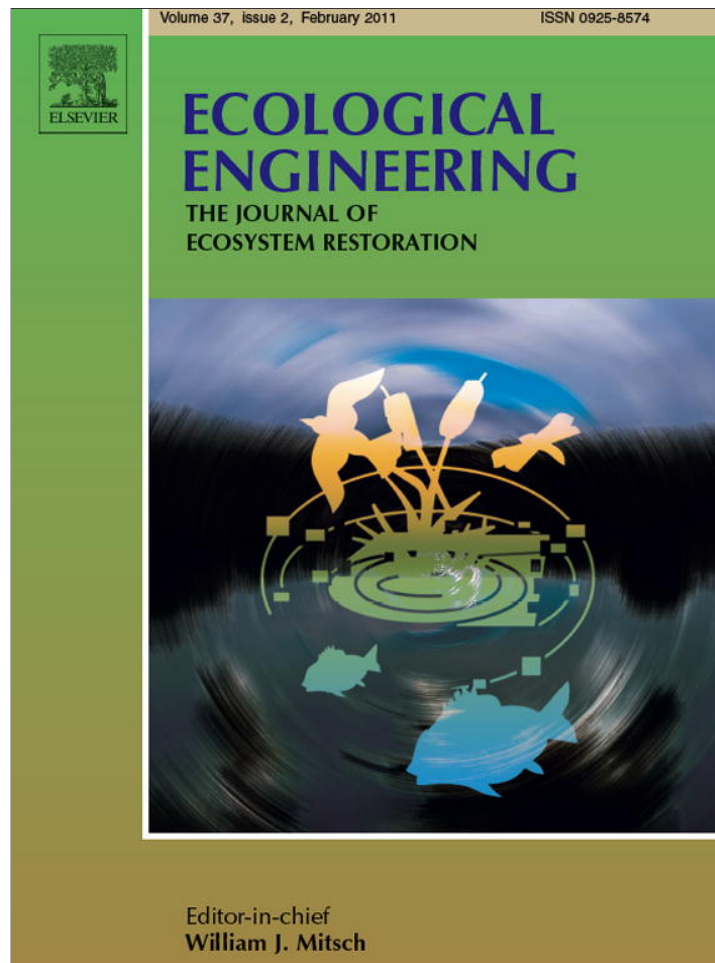


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## Purifying eutrophic river waters with integrated floating island systems

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## ABSTRACT

Concerns over the impacts of water pollution and a need for sustainable development have led to the exploration of various approaches to mitigating the nutrient enrichment in surface waters. An integrated floating island system consisted of aquatic vegetation near riversides and mosaic floating island with adsorptive biofilms was constructed to purify eutrophic river water in Jiaxing City, Zhejiang Province. This study indicated that average removal rates for total nitrogen (TN),  $\text{NH}_4^+\text{-N}$ ,  $\text{NO}_3^-\text{-N}$ ,  $\text{NO}_2^-\text{-N}$ , total phosphorus (TP) and chlorophyll a in summer–autumn season were 36.9%, 44.8%, 25.6%, 53.2%, 43.3% and 64.5%, respectively, which were 16.2%, 18.4%, 12.8%, 25.8%, 26.3% and 58.7% higher than those respective values in winter–spring season. In addition, it also effectively reduced the concentrations of total suspended substance (TSS), *Escherichia coli* and heavy metals. Due to greater biomass, alligator flag (*Thalia dealbata*) showed the greatest element uptake, with  $60.9 \text{ g N m}^{-2}$ ,  $8.2 \text{ g P m}^{-2}$ ,  $856.6 \text{ g C m}^{-2}$  and  $6.2 \text{ g S m}^{-2}$  respectively. The tested hydrophytes contained abundant crude protein ranging from  $128 \text{ g kg}^{-1}$  to  $255 \text{ g kg}^{-1}$  and Ca, Mg, Fe and Mn. Feasibility of the plant biomass used as animal feed to meet nutritional and safety requirements is discussed.

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## 1. Introduction

## 1.1. Severe eutrophication of water bodies

From the latter half of the last century, there has been increasing concern regarding the elevated nutrient status and the eutrophication of rivers and lakes (Sierp et al., 2009). One of the most widespread examples of pollution is eutrophication due to inputs of large quantities of inorganic nutrients, particularly nitrogen and phosphorus, to freshwater rivers, lakes, streams and reservoirs (Yang et al., 2008; Zhu et al., 2011). Water quality throughout south Florida has been a major concern for many years (Lu et al., 2010) and up to 66% and 22% of lakes in China are eutrophic or hypereutrophic (Jin and Hu, 2003). Nitrogen (N) and phosphorus (P) are the two major influencing factors on water eutrophication. Therefore, removing N and P in water is an effective approach to mitigating and preventing eutrophication.

