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The distribution pattern and ecological restoration technology of aquatic plants in a eutrophic water landscape belt

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ABSTRACT

Taking the eutrophic Taige canal and Caoqiao River in the upper reaches of North Taihu Lake as the experimental objects, 12 monitoring points were set up and data were recorded. The distribution pattern of aquatic plants in the water landscape belt was studied by variance/mean ratio, aggregation intensity index, negative binomial parameter, Cassie index and α–diversity index. Based on the principle of aquatic plants repairing eutrophic water, a suitable water environment was selected. The effect of ecological restoration was studied by photometry. The results showed that: the main aquatic plant communities in this area evolved from submerged to floating leaf and emergent plants, which shows that the vertical distribution pattern of the aquatic plant communities was greatly affected by hydrology; the distribution pattern of aquatic plant diversity showed a good single curve in the vertical direction and a single curve in the horizontal direction; the results of ecological restoration showed that the average removal rates of total nitrogen (TN) and total phosphorus (TP) by mixing the three plants were 86.76% and 93.89%, respectively. Among them, the best combination for TN removal was water hyacinth (Eichhornia crassipes) + lytchus (Lythrum salicaria) + calamus (Acorus calamus), and the best combination for TP removal was water hyacinth + lytchus + hibiscus (Nelumbonucifera).

Key words: aquatic plants, distribution pattern, ecological restoration, eutrophic water body, landscape belt

HIGHLIGHTS

- The competitive relationship between aquatic plants and phytoplankton is used to transform algae water into grass water, enrich water biodiversity and restore a water ecosystem.
- Plants have different allelopathy effects on different algae and play an active role in regulating the succession of phytoplankton population.

1. INTRODUCTION

The mechanisms and remediation of water eutrophication have long been a focus of attention. In the past 20 years, the eutrophication of various landscape water bodies has developed rapidly. Investigations over many years show that the proportion of eutrophic lakes in the investigated lakes has increased from 41% in the late 1970s to 61% in the late 1980s, and then to 77% in the late 1990s. The development trend of lake eutrophication in China is very severe, with high nitrogen and phosphorus pollution. A considerable number of lakes have also suffered from 'water bloom', and the proportion of eutrophic lakes accounted for 43.5%, and mesotrophic lakes accounted for 45% of the total survey. The eutrophic lakes are mainly distributed in the economically developed areas of Southeast China, mainly distributed in the cities and suburbs (Shi *et al.* 2020; Wang *et al.* 2020). Due to the serious pollution, part of the water has lost its function as a drinking water source.

At present, there are many kinds of water eutrophication remediation technologies, but from the technical principle, these technologies can be divided into physical methods, chemical methods, biological methods, ecological methods and so on. The traditional eutrophic water remediation technology is mainly nutrient control, which adopts dredging, nutrient passivation, bottom aeration, dilution and scouring measures, but this method is not suitable for large lakes, because it is difficult to maintain over the long-term due to the influence of economic conditions (Xing *et al.* 2018). Now, aquatic phytoremediation is a common technology amongst biological and ecological methods. Liu *et al.* (2021) isolated and identified the algae inhibiting compounds from Typha extract, and compared the different algae inhibiting effects. Aquatic phytoremediation is a new technology with low energy consumption and good effect. It has the characteristics of ecological and environmental protection and occupies an important ecological position in the water ecosystem. It can not only purify the water body, but also improve the water ecological environment and promote the restoration of a degraded water ecosystem (Sadchikov & Ostroumov 2019; Wang *et al.* 2019).

The distribution of any species in nature is regular, and the distribution of each species is its pattern. The settlement of individual plant in a certain area will inevitably form a certain spatial pattern, and the spatial distribution pattern of a population is the configuration of intraspecific plants in their living environment (Pan *et al.* 2020; Zhang *et al.* 2021). Aquatic plants are groups of plants that are physiologically attached to the water environment and have at least part of their reproductive cycle in or on the water surface. Generally, according to the relative position of leaves and water surface and their living habits, they can be divided into four types: floating water, floating leaves, emergent water and submerged water (Yu & University J. A. 2019). As a unique species in the water landscape, the application of aquatic plants is increasing year by year, which plays a great role in improving the quality of the water landscape, beautifying the urban environment, enriching the content of tourism activities, and improving quality of life.

2. DISTRIBUTION PATTERN OF AQUATIC PLANTS IN A EUTROPHIC WATER LANDSCAPE BELT

2.1. Survey objects and sampling methods

This study was carried out in Gehu Lake and its connecting rivers, Taige canal and Caoqiao River, where the nutrient load is increasing in the upper reaches of the Taihu Lake Basin. A total of 12 monitoring points were set up in the survey, which basically covers three sections (check cross-section, control section and reduction section) in different lake areas and river sections. The sample setting of different study areas is shown in Table 1.

In this paper, the biomass of aquatic plants was measured using a special underwater sickle, and the sampling area was 0.21 m^2. When collecting plant samples from lakes, the selection of sections and sampling points for biomass determination was distributed as evenly and widely as possible. The inverted 'W' sampling method was used to collect the river plant samples. According to the Gordon Thomas method (Sonia *et al.* 2021), there were 8 quadrats in each sampling point, which were evenly distributed in the river channel with a width of about 20–50 m, and the area of the quadrat was 0.21 m^2. The plant species were recorded during sampling. The plants in the quadrat were collected and stored at low temperature for analysis. A sampling diagram is shown in Figure 1.

