

Planted floating bed performance in treatment of eutrophic river water

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Abstract The objective of the study was to treat eutrophic river water using floating beds and to identify ideal plant species for design of floating beds. Four parallel pilot-scale units were established and vegetated with *Canna indica* (U1), *Accords calamus* (U2), *Cyperus alternifolius* (U3), and *Vetiveria zizanioides* (U4), respectively, to treat eutrophic river water. The floating bed was made of polyethylene foam, and plants were vegetated on it. Results suggest that the floating bed is a viable alternative for treating eutrophic river water, especially for inhibiting algae growth. When the influent chemical oxygen demand (COD) varied from 6.53 to 18.45 mg/L, total nitrogen (TN) from 6.82 to 12.25 mg/L, total phosphorus (TP) from 0.65 to 1.64 mg/L, and Chla from 6.22 to 66.46 g/m³, the removal of COD, TN, TP, and Chla was 15.3 %–38.4 %, 25.4 %–48.4 %, 16.1 %–42.1 %, and 29.9 %–88.1 %, respectively. Ranked by removal performance, U1 was best, followed by U2, U3, and U4. In the floating bed, more than 60 % TN and TP were removed by sedimentation; plant uptake was quantitatively of low importance with an average removal of

20.2 % of TN and 29.4 % of TP removed. The loss of TN (TP) was of the least importance. Compared with the other three, U1 exhibited better dissolved oxygen (DO) gradient distributions, higher DO levels, higher hydraulic efficiency, and a higher percentage of nutrient removal attributable to plant uptake; in addition, plant development and the volume of nutrient storage in the *C. indica* tissues outperformed the other three species. *C. indica* thus could be selected when designing floating beds for the Three Gorges Reservoir region of P. R. China.

Keywords Plants · Treatment performance · Dissolved oxygen (DO) · Hydraulic efficiency · Removal pathway

Introduction

Studies (Qin 2009; Nezhlin et al. 2009; Zhu et al. 2012; Burkholder and Glibert 2013; Herbeck et al. 2013) have reported that excessive loadings of N and P from a variety of point (industrial and domestic wastewater discharges) and non-point (agricultural runoff) sources, primarily due to ineffective treatment or a lack of adequate wastewater treatment facilities, input in water bodies often causes eutrophication. As one of most serious ecological problems worldwide, it usually occurs in lakes, reservoirs, and estuaries and often results in undesirable tastes, depletion of dissolved oxygen (DO), odor problems, increases in water treatment costs, and even shortage of water resources. Along these lines in P. R. China, algal blooms in Lake Taihu at the end of May

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2007 and in many tributaries of the Three Gorges Reservoir (TGR) in recent years have resulted in severe shortage of water supplies and other social problems (Zeng et al. 2006; Qin 2009). Therefore, effective measures should be taken to prevent eutrophication.

Countermeasures include treating wastewater, managing non-point sources before discharge and/or water body entry, treating eutrophic water, and restoring polluted rivers and lakes, and erecting many treatment facilities. Operating examples of the above with which considerable successes have been achieved include constructed wetlands (Białowiec and Randerson 2011; Li et al. 2013), marshland upwelling system (Evans and Rusch 2007), MBR (Hasar 2009; Singh and Thomas 2012), and lagoons Liu et al. (2013). But sometimes, they are limited by constraints such as high operating and management costs, especially for MBR in underdeveloped areas.

Floating bed (Sun et al. 2009; Zhou and Wang 2010; Zhu et al. 2011) is a promising ecological remediation technology that has attracted much attention from researchers and engineers and successfully treated polluted water and eutrophic water, coupled with advantages such as operating at a relatively higher hydraulic loading than other reactors, appreciable treatment performance, plants generating economic and ecological benefits, boosting oxygen, convenient and economic to construct and manage, and so on.

Reliable water treatment by floating bed system often closely correlates with its design, plant species, hydraulic characteristics, DO, and removal pathways. It is often difficult for designers and regulators to determine causes of treatment system failures, the optimal design parameters, and ways to bolster treatment performance. Thus, the objectives of this study were:

1. To treat eutrophic river water of the Linjiang River using floating beds.
2. To compare and select plant species used in the floating beds; and,
3. To provide fundamental information for the design and application of floating beds.

To those ends, we designed, constructed, and operated four pilot-scale floating bed units planted with *Canna indica*, *Acorus calamus*, *Cyperus alternifolius*, and *Vetiveria zizanioides* in parallel to study plant development, the removal performance and pathways, DO, and hydraulic characteristics of the system as treating eutrophic river water.

Materials and methods

The floating bed system

The floating bed system studied was located along the bank of the Linjiang River, a tributary in Jiangjin of Chongqing. Four parallel pilot-scale units with identical dimensions (2.7 m long, 2.3 m wide and 1.0 m deep with a water depth of 0.8 m) were established and vegetated with *C. indica* (U1), *Acorus calamus* (U2), *C. alternifolius* (U3), and *V. zizanioides* (U4), respectively. The plant species in the study were selected because they are abundant and most commonly used in Chongqing. The floating bed was made of polyethylene foam plate, with coverage of about 45 %. Plants were vegetated by hand in April 5 in 2009 with planting density of 28–32 plants per square meter, as shown in Fig. 1. The design allowed the polyethylene foam and plants to float on the surface of the water.

