Nitrogen and Phosphorus Purification in Simulated Wastewater By Two Aquatic Plants

Jianling Xu (xujl449@nenu.edu.cn)
Northeast Normal University https://orcid.org/0000-0001-5115-0517
Jiao Liu
Northeast Normal University
Jiaqi Hu
Northeast Normal University
Hanxi Wang
NENU: Northeast Normal University
Lianxi Sheng
NENU: Northeast Normal University
Xiaoliang Dong
Panhu Park,
Xiaodan Jiang
Nanhu Park,

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Abstract

Aquatic plants have attracted wide attention because of their low cost and high level of resource utilization. In order to study the effects of emergent and submerged plants on the purification of different concentrations of wastewater, two common aquatic plants found in Northeast China, *Iris ensata* Thunb. and *Potamogeton malaianus* Miq., were selected Under static conditions, nitrogen and phosphorus removal from simulated wastewater with different concentrations (high, medium and low) and lake samples of Nanhu Park, Changchun, Jilin Province, China, were studied. The results showed that the removal rate of total nitrogen (TN) in medium- and high-pollutant concentration water samples and total phosphorus (TP) in medium- and low-pollutant concentration water with *I. ensata* reached more than 75%. The removal rate of TN in the medium-pollutant concentration water with *P. malaianus* reached 71.4%, while the removal efficiency of TN and TP in the low-pollutant concentration water was higher than 80%. It is more advantageous to use plants to purify high-pollutant concentration water after further purification. The purification plants suitable for medium-pollutant concentration water are limited, but under low-pollutant concentration water conditions, there are more diverse options regarding the choice of wastewater purification plants. In the Nanhu lake samples, *I. ensata* had the highest removal rates of TN (80.38%), and TP (85.62%). This study shows that both *I. ensata* and *P. malaianus* can be used as aquatic plants to restore the water quality of urban lakes. A reasonable combination of different plants for addressing different pollutants is more beneficial to improve the purification effect. This research provides an important basis for the phytoremediation and treatment of urban domestic wastewater and urban surface water bodies in northern China.

Introduction

Water pollution is one of the most important environmental problems faced by humans, and it directly affects human production and life (Lu et al. 2019). Due to the limitation of water treatment technology and the lack of environmental management, domestic wastewater or greywater containing large amounts of nitrogen, phosphorus, sulphur and harmful pathogen is directly discharged into surface water bodies, causing serious eutrophication (Moeder et al. 2017; Wang et al. 2017; Liu et al. 2020). Eutrophication causes algal blooms, hypoxia, and degradation of freshwater ecosystems, directly endangering human health (Gao et al. 2014; Yu et al. 2016). Therefore, it is of great importance to adopt efficient, low-cost and reliable technical methods to remove nitrogen and phosphorus pollution from wastewater (Xin et al. 2012; Sun et al. 2019). Current water treatment methods include physical, chemical, and biological methods. The ecological treatment of wastewater is an important method of biological method. Ecological treatment methods have received widespread attention due to their reliability and relatively low cost (Valipour et al. 2014; He et al. 2019).

Ecological treatment methods mainly include constructed wetlands (CWs), ecological floating beds (EFBs), ecological ponds (ecological ditch) and biological filters. The high purification efficiency of CWs and EFBs has driven their wide use (Arheimer and Pers 2017; Li et al. 2019; Wang et al. al. 2020a). The purification of pollutants by CWs or EFBs is mainly accomplished through plant absorption, matrix adsorption, matrix ion exchange and microbial decomposition (Wang et al. 2020c; Gao et al. 2017). The triple synergy of the processes enacted by these systems' physical matrices, plants, and microorganisms achieves the purification of wastewater (Ilyas and Masih 2018; Hernández-Crespo et al. 2017; Wang et al. 2018a). Plants not only directly absorb pollutants, but also promote the growth and reproduction of microorganisms, and improve the decomposition of pollutants by microorganisms (Hu et al. 2016; Vymazal and Kröpfelová 2011; Wang et al. 2020b). Whether in CWs or EFBs, plants play an important role in the purification of pollutants in wastewater treatment systems.

Plants play an important role in nutrient removal (Wang et al. 2012; Gao et al. 2014). There are some differences in the purification of pollutants by different plants. It is important to select aquatic plants with strong purification abilities for use in CWs and EFBs. Aquatic plants used in CWs or EFBs include emergent plants, floating aquatic plants and submerged plants. Emergent plants have well-developed roots and purify pollutants mainly through root absorption (Zhou et al. 2019). Floating aquatic plants can purify pollutants through absorption of diameter and root system (Lin et al. 2019). Submerged plants can purify pollutants through absorption of leaves, diameters and roots (Yang et al. 2020). Emergent plants, floating aquatic plants and submerged plants all have the ability to adsorb pollutants, and different emergent plants, floating plants or submerged plants also have different purification effects (van Zuidam et al. 2012; Christiansen et al. 2016; Li et al. 2018). Wetland plants can absorb relatively large amounts of trace elements from water and sediments due to their well-developed root system, tolerance to toxic substances and high adsorption of pollutants (Bonanno et al. 2018). Wetland plants can absorb nutrients in wastewater through their roots, stems, and leaves to inhibit the growth of algae. The removal of nitrogen and phosphorus by submerged plants and emergent plants is stronger than that among other wetland plants (Yan et al. 2018; Spangler et al. 2019a; Lu et al. 2010). A comparative study found that the removal of nitrogen and phosphorus in a system with plants was better than that without plants (Fraser et al. 2004). When water spinach and glutinous rice are used as plants in hydroponic purification systems, the removal rate of total nitrogen (TN) and total phosphorous (TP) in the water is above 75%, with the removal rate of TP by water spinach exceeding 90% (Sun et al. 2017). The use of plants for purification aids in realizing the removal of pollutants while maintaining economic value. Studies have found that plant diversity and species richness are important factors that affect the removal of pollutants by plants (Dai et al. 2014; Zeng et al. 2017). Several combinations of wetland plants, such as *Iris minutoaurea*, *Acorus calamus* L. and *cattail*, can significantly increase the removal rates of TN and TP in wastewater (Zhu et al. 2017). Plants have good removal effects on nitrogen, phosphorus and heavy metals (Xu et al. 2017). At present, much research exists regarding the purification of wastewater by artificial wetland plants, whereas plants within EFBs have been less studied in relation to water purification. In particular, research on the differences in the purification of different pollutants by different types of plants is relatively scarce. Different types of plants have different ability to purify pollutants because of their own growth characteristics, growth cycle, root type and pollution tolerance. Therefore, it is necessary to study the purification of different pollutants by different plants.

