Succession characteristics of phytoplankton functional groups and water quality responsiveness evaluation in an artificial constructed wetland-reservoir ecosystem

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ABSTRACT
The artificial constructed wetland-reservoir ecosystem has become a research hotspot in the field of the pretreatment of micro-polluted water. In this study, the water purification efficiency and phytoplankton dynamics, the succession characteristics of phytoplankton functional groups and water quality responsiveness evaluation were investigated. The results showed that the Yanlong project can effectively purify water, and there were significant spatial differences in DO, pH, turbidity and transparency (P<0.001), while the temporal differences in water temperature, DO, electrical conductivity, TP and NH4+-N were the most significant (P<0.001). B, D, P, MP, X1, J and Lo were consistently dominant FGs, Group I, Group IV, Group V and Group VI were dominant MBFGs throughout the year. The results indicated that MBFG was better than that of the FG while water temperature, pH and BOD5 were the key environmental factors. Overall, our findings could provide important implications to improve sustainable safety of drinking water sources.

1. Introduction
Compared with water sources of lakes, reservoirs and groundwater, the water sources of rivers are more easily affected by environmental pollution and have poor anti-risk abilities. Therefore, it is difficult to fundamentally solve the problem only by the technological transformation of a certain unit in water plant. Therefore, taking effective measures to improve the water quality of river water sources and enhancing their ability to resist risks is very important [1]. In recent years, the construction of ecological water purification systems for the pretreatment of micro-polluted water with constructed wetland and reservoir as the core to facilitate the transition from river water sources to lake water sources has become a research hotspot in the field of water treatment [2–4]. The constructed wetlands can improve water quality and the subsequent reservoirs ensure water volume.

Meanwhile, aquatic plants, aquatic animals and hydraulic operating conditions in the artificial constructed wetland-reservoir ecosystem are different from those in natural water bodies, and these ‘non-natural’ factors lead to a high degree of spatial heterogeneity in the internal environment of the system. On one hand, with the decrease in water turbidity, the increase in transparency and under-water light intensity, the longer hydraulic retention time in local areas, and the release of nutrients into water by sediments under anaerobic or disturbed conditions provide favorable conditions for the proliferation of phytoplankton. On the other hand, the phytoplankton community structure and reproduction rate are controlled by the competition of aquatic plants to absorb nutrients, allelopathy among plants and food intake by aquatic animals. The unreasonable allocation of internal elements in the artificial wetland-reservoir ecosystem will not only lead to the ecological imbalance of water body but also to the abnormal reproduction of phytoplankton, which will affect the normal operation of the system, the subsequent water treatment process of the water plant, and the safety of human drinking water.

Phytoplankton are the primary producer and an important component of aquatic biological resources in aquatic ecosystems, which can change community structure and biomass and have significant effects on the stability and integrity of aquatic ecosystem [5,6]. The growth of phytoplankton is modified by the availability of essential nutrient elements and environmental factors such as water temperature and light intensity, among others [7,8]. Because of rapid propagation, a short growth period and sensitivity to environmental changes in phytoplankton, the community structure and biomass of phytoplankton can reflect changes in the water ecological environment in
a short period. Therefore, ecologists often use phytoplankton as an indicator to evaluate water health and ecological stability [9–11].

As phytoplankton are generally complex, they can be classified at different levels to facilitate the classification of ecological analysis [12]. Traditionally, community analysis is based on the species composition, classes or phyla [13]. However, traditional methods according to the changes in biomass and Chl-a of species composition, classes or phyla do not necessarily reflect the actual ecosystem function [14]. Therefore, phytoplankton functional groups have been proposed to study the ecological status of water bodies, such as oceans [15], lakes [16] and rivers [17]. Phytoplankton functional groups are established based on the similarity of phytoplankton community functions in aquatic ecosystems [18]. The growth of phytoplankton is determined mainly by the availability of light and nutrients, which also provide the primary influence on phytoplankton functional group assemblages [19]. Based on the physiological growth characteristics of phytoplankton and their environmental application mechanism, Reynolds grouped phytoplankton species with the same application characteristics and that easily coexisted under the same habitat conditions and formed a functional group of phytoplankton algae with ecological properties [20]. Kruk, based on the morphological characteristics of phytoplankton, grouped algae with similar morphological characteristics and formed a functional classification based on the morphological characteristic parameters of phytoplankton (MBFG) [21]. Previous studies have focused on phytoplankton functional groups in different types of lakes and reservoirs. However, studies on the functional group characteristics of phytoplankton in artificial constructed wetland-reservoir ecosystem, whether phytoplankton can be effectively controlled, which environmental factors are key for regulating phytoplankton, and what changes in the response of phytoplankton have not been conducted.

Therefore, the main purposes of this study were to (i) master the changing characteristics of the aquatic environment and phytoplankton functional groups in artificial constructed wetland-reservoir ecosystem, (ii) identify key environmental factors that drive the succession of dominant functional groups, and (iii) compare the habitat responsiveness of the phytoplankton functional groups FG and MBFG.

