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Contaminant removal from low-concentration polluted river water by the bio-rack wetlands

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Abstract

The bio-rack is a new approach for treating low-concentration polluted river water in wetland systems. A comparative study of the efficiency of contaminant removal between four plant species in bio-rack wetlands and between a bio-rack system and control system was conducted on a small-scale (500 mm length × 400 mm width × 400 mm height) to evaluate the decontamination effects of four different wetland plants. There was generally a significant difference in the removal of total nitrogen (TN), ammonia nitrogen (NH_3-N) and total phosphorus (TP), but no significant difference in the removal of permanganate index (COD_{Mn}) between the bio-rack wetland and control system. Bio-rack wetland planted with *Thalia dealbata* had higher nutrient removal rates than wetlands planted with other species. Plant fine-root (root diameter $\leqslant$ 3 mm) biomass rather than total plant biomass was related to nutrient removal efficiency. The study suggested that the nutrient removal rates are influenced by plant species, and high fine-root biomass is an important factor in selecting highly effective wetland plants for a bio-rack system. According to the mass balance, the TN and TP removal were in the range of 61.03–73.27 g/m^2 and 4.14–5.20 g/m^2 in four bio-rack wetlands during the whole operational period. The N and P removal by plant uptake constituted 34.9%–43.81% of the mass N removal and 62.05%–74.81% of the mass P removal. The study showed that the nitrification/denitrification process and plant uptake process are major removal pathways for TN, while plant uptake is an effective removal pathway for TP.

Key words: bio-rack; constructed wetland; fine-root biomass; low-concentration polluted river water; plants; uptake

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Introduction

Constructed wetlands (CWs) are frequently used as an alternative efficient means of river water treatment because of their low energy requirements and convenient operation and maintenance (Jing et al., 2001a, 2001b; Jing and Lin, 2004; Lu, 2009a; Wu et al., 2011). Aquatic plants play an important role in removing nutrients in wetlands. Plants take up nutrients from wastewater and substrates (Yang et al., 2007; Sheng and Masaak, 2008), provide good conditions for physical filtration, prevent wetland systems from clogging, insulate the surface against frost during winter, and provide a large surface area for microbial growth (Wood, 1995; Brix, 1997; Tanner, 2001). In addition, as the roots and rhizomes of plants grow, they disturb and loosen the matrix, maintaining the stability of the hydraulic conductivity in the system (Tanner, 1996; Kivaisi, 2001; Matheson et al., 2002). Conversely, in conventional CWs, the planting density is so low that the functions of the plants are limited.

Bio-rack is a new approach in wetland systems for wastewater treatment. The plant density of approximately 150 plants per m^2 in bio-rack wetlands is notably higher than that in conventional CWs. Plants root zones were obviously increased, where physicochemical and biological processes, induced by the interaction of plants, microorganisms, and contaminations, took place (Valipour et al., 2009). However, the bio-rack system has only been applied for treating domestic wastewater, and little was known concerning the treating efficiency for low-concentration polluted river water by the bio-rack. Additionally, in the bio-rack system, the functions of plants were strengthened, which was beneficial for studying the relationship between plant characteristics and contaminant removal efficiency.

The study was constructed with four bio-rack wetlands with different plants and a control system. The main objectives of this study were: (1) to investigate the feasibility of treating low-concentration polluted river water using a bio-rack system, (2) to compare the potentials of four aquatic macrophytes for treating low-concentration polluted river water using a bio-rack system, and (3) to investigate

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the roles of different wetland plants with an emphasis on understanding the relationships between biomass and removal efficiency.