In the selection of aquatic plants, the characteristics of plant type, local species and wastewater purification effect should be fully considered. Both *Iris ensata* Thunb and *Potamogeton malaianus* Miq. are local widespread aquatic plants. *I. ensata* could effectively remove TN and TP from wastewater

(Spangler et al. 2019b). *I. ensata* has a good purification effect on eutrophic water (Yuan et al. 2018). *P. malaianus* had a high removal rate of TN (Yan et al. 2018). However, the purification of pollutants by these two aquatic plants is lack of further research. In order to further study the purification effect of emergent plants and submerged plants on pollutants, *I. ensata* and *P. malaianus* plants with wide distribution, good landscape effect, strong environmental adaptability and well-developed root system were taken as examples. The main objectives were (1) to further explore the ability of different aquatic plants to remove nitrogen and phosphorus in wastewater, (2) to analyse the differences in the purification of wastewater with varying nutrient concentrations by the same plant, and (3) to analyse the purification of pollutants by different wetland plants to further elucidate the pollutant purification mechanism of plants.

Methods And Materials

2.1 Materials

Under different concentrations of TN and TP, the purification effects of emergent plants and submerged plants are different (Wei et al. 2012). *I. ensata* is the representative of emergent plants in temperate zone, and its ornamental value is very high (Tikhomirova 2017). *P. malaianus* has the characteristics of both floating and submerged plants, and it has ornamental value and can be used as animal food (Liu et al. 2021). At present, there is a lack of research on the purification of TN and TP by these two aquatic plants. These two plants are selected for water purification experiment, which is representative.

Two aquatic plants (*I. ensata* and *P. malaianus*) were selected for the experiment, and the height and growth of these species were essentially the same. The plant height of adult, vegetative-stage *I. ensata* is approximately 30 cm, and that of *P. malaianus* is about 15 cm. Before the experiment, the plants were washed with distilled water three times, and then transplanted into 3 L glass containers. The plants were pre-cultured in a greenhouse with natural light and no rain for 15 days. The simulated wastewater was prepared according to the national surface water environmental quality class V standard (China's Standard No: GB3838-2002) and the second-class standard of the national discharge standard of pollutants for urban sewage treatment plants (China's Standard No: GB18918-2002). Before carrying out this experiment, the author investigated the existing city tail water quality. The concentration range of TN and TP was set according to the water quality standard of city tail water and city surface eutrophication water. In order to make the experimental water quality closer to the actual water quality, not only make the laboratory water distribution consistent with the city tail water, but also collect the lake eutrophic water. The concentration gradient of TN was as follows: high (30 $mg{\cdot}L^{-1}$), medium (15 $mg{\cdot}L^{-1}$) and low (2.0 $mg{\cdot}L^{-1}$), and the concentration gradient of TP was as follows: high (8 $mg{\cdot}L^{-1}$), medium (4 $mg{\cdot}L^{-1}$) and low (0.4 $mg{\cdot}L^{-1}$). The specific concentrations were measured after configuration. In addition to the simulated wastewater, water samples from Nanhu Park Lake, a typical lake in the urban area of Changchun City, Jilin Province, China were used in the plant purification experiment. The water samples were collected in May. The location is shown in Fig. 1.

2.2 Experimental design

The experimental sampling period in the outdoor was from March to May 2019, and this period is the season of relatively poor water quality. The experimental location was the greenhouse of the Northeast Normal University School of Environment, with a temperature of 25 degrees. The two aquatic plants were transplanted from Yangmu River in Liaoyuan city to indoor cultivation. The soilless cultivation of aquatic plant was used to purify the wastewater. After pre-culturing, *I. ensata* and *P. malaianus* grew well and were placed in glass containers. In order to make the indoor model experiment consistent with the outdoor, the indoor prepared water is the concentration range of city tail water discharge, and the outdoor lake water is used for indoor experiment simulation. The results can be used as an important reference for the purification of city tail water, rivers and lakes. This study focuses on providing an important reference for solving the problem of water eutrophication. Therefore, only the purification of TN and TP by aquatic plants was studied.

Before the experiment, the water quality index of the experimental simulated wastewater and the water samples of Nanhu Park Lake were measured. The experimental simulated wastewater indices of the three concentration levels were as follows: high-pollutant concentration water concentration (TN 29.89 $mg{\cdot}L^{-1}$, TP 7.87 $mg{\cdot}L^{-1}$), medium-pollutant concentration water (TN 15.43 $mg{\cdot}L^{-1}$, TP 3.92 $mg{\cdot}L^{-1}$), and low-pollutant concentration water (TN 2.06 $mg{\cdot}L^{-1}$, TN 0.43 $mg{\cdot}L^{-1}$). The TN concentration of the Nanhu Park Lake water sample was 9.02 $mg{\cdot}L^{-1}$, and the TP concentration was 1.46 $mg{\cdot}L^{-1}$. A total of 12 experiments were designed, and the detailed grouping situations are shown in Table 1.