2. Materials and methods

2.1 Study area

The Yanlong project is located on the south bank of Mangshe River in Yancheng city, with a total area of 2.23 km² and purified water volume of $6.0 \times 10^5$ m³/d. The Yanlong project consists of three units, including a pretreatment unit, artificial wetland purification unit and reservoir deep purification unit (Figure 1). The pretreatment unit is the first purification unit of the system, with an area of 0.20 km² and a hydraulic retention time of 48 h. The function of the pretreatment unit is to facilitate the settlement of suspended particles by setting the vertical perforated partition to change the water flow state and promote the collision and aggregation of suspended particles. Simultaneously, aeration can further improve the dissolved oxygen content, the removal of suspended particles and volatile organic compounds from the water is enhanced by use of artificial medium suspended biological fillers. The wetland purification unit is composed of an emergent plant unit and a submerged plant unit with areas of 0.41 km² and 0.40 km² and hydraulic retention times of 12 hours and 55.2 hours, respectively. Many aquatic

![Figure 1. Sampling sites in Yanlong project.](image-url)
plants with good purification effects are planted in wetland purification units to purify water. The reservoir deep purification unit covers an area of 1.09 km², with an effective storage capacity of \(4.58 \times 10^6\) m³ and a hydraulic retention time of 367.2 hours. The function of the reservoir deep purification unit is to serve as an emergency storage area, which can provide a 15-day emergency drinking water supply for Yancheng city, while the interaction between aquatic organisms can further purify and stabilize the water quality.

2.2 Sampling and analysis

According to the structural characteristics of the Yanlong project, five sampling sites were selected (Figure 1). Y1 is the raw water from Mangshe River, and Y2, Y3, Y4 and Y5 represent the effluent from the pretreatment, emergent plant, submerged plant and deep purification units, respectively (Figure 1).

Samples were collected monthly from January 2018 to October 2019 at 0.5 m below the water surface at each sampling site. All water samples were collected in two independent 1 L acid-cleaned plastic bottles at each sampling site and then transported to the laboratory using insulated boxes with ice packs, where they were stored at 4°C in the dark. The pH, water temperature (WT), electrical conductivity (EC), and dissolved oxygen (DO) of the water were measured in situ with a YSI EXO1 portable multiparameter water quality probe. The turbidity (turb) was measured in situ with a portable turbidimeter 2100Q (Hach). Transparency (SD) was determined using a Secchi disk.

The potassium permanganate index (COD\(_{500}\)), ammonia nitrogen (NH\(_4\)+-N), nitrate nitrogen (NO\(_3\)-N), total nitrogen (TN) and total phosphorus (TP) were analyzed according to methods for monitoring and analyzing water and wastewater (The State Environmental Protection Administration of China, 2002). Five-day biochemical oxygen demand (BOD\(_5\)) was determined using BODTRAK-II from Hash. Chlorophyll a (Chl-a) was extracted in 90% ethanol and measured by spectrophotometry after filtering 1 L samples through GF/F filters (47 mm, Whatman). All samples were measured within three days. All samples were subjected to three calculations, and their averages were taken.

The phytoplankton samples were fixed with 1% Lugol reagent and then concentrated to 30 mL by the siphon method after standing for 48 ~ 96 h. After thorough shaking, the samples were aspirated in a 0.1 mL plankton counting box and counted under a microscope. Phytoplankton species identification mainly referred to freshwater algae in China: Systematics, Taxonomy and Ecology.

2.3 Statistical analysis

Dominance (Y) was used to characterize the variation characteristics of the dominant functional groups of phytoplankton [22], and the calculation formula was as follows:

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

where N is the total cell density of all functional groups in the sample; Ni is the cell density of the ith functional group in the sample; and fi is the frequency of occurrence of the ith functional group in each sample. The functional group is defined as a dominant functional group when Y ≥ 0.02 [23].

One-way analysis of variance (ANOVA) was used to test whether different environmental variables differed significantly on the spatial and temporal scales. Decision curve analysis (DCA) of density data of phytoplankton functional groups was employed to decide whether a linear or unimodal ordination method should be applied [24]. We found that the DCA of the largest gradient length of the four axes was lower than 3. Therefore, redundancy analysis (RDA) was selected to examine the relationships among the environmental variables and phytoplankton functional groups. Before analysis, phytoplankton functional group data and environmental variables (except pH) were transformed by log (x + 1) to satisfy the normal distribution. ANOVA was performed by using SPSS 22.0, and both DCA and RDA were performed using CANOCO 4.5.

3. Results

3.1 Environmental variables

Seasonal and spatial variations in conventional water quality indexes in Yanlong project are presented in Table 1 and Table S1. The values of WT and EC were not significantly different within the different units (p > 0.05), while the values of WT in summer (27.99°C) and the values of EC in winter (621.16 μS/cm) and autumn (594.93 μS/cm) were significantly higher than other seasons (p < 0.01). The values of pH and DO of the raw water (Y1) were significantly lower than those in other units (p < 0.01); moreover, pH values in spring (8.14) and DO (12.04) in winter were significantly higher than those in other seasons (p < 0.01). Turb values in influent (Y1) and SD values in the deep purification (Y5) unit were significantly higher than those of the other units (p < 0.01), while turb values and SD values were not significantly different within the other seasons (p > 0.05).

