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Comparative evaluation of total phosphorus removal performances for treatment of domestic and secondary wastewater using integrated vertical-flow constructed wetlands: two years' experience

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ABSTRACT

Four small-scale gravel-based integrated vertical-flow constructed wetlands (IVCWs) were established to treat domestic and secondary wastewater (SW) in parallel under two loading rates (LRs) for an operational period of about two years and the total phosphorus (TP) removal performances were investigated and compared. Highly effective TP elimination sustained for about 10 d, with remarkable declines followed to relatively stable efficiencies for both types of wastewater. Significant difference of TP removal performance for the two types of wastewater was observed. In period 1, under high LR, the IVCWs performed better when treating domestic wastewater (DW), achieving average removal efficiency and rate of 51.6% and 0.389 g m^{-2} d^{-1}, respectively, compared to those of 30.1% and 0.233 g m^{-2} d^{-1} for SW. However, in the operational period 2 fed with a low LR, better TP removal performance was achieved for SW, with reduction efficiency and rate of 41.5% and 0.057 g m^{-2} d^{-1} on average, while the corresponding value for the treatment of DW was just 12.5% and 0.023 g m^{-2} d^{-1}. Significant correlations between TP removal efficiency and plant growth detected during this period and better developed vegetation in systems fed with SW might suggest the considerable role of plant growth, which could be influenced by inlet properties, on *P* retention and lifespan extending of constructed wetland. Gravel-based IVCW could be employed to remove low load of phosphorus and wastewater properties, and plant growth cycle should be taken into consideration in future IVCW design and application.

Keywords: Phosphorus removal; Integrated vertical-flow constructed wetlands (IVCWs); Domestic wastewater (DW); Secondary wastewater (SW); Plant growth

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1. Introduction

Phosphorus is a crucial limiting nutrient for biological growth, but severely adverse effects, such as eutrophication and quality deterioration of aquatic ecosystem, can be caused by excess phosphorus content [1,2]. Thus, it is greatly necessary to eliminate phosphorus from various types of wastewater before their discharges, in which domestic wastewater (DW) and effluent from conventional wastewater treatment plant, namely secondary wastewater (SW), are two types of representative wastewater. Accordingly, a large amount of researches have been focusing on *P* removal by various technologies till today [3–6].

Among them, constructed wetland (CW), a relatively reliable and environmentally friendly ecological engineered system for treatment of diverse types of wastewater, such as domestic and industrial wastewater, urban and agricultural runoff, secondary effluent, with many other advantages, including low construction and operation costs, simple management, the feasibility of application in isolated and rural areas, high aesthetical value, etc. compared with conventional wastewater treatment plant [7–10], is a potential and viable approach for *P* retention and becoming a popular wastewater treatment approach worldwide [11–13]. It was well documented that contaminant introduced into CW can be eliminated by a combination of physical, chemical, and biological processes encompassing the integrated functions of substrate, plant, and microorganisms in the system [7–10]. With respect to phosphorus removal, it primarily involves adsorption, chemical precipitation, and complexation into substrate, assimilations of plant, algal, and microbiota [7,10,11,14]. *P* attenuation and cycle in CW can be influenced not only by the characteristics of substrate, but also hydraulic and *P* mass loading rate (LR), inflow *P* concentration, pH, dissolved oxygen (DO), plant species, and growth. [6,7,12]. Therefore, wastewater type, namely wastewaters with different pollutant compositions, may affect the processes for *P* retention, and further the *P* elimination performance of CW.

As one of the widely applied CW types for wastewater treatment and ecological restoration in China, integrated vertical-flow constructed wetland (IVCW) has been utilized in over 200 ecological engineering projects due to its relatively compact constitution and acceptable performance [15–17]. DW and SW were two types of representative wastewater frequently introduced into IVCW, but the information on the difference of *P* retention capacities of IVCWs dealing with them is not available, which is of great significance to specify real design for applicable large-scale IVCW system and suggestion for favorable operation and management strategies. In addition, the *P* retention capacity of CW could decrease with operation time; thus, long-term experiment is of great importance to provide relatively referable information for design and management of CW [18,19]. Nevertheless, most previous studies focused on *P* removal applying IVCWs had been conducted in column experiments employing various materials for *P* retention [15], less considering the cost and sustainability, consequently cannot probably provide practical information for the sustainable *P* removal of CW application project.