Table 1 Initial water quality in each experimental group

Group	Plant	Wastewater	TN ($mg \cdot L^{-1}$)	TP ($mg \cdot L^{-1}$)	Group	Plant	Wastewater	TN ($mg \cdot L^{-1}$)	TP ($mg \cdot L^{-1}$)
I_1	Blank control	High-pollutant concentration	29.89±0.25	7.87±0.11	III_1	Blank control	Low-pollutant concentration	2.06±0.02	0.43±0.01
I_2	*I. ensata*				III_2	*I. ensata*			
I_3	*P. malaianus*				III_3	*P. malaianus*			
II_1	Blank control	Medium-pollutant concentration	15.43±0.21	3.92±0.07	IV_1	Blank control	Nanhu Park	9.02±0.12	1.46±0.03
II_2	*I. ensata*				IV_2	*I. ensata*			
II_3	*P. malaianus*				IV_3	*P. malaianus*			

2.3 Water sample collection and analysis

Water samples were collected every 6 days. In order to reduce experimental errors, samples were taken in the same order at 9:00 in the morning. The collected water samples were placed into plastic bottles that were moistened with the water samples of the system. After being marked, the samples were acidified and fixed, and finally placed in a refrigerator at 4 °C for 72 hours. TN in the wastewater was determined by potassium persulfate oxidation ultraviolet spectrophotometry, and TP was determined by ammonium molybdate spectrophotometry. The purification efficiency of plants for nitrogen and phosphorus in water is calculated as shown in formula (1).

$$R=(C_{in}-C_{eff})/C_{in}\times 100\% \qquad (1)$$

where R represents the purification efficiency, and C_{in} and C_{eff} represent the total pollutant concentrations of the water in and out of the system, respectively.

The biomass and chlorophyll content of plants were measured before and after the water purification experiment. Chlorophyll a (Chl.a) and chlorophyll b (Chl.b) were determined by acetone extraction method.

Results

3.1 Concentration changes of TN and TP in water

The concentration changes of TN and TP in the wastewater under different conditions are shown in Fig. 2. The removal of pollutants differed according to the initial nitrogen and phosphorus concentrations and the plant treatment of each experimental group. Except for the I_3 experimental group with the high-pollutant concentration water, where the concentration of TP showed an upward trend, the nitrogen and phosphorus concentrations in the other experimental groups showed gradually decreasing trends. It can be seen from Fig. 2(a-c) that the purification of TN in the wastewater with *I. ensata* is higher than that of the blank control group. Among the plant groups, *I. ensata* has the highest nitrogen removal rate in the medium-pollutant concentration water, while the purification of nitrogen in low-pollutant concentration water is the weakest. In the experimental groups planted with *P. malaianus*, except for those with high-pollutant concentration water, the purification of TN was higher than that of the blank control group, and the highest purification efficiency was shown in the low-pollutant concentration water.

As shown in Fig. 2 (d-f), the TP concentration of the water in the experimental groups planted with *I. ensata* showed an overall downward trend, except for the high-pollutant concentration water experimental group (I_2), for which TP increased slightly during the later part of the experimental period before decreasing. The concentration of TP in the high-pollutant concentration water experimental group (I_3) planted with *P. malaianus* increased, and the purification efficiency of *P. malaianus* was also lower in the medium-pollutant concentration water experimental group (II_3). In low-pollutant concentration water, *P. malaianus* showed better purification ability, as the removal rates of phosphorus were higher in all experimental groups.

The concentration changes of nitrogen and phosphorus in the water of Nanhu Park Lake are shown in Fig. 3. It can be seen from the figure that the concentrations of TN and TP in all experimental groups show a gradually decreasing trend, and the removal capacity of nitrogen and phosphorus in the experimental groups with plants is stronger than that of the blank control group. The removal effect of TN is as follows: *I. ensata* (IV_2) > *P. malaianus* (IV_3) > blank control group (IV_1). The removal effect of TP is as follows: *P. malaianus* (IV_3) > *I. ensata* (IV_2) > blank control group (IV_1).

3.2 TN and TP removal rate

By measuring the concentration of nitrogen and phosphorus in each water sample, we analysed the nutrient removal capacity of each system. The removal rates of TN and TP in each experimental group are shown in Fig. 4. There are significant differences in the removal efficiency of nitrogen and phosphorus across groups and treatments. The removal rates of TN in high, medium- and low-pollutant concentration water with *I. ensata* are 75.78%, 80.69% and 47.57%, respectively, which were higher than those of the corresponding control group. However, the removal rate of TN in the low-pollutant concentration water treatment is much lower than those of the other treatments. The removal rates of TN in high, medium- and low-pollutant concentration water by *P. malaianus* are 23.45%, 71.74% and 83.98%, respectively. The experiment using Nanhu Park Lake water showed TN removal rates in the following order: *I. ensata* (80.38%) > *P. malaianus* (78.05%) > blank control group (42.24%).

The removal rates of TP in each experimental group are significantly different from those of TN. The removal rates of TP in high, medium- and low-pollutant concentration water with *I. ensata* are 36.59%, 75.26% and 79.07%, respectively. The removal rate of the high-pollutant concentration water treatment is lower than that of the blank control group (50.70%). *I. ensata* shows a strong removal effect on TN and TP in medium-pollutant concentration water. In the high-pollutant concentration water treatment, the concentration of TP in the experimental group with *P. malaianus* shows an increase, from 7.87 $mg \cdot L^{-1}$ at the initial stage to 13.87 $mg \cdot L^{-1}$ at the end. The removal rate of TP in the medium-pollutant concentration water treatment with *P. malaianus* experimental group is also much lower than that in the low-pollutant concentration water treatment, and even much lower than that in the Blank control group. However, the plant shows a very high TP removal rate in the low-pollutant concentration water treatment. The removal rates of TP in the Nanhu Lake water experiment show the following order: *P. malaianus* (85.62%) > *I. ensata* (76.03%) > Blank control group (49.32%). Similarly, the removal rates of TP in the plant experimental groups are much higher than those of the blank control group.