1 Materials and methods

1.1 Experimental system

The experiment was conducted in the research station at the Chinese Research Academy of Environment Sciences (31°24′18.54″N, 119°58′50.84″E) in Yixing, near Taihu Lake. The experimental system consisted of five small glass containers (500 mm length × 400 mm width × 400 mm height) with a working depth of 380 mm and a large glass container (1000 mm length × 800 mm width × 400 mm height) (Fig. 1). Twenty PVC pipes (400 mm height × 90 mm) were assembled as a rack within the four small containers. The pipes contained numerous perforations (20 mm diameter) to enable liquid transport. The selected plants including *Thalia dealbata*, *Acorus calamus*, *Zizania latifolia* and *Iris sibirica* of 40–60 cm in height were collected carefully near the pond and transported to the rack after flushing with top water. The bio-rack system was completely constructed. All of the species were selected because they are very common in subtropical China. Another small container with no plants was referred to as the control. In order to reduce the influence of the high death rate of plants resulting from human factors, two sets of four plants of similar fresh weight were selected at the beginning of the experiment. One set of about thirty plants per species was transported to the experimental systems, while the other was collected together for culture in a large glass container under the test conditions. The large glass container only cultured plants and samples were not measured. An inlet and outlet arrangement was constructed as per standard practice. Water was collected from the Hengtanghe River on a daily basis for experiments and performance evaluation. Water was pumped into a water tank and through the units using a constant flow pump with an equal flow loading in the six containers. Hydraulic loading was controlled at 0.24 $m^3/(m^2 \cdot day)$. The pH of the water ranged from 6.98 to 7.27, and the dissolved oxygen (DO) concentration ranged from 5.5 to 8.75 mg/L in the Hengtanghe River. The experiment was carried out from 1 June, 2010 to 21 December, 2010 for a period of 204 days, including 30 days for plant acclimation to the test conditions and 174 days for system operations. A freeze attributed to the low ambient temperature resulted in the experiment being completed on 21 December, 2010.

1.2 Samples and analysis

Water samples were collected from the inlet and outlet of each wetland five times per month (i.e., day 1 to 5) at 10:00 am. All of the samples were transported to the laboratory and analyzed immediately with standard methods (SEPA, 2002) for total nitrogen (TN), dissolved total nitrogen (DTN), ammonia nitrogen (NH_3-N), total phosphorus (TP), dissolved total phosphorus (DTP), soluble reactive phosphorus (SRP), and permanganate index (COD_{Mn}). The temperature, pH value and dissolved oxygen (DO) concentrations were noted during sampling. A Piccolo pH meter (sension^{TM}378, HACH Company, USA) was used to measure pH value. DO concentrations and temperature were determined using a Sension DO electrode (sension^{TM}156, HACH Company, USA). The plant height and root length were measured by the same person on a monthly basis. Three representative plants of four bio-rack systems were removed and dried in an oven at 70°C until constant weight during 1 July, 1 September and 1 December to

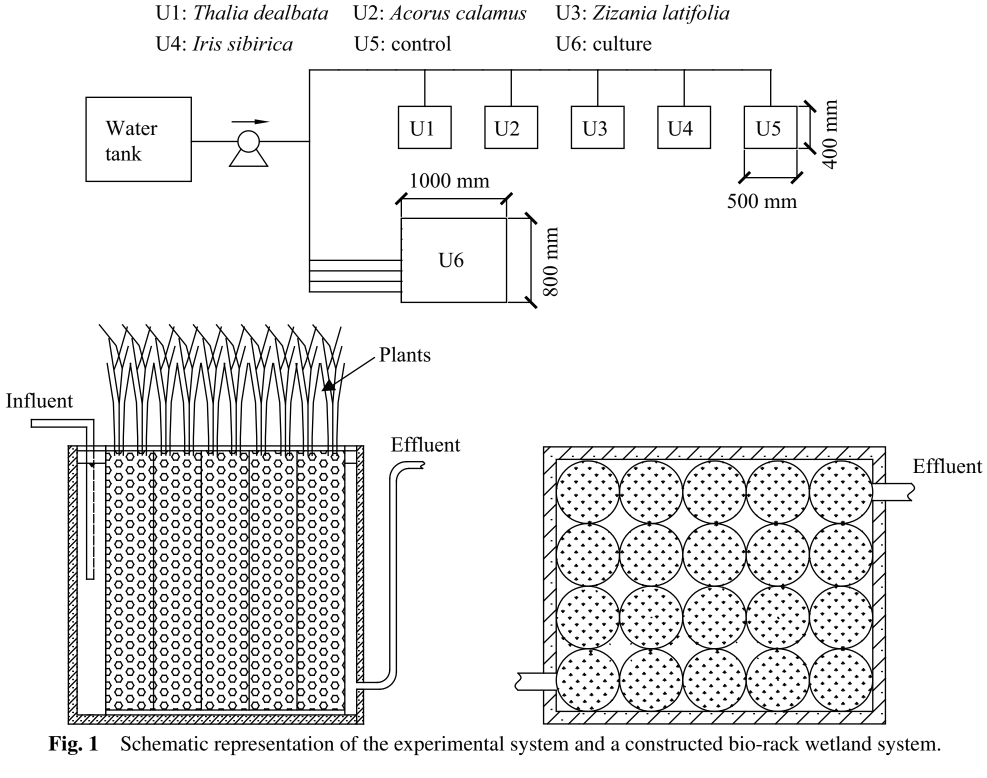

Fig. 1 Schematic representation of the experimental system and a constructed bio-rack wetland system.

calculate the fine-root biomass (root diameter ⩽ 3 mm) and total plant biomass. Missing plants removed from the experiment for measuring the biomass were replaced by cultured plants. When the experiment was complete, the bio-rack was removed from the experimental system, and the N and P contents of sediment were analyzed with standard methods (Nanjing Agricultural University, 2005). Analysis of variance (ANOVA) and multiple comparisons tests were used to analyze the data with SPSS version 13.0.

