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# Analysis on the effect of large-scale compound ecological engineering system on pollution control of the estuary of a lake

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## ABSTRACT

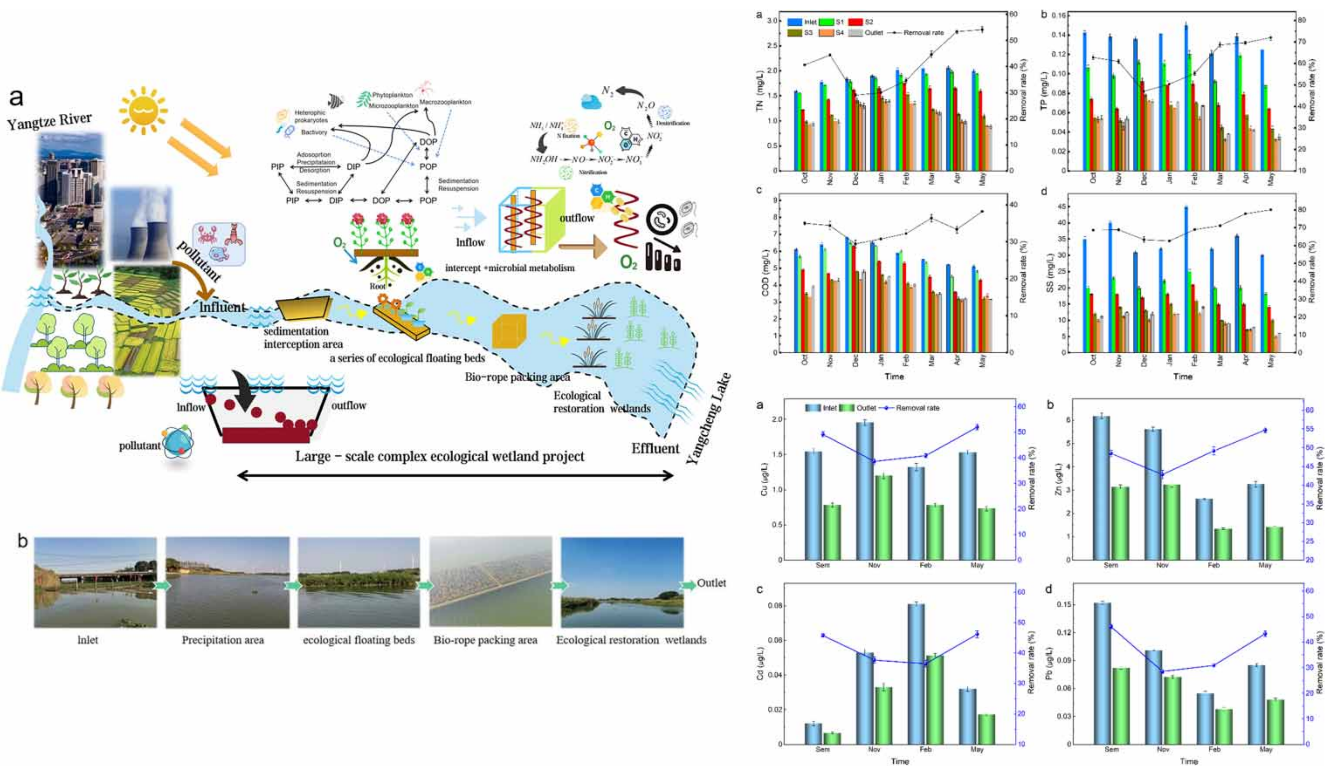
The quality of the water and the water environment in the estuary of a lake directly affect the water quality and ecological functions of the entire lake. Multi-technology systems, which integrate biotechnological analysis of a lake estuary and restoration of the ecological functions of the water *in situ*, have gradually been adopted for lake management and restoration. The Xielugang Estuary is located north of the Yangcheng Middle Lake and always exhibits a certain degree of eutrophic phenomena. To ensure the safety of the ecological environment in Yangcheng Lake, a multi-level purification and ecological system with 'intercept precipitation–ecological restoration–coupled biological treatment' was developed. Water quality monitoring results for the inlet and outlet of different units in the system from October 2020 to May 2021 showed that the system was effective. We also found that the purification capacity of the composite system was high and the system could significantly enhance the reduction of total nitrogen, total phosphorus, potassium permanganate index and total suspended solids. The average removal rates for these components were 41.34, 61.76, 35.21 and 67.21%, respectively, and the removal rate for typical heavy metals (Zn, Cu, Cd, and Pb) was 30.4–48.9%. The composite system substantially improved the water quality of the estuary and the wetland ecological function, demonstrating its effectiveness and significance.

**Key words:** composite system, ecological restoration, estuary, eutrophic phenomena, wetland ecological function

## HIGHLIGHTS

- Investigated pollutant removal in large-scale estuary ecological treatment project.
- Proposed a biological treatment system coupled with *in situ* ecological engineering.
- Conducted a seasonal comparative analysis of the ecological treatment area and units.
- Provided some suggestions for the operation and management of ecological engineering.