The eutrophic river water, directly taken from the Linjiang River was gravity fed through a rigid PVC pipe (with a valve to control flow) to four pilot units. Then, the treated water was collected at the outlet to be discharged by pipe, 0.2 m below the surface of the water. The duration of the investigation was continued from April to October in 2009. After accommodation of a week, plant growth and water quality monitoring was carried out, but plant development stopped in September and withered gradually coupled with decreasing in treatment performance, thereby the test was terminated in October. The hydraulic residence time (HRT) was maintained at 30 h in the test (at a flow rate of 4.42 m³/day in each unit)

Sampling and analysis

Water was sampled once a week. When sampling, three parallel samples with an interval of 2 h from 9:00 AM to 1:00 PM were collected from the influent and the effluent in each unit, respectively, and then the samples were mixed and immediately taken to a laboratory for analysis. Total nitrogen (TN) was measured using the alkaline potassium persulphate oxidation-UV spectrophotometric method (HACH DR/ 4000 UV, USA). Total phosphorus (TP) was determined by potassium persulfate oxidation-molybdenum-antimony spectrophotometric method (Model 721, China). Chlorophyll-a (Chla) concentration was measured after extraction in 90 % acetone by a freeze–thaw method (HACH DR/4000 UV, USA). COD was determined using a HACH DR/2800

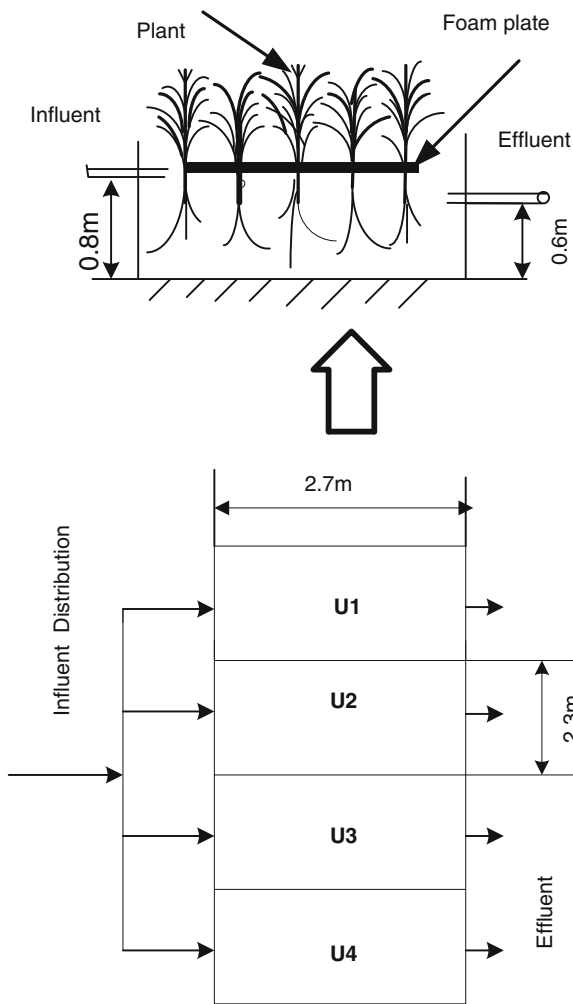


Fig. 1 Schematic diagram of the floating bed

spectrophotometer after digesting in a HACH COD reactor(USA) at 150 °C for 2 h. Water temperature and pH were determined using a pH meter (HACH sensION™, USA). DO was measured by a DO meter (HACH sensION6, USA) in situ.

The initial fresh plant weights were measured at the beginning of the test. Field observations of the total height of the plants, number of shoots, newly emerged main roots, and newly recruited shoots were conducted with the same frequency of water sampling. At the end of the study, plants were harvested and were removed from the foam plate by a hoe and a sickle manually after the water being discharged in the unit, to estimate the volume of nutrient that could be removed by plant uptake. Upon collection, the plant samples were cleaned, divided into above water and below water

tissues, gently washed with tap water, dried at 60 °C until a constant weight was achieved for analysis of TN and TP, as described in references (Zeng et al. 2008)

To identify sedimentation responsible for nutrient removal, sediment samples were collected from floating beds at the end of the study. These samples (2,000 g) were taken from the upper 10 cm in triplicate using a sediment sampler (Ø4 cm). After removing plant roots and other large particles (stones and debris), approximately 50 g of sediment samples were dried in an oven overnight at 105 °C until constant weight was reached. The samples then were digested with an H₂SO₄/HClO₄ (10:1) mixture for TN and TP analysis.