1.3 Mass removal and removal efficiency

Removal efficiency (E, %) and mass removal rate (R, g/(m^2·day)) were calculated for N and P according to Eqs. (1) and (2):

$$E = \frac{C_\mathrm{i}V_\mathrm{i} - C_\mathrm{e}V_\mathrm{e}}{C_\mathrm{i}V_\mathrm{i}} \times 100\% \qquad (1)$$

$$R = C_\mathrm{i}V_\mathrm{i} - C_\mathrm{e}V_\mathrm{e}/A \times \mathrm{HRT} \qquad (2)$$

where, C_i (mg/L) and C_e (mg/L) are the influent and effluent concentrations, respectively; V_i (L) and V_e (L) are the volume of the influent and effluent in liters fed and collected in the constructed microcosm wetlands, respectively; A (m^2) is the container area; HRT (hr) is the hydraulic retention time.

Total nutrient storage (S, g/m^2) in plants was estimated by Eq. (3):

$$S = \frac{B \times C}{A} \times 1000 \qquad (3)$$

where, B (g) is the average dry biomass, and C (mg/g) is the average nutrient concentration as percentage of dry weight. Total change in storage was calculated by subtracting the storage in July from the storage at the end of the experiment. The total mass removal of nutrients in the vegetated container was then compared to nutrient storage in the plants to determine the proportion of nutrient removal attributable to plant nutrient uptake.

2 Results

2.1 Removal of N, P, and COD$_\mathrm{Mn}$

Average influent TN concentrations varied from 1.69 to 5.41 mg/L, with an average of 3.05 mg/L, and had an increasing tendency with time. The average DTN and NH_3-N concentrations were 2.45 and 1.28 mg/L, respectively. Over 80% of the TN was in the form of DTN, and DTN and NH_3-N concentrations had tendencies similar to the TN concentration (Fig. 2). The average TN removal rates fluctuated widely by month in the four bio-rack wetlands (Fig. 3). Generally, the average TN removal rates tended to be high from July to October and low in November and December. The average removal rates of TN ranged from 40.79% to 78.07% in the four bio-rack wetlands, while from 15.2% to 32.24% in the control system. The bio-rack wetland vegetated by *T. dealbata* showed higher TN removal rates than the other wetlands, and lower TN removal rates were obtained in the *Z. latifolia* and *I. sibirica* systems. The average NH_3-N removal rates had tendencies similar to the removal rates of TN, but the highest NH_3-N removal rates were detected in November in the four bio-rack wetlands, while TN showed the highest rates in October. Average removal rates of NH_3-N ranged from 40.21% to 68.97% in the bio-rack systems, while they ranged from 9.67% to 41.84% in the control wetland. The bio-rack wetland vegetated with *T. dealbata* showed the highest NH_3-N removal rate, followed by *A. calamus*, *I. sibirica*, *Z. latifolia* and the control. The bio-rack wetlands had significantly higher TN and NH_3-N removal rates ($p <$ 0.01) than the control.

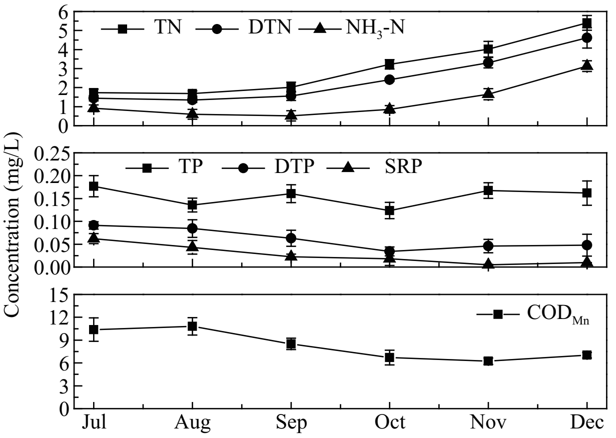

Fig. 2 Variations of the average influent concentration with month during the operational period. TN: total nitrogen; DTN: dissolved total nitrogen; NH_3-N: ammonia nitrogen; TP: total phosphorus; DTP: dissolved total phosphorus; SRP: soluble reactive phosphorus; COD$_\mathrm{Mn}$: permanganate index.