2.2. Research methods

Excel was used to process the data, and the data were classified, then the SPSS13.0 for Windows software package was used for statistical analysis. Finally, variance/mean ratio, clustering index I, negative binomial parameter K, Cassie index CA and the α–diversity index were used to test the distribution model of main aquatic plants in Gehu Lake and its connected rivers, as follows:

Table 1 | Distribution of aquatic plants in Gehu Lake, Taige canal and Caoqiao River. Data from the observation data of Taihu Lake Ecosystem Research Station, Chinese Academy of Sciences (See: http://www.geodata.cn/data/datadetails.html?dataguid=118072703401333&docId=3630)

River Distribution	Place	Latitude	Longitude
Gehu Lake	Gehu South	31°35.094N	119°47.172E
	In Gehu Lake	31°36.257N	119°49.238E
	Hubei Province	31°38.989N	119°51.375E
	Gehu East	31°36.798N	119°52.346E
Caoqiao River	Wanjia	31°32.101N	119°54.962E
	Caoqiao town	31°31.172N	119°57.435E
	Neutralization	31°30.124N	120°59.422E
Taige canal	Yuncun	31°32.434N	119°59.194E
	Huangnian Bridge	31°31.142N	120°03.221E
	In front of the workshop	31°34.998N	119°53.645E
Confluence of the two rivers	Renjia Village	31°30.227N	120°59.568E
	Estuary	31°29.385N	120°01.655E

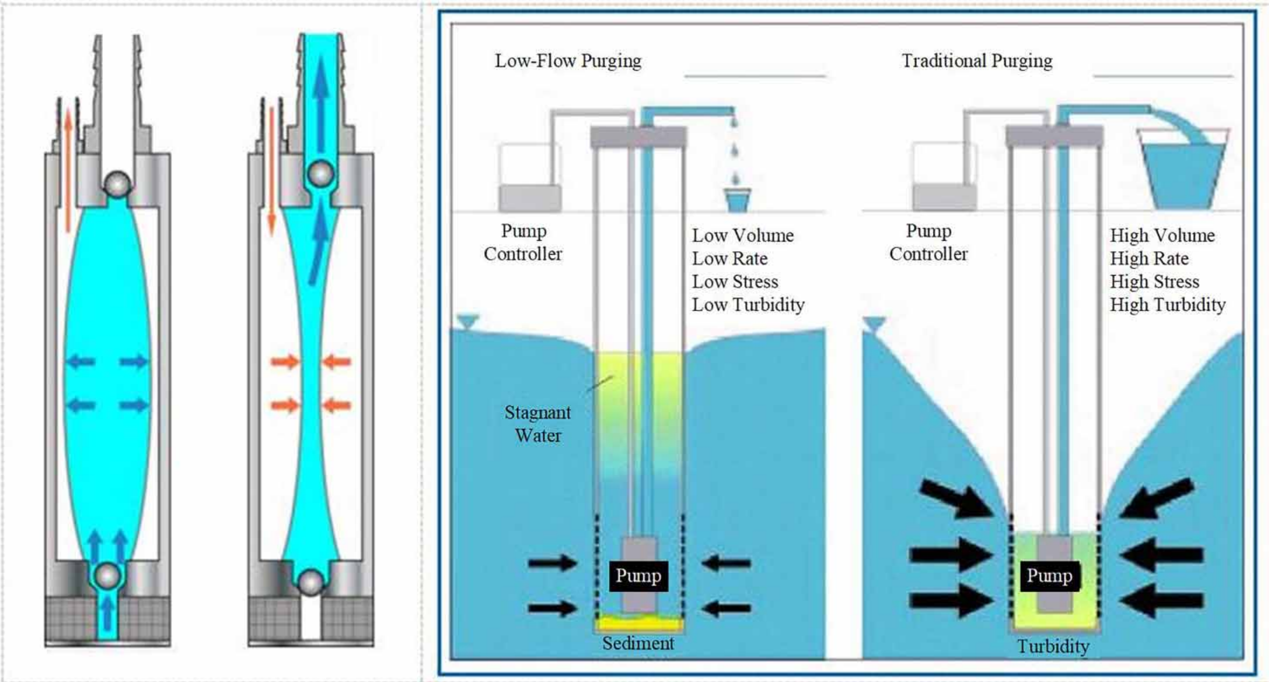

Figure 1 | Plant sampling diagram.

(1) Variance/mean ratio. Variance/mean ratio can be used as a measure of population pattern; also known as diffusion coefficient, it is a statistical description of population pattern. The calculation formula is C = S2/X, where X is the average number of individuals, S2 is the sample variance, and C is the variance/mean ratio. When C = 1, the population is a random distribution; when C > 1, the population is a cluster distribution; when C < 1, the population tends to uniform distribution.
(2) Cluster index, I = S2/X–1. When I < 0, it is uniform distribution; when I > 0, it is aggregate distribution; when I = 0, it is random distribution.
(3) The negative binomial parameter, KK = X/S2–X. The smaller the K value is, the greater the aggregation degree is. If the K value is above 8, it is a random distribution.
(4) Cassie R.M. index, CA = 1/K. CA < 0 is uniform distribution, and CA > 0 is aggregation distribution.
(5) α–diversity index is used to measure the number of biological species and the relative abundance of biological species in a community. In this paper, four measurement indexes were selected to analyze the characteristics of community species diversity: the species richness index, Shannon-Wiener index, Simpson index and Pielou evenness index. The calculation methods are as follows:

Species richness index (S) = the number of species in the sample.

Shannon-Wiener index (H):

$$H = -\sum_{i-1}^{s} P_i \ln P_i \tag{1}$$

Simpson index (D)

$$D = 1 - \sum_{i-1}^{s} P_i^2 \tag{2}$$

Pielou evenness index (J)

$$J = H/\ln S \quad (3)$$

where S is the number of species in the plot and P_i is the proportion of the individual number of the i-th species to the total individual number of all species in the plot.

3. PLANT-BASED ECOLOGICAL RESTORATION TECHNOLOGY IN A EUTROPHIC WATER LANDSCAPE

3.1. Principle of aquatic plants repairing eutrophic water

The fundamental problem of eutrophication is the eutrophication of a water body. In the process of competition for survival, the diversity of population in a water biological community is reduced, and a grass type water body is transformed into an algae type water body. In a water ecological environment, both higher aquatic plants and phytoplankton are primary producers. They compete for ecological resources such as nutrition, light and growth space. Higher aquatic plants can release chemicals, inhibit the growth of phytoplankton, and absorb nutrients such as nitrogen and phosphorus in water, so as to achieve the effect of purifying water (Tong *et al.* 2019). The mechanism of remediation of eutrophic water by higher aquatic plants is to use this 'competition' relationship to transform algae type water into grass type water, enriching water biodiversity and restoring the water ecosystem.