The concentration of TN in influent (1.76 mg/L) was significantly higher than that in other units (p = 0.038 < 0.05), and the concentration of TN in winter (1.66 mg/L) was significantly higher than
Table 1. Spatial variations in conventional water quality indexes in the Yanlong project.

|          | Y1         | Y2         | Y3         | Y4         | Y5         | P       |
|----------|------------|------------|------------|------------|------------|---------|
| WT (℃)   | 19.85 ± 0.92 | 19.86 ± 0.94 | 19.67 ± 0.93 | 19.57 ± 0.90 | 19.95 ± 0.99 | 1       |
| DO (mg/L)| 6.14 ± 0.37 | 6.80 ± 0.34 | 6.80 ± 0.32 | 10.02 ± 0.69 | 10.51 ± 3.66 | <0.001  |
| pH       | 7.53 ± 0.37 | 7.82 ± 0.43 | 7.66 ± 0.34 | 8.08 ± 0.38 | 8.29 ± 0.40  | <0.001  |
| EC (μS/cm)| 559.77 ± 97.98 | 543.73 ± 84.20 | 552.45 ± 91.70 | 539.00 ± 88.69 | 531.14 ± 75.69 | 0.838   |
| Turb (NTU)| 59.55 ± 20.65 | 39.53 ± 13.13 | 44.96 ± 17.67 | 50.43 ± 18.45 | 34.40 ± 17.91 | <0.001  |
| SD (cm)  | 33.10 ± 7.15 | 36.90 ± 7.33 | 33.10 ± 6.44 | 35.71 ± 10.64 | 47.62 ± 12.61 | <0.001  |
| TP (mg/L)| 0.15 ± 0.07 | 0.12 ± 0.07 | 0.10 ± 0.06 | 0.11 ± 0.06 | 0.09 ± 0.05  | 0.032   |
| TN (mg/L)| 1.76 ± 0.66 | 1.52 ± 0.48 | 1.37 ± 0.47 | 1.36 ± 0.51 | 1.31 ± 0.54  | 0.038   |
| NH4^+ (mg/L) | 0.76 ± 0.41 | 0.61 ± 0.38 | 0.67 ± 0.36 | 0.59 ± 0.36 | 0.48 ± 0.30  | 0.148   |
| NO3-N (mg/L)| 0.76 ± 0.32 | 0.69 ± 0.40 | 0.49 ± 0.35 | 0.58 ± 0.37 | 0.54 ± 0.38  | 0.087   |
| COD (mg/L)| 5.32 ± 1.34 | 5.27 ± 1.35 | 5.34 ± 1.04 | 5.07 ± 1.02 | 4.91 ± 0.99  | 0.725   |
| BOD (mg/L)| 7.33 ± 4.11 | 7.00 ± 4.71 | 6.97 ± 3.95 | 8.20 ± 4.97 | 7.41 ± 6.67  | 0.897   |

The concentrations of COD_mn and BOD_5 showed no significant differences within units (p > 0.05), but the concentrations of COD_mn (5.46 mg/L) and BOD_5 (8.82 mg/L) in summer were significantly higher than those in other seasons (p < 0.05).

3.2 Phytoplankton dynamics

The density of phytoplankton and Chl-a concentrations in different seasons are shown in Figure 2 and Figure S1. In winter, the highest Bacillariophyta density (2.23 × 10^6 ind/L) was found in raw water (Y1), accounting for 75.8% of the total phytoplankton density (2.94 × 10^6 ind/L), and Chl-a concentration was 42.55 μg/L. After entering the pretreatment unit (Y2), the total phytoplankton density increased to 3.40 × 10^6 ind/L, and Chl-a concentration (43.24 μg/L) increased slightly. In the emergent plant unit (Y3), the total phytoplankton density and Chl-a concentration decreased to 1.90 × 10^6 ind/L and 26.36 μg/L, while Euglenophyta and Cryptophyta increased, and a small amount of

![Figure 2. Seasonal and spatial variations in phytoplankton community and density (×10^6) in the Yanlong project.](image-url)
Chrysophyta \((0.48 \times 10^4 \text{ ind/L})\) was detected. In the submerged plant unit (Y4), the total phytoplankton density increased to \(3.21 \times 10^6 \text{ ind/L}\) while the densities of Euglenophyta and Pyrrophyta decreased, the densities of other phyla increased. In the reservoir deep purification unit (Y5), the densities of Chl-a and Bacillariophyta decreased, although the densities of other phyla increased, the total phytoplankton density decreased to \(3.00 \times 10^6 \text{ ind/L}\), which was slightly higher than that of the raw water. Although Chl-a concentration in the deep purification unit (27.12 \(\mu\text{g/L}\)) was slightly higher than that in the emergent plant unit and the submerged plant unit, it was much lower than that in the influent.