Tracer study

Tracer study (Furman and Stegowski 2011; Gao et al. 2012) was performed to investigate the hydraulic characteristics and effects of plant species on flow patterns in floating bed. And the residence time distribution (RTD) of electrolyte in a reactor can be represented by an exit age distribution curve $E(t)$. The mean retention time (τ), variance (σ_θ^2), the number (N) of continuous stirred tank reactors (CSTRs) connected in series, Peclet number (Pe), and the effective volumetric ratio (or hydraulic dead space, r) subsequently were calculated to describe the flow pattern in reactors, as shown in Eqs. 1–5.

$$\tau = \frac{\sum tE(t)\Delta t}{\sum E(t)\Delta t} \tag{1}$$

$$\sigma_\theta^2 = \frac{\sum t^2E(t)\Delta t}{\tau^2 \sum E(t)\Delta t} - 1 \tag{2}$$

$$N = \frac{1}{\sigma_\theta^2} \tag{3}$$

$$\sigma_\theta^2 = \frac{2}{Pe} - \frac{2}{Pe^2} (1 - e^{-Pe}) \tag{4}$$

$$r = \frac{\tau}{\bar{t}} \times 100 \% \tag{5}$$

where \bar{t} is the theoretical HRT (hours).

We also calculated the hydraulic efficiency (λ) of the floating bed systems based on e and r , a general measure of hydrodynamic conditions in reactors, defined as:

$$\lambda = e \frac{N-1}{N} \quad (6)$$

In each tracer experiment, a sodium chloride (NaCl) solution prepared in the field in a plastic container was injected into each unit immediately. The conductivity at the outlet was monitored at regular 1-h intervals until its background value was observed. The actual HRT thus was obtained through the retention time distribution curve.

Calculations and data analysis

The pollutant mass removal rate was calculated in grams per square meter per day.

$$M_{\text{in}}(\text{input}) = M_{\text{out}}(\text{output}) + M_1(\text{storage in plants}) + M_2(\text{storage in sediments}) + M_3(\text{loss}) \quad (9)$$

where M_3 is deduced from Eq. 9. Mass storage in the plants (sediments) was estimated using:

$$M_{\text{storage}} \left(\frac{\text{g}}{\text{m}^2} \right) = \text{biomass} \left(\frac{\text{kg}}{\text{m}^2} \right) \times \text{nutrient content} \left(\frac{\text{g}}{\text{kg}} \right) \quad (10)$$

The total mass removed in each unit subsequently was compared to determine the proportion of nutrient removal attributable to plant uptake and sedimentation.

Statistical analysis was conducted by SPSS 11.5 (SPSS Inc., Chicago, IL, USA). The data were analyzed through one-way analysis of variance to compare the performance of each unit (U1, U2, U3 and U4) concerning the plant development and the removal of COD, TN, TP, and so on. The data reported here were the average of three measurements, such as measurements of COD in U1 at day 1, so the effluent COD at day 1 in U1 was equal to the average of three measurements. The analytical precision for TN, TP, COD, and Chla was determined to better than ± 1.8 % ($n=3$), for plant samples better than

$$f = \frac{(C_i \times Q_i - C_0 \times Q_0)}{S} \quad (7)$$

where C_i is the influent concentration (milligrams per liter), Q_i is the influent flow rate (cubic meters per day), C_0 is the effluent concentration (milligrams per liter), Q_0 is the effluent flow rate (cubic meters per day), and S is the surface area of the floating beds (square meters). The total mass removed in grams per square meter was calculated using the mass removal rate and the operational time, as follows:

$$F = f \times T \quad (8)$$

where T is the days of operation (days). The mass balance equation was thus obtained based on the rule of mass conservation as follows:

± 3.2 % ($n=3$), and for DO, pH, water temperature better than ± 1.1 % ($n=3$).

Results and discussion

Plant development

Figure 2 illustrated plant developments in four units. After accommodation, the ratio of plant survival was 98.2 % for *C. indica*, 96.2 % for *Acorus calamus*, 93.5 % for *C. alternifolius*, and 82.4 % for *V. zizanioides*, and no difference in plant percentage coverage was observed. Thereafter, from the second week of sampling, the plants exhibited rapid growth, with the maximum heights and plant percentage coverage observed at days 91, 84, 77, and 91, respectively, 260 cm and 80 % for *C. indica*, 220 cm and 76 % for *Acorus calamus*, 196 cm and 68 % for *C. alternifolius*, 117 cm and 48 % for *V. zizanioides*. However, four species began to wither gradually from September to the end of the study coupled with the maximum rate occurring in *V. zizanioides* and the minimum rate in *C. indica*, and the plant coverage of 74 %, 70 %, 61 %, and 40 % respectively was

observed while terminating the test. Therefore, plant development under the same operating conditions was ranked: *C. indica*>*Acorus calamus*>*C. alternifolius*>*V. zizanioides*, and both seasons and plant species variety displayed profound impacts on plant growth.

Table 1 exhibited that the net biomass increase of four species was 4,215, 3,875, 3,214, and 1,861 g/m². The net increase in nutrient storage attributable to plant uptake, plant development, and net increase in biomass follows the same order, over the study. In addition, N and P were primarily accumulated in the above water tissues of all four species. Based on the difference in survival, growth rate, and the amount of nutrient storage capabilities, it can be concluded that *C. indica* outperformed the other three species in the design of floating beds.