3.1.1. Allelopathy

Aquatic plants can inhibit the growth of phytoplankton by releasing allelochemicals into the water, which is an effective strategy to gain advantages in terms of competition for nutrients, light, space and other resources in the aquatic ecosystem. The inhibitory effect of aquatic plants on algae is affected by many factors (Kawamoto 2018).

The inhibitory effect of higher aquatic plants is different for different algae. Charaglobularis has an inhibitory effect on the growth of *Scenedesmus obliquus*. Some phenolic compounds are released from Myriophylla to the surrounding water to inhibit the growth of cyanobacteria. The inhibitory effect of these phenolic compounds on *green algae* and *diatoms* is not very strong. The response of different phytoplankton and cyanobacteria to *Myriophyllum spicatum* is very different. *Megastrophe* and *Microcystis* aeruginosa are more sensitive than *Skeletonema Flos*, coronitum stellatum and *Scenedesmus obliquus* (Gourbesville *et al.* 2018; He *et al.* 2020). Plants have different allelopathic effects on different algae, and play a positive role in regulating the succession of phytoplankton population.

Different parts of plants have different contributions to allelopathy. The allelopathy of *Eichhornia crassipes* and *Acorus tatarinowii* is mainly released to water through plant roots. The inhibition of higher aquatic plants is also affected by environmental factors. The growth status of plants and light conditions are closely related to the effect of the release of allelochemicals from corals.

3.1.2. Absorption of nutrients such as nitrogen and phosphorus

Aquatic plants can directly absorb nutrients such as nitrogen and phosphorus and assimilate them into their own structural components. The storage of these nutrients is more stable, and it is easier to carry their fixed nitrogen and phosphorus out of the water through artificial harvest (Yu *et al.* 2020). In their experiment purifying secondary effluent by *Eichhornia crassipes*, the amount of nitrogen and phosphorus in plant tissue increased by 2.9% and 6.7% after 7 days. The growth of plants and the increase of nutrient content in plants make the nutrient content in water decrease, which indirectly affects the growth of phytoplankton.

3.1.3. Biochemical effects

First of all, there is a competition between floating island plants and algae, and the nitrogen, phosphorus and other nutrients that algae get from the water are reduced, and the growth is inhibited. Secondly, floating island plants reduce the light intensity on the water surface, which greatly reduce the necessary light for the growth and reproduction of phytoplankton, and can effectively reduce the photosynthesis of algae. Thirdly, some aquatic plants secrete chloramphenicol, which has an inhibitory effect on algae (Wang & Xu 2019). Through the research and analysis of *Alternanthera philoxeroides*, *Arachis hypogaea* and water hyacinth plants, the results show that the secretion extracted from the plants has an inhibitory effect on the growth and reproduction of *Chlamydomonas reinhardtii*, which fundamentally inhibits its growth. The water quality is further purified, and the purified water quality will reduce the occurrence of bloom and other phenomena (Zhang *et al.* 2021). Plants can also effectively remove microcystin (MC) in water. MC is a common pollutant secreted by algae in eutrophic water, which has serious harm to the health of human and aquatic organisms. Among these pollutants, MC is the most toxic and harmful. Aquatic plants can absorb and decompose MC, which can effectively ensure the safety of drinking water. Therefore, the existence of aquatic plants is conducive to the good development of an aquatic community, and can keep the water quality in a stable state.

3.1.4. Other ecological functions

The existence of an aquatic plant community provides a conditions for the change of aquatic biodiversity and dominant population. Aquatic plants provide a substrate and habitat for microorganisms and micro animals. Some micro animals prey on a large number of phytoplankton and effectively control the number of algae. The presence of aquatic plants reduces the wind wave disturbance in the water, which creates better conditions for the removal of suspended solids and reduces the possibility of solids resuspension (Chong *et al.* 2019). The metabolism of aquatic vascular plants can greatly accelerate the decomposition of organic colloids or suspended solids trapped around the roots, and increase the dissolved oxygen in the water through gas transmission and release of plant branches and roots.

3.2. Basic principles of aquatic plant selection

Plants are an important part of an artificial floating island. Aquatic plants can be divided into submerged plants, floating plants and emergent plants. Different types of plants have different ecological characteristics and suitable living conditions. They have different abilities of absorbing and enriching nutrients in water, and have different effects on dissolved oxygen and algae inhibition. The correct choice of plant will directly affect the treatment effect of the floating island technology on water quality. Because the aquatic roots of some soil culture plants are not very developed, when transplanted to the water surface, the roots cannot absorb the nutrients needed for plant growth, cannot achieve the effect of water purification, and even the survival rate is difficult to guarantee (Zharikov *et al.* 2018; Abbas *et al.* 2019). The growth cycle of plants also needs to be considered. When the Northern hemisphere enters the autumn and winter season, plants will wither and die, which cannot achieve the expected goal. Therefore, it is very important to select suitable floating island plants for water purification. The principles of choosing floating island plants are as follows:

(1) Strong adaptability. Artificial floating island technology should plant aquatic plants with the ability of purifying water quality, or plant improved and domesticated terrestrial plants on the carrier of the floating island, and place them on the surface of the polluted water body. The plants themselves need to have a certain pollution resistance, and withstand the high concentration of nutrients in the polluted water body. The plants used to change the living environment will have a period of adaptation. In order to purify the sewage, it is necessary to create a new growth environment and keep a good growth condition. At the same time, the floating island plants should have good adaptability to the local water quality conditions, temperature, humidity, etc., otherwise they can not achieve the expected goal. Therefore, under the same conditions, it is better to choose local species and avoid introducing alien species, so as to reduce possible uncontrollable factors.

(2) The purification ability is strong. Different plants have different absorption capacities for pollutants in sewage, and the same plant has different purification capacity for water at different growth stages. The more pollutants removed by plants per unit area, the stronger their purification capacity. The difference of purification ability is due to the biomass size and enzyme activity of different types of plants. The growth status of plants and their ability to accumulate pollutants are also factors affecting their purification ability (Ge *et al.* 2018).

