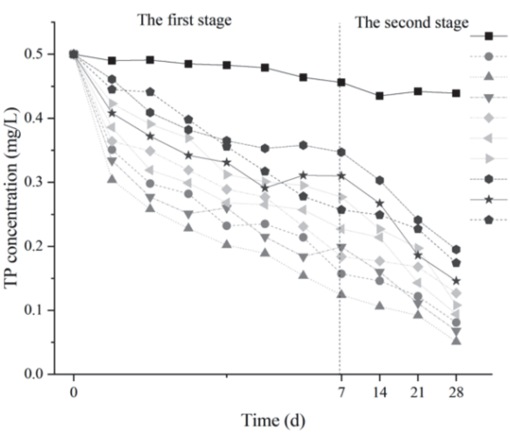

Figure 7 Comparison of TP removal by floating bed plants

At the end of the experiment, the removal rate of the blank control group was only 12.20%, that of the iris group was 83.80% - 89.80%, and that of the Thalia dealbata group was 74.60% - 81.20%. The removal rate of Scirpus group was 61.00% - 70.80%. The removal effect of three different aquatic plants on TP is relatively stable, and the removal effect of different plants is quite different. The removal rate of TP in the test water is ranked as iris > Thalia dealbata > Scirpus. It can be seen that the removal of TP in sewage is closely related to plant species, and the phosphorus content in plants is mainly affected by their habitat conditions [13]. At the initial stage of the experiment, the pH value of the test water dropped rapidly, which provided a good condition for the survival and reproduction of phosphorus accumulating bacteria, and enhanced the removal of TP from the water by ecological floating bed to a certain extent.

(4) Change of COD in water.

In the ecological floating bed system, the removal effect of COD mainly depends on the degradation of organic matter by microorganisms in the water body. Plant roots will continue to transport oxygen to the water body, providing a good breeding environment for aerobic microorganisms, and achieve the removal effect of COD by constantly consuming organic matter in the water body. As shown in Fig. 8, at the beginning of the experiment, the COD concentration in the test water was 30 mg/L. On the sixth day, the Scirpus ② group had the best COD removal effect, and the COD concentration in the water dropped to 16.04 mg/L, and the removal efficiency was 46.52%. At the end of the experiment, the COD removal rate of the blank control group was 10.13%, and the COD concentration of the Thalia dealbata ② experimental group with the best removal effect was reduced to 11.87 mg/L, and the removal rate was 60.42%. Among the three plants selected in the experiment, Thalia dealbata has the best purification effect on COD.

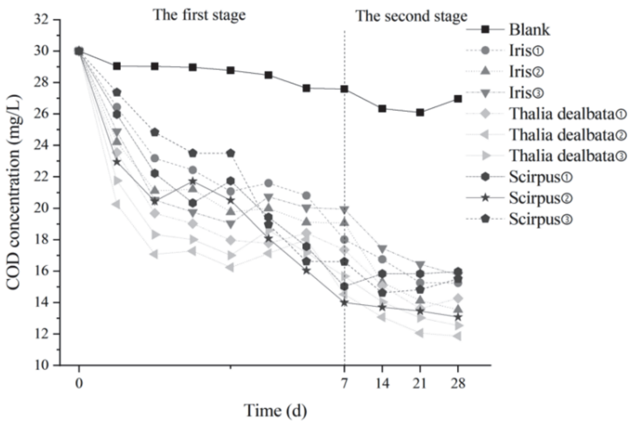

Figure 8 Comparison of COD removal by floating bed plants

4 DISCUSSIONS

4.1 Differential Analysis of Water Purification Capacity of Aquatic Plants

There are significant differences in the removal effects of different aquatic plants on pollutants in water. Therefore, the selection of appropriate aquatic plants should consider not only their water purification capacity, but also such physical factors as growth temperature, light duration and light intensity, as well as biological factors such as microbial richness and plant biomass [14]. Iris, Thalia dealbata and Scirpus selected in this experiment are perennial plants with rich roots and dense branches and leaves. Under low temperature conditions, although the above-ground part of the plants gradually dies, their rhizomes can still maintain biological activity and have certain sewage purification effect, so they are often used as floating bed plants to purify water. Under the environmental conditions of this experiment, the removal effect of Thalia dealbata and Scirpus on TN and NH_4^+−N is better than that of iris, and the removal effect of iris on TP is better than that of Thalia dealbata and Scirpus, and the removal effect of Thalia dealbata on COD is better than that of iris and shallot, which is similar to many previous research conclusions [15, 16].