Removal performance

The variation of water quality between influent and effluent, and the removal performance were illustrated in Table 2 and Fig. 3. When the influent COD ranged from 6.53 to 18.45 mg/L, 21.5 %–38.4 %, 19.6 %–35.1 %, 18.3 %–31.9 %, and 15.3 %–29.5 % (average, 32.4 %, 28.9 %, 25.2 %, and 22.7 %) of COD removal were obtained in U1, U2, U3, and U4, respectively. U1 exhibited the best COD removal.

Nitrogen was removed in floating beds by means of sedimentation, plant uptake, nitrification and denitrification, and other living organisms. With respect to TN, when the influent varied from 6.82 to 12.25 mg/L, the effluent was 3.69 to 8.41 mg/L for U1, 3.94 to 8.86 mg/L for U2, 4.21 to 9.19 mg/L for U3, and 4.51 to 9.52 mg/L for U4. Their respective removal efficiencies ranged from 32.9 % to 48.4 %, 29.6 % to 43.5 %, 28.2 % to 38.7 %, and 25.4 % to 30.9 % with averages of 42.3 %, 38.4 %, 33.2 %, and

28.3 %. U1 showed significantly higher TN removal efficiency than U2 ($p < 0.05, n = 23$), U3 ($p < 0.01, n = 23$), and U4 ($p < 0.01, n = 23$).

When the influent TP ranged between 0.65 and 1.64 mg/L, the floating bed system displayed removal efficiencies of 16.1 %–42.1 % where average removal efficiencies of 32.7 %, 28.9 %, 24.9 %, and 20.7 % for U1, U2, U3, and U4 were observed, respectively; U1 showed statistically similar higher potential for TP removal than the other units.

During the study, the influent ranged from 6.22 to 66.46 g/m³; Chla was reduced by 61.5 %–88.1 % (U1), 56.6 %–80.6 % (U2), 48.4 %–62.1 % (U3), and 29.9 %–44.1 % (U4), averaging 75.2 %, 67.2 %, 55.4 %, and 37.1 %, respectively. This suggests that floating bed system possess a great potential for algal growth inhibition. The effluent Chla in U1 was constantly lower than 11 g/m³, indicating that the trophic state of the Linjiang River water bodies was successfully changed from mesotrophic–eutrophic state to mesotrophic state after treatment by the floating bed (classified by Chla concentrations, OECD 1982). Therefore, the floating bed (U1) can effectively prevent eutrophication. Similar to COD, TN, and TP removals, U1 exhibited the best removal for Chla, and U4 ranked last. Additionally, a constantly higher removal efficiency of Chla than TN, TP, and COD removal was observed during the study.

In addition, the TN, TP, COD, and Chla removal increased over time during the operational period (reaching maximum removal in July) and subsequently decreased. This might be due to saturation of plant uptake and microbial activity. The removal efficiency against the operation time exhibited a similar trend with the variation of the plant height in each unit (Figs. 2 and 3). As can be seen in Table 3, a significantly positive relationship between plant height and removal efficiency was observed in each unit, suggesting plant development had profound effects on removal performance.

Therefore, it is clear from the study that the floating bed was an effective treatment option for eutrophic river water, especially in terms of inhibiting algal growth. The rank order of treatment performance was U1>U2>U3>U4. Furthermore, seasons and plant species showed profound impacts on removal performance, and *C. indica* is the best choice among the four floating bed plants studied.

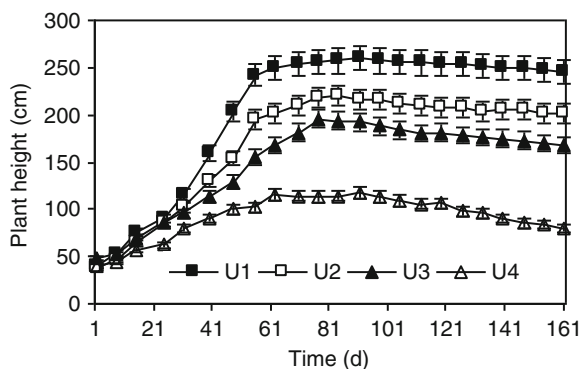


Fig. 2 Plant development in the floating bed

Table 1 The net increase in biomass and nutrient storage in plant tissues in floating bed

Item ^a	Biomass (g/m ²)	TN (g/m ²)			TP (g/m ²)		
		Above water	Below water	Total	Above water	Below water	Total
<i>C. indica</i>	4,215	68.25	18.71	86.96	11.24	1.87	13.11
<i>Acorus calamus</i>	3,875	62.46	13.31	75.77	9.98	0.91	10.89
<i>C. alternifolius</i>	3,214	46.74	9.21	45.95	6.46	1.78	8.24
<i>V. zizanioides</i>	1,861	29.87	7.64	37.51	5.12	0.84	5.96

^a The net increase (biomass and nutrient storage) is equal to the final amount (harvested) minus the initial amount

Removal pathways of TN and TP

Based on Eqs. 7, 8, and 10, the amount of the total TN and TP removed and storage in sediments was indicated in Table 4. Combined with Table 2, the percentage of the total nutrient removed attributable to plant uptake and sedimentation was calculated and shown in Table 4. It can be seen that U1 exhibited higher nutrient removal capabilities than the other three; furthermore, the amount of the total nutrient removed in each unit was constant with that of nutrient storage in plants and sediments. Therefore, it was also proven that *C. indica* outperformed the other three plant species in the test, which was used as floating bed plants.