As the main pollutants of eutrophic water are nutrients such as nitrogen and phosphorus, priority should be given to the removal effect on nitrogen and phosphorus when choosing floating island plants, and they should have good enrichment ability *in vivo*. The content of nitrogen and phosphorus in water is also an important factor affecting the purification ability of plants. In water with low eutrophication, the nitrogen and phosphorus content in water cannot meet the normal growth of plants, which also affects the effect of water treatment. Therefore, the selected plants should have strong purification ability under the condition of low nutrient content.

(3) The root system is well developed. The degree of root development and the growth of stems and leaves are the important factors affecting the purification ability of floating island plants. The more developed roots of plants form a larger contact area with the water body, forming a protective layer between the sediment and the water surface. When suspended particles and insoluble colloids flow through the water, they will be adhered by the roots and settle down, especially organic particles and plant debris in the water, so as to improve the transparency of the water and the sensory effect of the water. A huge root

system can increase the dissolved oxygen content of water, form an aerobic zone, anaerobic zone and facultative anaerobic zone, and become the habitat of various microorganisms, carrying active biological groups (Liu & Sun 2019). Using the metabolic process of microorganisms to remove pollutants in water, some macromolecular organic matter that cannot be absorbed by plants can also be degraded by microorganisms, and suspended particles and phytoplankton can be swallowed by protozoa. Therefore, root condition is an important reference index for the selection of floating island plants.

(4) Multi species collocation. The key to aquatic ecosystem restoration is to create a water environment with diverse species. Different organisms can form multiple food chains, and a complex food chain network is more stable than a single species ecosystem. As the producer of the whole aquatic ecosystem, aquatic plants are the energy provider of the whole ecosystem, so reasonable species allocation is particularly important for the development of the whole water environment. An ecosystem with a variety of plants is conducive to the complementary advantages of plant species, not only effectively playing its ecological function, but also creating a hierarchical landscape. Experimental studies show that in most cases, the removal rate of nitrogen and phosphorus by pairwise combinations of plants is higher than that of single plant floating island. There are more and more studies on the combination of multiple plants, and their water purification effects are also better. The selection of floating island plants should improve intra-species relationships, complement each other, and create a multi species aquatic ecosystem. In order to enhance the water purification effect and landscape effect of the artificial floating island, in the actual configuration process of aquatic plants, the principle of collocation is to select plant species according to different seasons, different plant types and different ornamental performance, so that different growth periods can be connected with each other, the artificial floating island has a higher purification effect, and forms a variety of evergreen waterscape.

3.3. Repair effect study

Potassium persulfate oxidation ultraviolet spectrophotometry and potassium persulfate digestion-ammonium molybdate spectrophotometry are used to detect the changes of TN and TP in water samples, and the removal rate is calculated to characterize the purification effect on water.

3.3.1. Test equipment

When plotting the total nitrogen and total phosphorus, a drying oven is needed to dry potassium nitrate (KNO_3) and potassium dihydrogen phosphate (KH_2PO_4) at 110 °C. When testing the nitrogen and phosphorus content of the test water sample, the solubility of potassium persulfate added is low, so the water temperature needs to be controlled below 60 °C and the sample shaken in a water bath to speed up the dissolution rate. The potassium persulfate added to the test solution needs to be digested at 120 °C for half an hour. This process needs to be carried out in a high temperature steam sterilization pot, and the digestion temperature and time should be strictly controlled. Finally, use an ultraviolet spectrophotometer to measure the absorbance of the test sample and find the corresponding concentration of the TN and TP labels. The experimental equipment used are shown in Table 2.

3.3.2. Determination method

(1) Determination of total nitrogen. Total nitrogen is determined by potassium persulfate oxidation ultraviolet spectrophotometry under alkaline conditions.

Principle: when the temperature of the aqueous solution is above 60 °C, potassium persulfate can be decomposed to produce potassium bisulfate and atomic oxygen. Potassium bisulfate dissociates in the solution to produce sulfate ions and hydrogen ions. Therefore, sodium hydroxide is added to the solution to make the solution in an alkaline state and promote the decomposition.

Table 2 | List of test equipment

Equipment	Model	Manufacturer
High temperature steam sterilizer	LS-50SII	AI Lai Bao (Jinan) Medical Technology Co., Ltd
Drying box	202-1	Nanjing Laibu Technology Industry Co., Ltd
Ultraviolet visible spectrophotometer	T6	Beijing Lianhua Yongxing Technology Development Co., Ltd
Digital constant temperature water bath	HH-8	Shanghai Yida Instrument Co., Ltd

Under the condition of an alkaline medium at 120–124 °C, the decomposed atomic oxygen can oxidize ammonia nitrogen and nitrite nitrogen to nitrate, and most organic nitrogen compounds can be oxidized to nitrate. $A220$ and $A275$ absorbance are measured by ultraviolet spectrophotometer at the wavelengths of 220 and 275 nm respectively. The corrected absorbance A is obtained by using the following formula:

$$A = A_{220} - 2A_{275} \tag{4}$$

The total nitrogen content corresponding to a value is found on the calibration curve.
The formula of total nitrogen content is as follows:

$$\text{Total nitrogen (mg/L)} = \frac{m}{V} \tag{5}$$

where m is the nitrogen content (ug) obtained from the calibration curve; V is the volume of water sample (mL).

(2) Determination of total phosphorus. Total phosphorus was determined by potassium persulfate digestion-ammonium molybdate spectrophotometry.

Potassium persulfate can oxidize phosphorus in water in combined form into soluble orthophosphate. Ammonium molybdate, potassium antimonoxide tartrate and sulfuric acid were prepared into a molybdate solution in a certain proportion. Under acidic conditions, orthophosphate reacts with molybdate to form phosphomolybdate heteropoly acid. Under the reduction of ascorbic acid, it turns into a blue complex, commonly known as phosphomolybdate blue, and at the wavelength of 700 nm, it is measured by spectrophotometry.
The formula of total phosphorus content is as follows:

$$\text{Phosphate (P, mg/L)} = \frac{m_0}{V_0} \tag{6}$$

where: m_0 is the phosphorus content (ug) obtained from the calibration curve; V_0 is the volume of water sample (mL).