3.3 Biomass and chlorophyll content of plants

Plant biomass and chlorophyll content can be used to characterize the growth of plants. The biomass and Chl.a+b content of each experimental group increased in varying degrees before and after the experiment, and the increase of *I. ensata* was significantly higher than that of *P. malaianus* (Table 2). After the experiment, the Chl.a/b ratio of *I. ensata* was significantly higher than that of *P. malaianus*.

Table 2 Biomass and chlorophyll content of plants

Plant	Group	Biomass (g)		Chl.a+b (mg/g)		Chl.a/b	
		BE	AE	BE	AE	BE	AE
I. ensata	I_2	50.62	75.62	0.67±0.13	6.25±0.37	2.82±0.48	5.15±0.34
	II_2	50.22	73.69	0.67±0.13	6.00±0.30	2.82±0.48	4.52±0.95
	III_2	50.76	65.89	0.67±0.13	6.14±042	2.82±0.48	5.13±1.19
	IV_2	50.45	67.23	0.67±0.13	6.17±0.44	2.82±0.48	4.16±1.15
P. malaianus	I_3	50.45	52.52	0.78±0.23	1.78±0.23	2.40±0.05	2.24±0.08
	II_3	50.26	56.57	0.78±0.23	2.38±0.34	2.40±0.05	2.65±0.18
	III_3	50.02	60.34	0.78±0.23	3.56±0.42	2.40±0.05	3.02±0.16
	IV_3	50.25	62.36	0.78±0.23	3.31±0.41	2.40±0.05	3.18±0.14

Note: BE is before the experiment, AE is after the experiment.

Table 3 Purification of TN and TP in wastewater by different aquatic plants

Water Quality	Time	Aquatic plant	TN		TP		Reference
	(d)		IR (mg/L)	RR (%)	IR (mg/L)	RR (%)	
Eutrophic water	42	*Oxalis triangularis*	3.74/6.22/11.22	68.32/59.73/72.90	0.37/0.39/0.86	89.57/83.76/86.54	Liu et al. (2011)
		Eichhornia crassipes (Mart.) Solms	3.74/6.22/11.22	68.45/71.49/71.53	0.37/0.39/0.86	90.11/85.07/91.46	
		P. stratiotes	3.74/6.22/11.22	89.05/90.18/73.50	0.37/0.39/0.86	93.58/97.72/96.65	
Eutrophic water	20	*J. effusus*	1.5/15	71.17/89.30	0.2/2	64.32/83.11	Wei et al. (2012)
		Nasturtium officinale R.Br.	1.5/15	75.28/58.48	0.2/2	93.00/53.18	
		Potamogeton crispus L.	1.5/15	69.01/72.47	0.2/2	86.32/74.83	
		Chara sp.	1.5/15	64.08/41.56	0.2/2	77.30/44.01	
Municipal wastewater	20	*Floscopa scandens*	24.4/43.8/68.5	62.16/72.97/60.76	2.5/4.2/8.3	80.00/91.43/80.48	Xie et al. (2019)
		Cyperus distans	24.4/43.8/68.5	91.75/85.55/82.66	2.5/4.2/8.3	88.80/93.57/83.32	
		Oenanthe linearis	24.4/43.8/68.5	57.59/64.50/48.10	2.5/4.2/8.3	70.80/68.33/64.82	
		Ranunculus sceleratus	24.4/43.8/68.5	38.52/54.27/37.26	2.5/4.2/8.3	54.62/65.00/52.30	
		Houttuynia cordata	24.4/43.8/68.5	85.50/83.52/85.08	2.5/4.2/8.3	66.40/53.62/35.87	
Eutrophic water	25	*A. calamus*	4.24/20.25/40.50	66.5/82.2/54.2	0.50/1.8/2.4	54.0/80.0/55.8	Xu et al. (2012)
		T. orientalis	4.24/20.25/40.50	64.1/77.0/74.3	0.50/1.8/2.4	44.0/60.5/61.6	
		Iris tectorum Maxim	4.24/20.25/40.50	69.0/88.8/69.9	0.50/1.8/2.4	70.0/87.7/77.5	
Simulation wastewater	15	*C. indica*	30/40/80	40.79/27.93/37.39	8/15/25	60.48/71.84/60.64	Cai et al. (2010)
		E. crassipes	30/40/80	47.72/34.15/40.42	8/15/25	70.11/80.15/69.58	
		Alternanthera philoxeroides (Mart.) Griseb.	30/40/80	14.39/35.68/33.22	8/15/25	63.74/75.74/67.22	
		Commelina communis	30/40/80	19.97/9.62/14.12	8/15/25	63.23/76.51/64.26	
		Cyperus alternifolius L.	30/40/80	38.62/37.44/28.07	8/15/25	54.47/77.86/68.42	
		Polygonum longisetum	30/40/80	22.61/19.13/20.58	8/15/25	50.86/72.18/65.46	
		Nelumbo SP	30/40/80	48.75/38.73/15.15	8/15/25	62.37/75.91/67.12	
		Zizania latifolia	30/40/80	40.68/52.23/17.78	8/15/25	63.57/71.57/59.64	
Eutrophic water	28	*P. orientale*	15/60	56.41/95.49	1/4	83.7/88.95	Yu et al. (2019)
		J. effusus	15/60	70.24/94.39	1/4	52.32/70.12	
		I. pseudacorus	15/60	50.49/93.29	1/4	91.05/92.09	
		P. australis	15/60	23.05/62.79	1/4	29.3/90.0	
		Iris sanguinea	15/60	81.22/92.20	1/4	83.72/84.76	
		T. orientalis	15/60	50.49/94.39	1/4	56.51/70.12	
Eutrophic water	28	*I. ensata*	2.06/15.43/29.89	47.57/80.69/75.78	0.43/3.92/7.87	79.07/75.26/36.59	This research
		P. malaianus	2.06/15.43/29.89	83.98/71.74/23.45	0.43/3.92/7.87	88.37/10.97/-76.24	

Note: IR is initial concentration, RR is removal rate, and the RRs in the table are mean value.