It is clearly evident that more than 60 % of TN (average, 68.4 %) and TP (64.8 %) was removed through sedimentation (storage in sediments), and plant roots may play an important role in sedimentation (see Fig. 4). It seems that root mats and large root surface area provided enough water residence time and sufficient contact for trapping and settlement of particle pollutants, thereby achieving removal. Previous studies (Claveau-Mallet et al. 2013; Moharami and Jalali 2013) have documented that adsorption and precipitation by a substratum surface containing free Ca²⁺, Fe²⁺, Mg²⁺, and Al³⁺ ions play a substantial role in P removal in aquatic systems, and inorganic

P can be found in the form of aluminum, iron calcium, and/or magnesium phosphate complexes. In our work, water quality analysis indicated that large volumes of Ca²⁺ (2.89–4.24 mg/L) and Mg²⁺ (0.3–0.8 mg/L) existed, but we suspect it was plant roots that provided desirable contact between inorganic P and Ca²⁺ and Mg²⁺ for sedimentation to achieve P removal.

Plant uptake played a minor role in TN and TP removal. Comparatively, plant uptake contributed more to TP removal (average, 29.4 %) than TN removal (20.2 %). In addition, U1 displayed a higher percentage of plant uptake relative to the total TN and TP removed, possibly resulting from the greatest volume of nutrient storage occurring in *C. indica*. It is difficult to find suitable comparisons, however, given the range of plant uptake capability, the percentage of plant uptake relative to nutrient removal, the type of plant used, and the condition of the water being treated. Despite these caveats, it is apparent that a substantial volume of nutrient could be removed through harvesting plants from the floating bed.

Nevertheless, the loss of TN and TP logically assumed to result from microbial activity through nitrification/denitrification was of the least importance responsible for TN and TP removal in the floating bed. In addition, the difference in actual percentage of TP removed that can be attributed to the loss in each unit

Table 2 Statistics of overall influent and effluent concentrations in each unit

Parameter ^a	Influent	U1 effluent	U2 effluent	U3 effluent	U4 effluent
COD (mg/L)	10.62 (6.53–18.45)	7.26 (3.89–14.37)	7.54 (3.96–14.51)	7.93 (4.13–14.61)	8.26 (4.25–14.83)
TN (mg/L)	8.21 (6.82–12.25)	4.61 (3.69–8.41)	4.92 (3.94–8.86)	5.33 (4.21–9.19)	5.91 (4.51–9.52)
TP (mg/L)	1.15 (0.65–1.64)	0.77 (0.35–1.24)	0.81 (0.37–1.31)	0.86 (0.39–1.36)	0.92 (0.42–1.46)
Chla (g/m ³)	25.14 (6.22–66.46)	8.81 (2.2–10.2)	10.4 (2.5–16.8)	13.8 (2.9–24.6)	15.7 (3.4–35.6)

^a Where data presented are mean value (minimum–maximum; n=23)