Consequently, in this study we set up four pilot-scale IVCW systems outdoors operating independently under identical design and hydraulic condition to deal with DW and SW in parallel, with common gravel employed as the substrate despite its inferior *P* binding capacity [14,20,21], since gravel is the most widely used media in large-scale CW projects due to its economical and easy availability, and relatively large porosity which can provide good hydraulic conductivity and reduce the probability of clogging. The aims of the study were (1) to investigate and compare the phosphorus removal capacities of IVCWs for the treatment of DW and SW under two LRs for about two years, and (2) to investigate the role of plant development on *P* removal.

2. Materials and methods

2.1. Integrated vertical-flow constructed wetlands

The pilot-scale IVCWs employed in this study have been depicted elsewhere [22,23]. Briefly, four parallel IVCWs, each composed of a sequence of a down-flow cell and another identical up-flow one, were constructed with bricks and concrete in a garden near the Donghu Lake, Wuhan, China (coordinates: 30° 33′ N, 114° 23′ E; elevation: 27 m). The two cells, each with an identical dimension of 1 m long, 1 m wide and 1 m deep, were separated by a wall which is pierced at the bottom. Therefore, the wastewater flows in a "U" pattern through the IVCW bed when a new dose was introduced. A wastewater tank was installed alongside each unit, with bottom being above the surface of the down-flow cell and feeding controlled by a valve, to provide wastewater through gravity automatically.

The gravel, obtained from a nearby market, was employed to be the wetland substrate. Grain size of 10–20 mm was filled as the bottom layer to a depth of 45 cm for both cells, and 2–10 mm as the upper layer to a depth of 40 and 30 cm for down-flow and up-flow cell, respectively. The 10 cm lower depth of up-flow cell allows the wastewater flow through the bed naturally by gravity in a subsurface mode.

Two perforated PVC pipes in diameter of 50 mm with 5 mm holes were installed at the surface of down-flow cell to evenly distribute the wastewater into the system and another two at the surface of up-flow cell to collect the outlet.

2.2. Operation conditions of the IVCWs

Artificial wastewater was used due to the unavailability of actual wastewater for a long-term trial and for the purposes of health and safety of people in laboratory, as well as controlling the wastewater properties to conduct reasonable comparison of *P* removal capacities of IVCWs for the two types of wastewater. Thus, Na_2HPO_4 and KH_2PO_4 were used as the *P* source. Simulated physically pretreated DW was poured into two of the IVCWs operating in parallel and SW into another two. The SW, characterized by high content of nitrate and low concentration of organic matter, was simulated based on the effluent of a membrane bioreactor in our previous study [24]. Actually, its properties were similar to the treated wastewater in other references [25,26]. Similar levels of total phosphorus (TP) and total nitrogen (TN) were contained in the two types of wastewater.

The whole experiment was carried out from August 2010 to June 2012, consisting of two phases with different pollutant loads. In period 1 (from August 2010 to January 2011, 155 d), an inlet flow of 500 L d^{-1} containing high pollutant concentrations was applied, and seedlings of *Typha orientalis* and *Arundo donax var. versicolor* were transplanted from a nearby wetland into down-flow and up-flow cell of two of the systems with different influent wastewaters, respectively, at density of 8 stems m^{-2} in May 2010 and similarly, *Canna indica* and *Pontederia cordata* into the other two. All senescent plants were removed from the systems in February 2011. While during period 2 (from April 2011 to June 2012, 410 d), we reduced inflow rate to 250 L d^{-1} with low levels of contaminants according to the performances of these systems during period 1. In addition, just *A. donax var. versicolor* and *C. indica* were chose as wetland plants and transplanted into down-flow and up-flow cell of all systems, respectively, due to that *T. orientalis* and *P. cordata* did not grow well during period 1. After each planting campaign, all systems were kept flooded with tap water for about four weeks to allow vegetation and microorganisms to develop sufficiently. Then, wastewater was introduced twice a day and within 30 min each time. The operation parameters and inlet water quality characteristics are listed in Table 1.

2.3. Sampling and analysis

The inlet and outlet samples of the four systems were taken on a weekly basis, with a total of 14 sampling campaigns during period 1 and 52 during period 2, respectively. Water temperature (*T*), pH, DO, and conductivity were measured *in situ* using a portable Orion 5-star multimeter (Thermo Electron Scientific Company, USA). Chemical indexes, including TP, TN, NH_4^+-N, and NO_3^--N, were determined according to standard methods [27]. Chemical oxygen demand (COD) was measured by a spectrophotometer (DR/2010, Hach Co., USA).