Table 4 Tolerance range of aquatic plants to nitrogen and phosphorus (Fan et al. 2017; Lin et al. 2016; Liu et al. 2008)

Aquatic plant	TN tolerance range ($mg\cdot L^{-1}$)	TP tolerance range ($mg\cdot L^{-1}$)
Iris wilsonii C. H. Wright	0-34 (not under duress)	0-4.5 (not under duress)
Vallisneria denseserrulata (Makino) Makino	0-4	0-0.4
Vallisneria natans (Lour.) Hara	0-4	0-0.4
Potamogeton wrightii Morong	0-2.18	0-0.5

Discussion

4.1 The effect of plants on water purification

According to the 2019 China Ecological Environment Bulletin, among the 107 lakes (reservoirs) monitored for water quality, oligotrophic status was found in 9.3%, mesotrophic status in 62.6%, mild eutrophication status in 22.4%, and moderate eutrophication status in 5.6%. Livestock and poultry manure, domestic garbage and domestic wastewater discharge are important factors in water pollution (Wang et al. 2018b, Wang et al. 2015a, Wang et al. 2018c). In particular, high loads of N and P can cause severe eutrophication of water bodies (Beusen et al. 2019; Aleksandra 2019). Phytoremediation technology is considered to be a promising method to address this issue (Yu et al. 2019). Plants absorb nutrients such as nitrogen and phosphorus through growth, and at the same time promote their own growth, so as to achieve the purpose of purifying water bodies (Vymazal 2013). Because different plants have different growth capabilities, root types, and nitrogen and phosphorus accumulation capabilities, they differ in their purification of wastewater (Zhu et al. 2011; Samal et al. 2017; Deane et al. 2018).

Aquatic plants can use their roots to absorb any form of soluble N and most forms of P from the wastewater. Aquatic plants transport oxygen to the roots through photosynthesis, and form an oxidative microenvironment in the root area, which further promotes nitrification (Li et al. 2020). In addition, the surface area of plant roots provides a place for microorganisms to attach and creates a microenvironment for the growth of various microorganisms (Chen et al. 2015; Li et al. 2020). Generally, the more developed the root system, the better the plant can treat wastewater. Wetland plants such as *Phragmites australis*, *Typha orientalis* Presl, *Iris pseudacorus* L., *I. ensata* and *Canna indica* L. are widely used because of their good purification effects (Choudhury et al. 2019). In particular, *I. pseudacorus* and *I. ensata*, which belong to the Iris family, show strong resistance to pollution and are widely used due to their adaptability to the environment, light and humidity tolerance and developed root systems. At present, there are many studies on these plants as CWs plants, and the purification effect is obvious (Li et al. 2021; Zhang et al. 2020; Chance et al. 2020). As an ecological treatment method of surface water, EFB should not only consider the purification capacity of plant, but also consider the landscape effect. Since emergent plants and submerged plants are distributed in different parts of water bodies, their combination not only improves water purification, but also has an obvious effect of the sense of landscape. Therefore, both emergent plants and submerged plants are important to research for use in EFBs. In this experiment, we used *I. ensata* and *P. malaianus*, and both emergent plants and submerged plants were taken into consideration.

Judging from the change in TN concentration, *I. ensata* and *P. malaianus* can remove nitrogen from wastewater, but the removal effect of the two plants is very different, even under the same concentration treatment. In the high-pollutant concentration water treatment, the TN removal rate of *I. ensata* increased significantly in the first 12 days of the experiment, reached more than 55% on the 12th day, and increased slowly after the 12th day. The absorption of nitrogen by *I. ensata* is mainly concentrated in the early stage, and is gradually reduced in the later period due to the slow growth of the plant (Yuan et al. 2018; Peng et al. 2020). In the high-pollutant concentration water treatment, the nitrogen removal of *P. malaianus* gradually stabilized on the sixth day, increased slightly by the twelfth day, and decreased in the later period. The *P. malaianus* had a low demand for nitrogen during growth (Liu et al. 2016). The nitrogen purification time of aquatic plants is related to the growth demand of plants (Su et al. 2019). The growth of *I. ensata* has a large demand for nitrogen, a long removal cycle and a high removal rate.

Under the conditions of medium-pollutant concentration water, the removal trend of *I. ensata* for TN was the same as that of the high-pollutant concentration water group, but its removal rate reached 51% on the sixth day, maintained an increasing trend, and was about 80% at the end of the experiment. This may be due to an insufficient nutrient supply under this pollutant concentration water treatment, and an excess supply under the high-pollutant concentration water treatment, so the purification effect of medium-pollutant concentration water environmental conditions is best (Dai and Li 2016). Compared with that of high-pollutant concentration water, the removal rate of TN under medium-pollutant concentration water conditions gradually increased, and the purification effect under these conditions was significantly better. Under low-pollutant concentration water treatment conditions, the nitrogen removal ability of *I. ensata* was much lower than that of the medium- and high-pollutant concentration water experimental groups. Although the removal rate gradually increased, the trend was relatively slow, which may be because the low concentration of nitrogen and phosphorus could not meet the needs of plant growth. Under low-pollutant concentration water conditions, *P. malaianus* showed a better removal effect (Zhou et al. 2018). The above results also show that the photosynthesis of submerged plants is significantly less than that of emergent plants, and the nitrogen demand of submerged plants is significantly smaller (Short et al. 2016). Compared with that of the control group, the removal rate of *I. ensata* was higher. The difference in purification was most obvious under medium-pollutant concentration water conditions, followed by high-pollutant concentration water conditions, which indicated that *I. ensata* had a higher demand for TN. Compared with that of the control group, the removal rate of TN in planted treatment with *P. malaianus* under low-pollutant concentration water conditions was significantly higher, while under high-pollutant concentration water conditions it was lower. Across the conditions of low, medium- and high-pollutant concentration water, the removal rate of TN showed a gradual decrease, which indicates that TN was released under the high-concentration simulated wastewater conditions. The main reason for this is that under high-pollutant concentration water conditions, plants grow and renew quickly, resulting in the release of TN from dead plant residues (Wang et al. 2011; Sun et al. 2012).