## 1.2. Floating islands for removal of nutrients and heavy metals

Due to inability of reduction of N and P by conventional wastewater treatment systems, other appropriate measures should be taken to lower the impacts of nutrient pollution (Wu et al., 2011). Ecological engineering for the removal of pollutants at low cost is an emerging field dedicated to the design and construction of sustainable ecosystems that provide a balance of natural and human values (Mitsch et al., 2002). Floating islands (FI) and constructed wetlands (CW) are increasingly used worldwide, especially in the developing countries. However, CW occupies a large area of lands, which is a limiting resource in countries such as China where human population density is high. Therefore, FI technique can be an alternative tool. Hydrophytes have been widely applied in FI for the remediation of surface water and wastewater due to their efficacy in assimilating nutrients and creating favorable conditions for the microbial decomposition of organic matter (Wang et al., 2009). Restoration using floating, floating-leaf, emergent and submersed hydrophytes is considered crucial to regulating lake biological structure, as aquatic plants limit algal growth by competing for nutrients and sunlight and can also increase herbivorous fish biomass by providing food and refuge (Li et al., 2010).

Although a number of technologies can be used to remove heavy metals from contaminated water such as filtration,

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adsorption, chemical precipitation and ion-exchange (Horsfall and Abia, 2003), these methods are not efficient in removing low heavy metal concentrations because of being relatively expensive and may fail to comply legal requirements (Southichak et al., 2006). Therefore, there is an urgent need for the development of innovative processes which can remove low concentrations of heavy metals economically (Volesky, 2001). It is conceivable that plant assimilation of metal elements may be higher in a floating island system compared to a sediment-rooted wetland, as the roots hanging beneath the floating mat are in direct contact with polluted water to be treated.

### 1.3. Utilization of the plant biomass from water remediation

However, plant biomass must be removed periodically from the water bodies to maintain purification efficiency. If not harvested, the nutrients that have been incorporated into the plant tissue may be returned to the water during the decomposition processes (Brix, 1997; Lu et al., 2010). On the other side, rapid population growth coupled with limited cultivable land also causes serious problems maintaining a steady supply of food. Natural treatment systems have been demonstrated to have significant potentials for both wastewater treatment and resource recovery (Xu et al., 2003). There are many potential economic opportunities for the use of plant biomass associated with hydrophytes (Licht and Isebrands, 2005). They could be dried and used as a food source for domestic animals and the food value could partially offset the cost of harvesting, if the plants were also grown and removed for nutrient abatement purposes (Boyd, 1970). The plants produced within constructed wetlands or on floating islands can be harvested and subsequently used as animal feeds, or even human food, or be processed into biogas, bio-fertilizer and bio-materials. This may justify the practical application of the technology using the potential economic returns (Li et al., 2007, 2010).

### 1.4. Objectives of this study

Until recently, although numerous studies on purifying efficiency of floating plantation have been conducted, most of these studies were performed with laboratory, microcosm or mesocosm experiments (Fang et al., 2007; Li et al., 2007, 2009, 2010; Stewart et al., 2008; Wang et al., 2009). There is limited information about plant purifying efficiency in open water environment (Lu et al., 2010), such as a river. In addition, fewer studies have been conducted to ascertain the performance of FI system in different seasons and the subsequent disposal of how to deal with the harvested biomass.

To evaluate the potential environmental benefits and the value as animal feeds for the aquatic plants used in the floating island treatment system, this study was designed to (1) analyze removal efficiency of nutrients and heavy metals and (2) evaluate the economic value of plant biomass as animal feed.

## 2. Materials and methods

### 2.1. Study site

The studied river with an average depth of 2.5 m and an average width of 22.1 m is situated at the suburb of Jiaying City, Zhejiang Province, PRC. This region is characterized with the northern subtropical monsoon climate. The flow rate of the river is lower, ranging from 0.2 m/s to 1.5 m/s. It is typical of monsoon alternation in winter and summer characterized by annual precipitation of 1169 mm and annual mean air temperature 15.9 °C.

**Table 1**

Nine aquatic plants applied to the integrated treatment system.

Common name	Scientific name	Ecotype
Water hyacinth	<i>Eichhornia crassipes</i> (EC)	Floating
Water lettuce	<i>Pistia stratiotes</i> (PS)	Floating
Water dragon	<i>Jussiaea repens</i> (JR)	Floating
Pennywort	<i>Hydrocotyle verticillata</i> (HV)	Floating
Frogbit	<i>Hydrocharis dubia</i> (HD)	Floating
Parrot weather	<i>Myriophyllum aquaticum</i> (MA)	Submerged
Pickeralweed	<i>Pontederia cordata</i> (PC)	Emerged
Canna	<i>Canna indica</i> (CI)	Emerged
Water arum	<i>Calla palustris</i> (CP)	Emerged

### 2.2. Construction of integrated floating island system

An integrated system consisted of two subsystems, i.e., aquatic vegetation near riversides (subsystem I) and floating island with adsorptive biofilms (subsystem II) was constructed (Fig. 1). The bed structure of System I was 4 bamboos ( $\varnothing$  100–150 mm in diameter) and covered with plastic net (20 mm  $\times$  20 mm). Floating plants were transplanted onto the nets. The bed structure of System II was PVC-pipes ( $\varnothing$  110 mm in diameter). And two adsorptive biofilm materials (multi-face hollow ball made of bamboo slice hollow ball and elasticity packing) were set under the plastic nets. Emerged plants were transplanted into 20-mesh nylon rhizo-bags filled with soil and bamboo charcoal (v:v=1:1), which were placed on the underlying net. Upper plastic net (60 mm  $\times$  60 mm) was set to prevent plant lodging. Nine aquatic plants were grown in the two subsystems. These consisted of the following ecotypes: five floating plants, one submerged plant and three emerged plants (Table 1).