2.4. Plant growth monitoring

During period 2, the plant growth in each cell was recorded through non-destructive measurements of stem height and density at around 10-d interval. In late November 2011, the plants were mostly senescent after the temperature decreased sharply and the aboveground part was cut to prevent nutrient from releasing back into the systems.

2.5. Removal rate calculation

Removal efficiency of *P* was calculated as the concentration alteration from inlet to outlet shown in Eq. (1), in which evapotranspiration was omitted due to the relatively high hydraulic loading rate (HLR). Actually, the evapotranspiration rate was estimated to be less than 5 mm m^{-2} d^{-11} even in summer.

$$\text{Removal efficiency}\,(\%) = (C_{\text{in}} - C_{\text{out}})/C_{\text{in}} \times 100\% \tag{1}$$

where C_{in} and C_{out} are the inlet and outlet TP concentrations (mg L^{-1}), respectively.

Mass loading and removal rate was calculated by Eqs. (2) and (3), respectively.

$$\text{Mass loading rate} = \text{C}_{\text{in}} \times \text{HLR} \tag{2}$$

$$\text{Mass loading rate} = (C_{\text{in}} - C_{\text{out}}) \times \text{HLR} \tag{3}$$

where HLR is hydraulic loading rate (m d^{-1}).

Further, removal rate constant (*k*) was calculated using area-based first-order model by Eq. (4) with the assumptions of an ideal plug flow throughout the wetland bed and a first-order reaction for *P* removal [7].

$$k = \text{HLR} \times \ln\left((C_{\text{in}} - C^*)/(C_{\text{out}} - C^*)\right) \tag{4}$$

Table 1
Main operational parameters and inlet water quality characteristics of the IVCWs

		Period 1 (August 2010–January 2011)		Period 2 (April 2011–June 2012)	
Item	Unit	DW	SW	DW	SW
Hydraulic loading rate	mm d^{-1}	250		125	
Feeding frequency	time d^{-1}	2			
Theoretical retention time	*d*	1.28		2.56	
pH	–	7.10 ± 0.21	7.34 ± 0.25	7.38 ± 0.88	7.71 ± 0.40
DO	mg L^{-1}	1.86 ± 1.62	5.63 ± 1.24	2.56 ± 2.13	6.01 ± 1.65
Conductivity	μs cm^{-1}	492 ± 66	464 ± 74	411 ± 54	394 ± 39
TP	mg L^{-1}	3.05 ± 0.39	3.15 ± 0.40	1.09 ± 0.23	1.04 ± 0.20
TP loading rate	g m^{-2} d^{-1}	0.76 ± 0.10	0.79 ± 0.10	0.14 ± 0.03	0.13 ± 0.03
COD	mg L^{-1}	299.8 ± 18.8	107.6 ± 15.4	49.50 ± 5.76	19.3 ± 5.62
NH_4^+	mg L^{-1}	20.31 ± 4.95	1.48 ± 0.33	7.12 ± 1.75	0.13 ± 0.19
NO_3^-	mg L^{-1}	2.30 ± 0.73	24.98 ± 3.03	1.26 ± 0.84	10.83 ± 1.63
TN	mg L^{-1}	32.44 ± 3.65	31.50 ± 2.94	11.60 ± 1.45	11.85 ± 1.75
n	–	14		52	

where C^* is background concentration of TP (mg L^{-1}) and is usually considered to be 0; thus, the above equation can be simplified as Eq. (5):

$$k = \text{HLR} \times \ln(C_{\text{in}}/C_{\text{out}}) \tag{5}$$

2.6. Statistical analysis

The SPSS 17.0 software was used to perform the statistical analysis of the experimental results. The difference of *P* removal performances of the two IVCW systems fed with different wastewaters under two LRs was assessed by one-way ANOVA test and significant difference between two values was identified by the least significant difference test at a level of $p < 0.05$. The correlations between plant growth and *P* removal efficiencies were detected by the linear regression test.