Average influent TP concentrations varied from 0.124 to 0.177 mg/L, with an average of 0.154 mg/L, and exhibited no significant monthly difference. The average influent DTP and SRP concentrations were 0.06 and 0.027 mg/L, respectively. More than 60% of the TP was in the form of particulate-P (PP), and DTP concentrations had a decreasing tendency with time (Fig. 2). Unlike N removal, high removal rates of TP were obtained consistently in the four bio-rack wetlands over the entire experiment period (Fig. 3). The removal rates of TP ranged from 54.24% to 86.08% in the four bio-rack wetlands, and from 46.27% to 70.62% in the control system. *T. dealbata* had the highest TP removal rate, followed by *A. calamus*, *I. sibirica*, *Z. latifolia* and the control. The bio-rack wetlands had significantly higher TP removal rate ($p < 0.05$) than the control.

The average influent COD$_\mathrm{Mn}$ concentrations varied from 6.22 to 10.79 mg/L, with an average of 8.27 mg/L, and were significantly higher in July and August than in other months (Fig. 2). The average removal rates of COD$_\mathrm{Mn}$ were low and unstable, ranging from 7% to 38.81% in the five bio-rack wetlands (Fig. 3), and there was no significant difference between the vegetated bio-rack wetlands and the control. The COD$_\mathrm{Mn}$ concentrations were sometimes higher in the effluent than in the influent, and this mostly occurred in the first month. The average removal rates were