3.3.3. Data processing methods

The calculation formula of the pollutant removal rate in the eutrophic water body is as follows:

$$\text{Removal rate (\%)} = \frac{(C_0 - C_1)}{C_0} \times 100\% \tag{7}$$

where C_0 is the concentration of pollutants in the initial water body and C_1 is the concentration of pollutants in the treated water body.

Excel software was used to process the data, analyze and calculate the change trend of total nitrogen and total phosphorus concentration and the change of removal rate, so as to draw the change trend curve.

4. EXPERIMENTAL RESULTS AND ANALYSIS

4.1. Distribution pattern of aquatic plants

4.1.1. Composition of aquatic plants

According to the survey data, 26 species of aquatic plants belonging to 15 families are found in the upper reaches of Taihu Lake Basin (Table 1). There are 10 emergent plants, accounting for 38.46%; 7 submerged plants, accounting for 26.92%; 6 floating leaf plants, accounting for 23.08%; 3 floating plants, accounting for 11.54%. The specific types and proportion of aquatic plants are shown in Figure 2.

According to the analysis of species composition in Figure 2, most of them are common species in lakes and streams, and the dominant aquatic species are Vallisneria, Potamogeton, duckweed and Myriophylla. The structure of families and genera is relatively simple, with 3 species of Nymphaeaceae, Gramineae and Potamogeton. They are not only the main builders of many farmland and stream plant communities, but also the dominant families of most community types in this area. The main aquatic plants are shown in Table 3.

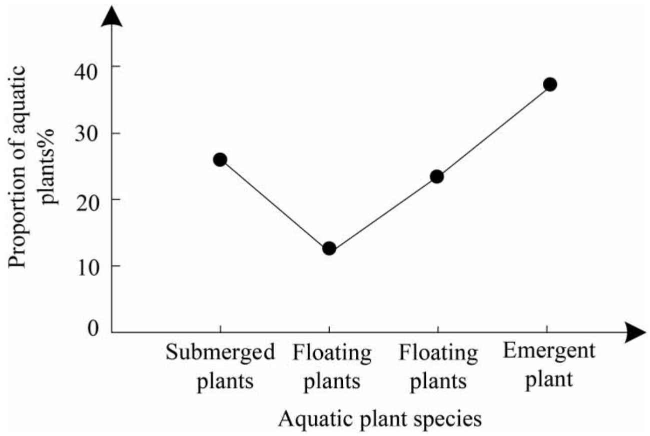

Figure 2 | Type and proportion of aquatic plants.

Table 3 | List of main aquatic plants

Plant type	Family/Genus	Species
Emergent plant	Gramineae	Trisetum bififum, Oryza sativa, Plragmites communis
	Polygonaceae	Polygonum hydropiper
	Chenopodiaceae	Chenopodium album
	Cyperaceae	Scirpus tabernaemontani
	Lythraceae	Lythrum salicaria
	Alismataceae	Sagitta riasagittifolia
	Umbelliferae	Oenanth esinensis, Oenanthe javanica
Floating leaf plant	Amaranthaceae	Altornanthdra, Alternanth erasessilis
	Tamaricaceae	Jussiaea repens
	Nymphaceeae	Nymphaea tragona, Nelwmbo nucifera, Brasenia schreberi
Submerged plant	Haloragaceae	Myriophyllum verticillatum, Myriophyllum spicatum
	Potamogetonaccac	Potamogetondistinctus, Potamogeton crispus, Potamogeto nmalainus
	Hydrocharitaccac	Vallisneria spiralis, Hydrilla verticillata
Floating plants	Ponteriaceae	Eichhornia crassipes
	Lemnaceac	Lemna minor, Spirodela

4.1.2. Distribution pattern of aquatic plants

Four parameter test methods (variance/mean ratio, aggregation intensity index, negative binomial parameter K, Cassie. R.M. index CA) were used to fit the distribution pattern of the aquatic plants.

(1) *Water hyacinth* and *Myriophylla* are evenly distributed. Even distribution is rare in nature. It is speculated that due to the small survey area, the individual distribution of *water hyacinth* and *Myriophylla* is equidistant, so there is a uniform distribution.

(2) The distribution of Vallisneria and polypodies is random. In the random distribution, the chance of each individual appearing at each point in the population field is equal, and the existence of one individual does not affect the distribution of other individuals. Random distribution is also relatively rare, because it is easy to produce random distribution when the distribution of environmental resources is uniform and there is no mutual attraction or exclusion among individuals in the population.

(3) *Alternanthera philoxeroides, Oenanthe javanica, Potamogeton crispus, myriophylla verticillata, Polygonum hydropiper, Allium fistulosum, Hydrilla verticillata, water lily, water shield, lotus, Alternanthera philoxeroides, Oenanthe javanica, Oryza sativa, Sagittaria Sagittaria, duckweed, Azolla, Lythrum, trichium tricolor, Phragmites australis* and *Chenopodium album* are aggregated. The results of variance mean ratio test are consistent with those of aggregation intensity index, K value and Cassie. R. M. test. The details of parameter inspection values are shown in Table 4.