## GRAPHICAL ABSTRACT




## 1. INTRODUCTION

Due to rapid industrialization, urbanization and population growth, the stability of aquatic ecosystems in rivers and lakes has decreased significantly worldwide, especially in municipal rivers in developing countries. To improve the water quality of lakes and rivers, it is essential for the control of pollution sources, the restructuring of river ecosystems, the regulation of water flow and the improvement of the river's self-purification (Lin *et al.* 2015; Mi *et al.* 2015). Eutrophication and algal blooms are considered the two most common and serious threats to the security of drinking water sources, nitrogen (N) and phosphorus (P) are the immediate causes of eutrophication in water, and removing them is an effective way to mitigate or prevent eutrophication (Yin *et al.* 2013; Fang *et al.* 2016). Water quality assurance and water ecological function restoration in water source areas have become important issues of common concern around the world (Nixdorff *et al.* 2021). In developing countries, due to the influence of hydraulic conditions and the topographical features of water beds, water quality pollution in estuaries has become an important reason for the destruction of lake ecosystems. Therefore, the treatment of estuary areas is not only important to reduce the pollution load that flows into lakes; it can also directly affect the self-purification function in lakes.

Currently, typical *in situ* ecological engineering techniques for water bodies include pre-storage technology, ecological floating island technology, lakefront ecological restoration technology, and artificial wetland restoration technology. However, in large-scale environmental applications, single *in situ* ecological engineering techniques often have disadvantages in terms of the purification stability and pollutant reduction (Wu *et al.* 2011, 2017; Lutterbeck *et al.* 2018; Nsenga Kumwimba *et al.* 2021). Consequently, the combination of biotechnology and engineering methods has attracted increasing attention from scholars all over the world (Sheng *et al.* 2013). At present, there are few reports on the application of this type of ecological engineering approach for river pollution control. To improve the technical applications in this field, we propose and report on a project for the ecological purification of the incoming estuary of a water body *in situ* through biotechnology-coupled engineering.

Yangcheng Lake is one of the most important freshwater lakes in the Taihu Lake Basin, and it is an important storage and ecological lake for flood control, drainage, diversion and irrigation in the Yangcheng Dianmao area, as well as an important drinking water source for Suzhou. With the increase in the population around Yangcheng Lake, the lake has taken on a large amount of pollutants while carrying drainage from upstream areas, leading to the increase of nitrogen, phosphorus, heavy metals (Zn, Cu, Cd, Pb, etc.) and other indicators entering the lake. As one of the two main waterways that enter the lake on the north shore, the Xielugang River is the main channel through which water flows into the lake from Qiputang River. This site is the object of the study in this paper. We conducted long-term monitoring of the water quality in and out of several treatment units during the water diversion period to explore the effectiveness of the estuarine ecological system for deep purification of incoming water from the upper reaches. Yangcheng Lake is an important drinking water source of Suzhou, the aim of the study was to deepen the purification of estuarine waters, reduce pollutants in the upper reaches of the estuary and provide a reference information for similar ecological restoration approaches of incoming estuaries.

## 2. MATERIALS AND METHODS

### 2.1. Study site

The study site was the compound ecological engineering system (CEES) in the Xielugang River Estuary (31°484′N–31°494′N, 120°797′E–120°816′E), situated on the northern shore of the Yangcheng Middle Lake. The water to be treated came from the Xielugang River, which feeds into the lake from Qiputang River. The Xielugang River is the boundary river between Xiangcheng City and Kunshan City in Suzhou. The main source of pollution is agricultural runoff flowing through the area. The width of the Xielugang River is about 55–65 m, and the average water depth ranges from 2.5 to 3 m (3.23 m in normal water level conditions). The flow into the lake during the diversion period ranges from 15 to 25 $m^3/s$, and the average river crossing section is 165.0 $m^2$ (All design parameters and project information from *the Design Report of Yangcheng Lake Comprehensive Remediation Project*, and same below). The Xielugang River bed meanders substantially; therefore, a pre-treatment ecological engineering area for the estuary was created to take advantage of the topography of the river. The incoming water enters the Yangcheng Middle Lake after being treated. The location and scope of the study area are shown in Figure 1.