### 2.3. Sampling and analysis

The experiment began in June 2008, and was completed in November 2008. Triplicate water samples of influent and effluent were collected 30 cm below the water surface monthly around mid-month, stored at 4 °C and analyzed within 48 h. A portion of each sample was filtered (Whatman GF/C glass-fiber 0.45  $\mu$ m pore size) and analyzed for ammonium nitrogen ( $\text{NH}_4^+$ -N) by the Nessler's reagent colorimetric method, nitrate nitrogen ( $\text{NO}_3^-$ -N) by ultraviolet (UV) spectrophotometry and nitrite nitrogen ( $\text{NO}_2^-$ -N) by N-ethylenediamine colorimetric method. Unfiltered subsamples were analyzed for total nitrogen (TN) by alkaline potassium persulfate digestion-UV spectrophotometry, total phosphorous (TP) by ammonium molybdate spectrophotometric method and chlorophyll a (Chl a) by spectrophotometry after 90% acetone extraction (Li et al., 2010). In June and October 2009, heavy metals in water samples were determined by an Agilent 7500a ICP-MS system (Agilent Technologies, USA) and total suspended substance (TSS) and *Escherichia coli* (*E. coli*) were also analyzed.

Plants within an area of one square meter were weighed after harvest. A part of the samples from every harvest (about 200 g) was weighed, dried at 80 °C and re-weighed to determine the moisture content, then dried, and ground to pass through 60 meshes for the analysis of plant composition. Nitrogen, carbon and sulfur content were determined with a CNS analyzer (Vario MAX CNS Macro Elemental Analyzer). After plant tissue samples were digested ( $\text{HClO}_4:\text{HNO}_3 = 5:1$ ), Major mineral components (including P, Ca, Mg, Fe, Mn, Zn, Cu, Pb, Cr and As) in the samples were determined by an Agilent 7500a ICP-MS system. Crude protein concentration was estimated as  $\text{N} \times 6.25$  (Chou et al., 2001). Total ash content was measured as loss of weight after combustion at 450 °C for 16 h in a muffle furnace. Crude fiber (CF) was determined by VELP Fire3 Raw Fiber Extractor (Vansoest et al., 1991).



**Fig. 1.** Subsystems of the integrated floating island system and demonstration of river water purification in water-net area. (I) Aquatic vegetation near riversides, (II) floating islands with adsorptive biofilms.

#### 2.4. Data analysis

One-way ANOVA and Tukey's comparison of means were performed with Statistical Package for Social Science (SPSS, version 16.0). The significance level was set at  $P < 0.05$ .

### 3. Results and discussion

#### 3.1. Purification performance of the integrated floating island system

Assimilation and removal of nutrients from water by integrated floating island system is an efficient phytoremediation approach. As shown Fig. 2A, TN concentrations of the influent water in the winter–spring season (from December 2008 to April 2009) ranged from  $6.9 \text{ mg L}^{-1}$  to  $8.3 \text{ mg L}^{-1}$  with an average of  $7.8 \text{ mg L}^{-1}$ , which was 1.4 fold of that in the summer–autumn season (from May 2008 to September 2009). Removal rate for TN in the summer–autumn season ranged from 34.3% to 45.1% with an average rate of 36.9%. This was 1.8 fold of that in the winter–spring season. Average  $\text{NH}_4^+\text{-N}$  concentration of influent water in winter–spring season was  $3.0 \text{ mg L}^{-1}$ , which was 1.9 fold of that in the summer–autumn season. The highest influent concentration of  $\text{NH}_4^+\text{-N}$  ( $3.6 \text{ mg L}^{-1}$ ) appeared in February (Fig. 2B). Average removal rate for  $\text{NH}_4^+\text{-N}$  in summer–autumn season was 44.8%, which was 1.7 fold of that in the winter–spring season. Seasonal trend for the influent  $\text{NO}_3^-\text{-N}$  concentrations was similar to TN (Fig. 2C). The highest and lowest removal rates for  $\text{NO}_3^-\text{-N}$  appeared on January and September, respectively. Influent  $\text{NO}_3^-\text{-N}$  concentrations in winter–spring season varied from  $3.5 \text{ mg L}^{-1}$  to  $4.6 \text{ mg L}^{-1}$ , with an average of  $4.1 \text{ mg L}^{-1}$ , which was 1.3 fold of that in the summer–autumn season. The removal rate for  $\text{NO}_3^-\text{-N}$  in summer–autumn season varied from 16.5% to 37.0%, with an average of 25.6%, which was 2.0 fold of that in the winter–spring season. Influent  $\text{NO}_2^-\text{-N}$  concentration increased from December 2008 with a maximum concentration of  $0.2 \text{ mg L}^{-1}$  (Fig. 2D). After peaking in July 2009, it gradually decreased. Average removal rate for  $\text{NO}_2^-\text{-N}$  in the summer–autumn season was 53.2%, which was 1.9 fold of that in the winter–spring season with 27.3% average removal rate.