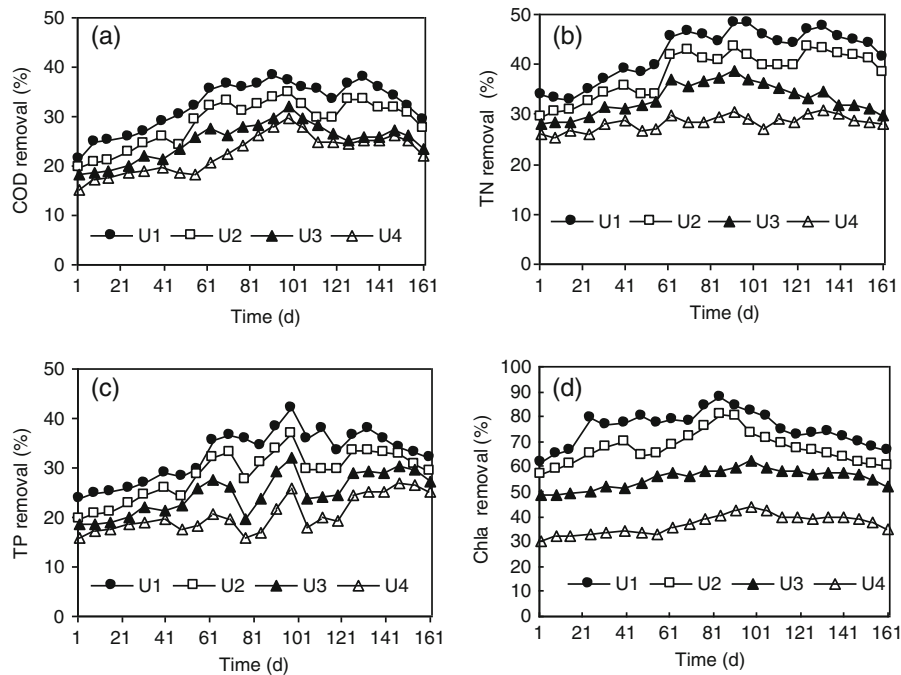


Fig. 3 Removal efficiency of COD, TN, TP, and Chla in the floating bed

was not as significant as to that of TN, due to the difference in removal processes between TN and TP. Since environmental and operating conditions such as temperatures (Lee et al. 2011; Gao et al. 2011) and plant species exhibited significant effects on microbial activity and the loss of TN was found to be more important than that of TP in the systems (Fig. 4), the difference in the loss of TN was more significant than that of TP.

Comparatively, the removal pathway of the floating bed differs from that of constructed wetlands (Chung et al. 2008; Wu et al. 2011). In the

former, sedimentation and filtration of plant roots are the predominant nutrient (N and P) removal processes; in the latter, N mainly is removed via microbial behavior attached to the substrate and partially by plant uptake, and adsorption by substrate and plant uptake were the dominant pathways for P removal. Furthermore, wetlands must be operated at low hydraulic loads to avoid clogging, a general problem occurring in wetlands. By contrast, floating bed systems make full use of plant roots to filter and can be operated under higher hydraulic loads, and they possess multiple

Table 3 Correlation coefficient between removal performance and plant height

	COD	TN	TP	Chla
U1 ^a	0.919*	0.931*	0.879*	0.741*
U2 ^b	0.939*	0.903*	0.899*	0.555*
U3 ^c	0.944*	0.889*	0.644*	0.919*
U4 ^d	0.687*	0.661*	0.568	0.724*

*Significant at $p < 0.01$ level

^a The correlation coefficient between removal efficiency in U1 and *C. indica* height

^b The correlation coefficient between removal efficiency in U2 and *Acorus calamus* height

^c The correlation coefficient between removal efficiency in U3 and *C. alternifolius* height

^d The correlation coefficient between removal efficiency in U4 and *V. zizanioides* height

Table 4 Amounts of the total TN and TP removed and stored in sediments

	TN (g/m ²)		TP (g/m ²)	
	Total removed	Sediment storage	Total removed	Sediment storage
U1	370.81	232.51	39.14	23.51
U2	338.81	212.12	35.02	22.14
U3	260.64	189.29	29.87	19.54
U4	216.89	164.15	23.69	16.58

other advantages such as low cost and convenient operation compared with constructed wetlands.

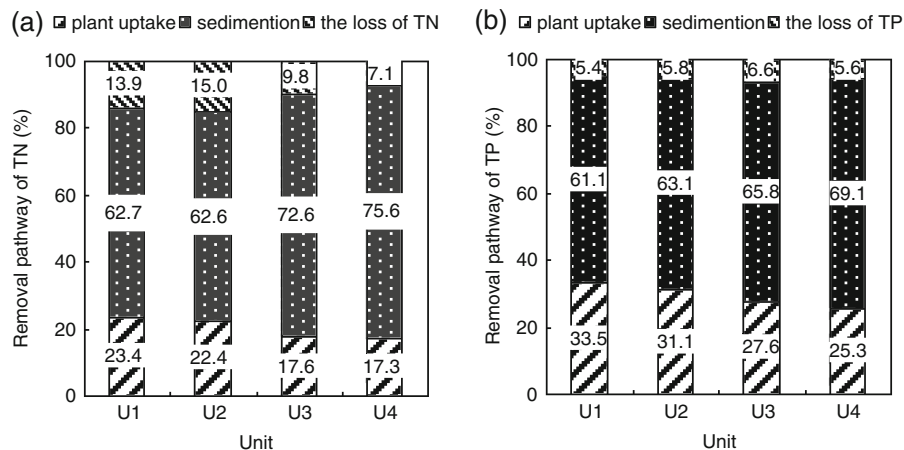
DO variation in the floating bed

DO, as an indicator of water quality, especially for river water, reflects the pollution magnitude and physical, chemical, and biological characteristics of a water column. Therefore, DO on a daily basis in June along the depth and the length (the direction of the water flow) of the system was continuously monitored, and results were presented in Fig. 5. As can be seen therein, a superior DO gradient distributions along the depth and the length was observed in the floating bed, among which U1 exhibited the best DO gradient distributions.

DO distributions affect simultaneous nitrification and denitrification (SND) substantially. The hypotheses that SND via stratification of the reactor—nitrification and denitrification occurring in different locations in the reactor are concurrently considered to determine the N removal mechanism in reactors (Li et al. 2008). A superior DO gradient distribution was thus beneficial for oxygen mass transfer and creating

for aerobic–anoxic–anaerobic microenvironments in the rhizosphere zone where conditions for nitrification and denitrification are favorable. In other words, plant roots in U1 had much more potential to develop desirable microsites for biological nutrient removal than those in the other three. Thus, superior DO gradient distribution of U1 may result in correspondingly higher removal volumes than the other three units.