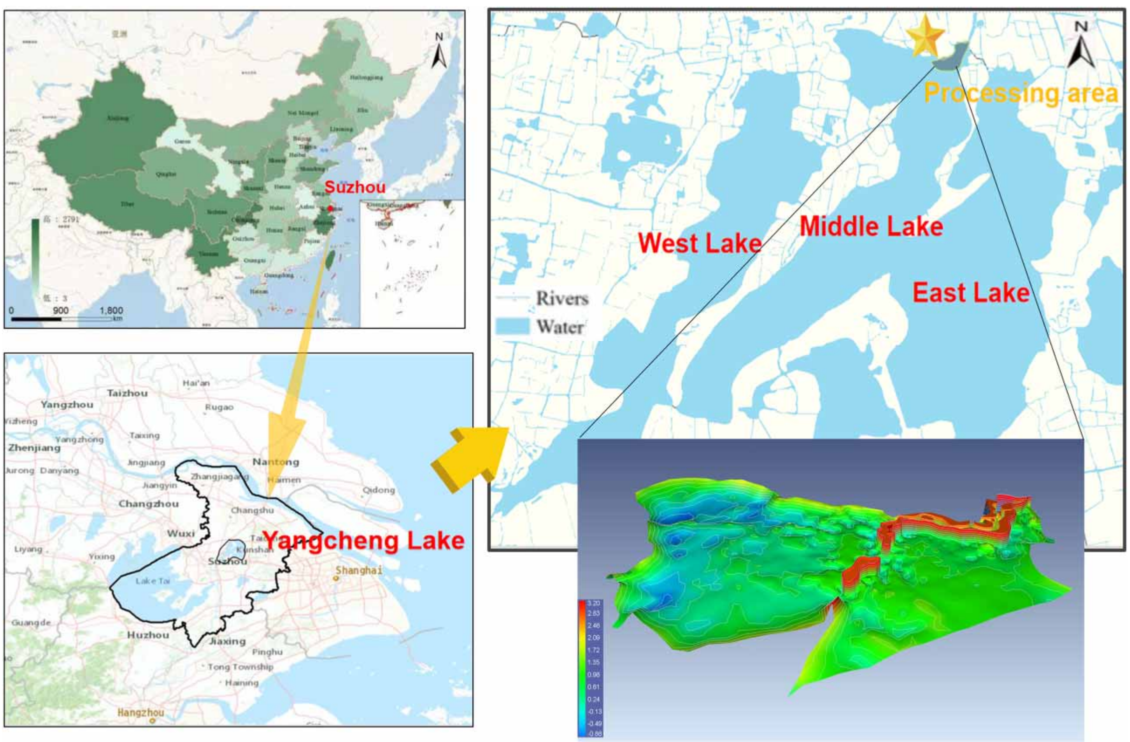



**Figure 1** | Location and range of the study area (map of Yangcheng Lake in Suzhou).

### 2.2. Description of the composite ecological engineering process

The total area of the treatment area at the estuary of the Xielugang River is 497,900 $m^2$. A multi-stage ecological purification concept of 'interception and sedimentation → strengthening purification → ecological restoration' was applied in the treatment area, and a sedimentation interception area, ecological floating beds, biological rope filling area and ecological restoration wetlands were set up (Figure 2).

#### 2.2.1. Sedimentation interception area

The sedimentation interception region, located in front of the estuary wetland and served as the front unit for incoming water treatment. The water body was appropriately deepened to increase the hydraulic retention time and meet the requirements for interception and sedimentation. The primary role of the sedimentation interception area was to precipitate sediment and suspended solids (SS) and to relieve the load impact of the water coming from the Xielugang River on the lake ecosystem. The engineering area has been in operation for some time and plays an important role in the initial purification of the water and reducing the impact of sediment on the subsequent wetland process. The bottom elevation of the engineering area was set at −0.5 m, the water depth was about 3.7–3.8 m under normal water level conditions and the unit covered an area of about 72,000 $m^2$.

#### 2.2.2. Ecological floating beds

This unit contained a composite ecological floating bed, which was placed directly behind the sedimentation area. A total of three groups were set up in this unit with a total area of 1,944 $m^2$. Each group consisted of 12 rectangular modules (the frame