As spring progressed, the total phytoplankton density \((1.54 \times 10^6 \text{ ind/L})\) and Chl-a concentration \((31.59 \mu\text{g/L})\) in the influent were significantly lower than those in winter, Bacillariophyta and Chlorophyta decreased while Cyanophyta, Euglenophyta and Pyrrophyta increased, the density of Cyanophyta increasing \(1.43 \times 10^5 \text{ ind/L}\), which was an approximate fivefold increase. The total density increased to \(2.00 \times 10^6 \text{ ind/L}\) in Y2, the density of other phytoplankton increased, except for the decrease in Cyanophyta and Euglenophyta. The total phytoplankton density decreased to \(1.79 \times 10^6 \text{ ind/L}\) in Y3 while Bacillariophyta and Euglenophyta increased slightly, the average concentration of Chl-a in water decreased from 42.20 \(\mu\text{g/L}\) to 38.30 \(\mu\text{g/L}\). The densities of all phyla, excluding Chlorophyta and Euglenophyta, decreased, and the total phytoplankton density \((1.78 \times 10^6 \text{ ind/L})\) decreased slightly in Y4. The total phytoplankton density and Chl-a concentration in effluent were as high as \(2.78 \times 10^6 \text{ ind/L}\) and \(55.88 \mu\text{g/L}\), respectively, which was nearly double that in the influent water in Y5, the densities of all phyla increased, with a Cyanophyta density of \(2.80 \times 10^5 \text{ ind/L}\), representing an increase of approximately five times.

The density of Cyanophyta increased rapidly \((3.09 \times 10^5 \text{ ind/L})\) in the influent with increasing temperature in summer, while the densities of Chlorophyta, Bacillariophyta and Euglenophyta decreased significantly, with the total density and Chl-a concentration dropping to \(9.56 \times 10^5 \text{ ind/L}\) and \(20.44 \mu\text{g/L}\), respectively. The density of total phytoplankton and average Chl-a concentration increased to \(1.43 \times 10^6 \text{ ind/L}\) and \(24.85 \mu\text{g/L}\) in Y2, the density of Cyanophyta \((7.00 \times 10^5 \text{ ind/L})\) increased more than twofold, the densities of Chlorophyta and Bacillariophyta increased slightly. The density of Pyrrophyta \((2.80 \times 10^5 \text{ ind/L})\) decreased significantly in Y3, and the total density \((9.30 \times 10^5 \text{ ind/L})\) and Chl-a concentration \((21.29 \mu\text{g/L})\) also decreased. In contrast, with a rapid increase in the density of Pyrrophyta \((9.36 \times 10^4 \text{ ind/L})\), the total algal density \((1.01 \times 10^6 \text{ ind/L})\) increased slightly, while Chl-a concentration \((41.36 \mu\text{g/L})\) increased nearly twofold in Y4. The density of Cyanophyta \((5.58 \times 10^5 \text{ ind/L})\) and Chlorophyta \((2.35 \times 10^5 \text{ ind/L})\) increased significantly in Y5, and the total density and Chl-a concentration increasing to \(1.15 \times 10^6 \text{ ind/L}\) and \(23.92 \mu\text{g/L}\), respectively.

As the water temperature decreased in autumn, the density of Bacillariophyta \((2.61 \times 10^5 \text{ ind/L})\) increased slightly in the raw water, while the density of other phyla decreased significantly, with the total density and Chl-a concentration dropping to \(6.32 \times 10^5 \text{ ind/L}\) and \(12.96 \mu\text{g/L}\). The densities of Cyanophyta, Chlorophyta and Bacillariophyta increased, the total density and Chl-a concentration increased to \(7.39 \times 10^5 \text{ ind/L}\) and \(19.05 \mu\text{g/L}\) in Y2. The densities of all phyla decreased, except for Euglenophyta and Pyrrophyta, where the density of Cyanophyta decreased by approximately 6 times in Y3. The total phytoplankton density and Chl-a concentration decreased to \(5.75 \times 10^5 \text{ ind/L}\) and \(10.76 \mu\text{g/L}\), respectively. The total density of phytoplankton increased to \(7.03 \times 10^5 \text{ ind/L}\), and the average Chl-a concentration \((29.26 \mu\text{g/L})\) increased approximately 3 times in Y4, Cyanophyta and Bacillariophyta decreased slightly. After entering the deep purification unit (Y5), only the density of Pyrrophyta decreased significantly, while the density of other phyla increased significantly, with the density of Cyanophyta reaching \(4.80 \times 10^5 \text{ ind/L}\, which was an increase of approximately 16 times. The total phytoplankton density increased to \(1.47 \times 10^6 \text{ ind/L}, while Chl-a concentration decreased significantly to \(21.46 \mu\text{g/L}\).