4.2 Difference Analysis of Water Purification Capacity with Different Planting Density

Plant height, root length and fresh weight are the most intuitive indicators to reflect plant growth. When ecological floating beds are constructed with plants placed in different densities, the plants in floating beds will face different degree of intraspecific and interspecific competition, which will lead to changes in plant growth status. Planting density is one of the important factors affecting plant growth population structure. There is a suitable planting density for a population of homogenous plants. When the planting density was lower than the appropriate planting density, the plant photosynthetic efficiency would increase with the increase of planting density. When the planting density was at the appropriate value, the photosynthetic efficiency of plants was the best, and the community growth rate was faster. When the planting density is higher than the appropriate value, the plant population is too large, resulting in colony closure and affecting the photosynthetic efficiency of plants [17]. In this experiment, when the planting density of iris, Thalia dealbata and Scirpus was 96 plants/m^2, the plant growth was worse than that of the experimental group with a planting density of 67 plants/m^2. This is because when the planting density was 96 plants/m^2, the planting density was higher than the appropriate planting density, and serious internal competition existed in the plant population, resulting in inhibited plant growth to a certain extent. The planting density of 33 plants/m^2 of the experimental group was lower than the appropriate planting density, and the plant photosynthetic efficiency was lower than the optimal value, resulting in slower plant growth. The results showed that the growth condition of iris, Thalia dealbata and Scirpus was good and could effectively purify the water quality of the test. The plant height, root length and fresh weight of iris, Thalia dealbata and Scirpus are the best when the planting density was as follows: 67 plants/m^2 > 96 plants/gm^2 > 33 plants/m^2. Therefore, the optimal planting density under this test condition was 67 plants/m^2.

4.3 Removal Effect of Nitrogen and Phosphorus in Water by Ecological Floating Bed System

In the process of growth and development, plants need to continuously absorb nutrients from the growing environment to maintain their life activities, so as to reduce the nitrogen and phosphorus elements in the water. The net nitrogen and phosphorus removal amount of aquatic plants in ecological floating bed is significantly positively correlated with plant biomass, which is the key factor affecting the water purification quality of aquatic plants [18]. Therefore, the removal rate of nitrogen and phosphorus elements in experimental water is consistent with the change trend of plant biomass. The results of this experiment fully proved this conclusion. When the planting density of three aquatic plants was 67 plants/m^2, the biomass of experimental groups increased significantly, and the TN removal rates of iris, Scirpus and Thalia dealbata were 80.28%, 92.50% and 92.99%, respectively. The removal rates of NH_4^+−N were 87.56%, 94.82% and 95.74%, and the removal rates of TP were 89.80%, 81.20% and 70.80%, respectively, which were higher than those of experimental groups with the planting density of 96 plants/m^2 and 33 plants/m^2. The increase of plant biomass can not only attach more nitrifying and denitrifying bacteria, phosphorus accumulating bacteria and microorganisms, but also reduce plant photosynthesis and dissolved oxygen concentration in water while increasing plant cover area with strong leaves and branches, making denitrifying bacteria in anaerobic environment. The oxygen secreted by aquatic plants supported the aerobic conditions required by nitrifying bacteria in the nitrification reaction, and realized the transformation from ammonia nitrogen to nitrate nitrogen. Root exudates of aquatic plants provide sufficient carbon source for denitrification [19]. The higher the plant biomass is, the more complex the root system is, and the anaerobic, anoxic and aerobic status appears alternately in the plant roots, and multiple sewage treatment units are formed. At the same time, nitrification and denitrification reactions are carried out [20], constantly improving the water purification efficiency of the ecological floating bed system.

5 CONCLUSIONS

(1) The planting density has an obvious impact on the growth of iris, Thalia dealbata and Scirpus, and the plant density is as follows:
67 plant/m^2 ＞ 96 plant/m^2 ＞ 33 plant/m^2.

(2) The TN and NH_4^+−N removal effect of Thalia dealbata and Scirpus were better than those of iris, and the TP removal effect of iris was better than that of Thalia dealbata and Scirpus. Thalia dealbata can remove COD in water more effectively than iris and Scirpus.

(3) When the planting density of the ecological floating bed system was 67 plants/m^2, the experimental water purification effect reached the best. The removal rates of TN of iris, Scirpus and Thalia dealbata were 80.28%, 92.50% and 92.99%, respectively, and the removal rates of NH_4^+−N were 87.56%, 94.82% and 95.74%, respectively. The removal rates of TP were 89.80%, 81.20% and 70.80%, and the removal rates of COD were 54.87%, 60.43% and 56.40%, respectively.

(4) In-depth study on the interaction mechanism between plant roots and inter-root microorganisms in floating beds to further explore the role of plant floating beds in the restoration of water bodies.

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