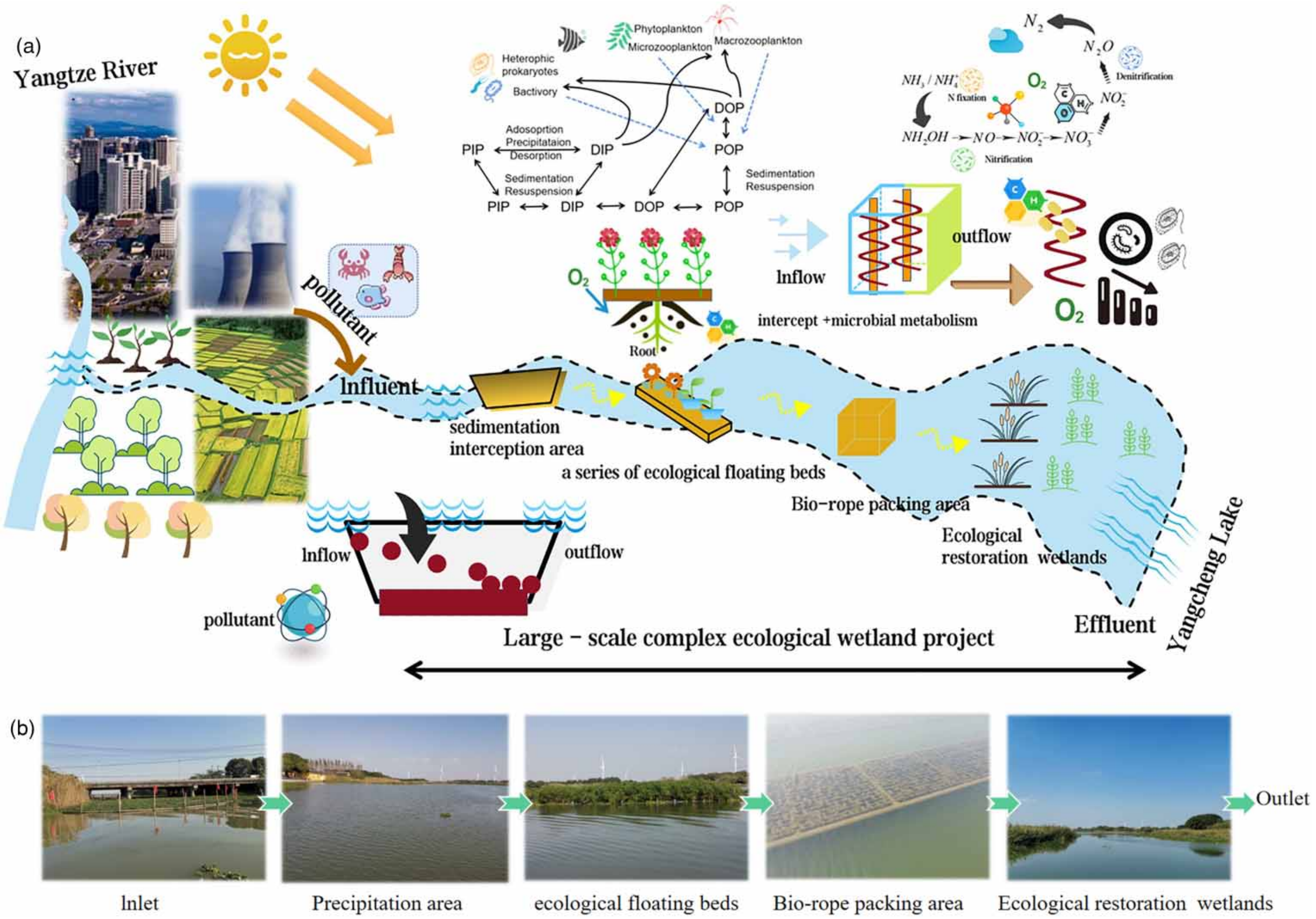



**Figure 2** | The process of composite ecological engineering (a) and site photographs (b).

size of a single rectangular module was 18 × 3 × 0.5 m). The frame spacing of each rectangular module was 1.5 m, the module plane frame was welded from 40 × 50 T-type steel and 40 × 4 angle steel, and the periphery of each module was fixed to the bottom of the lake with 2–4 galvanized steel piles. The steel column was 8.3 m long and 150 mm in diameter. The pontoon (L = 3 m) was mainly made of filamentous natural plant fiber and polyester fiber with a large specific surface area and high porosity. The main plants selected for the floating beds were dry umbrella grass, *Thalia dealbata*, *Iris pseudacorus*, etc.

#### 2.2.3. Bio-rope filling area

The biological rope filling area was laid out in a submerged stainless-steel frame totaling 1,008 $m^3$. The processing unit was located before the ecological wetland restoration area and was part of the bio-enhanced removal unit. The biological rope was arranged in a straight line in the main channel, with a total of four rows. To ensure maximum stability, the peripheral stainless-steel frame was welded with open hole wire. The top of the filler frame was 0.1–1.2 m below the normal water level and was completely submerged. The inlet water flowed through the filler area radially. A fiber filler with a large specific surface area, a high biological adhesion ratio and a biofilm structure was attached to the suspension rope. With different levels of oxygen, microorganisms could carry out nitrification and denitrification reactions as well as metabolism on the filler (Albuquerque *et al.* 2012).

#### 2.2.4. Ecological restoration wetlands

The wetland restoration area in the Xielugang Estuary was a riparian surface flow wetland, which was combined with the submerged topography to create a ‘deep channel water–shallow beach–land area’ with different substrates. The wetland is a rich habitat with natural meandering patterns of internal water channels and roaming beaches, forming a terrain condition-rich habitat, an internal water flow channel and a floodplain with a natural winding shape. This increases the effective residence time and contact area of the wetland to meet the diverse needs of wetland species and ensure wetland purification. The total area of the wetland restoration area was about 425,900 $m^2$, with the deep water area and open water surface accounting for about 60% of the total area and the shallow water area accounting for 40%. The average water depth in the deep water area was maintained at 1.2 m; that is, the elevation of the lake bottom terrain was maintained at about 1.1–2 m, and the average water depth in the shallow water area was controlled within 0.3 m. In other words, the elevation of the planting area was maintained at 2.6–3.2 m, the side slope ratio was 1:5, and the slope and bottom were compacted with the original soil and covered with planting soil. To meet the needs of birds and other foraging and roosting species, a relatively shallow gravel beach was created in the shallow water area and the elevation was generally maintained at 3 m or higher. Water-holding, floating-leaf and submerged plants were planted in different functional areas. The selected water-holding plants were mainly native reeds, calamus and balsam ferns, while the submerged plants were mainly black algae, foxtail algae, hardy water lilies, Malayan eyebright and bitter grass. The ecological wetland restoration area served to clean up pollutants while fulfilling the landscape needs of the estuary and the survival needs of animals around the lake.

### 2.3. Field sampling and laboratory analysis

The efficacy of the CEES to minimize pollutants from the Xielugang Estuary was evaluated. From October 2020 to May 2021, we took time samples once a month, monthly water samples were collected at the inlet and outlet locations of each treatment unit in the test area for the Xielugang Estuary Compound Ecological Purification Project (precipitation trap area – S1, ecological floating beds – S2, bio-rope filling area – S3 and ecological restoration wetlands – S4). Before sampling, all sampling equipment and storage containers were cleaned with distilled water. During field sampling, three parallel water samples were collected at 30 cm below each sampling point without disturbing the sediment–water interface and mixed in 500 mL polyethylene bottles. The water samples were labeled and sealed with airtight screw caps. All collected water samples were immediately refrigerated and transported on the day of sampling to the laboratory, where they were stored in a low temperature environment and subjected to analytical experiments within 48 h.