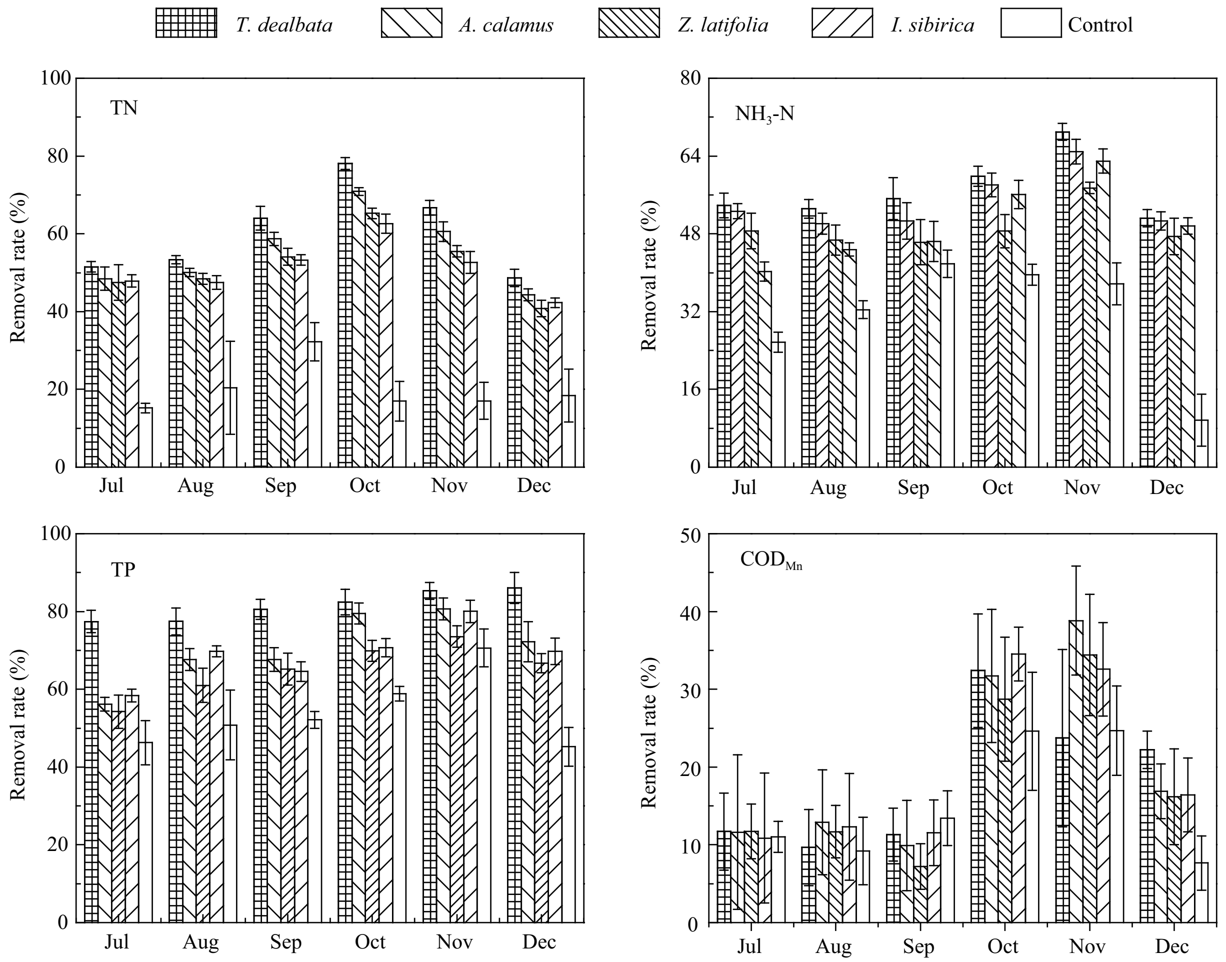

Fig. 3 Monthly average removal rates of total nitrogen (TN), ammonia nitrogen (NH_3-N), total phosphorus (TP), permanganate index (COD_{Mn}) by the control and bio-rack wetlands with different wetland plants.

significantly higher ($p < 0.01$) in Oct–Dec than in Jul–Sep.

2.2 Plant growth

During the acclimation period, all the plant species were established and started to grow. The results for plant establishment after plant acclimation were measured. The desired results were obtained for *T. dealbata*, *A. calamus, Z. latifolia* and *I. sibirica* in the bio-rack systems, and twenty-eight, twenty-nine, thirty and thirty plants were grown in those four systems, respectively.

Measurements of plant height and root length provided some insights into the growth patterns of the different wetland plants used in the study (Fig. 4). During the experiment, all the root lengths and plant heights for the four species had an increasing trend, but the growth was poor from November. In terms of height, *Z. latifolia* exhibited more growth and was larger than the other plant species, reaching a height of 151 cm. In terms of root length, *T. dealbata* exhibited more growth and was larger than the other plant species, reaching a length of 46 cm. *I. sibirica* had worse performance compared to the other plants; the root length and plant height were 20 and 70 cm, respectively. Most leaves wilted in November as both plant and root growth essentially ceased in the bio-rack systems, with the exception of *I. sibirica*. By the end of the experiment, the leaves of *I. sibirica* were still green, but plant height had not increased significantly since November.

Variations of fine-root biomass and total biomass in the bio-rack wetlands are shown in Table 1. Both fine-root biomass and total biomass in the bio-rack systems increased continually during sampling. *T. dealbata* had higher total plant and fine-root biomass than the other species, and the minimum total plant and fine-root biomass was obtained for *A. calamus* and *Z. latifolia*, respectively.

Table 1 Fine-root biomass (root diameter ⩽ 3 mm) and total biomass of the bio-rack systems vegetated with different plants

Species	Sampling time	Fine root biomass (g/m^2)	Total biomass (g/m^2)
T. dealbata	1 Jul	404.60 ± 45.68	2346.40 ± 105.96
	1 Sep	1033.67 ± 148.76	3427.20 ± 147.94
	1 Dec	1920.80 ± 174.86	5427.33 ± 220.57
A. calamus	1 Jul	149.83 ± 18.08	928.00 ± 51.60
	1 Sep	555.35 ± 24.72	1624.00 ± 89.384
	1 Dec	1034.33 ± 24.65	2450.00 ± 6377
Z. latifolia	1 Jul	164.50 ± 25.11	2370.00 ± 76.48
	1 Sep	293.50 ± 20.83	3252.00 ± 156.82
	1 Dec	440.00 ± 65.64	4301.00 ± 151.12
I. sibirica	1 Jul	101.00 ± 12.27	3489.50 ± 153.95
	1 Sep	289.15 ± 6.76	4269.00 ± 89.10
	1 Dec	503.00 ± 22.98	5380.00 ± 185.98