In terms of the change in TP concentration, *I. ensata* and *P. malaianus* differed greatly from their removal of TN. Under high-pollutant concentration water conditions, the TP removal rate of *I. ensata* was lower. However, *P. malaianus* did not remove any TP, but instead increased the concentration of TP, presumably due to the release of residues of plant growth. It has been confirmed by the study of water purification in CWs that plant residues can lead to the concentration of pollutants increases (Wang et al. 2020a). Under medium-pollutant concentration water conditions, the TP removal rate of *I. ensata* and *P. malaianus* increased over time, but the removal rate of *I. ensata* was higher compared with that of *P. malaianus*. In the low-pollutant concentration water treatment, *I. ensata* and *P. malaianus* both showed better purification effects. The purification effect of *I. ensata* was higher than that of the control under the conditions of medium and low-pollutant concentration water, while the purifying effect of *P. malaianus* was higher than that of the control only under low-pollutant concentration water conditions. Under high-pollutant concentration water conditions, the purification effects of the two plants were lower than that of the control. This shows that *I. ensata* is more suitable for growth in medium-pollutant concentration water, while *P. malaianus* is more suitable for low-pollutant concentration water treatment. Wastewater with high concentration of TP is not suitable for direct purification by aquatic plants. Under the low concentration condition of TP, more plants can be selected for water purification. The combination of emergent plants and submerged plants can significantly improve the purification of TP in water (Chen et al. 2020).

As shown in Table 3, each aquatic plant can basically achieve the optimal removal effect of TN and TP in the range of 20-28 days. No matter it is emergent plant or submerged plant, the removal rates of TN and TP are different under different concentrations. In general, the TP removal rate of most aquatic plants decreased with the increase of TP concentration in wastewater, and which indicates that the demand of aquatic plants for TP is limited. Only a small number of aquatic plants (*Juncus effusus*, *P. orientale*, *I. pseudacorus* and *T. Orientalis*) increased the removal rate of TN in wastewater with the increase of TN concentration. The removal of TN by most aquatic plants has no correlation with the change of TN concentration in wastewater, and which indicates that the removal of total nitrogen in wastewater by most aquatic plants is affected by external conditions. The highest removal rate of TN (60 mg/L) by *P. orientale* was more than 95%, and the highest removal rate of TN (6.22 mg/L) by *Pistia stratiotes* L. was more than 97%. The *I. ensita* has advantages in treating high concentration TN wastewater, and *P. malaianus* has advantages in treating low concentration TN wastewater. The *I. ensata* and *P. malaianus* have advantages in treating low concentration TP wastewater. The research on the removal of TN and TP in water by multiple plant cultivation needs to be strengthened.

4.2 Effect of pollutant concentration on plants in water purification

Nitrogen and phosphorus are essential nutrient elements for plant growth. Suitable concentrations of nitrogen and phosphorus can promote plant growth. The low concentration of nitrogen and phosphorus in wastewater will lead to the nutrient deficiency of aquatic plants, and then affect the growth of aquatic plants. However, high concentrations of nitrogen and phosphorus also inhibit the growth of aquatic plants (Li et al. 2017). The growth of *P. crispus* in the low nutrient environment was better than that in the eutrophic state (Qian et al. 2014). The high nutrient concentration limits the growth of *P. crispus*. Under the low biomass condition of aquatic plants, the inhibitory effect of ammonia nitrogen on plant growth is more obvious (Markou et al. 2014). Different plants have different adsorption of nitrogen and phosphorus due to their specific characteristics. When nitrogen and phosphorus in water exceed plant growth requirements, a stress effect on the growth of the plant will occur, resulting in a decrease in water purification. In plants, the nutrient tolerance range is usually greater than that suitable for growth. The nutrient tolerance range differs according to plant species (Table 4).

In this study, the growth status of *I. ensata* (an emergent plant) in the presence of high-pollutant concentration water was better than in the low-pollutant concentration water group, while the growth status of *P. malaianus* (a submerged plant) in the presence of low-pollutant concentration water was better than in the high-pollutant concentration water group. High-pollutant concentration water provided sufficient nutrients for the growth of *I. ensata*, and it grew vigorously throughout the experiment. On the contrary, the growth of *P. malaianus* was inhibited by the high-pollutant concentration water. In particular, plant leaf withering increased with the concentration of pollutants. In the low-pollutant concentration water experimental group, the growth of *P. malaianus* was good, and the removal rates of nitrogen and phosphorus were high. The results showed that the nutrient content in the presence of high-pollutant concentration water exceeded the tolerance of *P. malaianus*. The removal rates of nitrogen and phosphorus in low-pollutant concentration water were relatively high, which indicated that the contents of nitrogen and phosphorus under these conditions are suitable for the growth of *P. malaianus*. The Chl.a/b ratio of *I. ensata* is significantly higher than that of *P. malaianus*, which indicated that the growth ability of *I. ensata* was higher than that of *P. malaianus* (Table 2). *I. ensata* has strong tolerance to high concentration of nitrogen and phosphorus. The Chl.a/b ratio of *P. malaianus* was significantly lower at high concentration, which indicated that *P. malaianus* was not suitable for growth at high concentration.