3. Results

3.1. The overall TP retention capacities of the IVCWs for DW and SW

Table 2 lists the overall TP removal performances of the IVCWs when treating DW and SW under two LRs. In phase 1, the systems performed notably better when dealing with DW ($p < 0.05$), with average removal efficiency of 51.55% and mass removal rate of 0.389 g m^{-2} d^{-1} compared with that of 30.11% and 0.233 g m^{-2} d^{-1}, respectively, for the SW. On the contrary, significantly greater removal were obtained for the treatment of NW during phase 2 ($p < 0.05$), with an efficiency of 41.53% and a mass removal rate of 0.057 g m^{-2} d^{-1} on average, while the corresponding value for DW was just 12.53% and 0.023 g m^{-2} d^{-1}. Remarkably lower mass removal rates were attained in phase 2 due to the much lower LR compared to period 1.

Table 2
Outlet concentration and removal performance (mean value ± SD) of TP of the IVCWs

		High LR		Low LR	
Item	Unit	DW	SW	DW	SW
TP concentration	mg L^{-1}	1.49 ± 0.94a	2.22 ± 1.00b	0.90 ± 0.27c	0.59 ± 0.22d
Removal efficiency	%	51.55 ± 31.03a	30.11 ± 30.68c	12.53 ± 32.98b	41.53 ± 25.82a
Removal rate	g m^{-2} d^{-1}	0.389 ± 0.224a	0.233 ± 0.227c	0.023 ± 0.051b	0.057 ± 0.038d
Removal rate constant	m d^{-1}	0.256 ± 0.234a	0.178 ± 0.343b	0.026 ± 0.050c	0.080 ± 0.057d
n		28		104	

Notes: Values with different right letters in the same row demonstrate a significant difference at a level of $p < 0.05$.

3.2. The temporal variations of TP removal during the experimental period

The variations of inlet and outlet concentrations, removal efficiencies, rate constants of TP, and outlet temperature over the experimental period were illustrated in Fig. 1. In addition, in order to better inspect and compare the *P* removal capacities of the IVCWs for the two types of wastewater, mass removal rates as well as cumulative mass removal of TP during the trial was described in Fig. 2.

Obvious seasonal variations of outflow temperature (T) were recorded with the range between 3.9 and 35.5℃ (Fig. 1(C)). Similar trends of *P* removal for the two types of wastewater were observed. Greatly, high elimination performance, as reflected in efficiency and *k* value for TP removal, was achieved at the beginning of the operation due to the fresh substrate for substantial phosphorus adsorption, but it only lasted for about 10 d, with sharp drops following, until a relatively steady state reached (Figs. 1(B) and 2). Nevertheless, from September to November 2010, the IVCWs performed substantially better when treating DW, with mean removal efficiency of 55.1% and *k* value of 0.21 m d^{-1}, compared with that of 20.6% and 0.06 m d^{-1} for SW. During this stage, 0.45 g m^{-2} d^{-1} TP was eliminated on average by the units fed with DW, with the average cumulative mass removal reaching 96.0 g at the end of November (Fig. 2), which were significantly higher than the corresponding value of 0.17 g m^{-2} d^{-1} and 46.8 g obtained for SW. The larger standard deviation of phosphorus mass removal for SW (Fig. 2(C)) might be attributed to that *C. indica* and *P. cordata* in the IVCW fed with SW have not grown well, with the latter decayed early, resulting in large difference of *P* mass removal for the two parallel IVCWs treating SW.

After that, the retention rates for both types of wastewater decreased remarkably again since the middle of December, and negative values were observed during January.

When period 2 began, these IVCW systems performed greatly poor for TP removal. As far as the units fed with DW concerned, negative removal lasted over two months, with retention efficiency declining to as low as −53.2% and more than 5.0 g *P* exported from the systems (Figs. 1(B) and 2). In contrast, as for another two IVCWs dealing with SW, net *P* release just occurred in the first week with a mass of 0.01 g, and the TP removal rate increased gradually. Relatively satisfactory removal of TP was attained for SW between July and the middle of December 2011, with average efficiency and *k* value of 62.1% and 0.13 m d^{-1}, respectively, which was notably higher than that of 33.9% and 0.06 m d^{-1} for DW. During this stage, greater TP mass was removed for SW (0.086 g m^{-2} d^{-1} and a total of 28.7 g) compared with DW (0.055 g m^{-2} d^{-1} and a total of 18.1 g). However, being similar to the operational period 1, the removal rates decreased markedly since the middle of December 2011, with *P* releases observed until