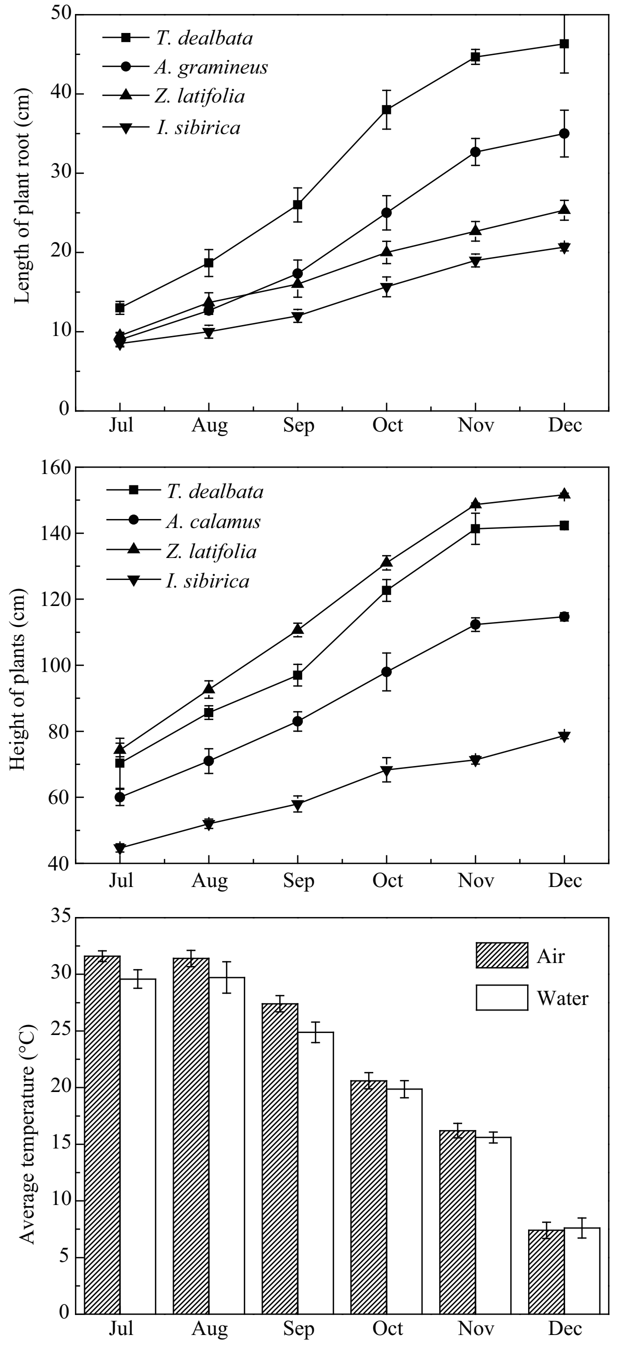

Fig. 4 Variation of root length and plant height air and water temperature during the operational period.

2.3 Correlation between biomass and contaminant removal efficiency

Correlation analysis was conducted to explore the relationship between biomass and removal efficiency. *T. dealbata* had larger fine-root biomass and this generally represented higher removal rates of nutrients. In contrast, *I. sibirica* and *Z. latifolia* produced smaller fine-root biomass and had lower removal rates, and the TN removal rates showed the best relationship with fine-root biomass (Table 2). The correlation was not significant between total biomass and nutrient removal rates. The COD_{Mn} removal rates had no significant relationship with biomass in the four bio-rack systems.

2.4 Nutrient mass balance in the bio-rack wetland

Analysis of total N and P mass balance was conducted for the bio-rack wetlands during the operational period (Table 3). TN removal in the bio-rack systems was 73.27 g/m^2 for the unit planted with *T. dealbata*, 67.04 g/m^2 for the unit planted with *A. calamus*, 62.29 g/m^2 for the unit planted with *Z. latifolia*, and 61.03 g/m^2 for the unit planted with *I. sibirica*. Accordingly, TP removal was 5.20, 4.48, 4.14 and 4.39 g/m^2, respectively.

By multiplying N and P concentrations and the whole biomass at the end of the experiment, the total net nutrient accumulation was 32.10 g N/m^2 and 3.89 g P/m^2 for *T. dealbata*, 26.63 g N/m^2 and 2.78 g P/m^2 for *A. calamus*, 24.70 g N/m^2 and 2.57 g P/m^2 for *Z. latifolia* and 21.3 g N/m^2 and 2.92 g P/m^2 for *I. sibirica*. Hence, comparing the plant uptake of N and P with the mass removal as recorded in planted containers during the operational period, the uptake of N and P by plants constituted 34.9%–43.81% of the mass N removal and 62.05%–74.81% of the mass P removal, respectively.

3 Discussion

The four species of plants grew well in microcosm containers under the same culture conditions when loaded with simulated polluted river water, demonstrating that the quality of low-concentration polluted river water can meet the growing requirements of high-density plantings. All of the plants increased rapidly from July to October due to the high temperature. At the end of the experiment, most plants started to decay and died off because the air temperature fell (Lu et al., 2010).