Table 4 | Parameter inspection value list

Species name	Variance	Mean value	Clumping index	K value	Cassie.R.M.
Trisetum bifidum	2.64	0.74	2.61	0.28	3.64
Oryza sativa	3.27	0.88	2.77	0.31	3.25
Plragmites communis	4.57	3.03	0.52	5.73	0.18
Polygonum hydropiper	3.7	2.55	0.48	5.53	0.18
Chenopodium album	2.31	1.63	0.44	3.66	0.26
Scirpusta bernaemontani	4.07	0.92	3.36	0.28	3.61
Lythrum salicaria	1.67	1.32	0.25	5.33	0.19
Sagittaria sagittifolia	3.54	0.87	3.01	0.29	3.58
Oenanthe sinensis	8.74	3.85	1.29	2.95	0.34
Oenanthe javanica	4.42	1.87	1.36	1.38	0.73
Alternanthera	2.24	0.67	2.36	0.28	3.54
Alternanthera sessilis	9.78	1.26	6.72	0.19	5.31
Jussiaea repens	1.68	1.59	0.05	29.77	0.03
Nymphaea tragona	135.28	1.12	10.97	1.02	1.03
Nelumbo nucifera	60.01	3.62	15.66	0.23	4.35
Brasenia schreberi	4.35	0.95	3.66	0.88	1.15
Myriophyllum verticillatum	2.51	1.94	0.3	6.66	0.15
Myriophyllum spicatum	3.12	3.19	−0.05	-60.01	-0.02
Potamogeton distinctus	5.58	4.22	0.34	12.58	0.08
Potamogeton crispus	8.84	5.87	0.51	11.58	0.09
Potamogeton malainus	6.64	3.09	1.17	2.63	0.38
Vallisneria spiralis	2.32	2.18	0.05	44.11	0.026
Hydrilla verticillata	10.69	3.42	2.14	1.59	0.63
Eichhornia crassipes	1.03	1.21	−0.14	−8.4	-0.12
Lemna minor	21.96	6.33	2.47	2.57	0.39
Spirodela	17.78	4.12	3.38	1.21	0.83

As can be seen from Table 4, the main aquatic plant communities in this area evolved from submerged type to floating leaf type and emergent type. The overall coverage of the submerged and floating leaf community is greater than that of the emergent community, which is not conducive to the growth of associated species. From shallow water to land, submerged plants are mainly composed of *Vallisneria, Myriophylla* and *Potamogeton.* The dominant species appear in the floating community, such as water hyacinth. It can be seen that the vertical distribution pattern of the aquatic plant community is greatly affected by hydrology, and the interference of human activities on hydrology will affect the structure and composition of the aquatic plant community, thus affecting the distribution of aquatic plants.

4.1.3. Distribution pattern of aquatic plant diversity

The results of diversity index analysis show that there are significant differences in the species richness index among aquatic plant communities, among which the species richness of the emergent plant community is the highest, and the species number of the floating plant community is the least, with only three species. The Shannon-Wiener and Simpson diversity indexes of aquatic plant communities show the same trend, and the specific α–diversity index is shown in Table 5.

Correlation analysis between community diversity indexes and environmental factors show that only species richness is positively correlated with salinity and total dissolved solids.

The vertical and horizontal distribution patterns of aquatic plant diversity in this area are shown in Figure 3.

Table 5 | α–diversity index

Plant type	Species richness index	Shannon-Wiener index	Simpson index	Pielou evenness index
Emergent plant	10	2.21	0.86	0.52
Floating leaf plant	6	1.32	0.63	0.24
Submerged plant	7	1.76	0.78	0.35
Floating plants	3	0.59	0.31	0.12

It can be seen from Figure 3(a) that the distribution pattern of aquatic plant diversity in the vertical direction presents a good single curve. With the increase of altitude, the diversity of aquatic plant species first increases and then decreases, and the highest value appears between 1,400 m and 1,600 m above sea level. In the case of 95% confidence, the linear regression analysis results show that the correlation between the survey value and the predicted value is very significant (*P*, 0.001), which further shows that the proposed repair technology is effective. The domain effect could explain 63.5% of the variation of aquatic plant richness along the altitude gradient in this area.

It can be seen from Figure 3(b) and 3(c) that the distribution pattern of aquatic plant diversity presents a unimodal distribution in the horizontal direction. Under the condition of 95% confidence, linear regression analysis shows that the correlation between the survey value and the predicted value is not significant ($P > 0.05$), and the medium effect has a low explanatory power to the diversity pattern, which is only 16.31%. The results of linear regression analysis show that there is a significant correlation between the survey value and the predicted value ($P < 0.05$) under the condition of 95% confidence level, and the mid-range effect has a high explanatory power to the latitudinal distribution pattern of aquatic plants in this region, with a value of 57.56%.

4.2. Effect of aquatic phytoremediation

4.2.1. Total nitrogen (TN) removal efficiency

Water hyacinth, *water hibiscus*, *Lythrum* and *Acorus calamus* were selected. In order to study TN removal efficiency in water by any three mixed plants, four groups of mixed plants were selected as follows: *Lythrum* + *Acorus calamus* + *hibiscus mutabilis*, *water hyacinth* + *water hibiscus* + *Acorus calamus*, *water hyacinth* + *water spinach* + *water hibiscus*, *water hyacinth* + *Lythrum* + *Acorus calamus* and a blank control group was added. Under the internal static condition, the TN absorption of different combinations of water samples in each stage was detected. The TN purification effect of three kinds of plants on the water body is shown in Figure 4.

It can be seen from Figure 4 that the TN content of the water samples treated by a mixture of three plants shows an obvious downward trend. When it drops to a certain extent, the fluctuation of TN content becomes smaller and the curve shows a weak change. The results show that the removal rates of the three mixed plants are close, and the removal rates are all high. The best combination was *water hyacinth* + *Lythrum chinense* + *Acorus calamus*. The initial concentration of TN in each water sample was 4.52 mg/l. After 22 days of mixed plant purification, the total nitrogen content in the test water sample ranged from 0.46 to 0.97 mg/L, and the average removal rate was 86.76%, which indicates that the three plants have an obvious effect on TN removal.