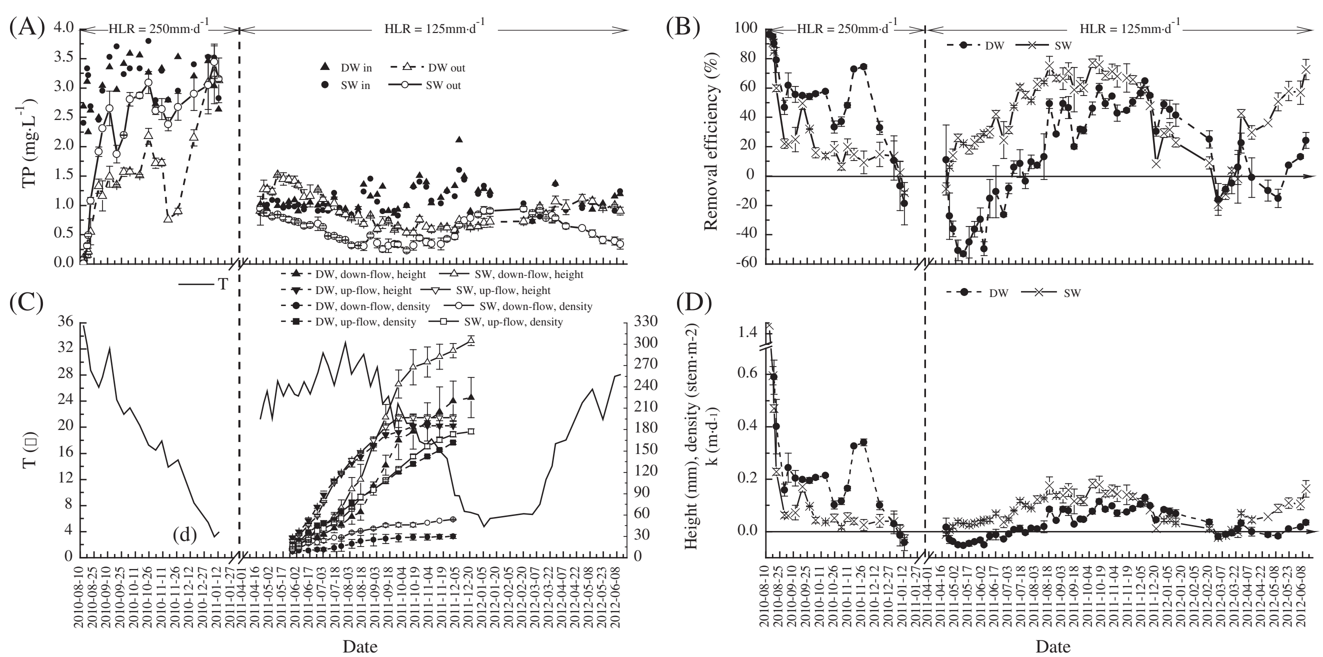

Fig. 1. Temporal variations of inlet and outlet TP concentrations (A), TP removal efficiencies (B), outlet water temperature and plant growth (C), and TP removal rate constants (D).

March 2012. Subsequently, highly similar retention trends to the year 2011 were observed for both types of wastewater, with mean elimination efficiency of 18.7 and 64.6% achieved for DW and SW in June 2012. Until the trail finished, a total of 128.1 g TP was eliminated by each IVCW fed with DW on average, and the value was 100.7 g for the unit treating SW.

3.3. Plant growth and its relationship with TP removal

The vegetation development in these CWs during period 2 is depicted in Fig. 1. The plants grew at a slow rate during the first 60 d after transplanting and at a notably increased rate thereafter. Stem height developed rapidly between August and October, while stem density exhibited a smooth increase throughout the phase. The plants in IVCWs fed with SW developed more luxuriantly, with stem height of 305 and 197 cm, density of 54 and 178 stem m^{-2} in down- and up-flow cell, respectively, in comparison to those of 225 and 186 cm, 30 and 162 stem m^{-2} in units with DW, which was conformed to the better TP retention capacity for SW. Actually, highly significant correlations between plant growth and TP removal