The present study indicated that over 50% of the TN and 60% of the TP were removed from the influent in the four bio-rack wetlands during the long-term operational period, demonstrating the feasibility for bio-rack wetland treating low-concentration polluted river water. These results are in agreement with findings from wetlands receiving polluted river water (Jing and Lin, 2004; He et al., 2007). Different efficiencies were obtained by the studied bio-rack wetlands, which indicated that removal rates were impacted by plant species. The removal efficiency for the control system was limited because there was no bio-rack. The present results illustrate that the bio-rack system enables nutrient removal to increase compared to the control, and thus plays an important role in nutrient removal for low-concentration polluted river water treatment.

Several mechanisms are considered to be responsible for the removal of TN in treated wetlands. These include gravitational settlement, nitrification/denitrification, direct plant uptake, and interception by the extensive root system. About 34.9%–43.81% of nitrogen removal was accumulated by plant uptake in the four bio-rack systems (Table 3), suggesting that nitrogen was removed effectively by plant uptake. The results are in agreement with Peterson and Teal (1996). Nitrogen accumulated in the bio-rack wetland by gravitational settlement and interception was slight (Table 3). Microbial nitrication/denitrification was

Table 2 Correlation between removal rate and plant biomass for different plant species

Month	Fine root biomass				Total biomass			
	TN	NH_3-N	TP	COD_{Mn}	TN	NH_3-N	TP	COD_{Mn}
Jul	0.95*	0.68	0.94	0.55	–0.10	–0.79	0.12	–0.69
Sep	0.99*	0.99**	0.98*	0.45	–0.31	–0.28	–0.00	0.30
Dec	0.99**	0.81	0.98*	0.92	0.20	–0.02	0.35	0.53

** $P < 0.01$; * $P < 0.05$.

Table 3 Nitrogen and phosphate mass balance in the bio-rack wetlands through the operational period

Plant species	Total removal (g/m^2)		Plant uptake (g/m^2)		Sediment (g/m^2)		Other (g/m^2)	
	TN	TP	TN	TP	TN	TP	TN	TP
T. dealbata	73.27	5.20	32.10	3.89	1.26	1.13	39.91	0.18
A. calamus	67.04	4.48	26.63	2.78	2.87	1.44	37.54	0.26
Z. latifolia	62.29	4.14	24.70	2.57	3.01	1.33	34.58	0.24
I. sibirica	61.03	4.39	21.30	2.92	3.12	1.25	36.61	0.19

* The influent loadings of N and P were 118.84 and 6.39 g/m^2 during the operational period, respectively.

also a main nitrogen removal mechanism in the bio-rack wetlands (Table 3). In the bio-rack systems, plant roots replacing the conventional matrix became the main carrier of microbial species, and more root biomass could provide more surface area for microorganism growth, larger effective space and chance of attachment for microorganisms and nutrients, and a more significant anaerobic/aerobic microenvironment, which was beneficial to the processes of nitrification/denitrification. Therefore, *T. dealbata* with larger root biomass had the highest nitrogen removal efficiency, and *I. sibirica* and *Z. latifolia* with smaller root biomass had lower nitrogen removal efficiencies. The results also showed that the TN removal rate had a significantly increasing trend in the warmer season (i.e., July to October), while decreasing in the colder season (i.e., November to December), indicating that temperature had an important effect on the removal of TN, which is in agreement with other reports (Reddy et al., 2001; Poach et al., 2004; Lu et al., 2009b). There were many reasons for the lower TN removal in December and November. Nitrification/denitrification was the main nitrogen removal mechanism in the bio-rack wetland. However, the growth or action of microorganisms was inhibited by the lower temperature at the end of the experiment, especially in December. In addition, when plants entered the mature phase in the winter, the plant metabolism was slowing down, especially enzyme activity in plants. The plants started to decay and died off at the end of the experiment and the plants no longer assimilated nitrogen.

It is believed that nitrification occurs when oxygen is present in a high enough concentration to support the growth of strictly aerobic nitrifying bacteria. The highest removal rates were obtained for the four bio-rack systems in November, which would be attributed to the high pollution loading and the large plant root biomass. The previous study showed that the NH_3-N removal rate increased as the pollution loading increased when the temperature was in the range of 15–32°C (Jing and Lin, 2004). The influent NH_3-N loadings and fine-root biomass were higher in November than those from July to October, which were beneficial to the NH_3-N removal through the nitrification process. However, the NH_3-N removal rates decreased suddenly in December, although the NH_3-N pollution loading and fine root biomass were raised to the maximum. The reason for this might be the low temperature. The highest removal rates of TN and NH_3-N were obtained in different months. This may be caused by the action of denitrifying bacteria. Volokita et al. (1996) study showed that the action of denitrifying bacteria dropped by 60%, when the temperature changed from 19–24°C to 14–19°C.