Compared with the background value, the removal rates of TN at various nutrient concentrations in the *I. ensata* groups were higher, while the removal rate of TP was only higher than the background value in the medium- and low-pollutant concentration water experimental groups. This indicated that the tolerance range of *I. ensata* to TN was greater than the experimental value (> 29.89 $mg \cdot L^{-1}$), while the tolerance range to TP was less than the experimental value (< 7.87 $mg \cdot L^{-1}$). The tolerance ranges of *I. ensata* to TP and TN was significantly lower than *E. crassipes*, I*ris sibirica* L., *I. pseudacorus*, *Thalia dealbata* Fraser, *Oenanthe javanica* (Blume) DC and *T. orientalis* (Feng et al. 2020; Xu et al. 2012). The removal rates of TN and TP by *P. malaianus* were only higher than the background value under the low-pollutant concentration water treatment, and this indicated that the tolerance range of *P. malaianus* to TN and TP was less than the experimental value (< 2.06 $mg \cdot L^{-1}$ and < 0.43 $mg \cdot L^{-1}$). The purification effect of *Chara inconnexa* in high eutrophic water (TN = 15, TP = 2) was lower than that in low eutrophic water (TN = 1.5, TP = 0.2), which showed high concentration inhibition (Wei et al. 2012). On the whole, the tolerance concentration of emergent plants to pollutants is higher than that of submerged plants, which may be related to the fact that the tolerance of submerged plants leaves to pollutants is lower than that of emergent plant roots. Because the demand of aquatic plants for nitrogen is higher than that for phosphorus (Xing et al. 2020), in addition, the rapid release of phosphorus from roots and leaves to the water during the decay process also reduces the reduction of phosphorus concentration in polluted water (Wang et al. 2011). Therefore, the tolerance range of aquatic plants to TN is higher than that to TP. These results provide an important basis for plant selection for wastewater treatment, but it is recommended that further research be conducted on the nutrient tolerance ranges of other plant species.

4.3 Economic analysis

I. ensata and *P. malaianus* not only have the function of water purification, but also have high economic value. The economic value of *I. ensata* and *P. malaianus* was different. *I. ensata* has tender leaves, which is the food of goats (Zhao et al. 2020). *I. ensata* also has high ornamental value and is favored by more citizens (Zhao et al. 2008; Zhu et al. 2013). After being harvested, *P. malaianus* can be used as food for livestock and fish. In the indoor water ornamental culture, *P. malaianus* also has ornamental value. The ornamental value of *I. ensata* is higher than that of *P. malaianus*, and *P. malaianus* is more valuable as food than *I. ensata*. *I. ensata* and *P. malaianus* can also be used as raw materials for biogas fermentation (Zhou et al. 2016). *I. ensata* and *P. malaianus* also have good carbon fixation (Xiong et al. 2018; Wang et al. 2015b). Further studies are needed on the economy of *I. ensata* and *P. malaianus*.

Conclusions

From the study of the removal of nitrogen and phosphorus in wastewater with two common aquatic plants in Northeast China, the main conclusions are as follows:

(1) *I. ensata* has a high removal efficiency of TN in medium- and high-pollutant concentration water, and of TP in medium- and low-pollutant concentration water, both reaching more than 75%.

(2) The growth of *P. malaianus* was inhibited by stress in high-pollutant concentration water. The removal rate of TN was 71.4% in medium-pollutant concentration water conditions, while the removal efficiency of TN and TP in low-pollutant concentration water conditions was higher than 80%.

(3) In the water samples of South Lake, *I. ensata* had the highest removal rate of TN (80.38%), while *P. malaianus* had the highest removal rate of TP (85.62%), indicating that both plants can be used to improve the water quality of the lake.

(4) From the perspective of wastewater purification, it is more advantageous to use plants to purify high-pollutant concentration water after further purification. Under medium-pollutant concentration water conditions, the applicable purification plants are limited, while under low-pollutant concentration water conditions, the options for the selection of water purification plants are more numerous.

(5) A reasonable combination of plants for different pollutants is more beneficial to improve the purification effect. In addition, increasing in-depth studies of the tolerance ranges of different plants are needed to improve the selection of plants for wastewater purification.

Declarations

Authors' contributions Jianling Xu conceptualized and designed the study, Jiao Liu drafted the initial manuscript and analyzed the data, Jiaqi Hu carried out the experiment of this paper and analyzed the data, Hanxi Wang analyzed the data, reviewed and revised the manuscript, Lianxi Sheng carried out the initial analyses, reviewed and revised the manuscript, Xiaoliang Dong carried out the experiment of this paper and revised the manuscript, Xiaodan Jiang carried out the experiment of this paper and revised the manuscript. All authors approved the final manuscript.

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Availability of data and materials All data generated or analyzed during this study are included in this published paper.

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

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Figures

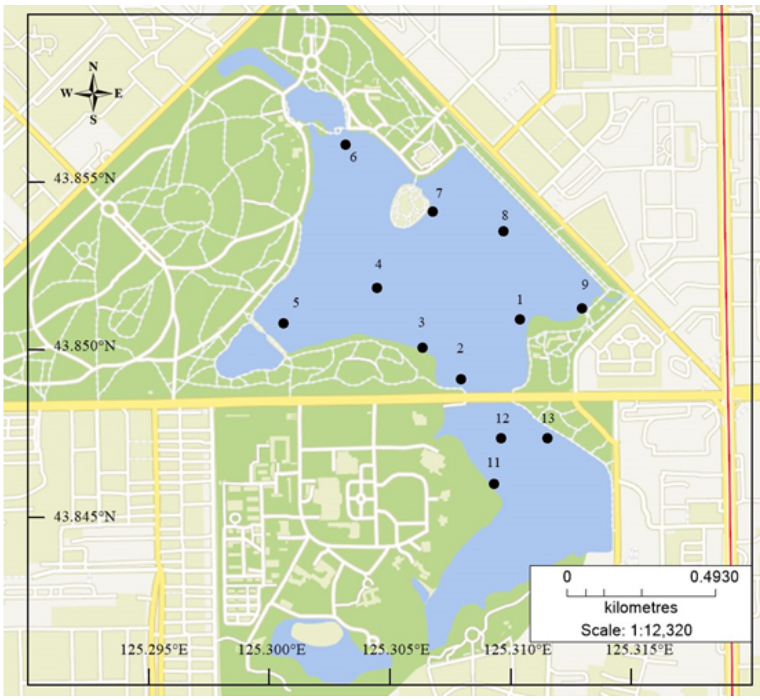
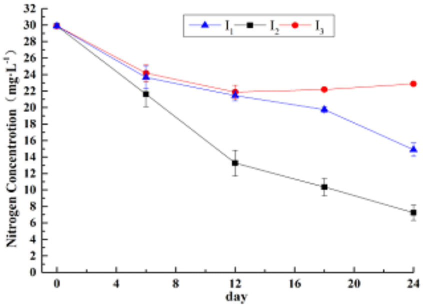
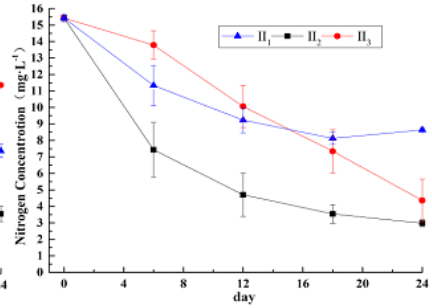