3.3 Phytoplankton functional groups variation

The FGs and MBFGs were identified according to the functional group classification methods proposed by Reynolds et al. (2002) [20], Kruk et al. (2010) [21] and Padišák et al. (2009) [25]. As shown in Table S2 and Table S3, forty-eight genera from seven phyla, including Cyanophyta, Chlorophyta, Bacillariophyta, Euglenophyta, Pyrrophyta, Cryptophyta, Chrysophyta, were identified and belonged to 23 FGs (B, C, D, N, NA, P, MP, Tc, S1, X3, X1, E, Y, F, G, J, K, H1, Lo, M, W1, W2, Wo) and 7 MBFGs (Group I, Group II, Group III, Group IV, Group V, Group VI, and Group VII). FGs and MBFGs with a degree in dominance \((Y)\geq0.02\) were classified as the dominant groups. To master the spatial-temporal distribution of the Yanlong project, the dominant FGs (Figure 3a) and MBFGs (Figure 3b) in each unit in different seasons were analyzed.

As shown in Figure 3a, the dominant FGs in winter, spring, summer, and autumn were composed of 9 functional groups (B, D, N, P, MP, X1, Y, J, W1), 10 functional groups (B, D, P, MP, X1, J, Lo, W1, W2, Wo), 12 functional groups (B, D, P, MP, Tc, X1, G, J, Lo, M, W1, W2), and 12 functional groups (B, D, P, MP, Tc, X1, J, Lo, M, W1, W2,
Wo), respectively. The dynamic changes in the predominant FGs in each unit of the Yanlong project in winter, spring, summer and autumn were as follows: P → P → B → B → B, B → B → B → B, Lo → Lo → Lo → Lo → Lo, B → Lo → B → B → B. The predominant FG in the water source ecological purification system of Yanlong Lake in winter and spring was Group B, while group Lo was the predominant group in autumn.

As shown in Figure 3b, the dominant MBFGs in winter, Spring, Summer, Autumn were composed of 4 functional groups (Group I, Group IV, Group V, Group VI), 6 functional groups (Group I, Group III, Group IV, Group V, Group VI, Group VII), 6 functional groups (Group I, Group III, Group IV, Group V, Group VI, Group VII), and 6 functional groups (Group I, Group III, Group IV, Group V, Group VI, Group VII), respectively. The dynamic changes in predominant MBFGs in each unit of the Yanlong project in winter, spring, summer and autumn were as follows: Group VI → Group VI → Group VI → Group VI → Group VI → Group VI → Group VI → Group VI → Group VI → Group VI → Group VI → Group VI → Group VI → Group VI → Group VI → Group VI → Group VI → Group VI → Group VII → Group VII → Group VII → Group VII → Group VII →
Group VI → Group VI → Group VII, Group VI → Group VI → Group VII, respectively. The predominant MBFG in each unit of the Yanlong project in winter, spring and autumn was Group VI, while Group VII was the predominant group in the wetland purification unit, and Group VI was the predominant group in other units in summer.

3.4 Phytoplankton functional group-environment relationship

As shown in Figures 4 and 5, redundancy analysis (RDA) was performed to reveal the relationship among the environmental factors and the density of FGs and MBFGs in different seasons.

In winter, the dominant functional groups within the Yanlong project were B, D, N, P, MP, X1, Y and J. In particular, Groups B and P were consistently the dominant groups in winter and were positively correlated with TP, DO, pH, turbidity, COD\text{Mn} and BOD\text{S} but negatively correlated with NO\text{3-N}, EC, and WT. Compared with winter, the new dominant functional groups Lo, W1, W2 and Wo were added to the system in spring and group B remained dominant in each unit. Environmental variables, such as NO\text{3-N}, TN, DO, BOD\text{S} and COD\text{Mn}, were positively associated with functional groups W1 and Wo. The functional groups Tc (Oscillatoria) and M (Microcystis) began to dominate, and group Lo became predominant throughout the system in summer. The RDA results showed that WT was significantly positively correlated with functional group Tc and positively correlated with functional Group M, while functional Group M was significantly positively correlated with BOD\text{S}. In autumn, Group B was always predominant in most units, while group Lo was predominant in the pretreatment unit. In addition, Group J was also highly dominant in each unit. The RDA results indicated that Group B was significantly positively correlated with pH.
As shown in Figure 5, Group VI was significantly positively correlated with pH and was predominant in the Yanlong project in winter. Group VI occupied absolute dominance in spring and was significantly positively correlated with WT. The dominance of Group I was second only to Group VI. Group VI and Group VII are the main dominant functional groups in summer. Among them, Group VI occupied an absolute dominance in the wetland purification unit, and Group VII occupied an absolute dominance in other units. RDA showed that Group VII was significantly negatively correlated with turbidity, significantly positively correlated with BOD$_5$, COD$_{Mn}$, and WT, and positively correlated with SD. In autumn, Group VI was predominant in the Yanlong project, while Group I (consisting mainly of Chlorella and Crucigenia) was also dominant. Both functional groups were significantly positively correlated with WT and pH and negatively correlated with nutrient indicators.