The total suspended solids (TSS), total nitrogen (TN), chemical oxygen demand ($COD_{Mn}$) and total dissolved phosphorus (TP) were measured using the standard procedures specified in the Analytical Methods for Water and Wastewater Monitoring (4th edition, 2002). Dissolved oxygen (DO), pH and temperature were measured using the YSI 550A Handheld Dissolved Oxygen and Temperature System purchased from TechTrend International Limited, USA. A Secchi disc was used to measure water clarity. In the laboratory, TN was directly analyzed with alkaline potassium persulfate digestion-ultraviolet-visible (UV) spectrophotometry in unfiltered water samples, and TP was directly analyzed using the ammonium molybdate spectrophotometric method. TSS was calculated by dry weighing analysis and $COD_{Mn}$ was analyzed with HACH ultra-low range ablation spectrophotometry.

The seasonal removal of heavy metals (Cu, Zn, Pb, Cd, etc.) by the whole system in the test area was also evaluated. In September 2020, November 2020, February 2021 and May 2021, samples were collected at the inlet and outlet of the estuary test area. Water samples were pre-filtered through a 0.45 um microporous membrane, subjected to microwave digestion (CEM Mars6, USA) and then analyzed with inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7700, USA). All analyses were carried out according to the standards defined in the Analytical Methods for Water and Wastewater Monitoring.

## 3. RESULTS AND DISCUSSION

The monthly average concentrations of different nutrients and conventional physical and chemical indicators before and after treatment with the CEES (sampling and analysis times were from October 2020 to May 2021) are listed in Table 1. The average monthly effluent from the treatment area fully met the Class IV standard in the Environmental Quality Standard for Surface Water (GB 3838-2002), and some indexes involved met the requirement of the Class III level.

### 3.1. The removal rate of TN

Nitrogen is one of the main factors that lead to eutrophication in lake and reservoir water bodies. The primary methods through which the ecological purification system removes nitrogen from water bodies are nitrification and denitrification reactions by microorganisms, absorption and transformation by plants and adsorption by filler media (Vymazal 2007; Nsenga Kumwimba *et al.* 2021). The changes in concentration at different sampling locations at different times during the test period are shown in Figure 3(a). The removal rate of TN by the ecological purification system in the estuary was also calculated.

As can be seen from Figure 3(a), the sedimentation interception area had a low contribution to TN removal. The purification and removal of TN relied on synergistic effects from the ecological floating bed zone, the biological rope filling zone and the wetland restoration zone. The removal rate of TN in the whole ecological purification system ranged from 29 to 55%. The removal rate in May was the highest and was 1.9 times higher than that in December. The biological rope filler area played a leading role in TN removal, and the highest contribution from this area reached 43.13%. The removal rates in autumn and spring were obviously higher than that in winter, mainly because a large number of plants in the floating bed and wetland withered, died and were not harvested in the winter, which had a substantial impact on TN absorption, absorption and transformation. The low temperatures also influence the metabolism of microorganism, and this reduces the effectiveness of the system to treat these pollutants in the winter (Newcomer Johnson *et al.* 2016). In addition, the nitrifying and denitrifying microorganisms on the biological rope filler were less active in low temperature conditions (Sheng *et al.* 2013). As the temperature rose, the removal rate increased, reaching the highest value in May. The overall operation of the ecological purification system was stable and the impact of this area was more obvious in the removal of TN from incoming water from the upper reaches of the lake. In addition, seasonal variations had some impact on the operation of the system in the project area (Vymazal 2007; Li *et al.* 2020).

**Table 1** | The parameters for river water sample (unit: mg $L^{-1}$)

| Item | Sort | TN | TP | TSS | $COD_{Mn}$ | DO | pH | Water clarity (cm) |
|---|---|---|---|---|---|---|---|---|
| Inlet | Average | 1.90 | 0.136 | 35.25 | 6.05 | 7.45 | 7.98 | 48 |
| | Range | 1.60–2.06 | 0.12–0.15 | 30–45 | 4.8–7.2 | 6.78–8.96 | 7.50–8.43 | – |
| Outlet | Average | 1.08 | 0.052 | 11.56 | 3.92 | 8.24 | 8.08 | 73 |
| | Range | 0.88–1.32 | 0.04–0.07 | 6.0–12.5 | 3.15–4.3 | 7.02–9.23 | 7.46–8.43 | – |
| Standard (IV) | – | 1.50 | 0.10 | – | 10 | ≥3 | 6–9 | – |
| Standard (III) | – | 1.00 | 0.05 | – | 6 | ≥5 | 6–9 | – |
| Removal rate (%) | – | 28.96–54.17 | 47.02–71.23 | 62.50–80.12 | 29.41–36.36 | – | – | – |

These values are means calculated from the data from October 2020 to May 2021.