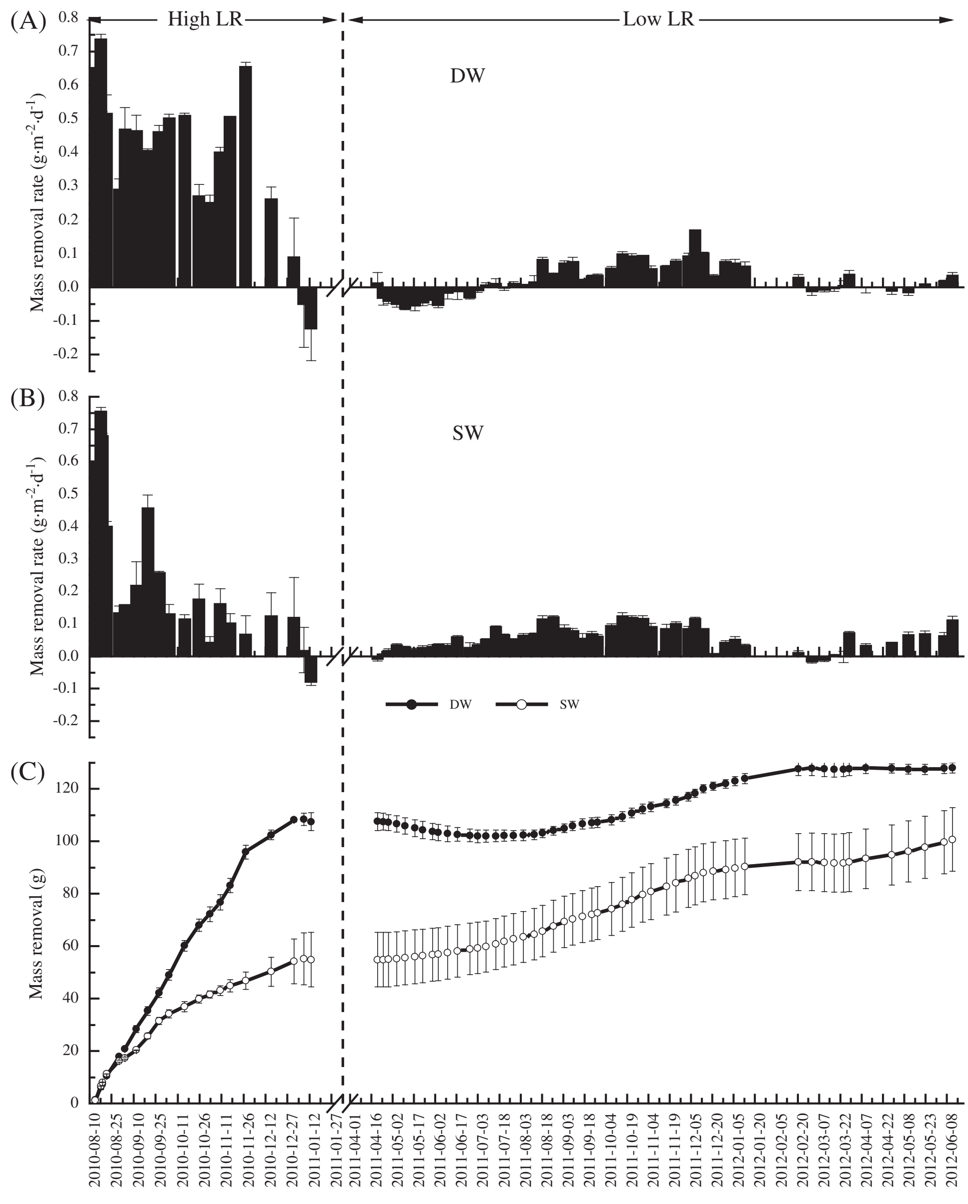

Fig. 2. Variations of TP mass removal rates for DW (A) and NW (B), and cumulative TP mass removal of the IVCWs (C) over the whole experimental period.