The high concentrations of  $\text{NH}_4^+$  and  $\text{NO}_3^-$  in the river were attributed to discharge of domestic wastewater and eutrophic runoff water from agricultural fields. The processes of nitrogen removal from eutrophic water may include nitrification/denitrification, plant uptake, microbial uptake, and volatilization (Tanner et al., 1999). The average removal rates of TN,  $\text{NH}_4^+\text{-N}$ ,  $\text{NO}_3^-\text{-N}$  and  $\text{NO}_2^-\text{-N}$  in the summer–autumn season were 16.2%, 18.4%, 12.8% and 25.8% higher than those respective values in the winter–spring season. This could be attributed to the

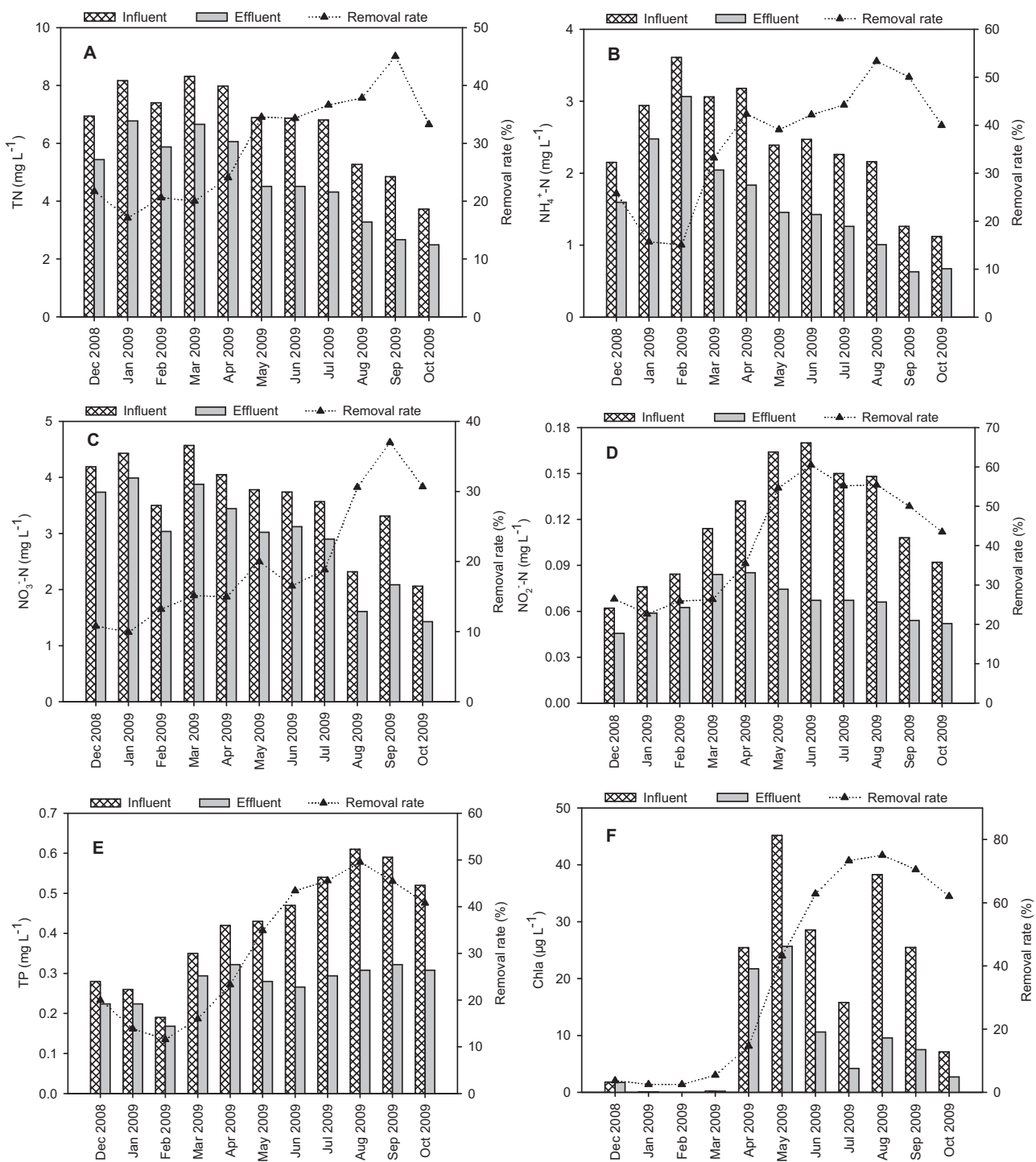
differences in plant uptake and microbial activities as a result of seasonal change in temperature.

The entire underwater surface of the plants serves as a base for the periphytic microorganisms, which favors the break-down of pollutants and the entrapment of suspended solids. Moreover, the plants are enforced physically to attain nutrition directly from the water column as they are not rooted in any substrate, which may improve the uptake rates of nutrients (Stewart et al., 2008; Li et al., 2010). The direct contribution of plant uptake to the N removal was in range from 25% to 47% in other studies (Korner and Vermaat, 1998; Zimmo et al., 2004). Temperature also affects the removal of nutrients (Wood et al., 1999). The optimum temperature was  $30^\circ\text{C}$ , which was close to the average temperature in the summer–autumn season at the pilot-scale site. Moderate temperature in the summer–autumn season favored the growth of hydrophytes and microbial activities. Vigorous growth of the nine aquatic plants, particularly water hyacinth, water lettuce and water dragon, was observed in the summer–autumn season and began to wither in November 2009. Moreover, the planted floating island system provided a large specific area of biofilm for the efficient purification of nitrogen by both microbes and periphyte (Hu et al., 2010). Ammonia oxidization, nitrification and denitrification may be critical for the proper functioning and maintenance of the FI system.