4. Discussion
4.1 Seasonal and spatial variations in conventional water quality indexes

In the pretreatment unit, aeration oxygenation, natural sedimentation and artificial media biofilm adsorption technology were adopted, which can remove the taste of water, regulate the settlement of particles increase dissolved oxygen in water, improve water transparency and preliminary purification of water quality. After the influent flowed through pretreatment unit, DO and SD increased, turb, COD$_{Mn}$ and BOD$_5$ decreased, but pH and chl-a concentration increased. The pretreatment unit can obviously remove biodegradable organic matter in raw water.

The core unit of constructed wetland adopted three-dimensional composite surface flow wetland. Emergent plants, submerged plants, soil and microorganisms combined to play the interception and purification functions. The emergent plant unit
served to control algae growth, decrease chl-a concentration, decrease the concentration of TP and TN due to the absorption of nutrients by plants and the influence of light intensity under water, while the decrease in DO levels in the emergent plant unit was mainly associated with the consumption of dissolved oxygen by soil. When water flowed through submerged plant unit, the increase of hydraulic residence time and underwater illumination intensity provides favorable conditions for the proliferation of algae. At the same time, DO and pH of water body were effectively improved. In addition, there was a tendency for turb values to increase after entering the wetland purification, which was mainly caused by the lower depth and faster flow rate of the wetland purification unit and the tendency for the bottom substrate to be suspended by fish disturbance.

The deep purification unit as water storage unit, the long hydraulic retention time was beneficial to the tiny suspended solids in water precipitation, but at the same time because of the increasing of underwater illumination intensity and the hydraulic retention time, there was a risk of algae blooms. Filtering-feeding fish and shellfish had been added, some submerged plants with good purification efficiency were planted to build a healthy ecosystem, which can effectively control the growth of algae and further purify water quality.

After the influent flowed through the processing unit of Yanlong project, DO and pH levels showed an overall upward trend. The increasing pH value was related to the photosynthesis of aquatic plants that consume CO₂ and increase the carbonate content of the water. Zhang reported that a higher pH value was suitable for large-scale algae reproduction within a certain range [26], and a pH varying from 8.0 to 9.5 could promote the reproduction of cyanobacteria phytoplankton. Therefore, it is necessary to pay attention to the change in pH in deep purification unit and set up an algae capture device to control the density of algae cells in the deep purification unit. The system had a high concentration of TN and TP in the influent and it decreased after treated, but the average concentration of TP remained high. The existence of plentiful nitrogen and phosphorus in water resource contributes to eutrophication, resulting in further deterioration of water quality [27,28]. Additionally, the concentration of COD_{Mn} in the effluent water was slightly lower than that in the inflow water while the concentration of BOD_{5} in the effluent water was slightly higher than that in the inflow water.

DO levels were highest throughout the whole system in winter and lowest in summer because with the increase in WT, the DO saturation in water decreases. Moreover, the rate of decomposition of oxygen-consuming organic matter accelerated, and respiration by aquatic animals further accelerated the consumption of oxygen, resulting in low DO levels in summer [29]. Turb and EC were relatively high in autumn and winter, which was caused by the decay of aquatic plants during autumn and winter seasons, when aquatic plant residues fall into the water and a large amount of plant debris was mixed into the water and the beach surface. After decay, nutrients and organic substances were released to the outside, contributing to the increase in turb and conductivity value.

The reduction in TN in the Yanlong project was higher in spring and summer, which was related to the increase in temperature in those seasons, the vigorous growth of aquatic plants and the effective use of large amounts of nitrogen nutrients in water. The lower NO₃-N values in summer were due to lower DO values in summer, which inhibit nitrification by nitifying bacteria [30], and the inhibition of nitrification in the water by chemosensitive substances secreted by the mature and well-developed root systems of actively growing aquatic plants. The concentration of NH₄⁺-N was higher in winter and summer. Especially in winter, after the harvesting of emergent plants, a large amount of plant debris was mixed into the beach surface and water, decaying and releasing nutrients into the water. In summer, the water quality was mainly affected by heavy rainfall, which increased the concentration of NH₄⁺-N. The removal efficiency of NH₄⁺-N in the deep purification unit was better, which was mainly related to the reduction of particulate matter in water by sedimentation. The exceedance of the TP concentration in the influent water in summer was due to the rainfall carrying a large amount of phosphorus in particulate form, while the scouring and disturbance of the bottom substrate released phosphorus into the water. In winter, affected by the dredging in the pretreatment unit and the harvesting of aquatic plants, the concentration of TP in the system was high, especially in the pretreatment area, where the average concentration was higher than that in the influent.