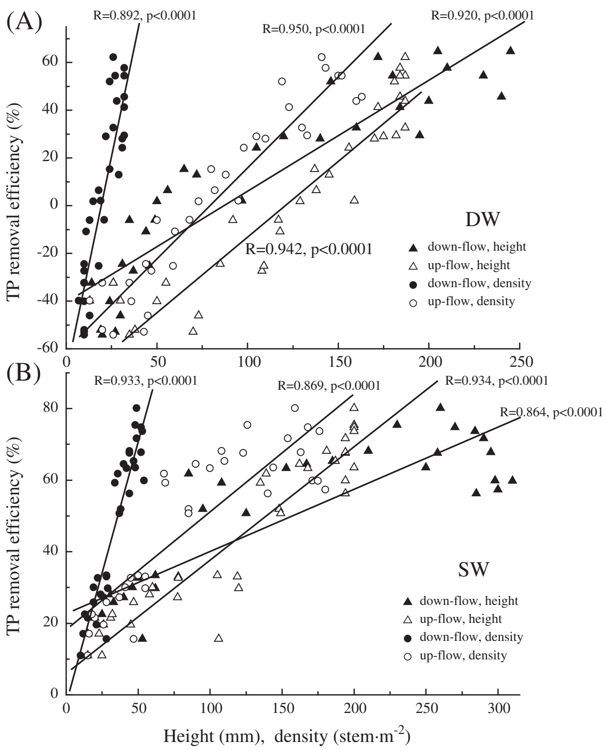

Fig. 3. The correlations between plant growth and TP removal efficiencies of the IVCWs for the treatment of DW (A) and SW (B).

efficiencies (p < 0.0001) were detected for both types of wastewater (Fig. 3).

4. Discussion

4.1. *P* removal performance of the IVCWs

Rapid adsorption and slower precipitation in the material of CW bed are regarded as the main pathways for *P* removal [7,8,28]. Greatly, effective initial TP removal just maintained 10 d approximately and drastic declines were followed for both types of wastewater. It might probably be resulted from that adsorption, the principal mechanism for *P* retention at this stage, reduced sharply due to the sorption sites within the bed might nearly be exhausted as a result of the high *P* LR and inferior *P* adsorption capacity of the gravel. Indeed, adsorption process was reported to just take a low occupation in *P* removal by substrate [29], and declines of *P* removal performance after a short period of loading due to the exhausted *P* sorption capacity of bed media were also observed by other authors [21,29,30].

After that, the relatively steady state of *P* removal might be resulted from that complexation and precipitation reactions with the metallic cations, such as Ca, Fe, Al, and Mg, to form a solid phosphate phase had become the major pathway involved in the *P* removal [31]. Nevertheless, the quantities of these minerals contained in gravel are usually low [20,21,30,32], resulting in a low and extensively varied removal rate of *P*. Besides, media size also plays an important role in *P* removal, with high sorption capacity for fine gravel due to larger surface areas [33]. However, clogging is apt to happen in media with fine size; thus, medium to large sized media was applied in this study, which was another reason for the low *P* removal rate.

The processes of adsorption and precipitation can be saturable and reversible, with the equilibrium broken and shifted when physicochemical and operational conditions were altered [34,35]. Therefore, at the beginning of the period 2, when the influent TP concentrations decreased substantially, negative removal occurred, which meant a rise of *P* content after the wastewater passed through the wetland, due to the desorption and release of some accumulated *P* in period 1 from the bed media. Similar result was also recorded by Sharma et al. [36]. Generally, phosphorus was regarded as one of the pollutants most difficult to be eliminated by CWs especially for matured systems [8,37].

In spite of the seemingly saturated status of the bed media at the end of period 1, it was out of our expectation that substantial *P* was still removed by the CWs during period 2 with plant acclimatization and growth. Other *P* removal pathways except adsorption and precipitation, such as assimilations by plant, algal and micro-organisms, storage in humic substances, sedimentation, chemical accretion, and weathering of the minerals [7,11], can enhance the *P* retention capacity of a CW and extend its lifespan [29], although materials with high *P* binding capacity is still required to be used to achieve satisfactory *P* removal performance.

On the whole, the *P* removal performance of the IVCWs was unsatisfactory and fluctuated greatly since the wetlands were not specially designed for *P* retention. Line et al. [38] also reported that the *P* reduction efficiency of a CW in North Carolina, USA treating storm water ranged from −95 to 70%. Nevertheless, concerning the CWs employing gravel as substrate, the TP removal performance obtained in this study were comparable to the values reported in other references (Table 3).