TP concentration of the influent water increased quickly from February to August with the increases in water temperature a (Fig. 2E) and then decreased with the decreases in water temperature. The average TP removal rate in the summer–autumn season was 43.3%, which was 2.6 fold of that in the winter–spring season with 17.0% average removal rate. The high growth of emerged plants on the floating island in the summer–autumn season was likely responsible for the rapid uptake of phosphate from the influent.

Chl a concentration peaked in May ( $45.2 \mu\text{g/L}$ ) and August ( $38.3 \mu\text{g/L}$ ). The inclusion of floating vegetation over the water surface provides a barrier against light penetration into the water column, and deficiency in nutrients due to the competition by hydrophytes, thereby inhibiting algae growth. Average Chl a removal rates of summer–autumn season was 64.5% being in range from 43.2% to 75.0%, which was 11.2 times that of winter–spring season being in range from 2.5% to 14.6%.

The growth of plant roots in the water column can alleviate water fluctuations and remove harmful heavy metals (Headley and Tanner, 2006). Our results based on the measurements on June 16 and October 18, 2009, showed removal of TSS at 41% and 54% respectively (Tables 2 and 3). Although *E. coli* in the river was extremely low, meeting Grade II of Chinese National Surface Water Quality Standards (GB 3838-2002), the integrated island system



**Fig. 2.** Time courses of total nitrogen (TN), ammonia nitrogen (NH<sub>4</sub><sup>+</sup>-N), nitrate nitrogen (NO<sub>3</sub><sup>-</sup>-N), nitrite nitrogen (NO<sub>2</sub><sup>-</sup>-N), total phosphorus (TP) and chlorophyll a (Chla) concentration and removal efficiencies of integrated floating island system from December 2008 to October 2009.

**Table 2**  
Concentrations of SS, *E. coli* and heavy metals in influent and effluent on June 16 and October 18, 2009.

Date	Items	SS (mg L <sup>-1</sup> )	<i>E. coli</i> (cfu/L)	Cr (µg/L)	Cu (µg/L)	As (µg/L)	Cd (µg/L)	Hg (µg/L)	Pb (µg/L)
June 16th	Influent	9.7	3500	0.38	10.06	2.02	0	0.29	0.24
	Effluent	4.5	1000	0.05	4.51	1.15	0	0.16	0.11
	Removal (%)	53.6	71.4	86.8	55.1	42.9	-	43.9	54.2
October 18th	Influent	7.41	2250	1.26	26.08	3.54	0.1	0.35	0.41
	Effluent	4.33	875	0.36	17.58	2.09	0.07	0.22	0.27
	Removal (%)	41.6	61.1	71.6	32.6	41	30	38.6	32.8

**Table 3**  
Root parameters of nine aquatic plants from the floating islands.

Species	Root length (cm g <sup>-1</sup> )	Root surface area (cm <sup>2</sup> g <sup>-1</sup> )	Root average diameter (mm)	Root volume (cm <sup>3</sup> g <sup>-1</sup> )	Lateral roots (number g <sup>-1</sup> )
Water hyacinth	651.4 ± 52.7	147.3 ± 17.2	0.59 ± 0.17	2.72 ± 0.89	1805.6 ± 223.8
Water lettuce	740.4 ± 111.4	102.1 ± 13.0	0.76 ± 0.06	1.12 ± 0.13	2826.2 ± 249.3
Water dragon	235.6 ± 34.3	58.2 ± 16.3	0.23 ± 0.05	0.66 ± 0.11	242.5 ± 40.8
Pennywort	305.8 ± 28.0	86.0 ± 8.2	0.17 ± 0.03	1.87 ± 0.13	547.7 ± 69.9
Frogbit	164.6 ± 33.9	87.2 ± 10.0	0.16 ± 0.02	0.54 ± 0.08	442 ± 45.8
Parrot weather	661.2 ± 84.9	102.0 ± 36.4	0.30 ± 0.08	1.26 ± 0.20	1575.5 ± 188.7
Pickernelweed	491.6 ± 93.9	83.7 ± 22.7	0.20 ± 0.05	1.16 ± 0.20	1620.1 ± 179.5
Canna	167.4 ± 45.0	38.9 ± 4.7	0.22 ± 0.03	0.74 ± 0.11	434.3 ± 45.3
Alligator flag	452.1 ± 76.4	78.8 ± 16.0	0.24 ± 0.03	1.09 ± 0.26	1977.4 ± 307.4

still removed most of *E. coli* (61–71%) in the water. The removal rates for Cr in June and October were 72% and 87%, respectively. Although lower than Cr, the removals of Cu, As, Cd, Hg and Pb were from 43 to 55% in June and 30 to 41% in October. Tanner and Headley (2011) also found that the planted floating system had >6-fold better removal of Cu than the control. This might be attributed to more prolific biofilms developed on the living plant roots which provide organic substrates for the growth of microbial biofilms.