The reason for the highest concentration of organic matter in summer was due to the summer monsoon rainfall, and a large number of exogenous organic pollutants were imported, so that the average concentrations of COD_{Mn}, and BOD₅ in water were the highest. After treatment, although significantly reduced, organic pollutants were still high compared with the levels in other seasons. The concentration of BOD₅ increased rapidly after entering the summer, indicating an increase in the biochemical properties of organic matter and a shift of organic composition in water. This phenomenon was closely related to the strong growth of aquatic plants in summer, the large consumption and utilization of refractory organic matter in water, and the secretion of organic matter for microbial decomposition by rhizosphere activities. The higher water temperature, the rapid reproduction and the
higher activity of bacteria increased the efficiency of the decomposition and utilization of biodegradable organic matter in water, explaining why the Yanlong project could significantly reduce the concentration of organic matter in summer. Overall, only deep purification units could maintain the role of reducing the BOD₅ content.

Overall, the environmental variables of the Yanlong source ecological purification system in Yanlong Lake had strong temporal and spatial heterogeneity. The one-way ANOVA results showed that DO, pH, Turb and SD were significantly different between different units (P < 0.001). In different seasons, the differences in WT, DO, EC, TP and NH₄⁺-N were the most significant (p < 0.001). According to the variations in the mean values of the environmental variables, the pretreatment and deep purification units in the Yanlong project mainly played the roles of improving DO, Turb removal and SD. The wetland purification unit mainly played the role of reducing the TN concentration.

### 4.2 Phytoplankton community and phytoplankton functional groups spatiotemporal variation

The density of phytoplankton and Chl-a concentration in the water source ecological purification system were closely related to environmental variables, and they would be greatly changed due to the difference in environmental variables between different units. If the operation of the Yanlong project configuration is unreasonable, it will not be able to effectively control the stability of phytoplankton communities, and there is a risk of phytoplankton outbreaks. The average concentration of Chl-a in the Yanlong project ranged from 10.76 to 55.88 μg/L, and the average concentration of Chl-a in the influent decreased gradually from winter to autumn. The trends in the average concentration of Chl-a and total phytoplankton within the system were generally consistent. The average concentration of Chl-a in the submerged plant unit reached the highest level in summer and autumn, and although the rapid increase in densities of Cyanophyta and Chlorophyta was quantitatively overwhelming, the average concentration of Chl-a was only slightly higher in the pretreatment unit where these same two phytoplankton were rapidly increasing. The phenomenon was related to the large number of reproductions of Pyrophya with a small density but large volume. In the pretreatment and deep purification units, the concentration of Chl-a increased with an increasing phytoplankton density. The densities of Cyanophyta, Chlorophyta and Bacillariophyta increased in spring and summer, while the densities of Chlorophyta and Bacillariophyta increased in autumn and winter. In the deep purification unit, the density of most phyla increased, as did the density of total phytoplankton. In spring and autumn, the density of total phytoplankton in the deep purification unit could be increased by approximately 2 times. Most of these changes are related to the low turbidity of the water column and sufficient underwater light and space in these two treatment units, which are conducive to the reproduction of phytoplankton.

The number of dominant FGs in the influent in winter was less than that in other seasons, and its community structure was the most homogeneous. In winter and spring, the absolutely dominant FG in the Yanlong project was functional Group B, which was composed of Cyclotella with tolerance to a low light environment. Although the water temperature gradually increased in spring, it was basically below 15°C, which was the most suitable temperature for the large-scale reproduction of Bacillariophyta [31,32], while Chlorophyta and Euglenophyta also rapidly propagated, resulting in an increase in the number of dominant FGs in the source water. As the water temperature continued to rise in summer, a large number of Cyanophyta bloomed, and the functional group Lo occupied an absolute dominance in the system when the water temperature was above 22°C. Group Lo was mainly composed of Merismopedia, which was one of the most common phytoplankton in summer when there were sufficient nutrients and strong light in the water [33,34]. In addition, in autumn and winter, due to the decline in aquatic plants in the ecological purification area, the unit almost did not play a role in water quality purification, and the changes in dominant FGs in water were more variable than those in spring and summer.

The dominant MBFG change in the Yanlong project was relatively obvious: in winter, the number of dominant functional groups was the lowest, the community structure was homogeneous, and Group VI maintained absolute dominance. Group VI was mainly composed of Bacillariophyta with siliceous crusts, such as Cyclotella, Navicula and Melosira granulata, which were suitable for survival in the environment with low water temperature. Although the temperature gradually increased in spring and the number of dominant MBFGs increased, the water temperature was still suitable for Bacillariophyta to survive; thus, Group VI remained absolutely dominant in the ecological purification system. During the high-temperature period in summer, the community diversity of the dominant groups in the system was the highest, and Group VII was absolutely dominant in the influent, pretreatment unit and deep purification unit. Group VII was composed of groups of phytoplankton with gelatinous envelopes and low specific surface areas, which were mainly Merismopedia and Microcystis. Due to the low specific surface area and high light utilization efficiency of Group VII, it is suitable for colonization in well-lit environments [35], especially in pretreatment and
deep purification units where the turbidity is low and the transparency is high. The aquatic plants grew vigorously in the stage of cumulative biomass in the wetland purification unit, and branching and foliage occupied a large amount of space while reducing the intensity of underwater light, resulting in the decrease in Group VII dominance, which no longer had absolute dominance. Compared with other seasons, the dominant MBFGs in the ecological purification system showed a greater change in autumn, although Group VI remained dominant.