More than 60% of the phosphorus removal was accumulated by plant uptake in all four bio-rack wetlands (Table 3). This indicated that plant uptake was the main phosphorus removal mechanism and a given proportion of PP was converted to SRP to enable plant growth, because over 60% of TP was in the particulate form. Previous studies had reported that P removal by plant uptake was less than 30% of total P removal in conventional CWs (Cheng et al., 2002; Chung et al., 2008). This discrepancy can be attributed to two causes. First, physicochemical processes, such as the fixation of phosphate by iron and aluminum in the substrate, are the key mechanisms of phosphorus removal from wastewater in conventional CWs (Arias et al., 2001), and the plant density is quite low, which limits the capacity for plant uptake. However, in bio-rack wetlands, the plants density was nearly 150 $plants/m^2$, and sufficient nutrients were sequestered by plants to maintain growth. Therefore, P removal by plant uptake was significant increased. Second, the lower P loadings were beneficial for P removal by plant uptake. Ge et al. (2010) studied N and P removal from polluted water by *A. calamus* cultivated in four series of floating bed systems, and reported different P removal proportions under densities of 45 $plants/m^2$. As the river water flowed through the third floating-bed system to the last, the phosphorus loads decreased significantly. Specifically, the maximum proportion of plant uptake was approximately 65.75% for TP in the last floating-bed, suggesting that P removal by plant uptake was negatively related to P loads under higher plant density conditions. This conclusion is in agreement with results reported by Jiang et al. (2004). Long-time monitoring data showed that the average P concentration of the Hengtang River was less than 0.2 mg/L. In the present study, the influent flow rates and pollution loads in the bio-rack wetlands were so low that the plants sequestered a large proportion of P to maintain plant growth. The results also showed that there was no significant variation in TP removal with changing temperature during the whole experiment. That could be attributed to the following reason: in the warmer season, phosphorus as nutrient was taken up rapidly by the high-density plants, and in the colder season, particulate-P was intercepted effectively by the flourishing roots of the plants.

There was no significant correlation between COD_{Mn} removal rate and plant biomass for the four species in the bio-rack systems (Table 2), and low COD_{Mn} removal rates were obtained in all four bio-racks during the first three months. This may have been due to dead plant roots that were produced in the process of upgrading. The dead tissue acts as COD_{Mn} and consumes oxygen, thus causing a low COD_{Mn} removal rate. A major part of the degradation of pollutants (COD) in the wastewater is attributed microorganisms that may establish a symbiotic relationship with the plants. The oxygen supply from the macrophyte root zone can enhance organic removal by microorganisms in the sediment or on the surface of stems and roots of the macrophytes (Sooknah and Wilkie, 2004). However, the present study showed that the overall removal rates of COD_{Mn} were low in the bio-rack systems, which would be explained by the organic compounds released from these systems. Plant roots can release a wide range of organic compounds (Cronk, 1996; Weiss et al., 2004). The magnitude of this release is still unclear, but reported values are generally in the range of 5%–25% of the photosynthetically fixed carbon (Brix, 1997).

Previous studies had indicated that several processes in constructed wetland wastewater treatment were strongly related to the functional characteristics of the wetland plants (Stottmeister et al., 2003; Stein and Hook, 2005; Chen et al., 2007). In present study, the result demonstrated that fine root biomass rather than total biomass had a strong relationship with nutrient removal. Plants are an important part of CWs, however how to select plants that can increase the nutrient removal rate in CWs has not been settled. The present study suggests that particular attention should be given to plant species having larger fine-root biomass.

4 Conclusions

The bio-rack wetland was found to be an effective method for treating low-concentration polluted river water. The bio-rack planted with *T. dealbata*, accomplished better nutrient removal than those planted with the other species. Removal rates were 48.65%–78.07% for TN, 51.22%–68.96% for NH_3-N, and 77.4%–86.07% for TP in the *T. dealbata* system during the operational period, respectively. The COD_{Mn} removal rates varied from 9.65% to 32.4% in the *T. dealbata* system, and showed no significant differences from the rates of the bio-racks planted with other plants. The nitrification/denitrification process and plant uptake process were the major removal pathways for TN, while plant uptake was the most effective removal pathway for TP. The plant root biomass had a significantly positive relationship with nutrient removal in the bio-rack wetlands. This indicated that selecting plants species possessing larger fine-root biomass in the bio-rack system was beneficial in improving the nutrient removal rate.

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