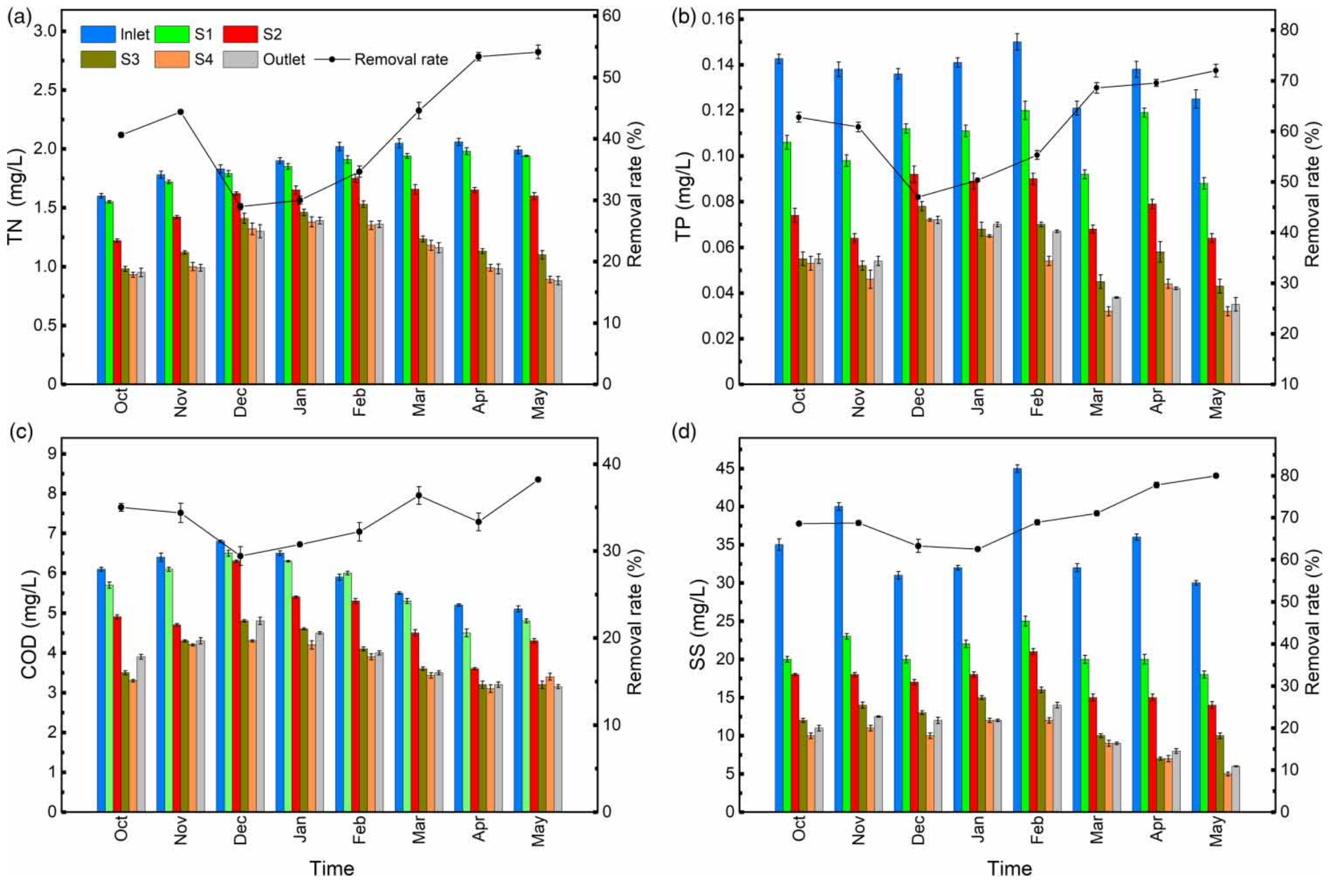



**Figure 3** | Variations and removal rates of TN (a), TP (b), COD (c) and SS (d) for the system.

## 3.2. The removal rate of TP

The phosphorus removal methods in the ecological purification system were different from those used for nitrogen removal. The removal methods for phosphorus were complex and involved physical, biological and chemical effects. The physical effects mainly consisted of pollutants gradually settling at the bottom of the precipitation area due to gravity and interception by emergent plants in shoals (Nsenga Kumwimba *et al.* 2021). The biological action mainly consisted of microbial uptake, plant and algae uptake at the biological rope filler and plant roots. Plants and algae need to absorb a large amount of soluble phosphate for growth, and microorganisms need to absorb a large amount of inorganic phosphorus, which is assimilated into their bodies in the form of polyphosphate and fixed in the process of growth. (Vymazal 2007; Wu *et al.* 2017; Nsenga Kumwimba *et al.* 2021). The higher the DO is, the more phosphorus will be absorbed. The chemical effects mainly consisted of phosphorus binding to ions in the matrix filler to form particles that were intercepted and precipitated for removal and adsorption on the surface of the matrix (Benvenuti *et al.* 2018). Elemental phosphorus is a major factor in the eutrophication of lake and reservoir waters. Variations in the TP concentration at different sampling locations at different times during the experiment are shown in Figure 3(b). The removal rate of TP by the estuarine ecological purification system was calculated for matrix surface adsorption.

Figure 3(b) shows that the removal rate of TP in the precipitation interception area was greater than that of TN. The average contribution of this area in TP removal was maintained at about 37.03%, primarily due to the sedimentation from the particulate phosphorus in TP. The waterfront plants on both sides of the shoreline also played a part in the interception and sedimentation effect.

The TP removal rate of the whole ecological purification system ranged from 47 to 72%. The highest removal rate was observed in May and was as high as 72%. The removal rate in winter was relatively low, because the plants growth and microbial metabolism required less nutrients accordingly under the conditions of low temperature. The microorganism metabolism was also slower and less active at low temperatures in winter. Excess phosphorus originally absorbed by the polyphosphorus bacteria may also be released in low DO conditions (Newcomer Johnson *et al.* 2016). Therefore, TP removal in the winter mainly relies on physical sedimentation, adsorption by substrate fillers and interception by the roots of water-holding plants, submerged plants, etc. To improve the phosphorus removal capacity of the system, it is necessary to improve the interception settlement capacity (Lin *et al.* 2015; Mi *et al.* 2015).