4.3 Phytoplankton functional group-environment relationship

The dominant groups (B and P) in winter were composed of Cyclotella and Melosira granulate, which are more suitable for a low light intensity, high DO content, high turbidity and nutrient enrichment, which was consistent with the indicator results of the dominant functional groups. In spring, Group B, which remained the dominant in each unit, was positively associated with WT for increasing Cyclotella with increasing water temperature and light intensity. And Group W1 (Euglena and Phacus) and Group Wo (Chlamydomonas) indicate habitats with rich organic matter content [36], and Group W1 was sensitive to high concentrations of BOD₅ in the water environment, consistent with the higher nitrogen nutrient concentrations in the system in spring and significantly higher BOD₅ levels than in winter. At the same time, Group Lo consisted mainly of Merismopedia, which are indicative of eutrophic habitats. Turbidity in spring was significantly lower than that in winter, and the underwater light was enhanced, which was suitable for the reproduction of Merismopedia. However, the RDA results showed that group Lo was significantly positively correlated with turbidity and significantly negatively correlated with SD. Combined with the one-way ANOVA results, these features were mostly related to the small difference in turbidity and SD between winter and spring, and there was no significant seasonal difference. The dominant functional groups (Tc and M) in summer were indicative of eutrophic water and were resistant to the scouring effects of water flow [14], which coincided with the highest water temperatures, frequent heavy rainfall, increased eutrophication of water and highest BOD₅ levels throughout the year. While, pH of the water was elevated in autumn, which effectively corresponds to the sensitivity of functional Group B to elevated pH in the aquatic environment [35].

The dominant group (VI) in winter was mainly composed of Bacillariophyta with siliceous crusts and no flagella, such as Cyclotella and Navicula, which have low requirements for light and nutrients. WT gradually increased to the range of suitable growth and reproduction of diatoms, which enabled group VI to maintain absolute dominance in spring. Group I was mainly composed of Chlamydomonas, Chlorella and Crucigenia, which had small cell sizes and high specific surface areas and were more efficient in using light [37]. This finding was consistent with the RDA results showing a significant negative correlation between Group I and turbidity. The dominant group (VII) in summer was mainly composed of population cells with low surface areas, such as Merismopedia and Microcystis, which had a low light utilization efficiency due to their small specific surface areas. The result of RDA was highly consistent with the significant increase in WT and organic matter concentration in summer, high turbidity in the water column and intense solar radiation. In addition, Group III became one of the dominant MBFGs within each unit as summer progressed. This group consisted of filamentous Cyanophyta with air sacs, such as Oscillatoria and Anabaena, which prefer environments with high light and water temperatures. In autumn, despite the lower WT and pH in autumn than in summer, the system was suitable for phytoplankton blooms of Bacillariophyta and Chlorophyta. Although most of the nutrients in the Yanlong project were lower in autumn, the levels were sufficient for phytoplankton growth and reproduction.

The RDA results during the study period between the two phytoplankton functional groups and environmental factors in the Yanlong Lake purification system are shown in Table S4. By comprehensively comparing the redundancy analysis results of FG and MBFG, we found that the response of the MBFG functional group to habitat in the ecological purification system of Yanlong Lake was better than that of the FG functional group. In addition, the two functional groups had the highest response to habitat changes in winter, followed by autumn, and the lowest response to habitat changes in summer.

5. Conclusions

In this study, the seasonal distribution characteristics and spatial differences in the aquatic environment and the succession characteristics of plankton functional groups in the Yanlong project were preliminarily mastered. We found that the temporal and spatial heterogeneity of the water ecological environment within the Yanlong project was strong and that the growth of aquatic plants in the ecological purification unit had a great influence on the aquatic environment. In winter, spring and autumn, the absolute dominant functional groups in the water ecological purification system were B and Group VI, while functional groups Lo and Group VII had a higher dominance in summer. The composition of the dominant functional groups of plankton in each unit changed little and was relatively stable. The environmental variables driving the
succession of dominant functional groups of plankton in the ecological purification system of water sources in Yanlong Lake were mainly WT, pH, turbidity and BOD₅. The habitat response of MBFG was better than that of FG.

**Author contributions**

Conceptualization, Z.M., W.M. and C.D.; methodology, X. L. and C.D.; validation, Z.M., Z.L and M.P.; formal analysis, W.M.; investigation, W.M. and M.P.; resources, Z.L., W.M. and C.D.; data curation, Z.M.; writing—original draft preparation, Z.M. and W.M.; writing—review and editing, X.L., M.P. and C. D.; visualization, Z.M.; funding acquisition, W.M. and C.D. All authors have read and agreed to the published version of the manuscript.

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