DO levels also show a profound effect on nutrient removal. A higher DO level is not only beneficial for P absorption under aerobic conditions and restricting nutrient precipitated to resuspend but also for N removal (nitrification). The effluent DO increased after treatment by the floating bed in all four units by differing magnitudes (Fig. 6). The difference in DO level between influent and effluent suggests that plants in floating bed system could transfer oxygen by photosynthesis to the rhizosphere thus boosting DO level in the water column and improving water quality. Ye and Li (2009) reported that root oxygen release rates from a number of submerged aquatic plants is in the range of 0.5–5.2 g/(m d) and 0.3–9.6 g/(m d) from free-

**Fig. 4** Removal pathways of TN and TP in the floating bed

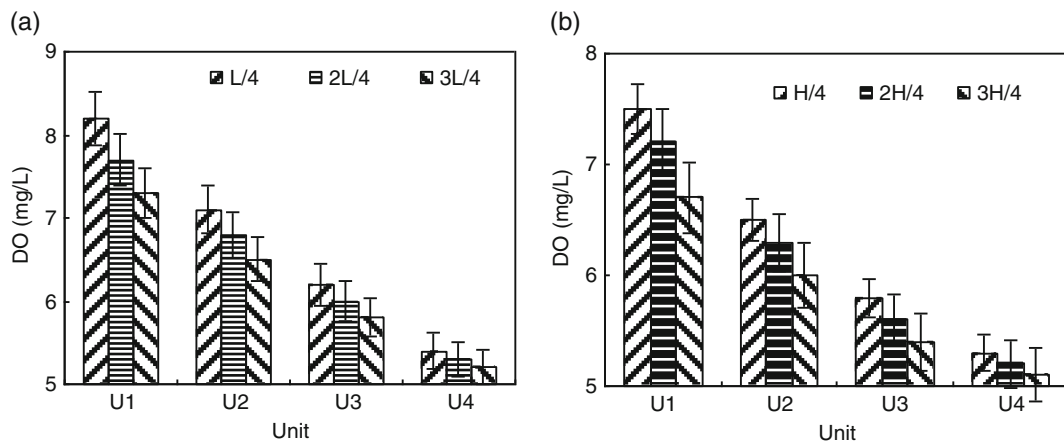


Fig. 5 Variation of DO in the floating bed: **a** along the length; **b** along the water depth

floating plants. So as a simpler, less costly alternative of promoting DO level, floating beds exhibited great promise for polluted river restoration and water improvement.

From the differences in the DO levels and distributions in the four test units, it also could be concluded that *C. indica* is the best choice for constructing floating beds.

Hydraulic characteristics in the floating bed

As shown in Fig. 7, the ascending of the tracer curve peaked close to the maximum conductivity after a lag

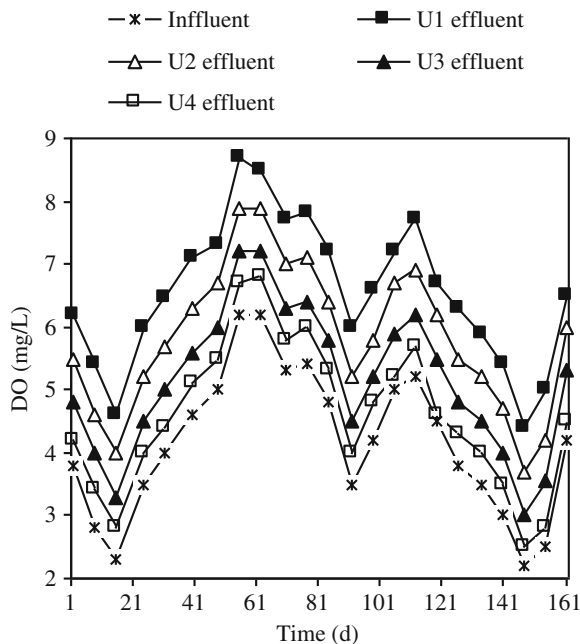


Fig. 6 Variation in DO between influent and effluent

peak and then gradually fell to the background value, similar to other studies (Kanaris and Mouza 2011; Simcik et al. 2012). An earlier peak of the RTD curve illustrated short circuiting, however. Although the term “short circuiting” has no precise technique definition, it usually applied to a situation in which a part of the flow exits a reactor in much less time than the actual HRT. In this study, a short circuiting effect occurred in each unit.