### 3.2. Growth response of different hydrophyte species

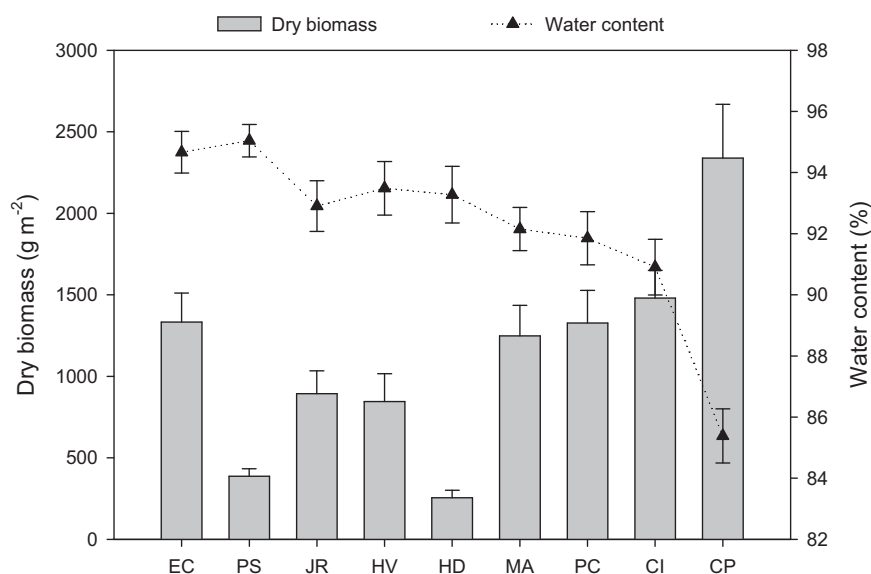
The efficiency of aquatic plant systems to remove nutrients depends upon plant biomass production and nutrient concentrations in the biomass. In the present study, all the nine plant species grew well in the eutrophic river. Dry matter (DM) of the aboveground tissues from the nine aquatic plants ranked from a low of 255.5 g m<sup>-2</sup> for hydrocharis to a high of 2338.9 g m<sup>-2</sup> for water arum (Fig. 3), which were comparable to the four emergent macrophyte species (834–2350 g m<sup>-2</sup>) reported by Tanner and Headley (2011). Biomass yields varied with plant species and were affected by environmental conditions and physiology and morphology of the plant, as many species have various mechanisms for aquatic/drought adaptation, including the enhancement of root systems, adjustments to growth rate, modifications to plant structure, and more efficient water utilization (Ma et al., 2010; Zhu et al., 2011). Compared with floating plants, three emerged plants contained lower water, particularly alligator flag which only contained 85.4% of water content.

Water lettuce produced the greatest root length, root average diameter and number of lateral roots, which were 740 cm g<sup>-1</sup>, 0.8 mm and 2826 g<sup>-1</sup> respectively (Table 4). Its root surface area was second only to water hyacinth. Meanwhile, to remove N and P in the water column, it is necessary that the plant roots provide a large surface area for microbial growth and allow for biofilm formation (Farahbakhshazad and Morrison, 1997; Gopal, 1999; Mitsch et al., 2002). Although pickernelweed and alligator flag (with a tap root system) had more lateral roots and a greater root volume, their root surface area was significantly less than water hyacinth or water lettuce.

### 3.3. Nitrogen, phosphorus, carbon and sulfur uptake by different hydrophyte species

Nitrogen (N) content of nine aquatic plants in aboveground tissues were all above 20 g kg<sup>-1</sup> DM (Fig. 4A), ranking from a low of 21.5 g kg<sup>-1</sup> DM for canna to a high of 39.9 g kg<sup>-1</sup> DM for parrot weather. Parrot weather, pennywort, water lettuce and frogbit each had a significantly higher N content (36–40 g kg<sup>-1</sup>) than the other hydrophytes. The three emerged plants had lower N content, 22–26 mg g<sup>-1</sup>. However, alligator flag demonstrated the greatest N uptake, 61 g N m<sup>-2</sup> due to its larger biomass. N uptake of parrot weather was 49 g N m<sup>-2</sup>, second only to alligator flag.

Compared with the three emerged plants, the floating plants contained higher phosphorus (P) in aboveground tissues (Fig. 4B). The average P content of six floating plants was 8.0 g kg<sup>-1</sup>, which was almost twice as much as that of three emerged plants. It could



**Fig. 3.** Comparisons of dry biomass and water content of eight aquatic plants. EC, PS, JR, HV, HD, CP, MA, PC and CI stand for *Eichhornia crassipes*, *Pistia stratiotes*, *Jussiaea repens*, *Hydrocotyle verticillata*, *Hydrocharis dubia*, *Myriophyllum aquaticum*, *Pontederia cordata*, *Canna indica* and *Thalia dealbata* respectively.

**Table 4**

Chemical compositions in aboveground tissues of nine aquatic plants growing on floating islands and maximum tolerable levels (MTL) in animal feed.