The change of TN concentration in the treated water samples of different plant combinations is first fast and then slow. The main reason may be as follows: this experiment is a static indoor experiment. In the initial stage of the experiment, part of the organic nitrogen in the water sample will settle, part of the soluble ammonia nitrogen and nitrate nitrogen will be absorbed and enriched in the body by plants, and part of the ammonia nitrogen will be used by microorganisms in the water. Before the experiment, the plants had been cultivated adaptively, and the plants could adapt to the new water environment and grow rapidly, which resulted in the rapid removal of TN content in the early stage of the experiment. In the middle stage of the experiment, the sedimentation is reduced, and a large amount of dissolved oxygen around the roots of the aquatic plants make the aerobic microorganisms in the water multiply. The organic nitrogen in the form of particles is decomposed into dissolved nitrogen by microorganisms and returned to the water body, which slows down the decline rate of TN content in the water body and makes the TN removal rate curve tend to be flat. In the later stage of the experiment, due to the decrease of TN concentration in the water, the normal growth needs of the aquatic plants cannot be met, the dissolved oxygen content in the root system is reduced, the number of aerobic microorganisms in the water is reduced, the biofilm

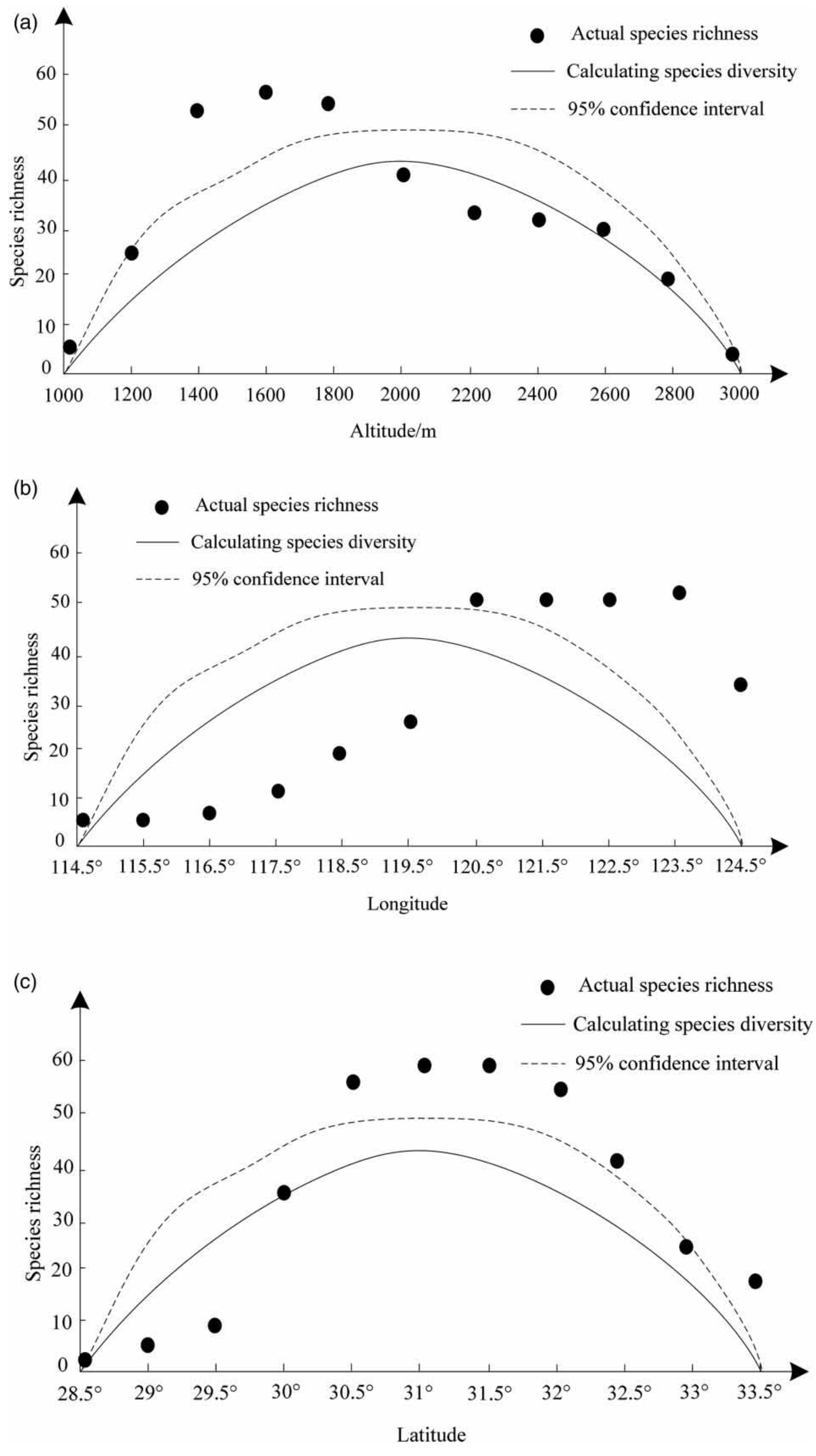

Figure 3 | Vertical and horizontal distribution pattern of aquatic plant diversity in the corridor. (a) Altitude distribution map. (b) Longitude distribution map. (c) Latitude distribution map.

falls off, and the organic nitrogen stored in the body is returned to the water, resulting in the total nitrogen removal rate almost unchanged in the later stage. Sedimentation is the main reason for the decrease of TN in waste water, and microbial decomposition can also remove part of nitrogen in water.

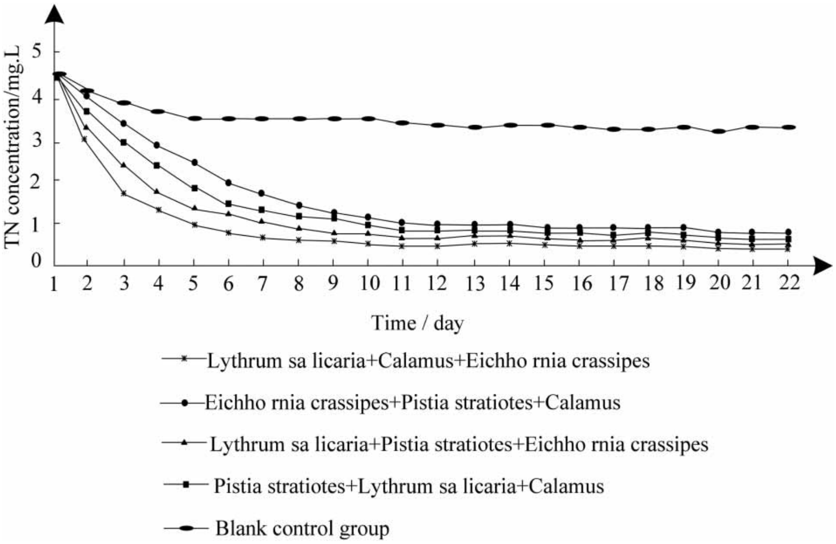

Figure 4 | Purification effect of various combinations of three plants on TN in water.