4.2. The role of vegetation development on TP removal performance of the IVCWs

Apart from the adsorption and precipitation of *P* in the material of CW bed, the role of plant

Table 3
TP removal efficiencies of different CWs employing gravel as substrate

Location	Wetland type	TP removal efficiency	Operation time	Reference
Turkey	Horizontal subsurface flow	Less than 20%	2 years	[21]
Richmond, Australia	Trench	−40–40%	2 years	[14]
Shanghai, China	Horizontal subsurface flow	22.4% (6.8–54.4%)	4 months	[39]
Ankara, Turkey	Vertical subsurface flow	4.3% (−50.1–40.4%)	1 year	[30]
Ain, France	Horizontal subsurface flow	10.3%	30 months	[18]
Cairns, Australia	Surface flow	21–28%	3 years	[40]
Tomar, Portugal	Pot	Around 2–18%	6 months	[41]

assimilation in *P* removal could not be ignored as well. Clear seasonal variations of TP removal observed for both types of wastewater, although not following the temperature fluctuations exactly suggested a dependence of temperature on TP retention, confirming the results reported by other authors [19,42,43], who recorded high *P* removal efficiency in summer and low value in winter. Within a certain scope, high temperature was beneficial to improve *P* retention capacity through favoring precipitation [44], which could partly explain the gradual increase of TP removal rate as the temperature rose since the period 2 and the negative removal during winter.

Furthermore, temperature is also a crucial factor impacting biological processes including plant growth. The contribution of plant uptake to *P* removal was reported to be negligible under high *P* loads [31,41], but it is significant under low loads [11,12,45]. The results of many studies showed significantly higher TP removal efficiency achieved in planted CWs compared with non-planted systems [33,42]. Fast plant development is greatly favorable for *P* retention in CWs. Variations in *P* removal performance of CWs depended on the growth rate of macrophyte greatly [46] and the range of removal validity increased at the presence of plant and microbial biomasses. It was observed that TP removal efficiency of CW during the plant growth was higher than that with fully developed vegetation [47]. The significant correlations between TP removal efficiency and stem height and density of plants of the IVCW systems (Fig. 3) indicated the considerable contribution of vegetation development to TP removal. Mateus et al. [41] and Cheng et al. [48] also found a remarkable benefit of plant development to TP removal in CWs. Accordingly, the faster developed plants in IVCWs fed with SW compared with DW was a part of the reasons for its better TP removal performance during the operational period 2, which meant that the wastewater type might affect plant growth, consequently the contribution of plant to *P* elimination. Except direct uptake, the plant development dynamics can influence the physicochemical conditions and *P* storage and sorption potentials within the CWs through photosynthesis, biomass death, and decay, and then influence the *P* removal performance [42]. In addition, the significantly higher DO and nitrate concentrations in IVCWs dealing with SW (Tables 1 and 2) might increase redox potential within the wetland beds, enhancing chemical precipitation of *P* and hindering it from escaping from the substrate [7,32].

Moreover, algal and micro-organisms also developed alone with plants, contributing to *P* removal through assimilation [11,30,45]. The significant roles of plants and micro-organisms in sediment on *P* removal performance and life expectancy of CW had been verified by some researches [26,45]. Vegetation could influence sediment microbial biomass and communities, and then impact *P* retention performance of wetland.

Nevertheless, it should be noted that the *P* assimilations, by biological processes, were short-term storages and can be returned after decay and decomposition of organisms [11,34]. Consequently, the aboveground plant part was harvested at the end of November 2011 when the plants almost senesced.

The declines of removal rates observed since December during both operational periods (Figs. 1 and 2) might partly be caused by the decreased *P* assimilation capabilities of organisms. The higher outlet TP concentrations than inlet probably resulted from releases of *P* back into wastewater from decomposition of belowground plant litter, micro-organisms and algal [7,8,11]. In these gravel-based systems, almost no *P* could be retained in winter, thus lowering *P* load substantially and/or providing appropriate pre/post-treatment during winter were required for satisfactory *P* removal in CW management.

5. Conclusions

The study provided information on *P* removal capacities of IVCWs employing common gravel as bed media for the treatment of domestic and SW in parallel for about two years, and the major conclusions included:

(1) Significantly different *P* removal performances were obtained for the treatment of DW and SW, indicating that the inflow property was an important factor for CW design and management.
(2) The plant development in the IVCWs was positively correlated with TP removal efficiency greatly and might play a considerable role on TP removal and extending the lifespan of CW system.
(3) Efficient *P* removal was achieved during plant growth, while net *P* export occurred during winter, suggesting that adjusting *P* load and/or providing appropriate pre-/post-treatment in accordance with vegetation development in CW was required.
(4) Although the *P* removal performance of the gravel-based IVCW was not satisfactory, it was comparable to the values obtained in other CWs using gravel as the substrate, and the IVCW can be employed to eliminate a low load of *P*.

Acknowledgments

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