Species	Crude protein (g kg <sup>-1</sup> )	Crude fiber (g kg <sup>-1</sup> )	Ca (g kg <sup>-1</sup> )	Mg (g kg <sup>-1</sup> )	Fe (g kg <sup>-1</sup> )	Mn (g kg <sup>-1</sup> )	Zn (mg kg <sup>-1</sup> )	Cu (mg kg <sup>-1</sup> )	Pb (mg kg <sup>-1</sup> )	Cr (mg kg <sup>-1</sup> )	As (mg kg <sup>-1</sup> )
Water hyacinth	162.5	196.6	22.16	4.08	0.78	0.74	0.17	12.61	3.18	2.09	0.46
Water lettuce	219.4	154.7	19.76	3.45	0.57	1.32	0.08	14.01	3.93	3.57	0.88
Water dragon	167.5	144.7	7.36	1.98	1.04	6.74	0.11	13.84	2.57	2.07	0.71
Pennywort	236.6	152.8	18.28	2.53	0.46	3.64	0.12	15.85	4.32	3.19	1.51
Frogbit	230.2	111.1	6.92	4.59	1.19	1.38	0.08	16.74	4.8	5.83	1.78
Parrot weather	255.4	144.5	20.51	3.39	0.5	1.03	0.09	19.74	3.32	2.27	1.04
Pickelweed	150.6	197.7	11.62	2.4	1.81	3.57	0.16	11.15	4.14	3.57	0.84
Canna	127.8	190.7	6.18	2.8	0.27	0.93	0.08	12.45	3.07	2.59	0.43
Alligator flag	157	248.9	4.99	3.11	0.37	1.31	0.04	5.01	3.25	1.39	0.43
MTL in China	NG <sup>e</sup>	NG	NG	NG	NG	NG	250 <sup>a</sup>	25–200 <sup>b</sup>	5.0–40 <sup>c</sup>	10–200 <sup>c</sup>	2.0–10.0 <sup>c</sup>
MTL in USA <sup>d</sup>	NG	NG	NG	4.0	1.0	1.0	500	50	30	1000	50

<sup>a</sup> Agricultural Standard of China (NY 929-2005).

<sup>b</sup> National Standard of People's Republic of China (GB 26419-2010).

<sup>c</sup> Hygienical standard for feeds of China (GB 13078-2001).

<sup>d</sup> NRC (2000).

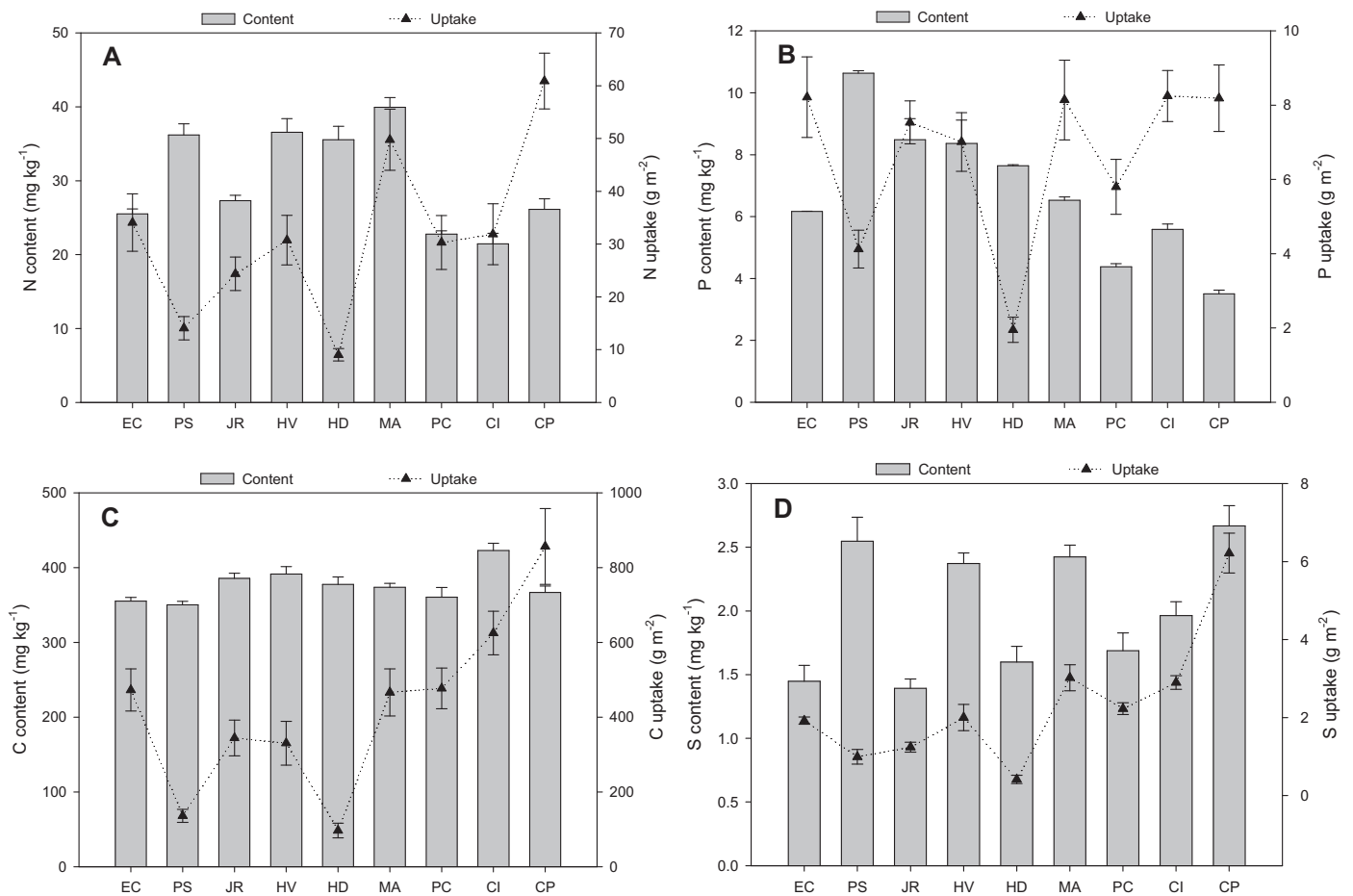
<sup>e</sup> Not given.

also be because the floating plants are forced to take up nutrients from the water column, although they had a smaller biomass except for water hyacinth. Water lettuce had the highest P content of 10.6 g kg<sup>-1</sup>. Water hyacinth, canna, alligator flag and parrot weather showed greater P uptake, which was up to 8 g P m<sup>-2</sup>.