4.2.2. Total phosphorus (TP) removal efficiency

A mixed floating island composed of any three plants of *water hyacinth, water hibiscus, Lythrum* and *Acorus calamus* was also selected to test TP removal efficiency. Four mixed plant combinations were established, which were *water hyacinth* + *water hibiscus* + *Lythrum*, *water hyacinth* + *Acorus calamus* + *Lythrum*, *Lythrum* + *Acorus calamus* + *water hibiscus*, *water hibiscus* + *water hyacinth* + *Acorus calamus*, and a blank control without any plants was added. The TP changes of water samples at different stages were detected. The purification effect of three kinds of plants on TP is shown in Figure 5.

It can be seen from Figure 5 that TP content in different combinations of mixed plants shows an obvious downward trend, with the most obvious decline rate in the early stage of the experiment and almost unchanged in the later stage. A mixed floating island composed of *water hyacinth*, *Lythrum* and *hibiscus* has the best removal effect. The initial concentration of TP in each water sample was 0.45 mg/L. After the purification effect of the test plants, the total phosphorus content in the test water samples ranged from 0.024 to 0.032 mg/L, and the average removal rate was 93.89%. Comparing the mixed plants, it can be seen that they can effectively reduce the TP content in the water sample, and have a higher purification effect.

This experiment is a static indoor experiment, and some insoluble phosphorus and organic phosphorus in static water will have sedimentation, some soluble phosphate will be absorbed into the body by plants through the root system, and some will

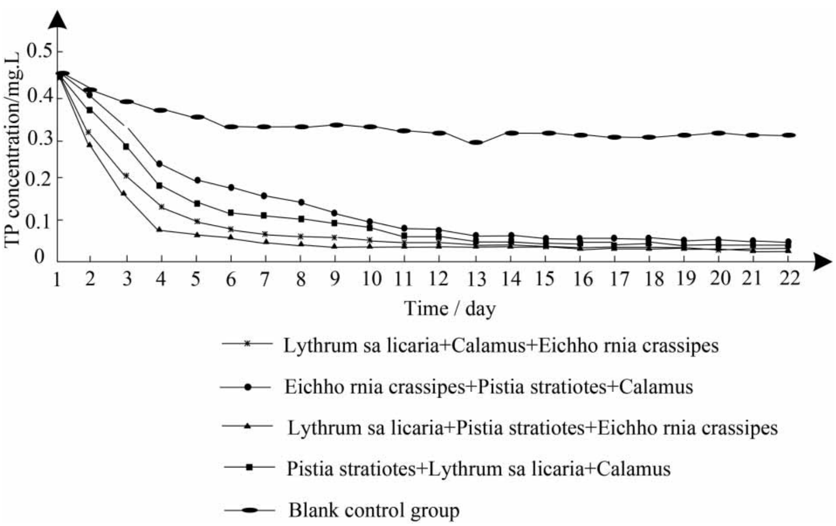

Figure 5 | Purification effect of various combinations of three plants on TP in water.

be used by microorganisms and removed by metabolism. In the early stage of the experiment, the plants were cultivated adaptively, and the plants could grow well. They can adapt to the new water environment quickly and grow rapidly, so the TP in the early water decreased faster. With the middle stage of the experiment, the sedimentation effect decreases, the oxygen generated by plant photosynthesis dissolves into the water through the root system, and the aerobic microorganisms are multiplied in the aerobic area. The insoluble phosphorus and organic phosphorus are decomposed by sedimentation, and the dissolved phosphorus is returned to the water after decomposition. This phosphorus will be absorbed and utilized by the plants, making the decline rate of TP tend to be flat. In the later stage of the experiment, the substrate concentration in the water cannot meet the normal growth of plants, and the dissolved oxygen content in the root will also be reduced, which cannot meet the demands of rhizosphere aerobic microorganisms. A large number of aerobic microorganisms die, and the biofilm falls off. The dead microorganisms will return the phosphate stored in their body to the water body, resulting in almost constant TP content in the treated water. Sedimentation is the main reason for the decrease of TP concentration in the waste water sample, and the decomposition of microorganisms can also remove part of the phosphorus.

5. CONCLUSIONS

Excessive interference of human activities will lead to the loss of aquatic vegetation, especially the underwater vegetation which plays an important role in maintaining stability. In the North Taihu lake, *water hyacinth* and *algae* were evenly distributed, *valerian* and *polyspora* were randomly distributed, and others gathered. The spatial pattern of aquatic plant diversity presents a single-mode pattern, which is mainly controlled by geometric (boundary) constraints, stochastic processes and other unknown factors. In this paper, through the study of the distribution pattern of aquatic plants, purification experiments of TN and TP in three kinds of plant water samples were carried out, and it was proved that the removal of TN and TP can play a good purification effect, which has far-reaching significance for the restoration of ecological balance.

There are still some problems in the research into aquatic plant application in the ecological restoration of eutrophic water bodies, which needs to be further studied. The influencing factors and mechanism of allelopathy and algae inhibition of aquatic plants have been studied. Aquatic plants are greatly affected by various environmental factors in engineering applications, and there are some problems, such as long treatment period, continuous search and selection of species with strong adaptability and high purification efficiency. At the same time, we need to improve the quality of aquatic plants. How to select the plant species and match the plant communities in different water bodies to achieve the best purification effect has become the main research topic in the future. In particular, allelic diseases of aquatic plants in aquatic ecosystems will become the focus of eutrophic water ecological restoration. The application of aquatic plants in water ecological restoration has the characteristics of economy, high efficiency and environmental protection. Undoubtedly, it provides a good solution to alleviate the deterioration of water environments in China, and has good research and application prospects.

DATA AVAILABILITY STATEMENT

All relevant data are available online.

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