### 3.3. The removal rate of $COD_{Mn}$

$COD_{Mn}$ is one of the indicators of the relative content of organic matter in water. The removal of $COD_{Mn}$ from water bodies by ecological purification systems mainly occurs through interception and adsorption by substrates, absorption by plants, algal root growth, precipitation and microbial degradation. Related studies have shown that microbial degradation is the most important method (Newcomer Johnson *et al.* 2016; Nsenga Kumwimba *et al.* 2021). Specific concentration changes and removal rates are shown in Figure 3(c).

Figure 3(c) shows that the removal rate of $COD_{Mn}$ for the whole ecological purification system was weaker than those of nitrogen and phosphorus, and the overall removal rate ranged from 30 to 38%. Comparison of each treatment unit revealed that the degradation rate of $COD_{Mn}$ in the bio-rope packing area was significantly greater than that in the other unit treatment areas, with an average contribution of 44.36%. The biological rope packing area mainly relied on the metabolic degradation of a large number of microorganisms attached to inorganic substances on the surface layer of the filler. Insoluble organic matter was filtered and intercepted by the substrate in the wetland system, and some dissolved organic matter was directly absorbed by plants and algae to synthesize their own substances (Fang *et al.* 2016). The roots of plants also absorbed and adsorbed a certain amount of dissolved organic matter, which was then removed by the action of biofilm on their surface. Therefore, wetland plants in the ecosystem should be harvested in time to prevent residual organic matter from being retained and released, to ensure the treatment effectiveness and water safety in the project area (Sheng *et al.* 2013; Yin *et al.* 2013; Fang *et al.* 2016).

### 3.4. The removal rate of suspended solids

The main methods by which the ecological purification system removed suspended solids in the water body were natural gravity sedimentation, plant root adsorption, interception, etc. (Vymazal 2007; Sheng *et al.* 2013).

As can be seen from Figure 3(d), the whole ecological purification system had a high rate of SS removal. The removal efficiency ranged from 61 to 80%, which effectively increased the transparency of the water body. The sedimentation interception area had the most significant effect on SS removal, with a monthly average contribution of 44.4%, mainly because the sedimentation area had a slower flow rate, which maximized the natural sedimentation effect of SS. The removal rate in winter was slightly lower than that in other seasons, further indicating that wetland plants have a strong interception effect on SS (Fang *et al.* 2016). In addition, the removal rates of SS and TP showed a positive correlation, indicating that greater interception and sedimentation of SS, which is a natural substrate carrier and adsorbent, was related to better TP removal (Sheng *et al.* 2013; Nsenga Kumwimba *et al.* 2021).

### 3.5. Trace metal reduction efficiency

The removal mechanism for heavy metals in the estuary complex ecological purification system mainly consisted of matrix adsorption, filtration, precipitation, plant absorption and microbial degradation. Many studies have shown that in wetland treatment systems, clay particles and organic matter on the surface of the substrates play a major role in the adsorption and precipitation of heavy metals, and that absorption and root adsorption by plants have little effect on the removal of heavy metals (Fang *et al.* 2016; Colares *et al.* 2020). The migration and transformation of heavy metals between the substrate and the water body refers to the adsorption and release of heavy metals by solid substrate particles, as well as the physical, chemical, and biological processes that accompany this process (Arini *et al.* 2012; Colares *et al.* 2020). The main physical processes were adsorption, filtration and deposition. The chemical processes involved mainly included adsorption, precipitation, ion exchange, oxidation and hydrolysis. The substrate in ecological wetlands is an active filter. After the river water enters the ecological wetland system, the suspended matter is intercepted, filtered and deposited in the matrix. The heavy metals in the water body interact with the surface clay particles in the matrix for the adsorption and enrichment of heavy metals. Therefore, the surface of fillers is the location where heavy metals gather, and it is also a potential source of heavy metal pollution. Proper disposal of the surface matrix is particularly critical. The migration, transformation and accumulation of heavy metals in plants mainly occur due to plants directly absorbing, adsorbing and enriching heavy metals from polluted water bodies (Rezania *et al.* 2016). Heavy metals migrate from the roots to the above-ground parts in