There are two ideal flow patterns in reactor theory: One is perfectly mixed, which gives perfect mixing with the effluent concentration equal to the concentration inside the reactor and $\sigma_\theta^2=1$; the other is complete plug flow in which fluid bypasses the same way and flows out at the same time and $\sigma_\theta^2=0$. The actual flow pattern of the floating bed (see Table 5) was intermediate between the ideal plug flow and a perfectly mixed flow, but much closer to ideal plug flow in U1 than in U2, U3, or U4. This is confirmed by the values of *Pe* and *N*, which usually describe hydraulic characteristics in reactors and details have been documented by Wong et al. (2006) and Simcik et al. (2012), respectively. Furthermore, Fu et al. (2001) reported that, for first-order reaction, reactors with a plug flow have higher reaction rate and volumetric efficiency than those with a mixed flow. Correspondingly, U1 had higher reaction rate (removal performance) than other three units which resulted in superior treatment performance.

At the same time, the *r* values show that U4 had the minimum effective volumetric ratio and the maximum volume of dead space. Hydraulic dead space consists of both hydraulic and biological dead spaces, however

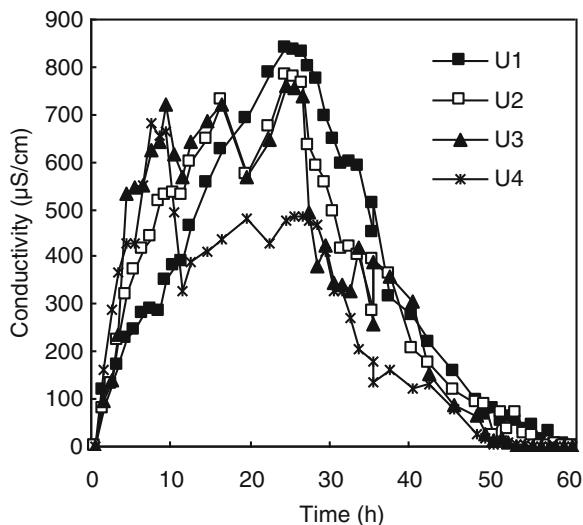


Fig. 7 RTD curve of the floating bed

(Krishna et al. 2009). Hydraulic dead space is a function of the flow rate and the number of compartments in a reactor while biological dead space is a function of biomass concentration and activity. At a higher HRT, more mixing occurs in a reactor, thus creating less (biological) dead space and less channeling (hydraulic dead space). Therefore, an increase in the (hydraulic) dead space was expected with a decrease in HRT due to more channeling in the reactor. The research indicated that the volume of dead space decreased with an increase in HRT.

In addition, the λ in Table 5 also revealed that U1 had a higher hydraulic efficiency than the other three. Therefore, a relatively higher hydraulic efficiency in U1 was another critical factor leading to better removal, also suggesting that *C. indica* was the best plant species among this group adapted to floating bed design. Moreover, the hydraulic efficiency of the floating bed system was substantially higher than some constructed wetlands reported on elsewhere (Muñoz et al. 2006), possibly due to clogging by substrate and

plant roots connected after extended operation in wetlands.

Conclusions

Four parallel pilot-scale floating beds were operated to investigate treatment performance on eutrophic river water and to select the optimal plant species for designing floating beds through comparative study of treatment performance and removal pathway, plant development volume of nutrient removal and storage in plant tissues, DO level and distribution, and hydraulic efficiency. The most important conclusions are as follows:

1. Floating bed is an effective treatment option for eutrophic river water, especially for inhibiting algal growth. Over the study, U1, U2, U3, and U4 achieved an average removal of 32.4 %, 28.9 %, 25.2 %, and 22.7 % for COD, 42.3 %, 38.4 %, 33.2 %, and 28.3 % for TN, 32.7 %, 28.9 %, 24.9 %, and 20.7 % for TP, and 75.2 %, 67.2 %, 55.4 %, and 37.1 % for Chla. Among which, U1 exhibited the greatest potential for purifying eutrophic river water. In addition, the plants in floating bed were capable of boosting DO levels in the water column, thereby improving water quality. The results have implications for floating beds for water treatment.
2. Sedimentation was the predominant removal process for both TN and TP, averaged 68.4 % of TN and 64.8 % TP of the total removed; plant uptake played a minor role and ranked last by the loss of TN (and TP).
3. The actual flow pattern of the floating bed system was intermediate between the ideal plug flow and a perfectly mixed flow, and the *C. indica* unit was much closer to ideal plug flow and higher reaction rate than in the other three.

Table 5 RTD results in the floating bed

Item	τ (h)	σ_{θ}^2	Pe	r (%)	λ	N
U1	24.1	0.22	0.931	80.2	0.741	5
U2	21.6	0.29	0.903	71.8	0.555	4
U3	19.4	0.34	0.889	64.6	0.919	3
U4	17.8	0.41	0.661	59.4	0.724	2

4. The order of plant development and volume of nutrient storage in plant tissues was *C. indica*(U1) > *Acorus calamus*(U2) > *C. alternifolius*(U3) > *V. zizanioides*(U4), coupled with the same rank in terms of the amount of TN and TP removed, the percentage of nutrient removal attributable to plant uptake, DO distributions and levels, and hydraulic efficiency in the floating bed, therefore *C. indica* outperformed the other three species studied and should be selected when designing floating beds in the Three Gorges Reservoir Region.

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