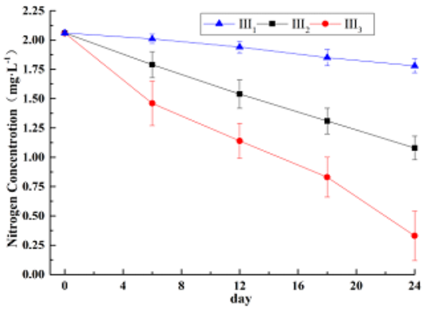
Figure 1

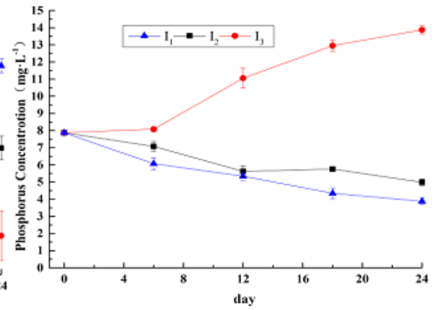
Location of sampling points in Nanhu Park Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



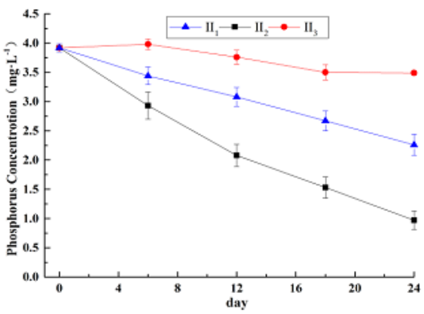


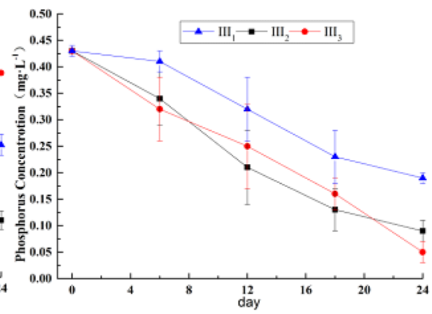
(a). TN in high-pollutant concentration water. (b). TN in medium-pollutant concentration water.





(c). TN in low-pollutant concentration water. (d). TP in high-pollutant concentration water.

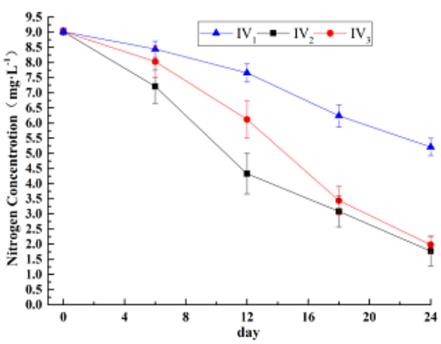




(e). TP in medium-pollutant concentration water. (f). TP in low-pollutant concentration water.

Figure 2

The concentration changes of TN and TP in simulated wastewater under different conditions



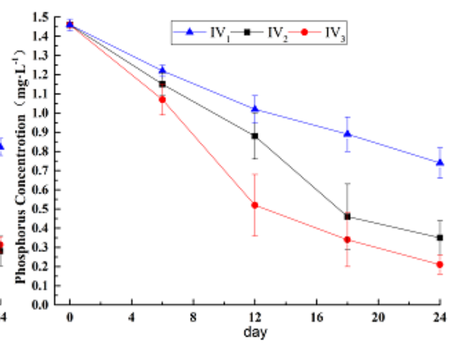


Figure 3

Concentration of TN and TP in water of Nanhu Park Lake

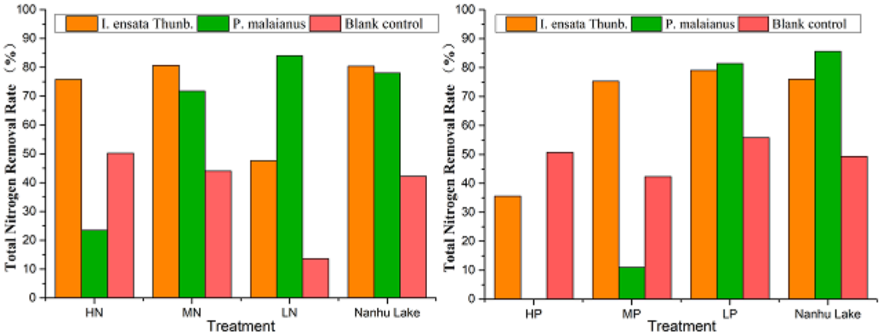


Figure 4

Removal rate of TN and TP across experimental treatments and groups