Carbon (C) content of the aboveground tissues ranked from a low of 350 g kg<sup>-1</sup> DM for water lettuce to a high of 423 g kg<sup>-1</sup> DM for canna (Fig. 4C). However, due to the greater biomass in its above

ground tissues, alligator flag demonstrated the greatest uptake (845 g C m<sup>-2</sup>). Canna and pickerelweed ranked second and third, respectively, with 625 g C m<sup>-2</sup> and 477 g C m<sup>-2</sup>.

Sulfur (S) contents of nine aquatic plants showed greater differences than the carbon contents (Fig. 4D). Alligator flag, water lettuce, parrot weather and pennywort with an average of 2.5 g m<sup>-2</sup> was 1.5 times that of the others. Alligator flag demonstrated the greatest S uptake, which was 6.2 g S kg<sup>-1</sup> DM.



**Fig. 4.** Nitrogen (N), phosphorus (P), carbon (C) and sulfur (S) content and uptake by different aquatic plants. EC, PS, JR, HV, HD, CP, MA, PC and CI stand for *Eichhornia crassipes*, *Pistia stratiotes*, *Jussiaea reppens*, *Hydrocotyle verticillata*, *Hydrocharis dubia*, *Myriophyllum aquaticum*, *Pontederia cordata*, *Canna indica* and *Thalia dealbata* respectively.

### 3.4. Utilization of biomass as animal feeds

If hydrophytes were used for animal feeds, it could be beneficial to purify water and feed poultry and livestock. In the present study, crude protein contents of the tested hydrophytes were measured from a low of  $128 \text{ g kg}^{-1}$  for canna to a high of  $255 \text{ g kg}^{-1}$  for parrot weather (Table 4). Crude fiber content ranked from a low of  $111 \text{ g kg}^{-1}$  for frogbit to a high of  $249 \text{ g kg}^{-1}$  for alligator flag. The nine aquatic plants from this study contained  $5.0\text{--}22.2 \text{ g kg}^{-1}$  Ca, which is higher than all pasture grasses ( $1.0 \text{ g kg}^{-1}$ ) and all cereal grains ranging from  $0.6 \text{ g kg}^{-1}$  to  $3.1 \text{ g kg}^{-1}$  (Lander, 2001). The top three plants regarding Mg content were frogbit, water hyacinth and water lettuce within the range of  $3.5\text{--}4.6 \text{ g kg}^{-1}$ . The plants with the top Fe content were pickerelweed, frogbit and water dragon within the range of  $1.0\text{--}1.8 \text{ g kg}^{-1}$  and the top Mn contents were water dragon, pennywort and pickerelweed among  $6.7\text{--}3.6 \text{ g kg}^{-1}$  respectively. For Zn, the top three were water hyacinth, pickerelweed and pennywort with a range of  $0.12\text{--}0.17 \text{ mg kg}^{-1}$ .

Although Zn level of harvested biomass from remediation plants cannot meet the requirement, crude protein, Ca, Mg, Fe and Mn can meet the daily requirements of livestock and poultry at different growth stage according to National Research Council (NRC, 2000) and China Feed Database (2009). The accumulation of trace mineral elements in the tested plants was in the order of  $\text{Cu} > \text{Pb} > \text{Cr} > \text{As}$  (Table 4). They were below the standard of NRC (2000) and Hygienical Standard for Feeds in China (GB 13078-2001). Therefore, it should be safe when used as animal feed. Noticeably, aquatic plants are known to differ widely in their chemical composition depending on species, season and location. Crude protein in plant tissues generally decline as the plants age (Boyd and Blackburn, 1970), while crude fiber increases. Therefore, if the plants are harvested young, higher tissue concentrations for the most important constituents would be assured.

## 4. Conclusions

Integrated floating island system consisted of aquatic vegetation near riverside and mosaic floating islands with adsorptive biofilms had better removal effects on nitrogen, phosphorus, metal elements, SS, *E. coli*, and Chla in summer–autumn season than winter–spring season. And it could reduce the concentrations of SS, *E. coli* and heavy metal elements effectively. Nine aquatic plant species utilized in enhanced floating island engineering demonstrated significant environmental benefits over the first year. Due to its greater biomass of  $2339 \text{ g DM m}^{-2}$ , alligator flag (*Thalia dealbata*) showed the most N, P, C and S uptake, with  $60.9 \text{ g N m}^{-2}$ ,  $8.2 \text{ g P m}^{-2}$ ,  $856.6 \text{ g C m}^{-2}$  and  $6.2 \text{ g S m}^{-2}$  respectively. Rich in protein and microelements, the plant biomass from the integrated floating island system can be used for animal feed.

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