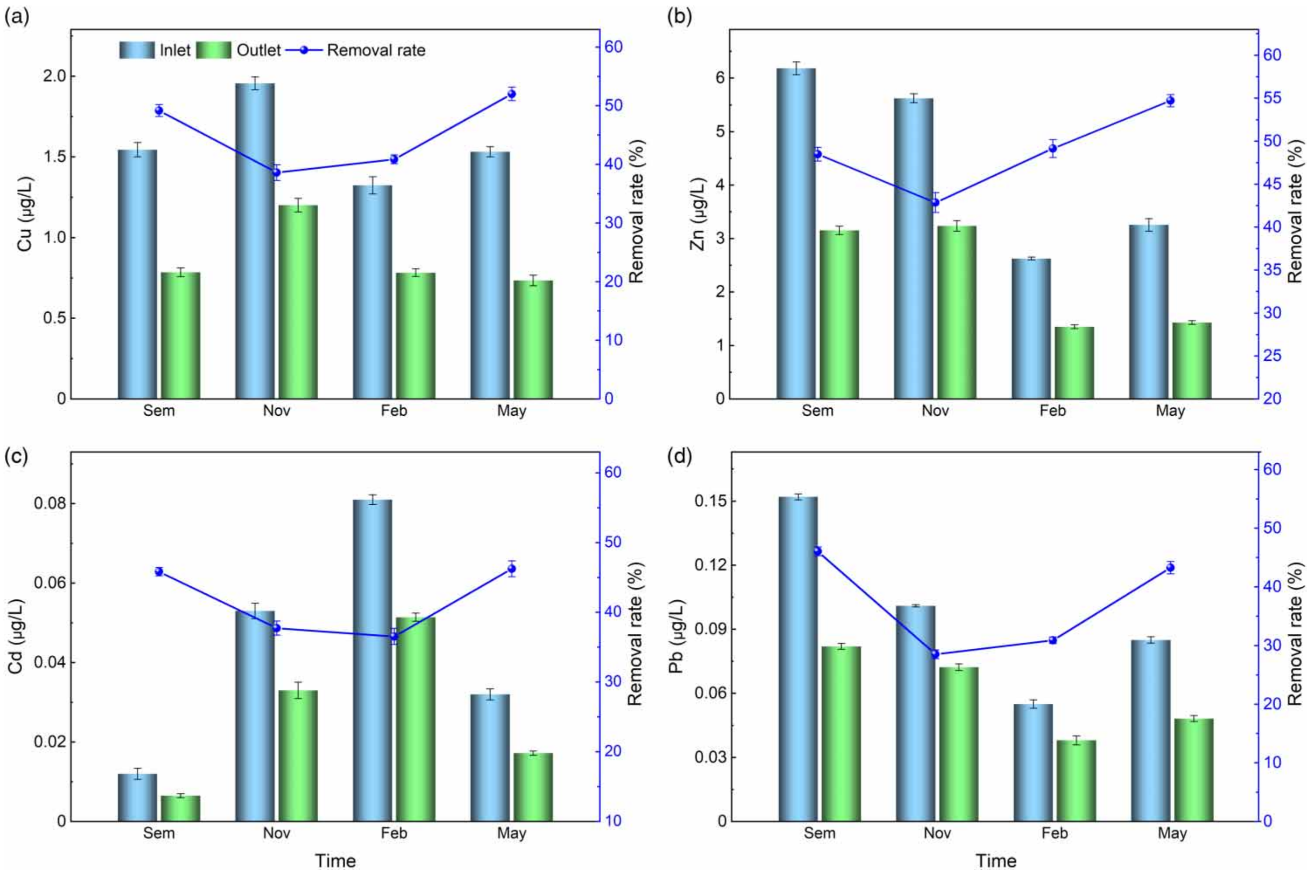



**Figure 4** | Variations and removal rates of Cu (a), Zn (b), Cd (c) and Pb (d) for the system.

plants and are removed when the above-ground parts are harvested. The activity of heavy metals is reduced by plants. To facilitate the precipitation of heavy metals and inhibit their migration, wetland plants should be harvested regularly in autumn and winter to avoid potential risks (Gill *et al.* 2017).

Figure 4 shows that the average removal rate of heavy metals by the composite ecological purification system was higher in September (47.52%) and May (49.41%) than in November (36.83%) and February (39.3%). In terms of the average removal rate of individual heavy metals, Zn (48.9%) > Cu (45.1%) > Cd (41.6%) > Pb (30.4%). The seasonal changes of pollutants removal were obvious, mainly because the plants in the estuary purification system had stopped growing and adsorbing, which resulted in a poor removal rate for heavy metals. The amount of water drawn into the lake from Qiputang River decreased in the winter, and the flow rate of the water was slow. The removal of heavy metals mainly depended on natural precipitation. In summer, the temperature was high, the plants in the system grew the most luxuriant and the developed root tissues of the plants enhanced the absorption and transport of heavy metal ions (Rezania *et al.* 2016; Wu *et al.* 2017). Though the heavy metal content in the influent water in summer was high, CEES maintains higher removal rates. The removal rate of heavy metal ions in constructed wetlands was highest in the summer (Colares *et al.* 2020).

## 4. CONCLUSION

1. During the operation period for the estuary coupled with a purification system, the treatment effect of each unit was relatively stable, and the content of typical pollutant entering the lake met the Class IV standard of *Surface Water Environmental Quality Standard* (GB 3838-2002). The average removal rates for TP, $COD_{Mn}$ and SS were 41.34, 60.82, 33.75 and 69.85%, and the average removal rates for heavy metals Zn, Cu, Cd and Pb in water were 48.9, 45.1, 41.6 and 30.4%, respectively. Seasonal changes had a greater impact on the overall operation of the system, and the removal rate for the entire system in winter was not as good as that in autumn and spring.

2. With regard to the characteristics of the removal of different pollutants, each treatment unit in the coupling system had individual merits. The sedimentation zone had a good purification effect on TP and SS, and was less affected by seasonality. The bio-rope packing area played a leading role in the removal of TN and $COD_{Mn}$, which are greatly affected by seasonality. The removal efficiencies of different pollutants in the ecological floating bed area and the wetland restoration area were relatively stable, and the ecological restoration function was more apparent. Therefore, the units of the estuary complex ecological system played an effective complementary role in time and space, and substantially improved the estuary water quality and wetland water ecological function.
3. In system management, it is necessary to pay attention to the harvesting and disposal of plants in the floating island area and the wetland restoration area. It is also necessary to pay close attention to the seasonal filming of the biological rope filling area and regularly collect samples for microbial character testing. In terms of internal sources, the sedimentation interception area has a long running time and regular dredging and remediation work should be carried out.

## ACKNOWLEDGEMENTS

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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