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Pennisetum sinese Roxb and *Pennisetum purpureum* Schum. as vertical-flow constructed wetland vegetation for removal of N and P from domestic sewage

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ABSTRACT

In this study, two bioenergy plants, namely the *Pennisetum sinese* Roxb and *Pennisetum purpureum* Schum., were selected as wetland vegetation to remove nitrogen (N) and phosphorous (P) in vertical-flow constructed wetland (CW) systems. The total net nutrient accumulation by CW plants was 104 g N/m^2 and 7.6 g P/m^2 for *Pennisetum sinese* Roxb, 144 g N/m^2 and 8.71 g P/m^2 for *Pennisetum purpureum* Schum. Three CW systems (System A planting with *Pennisetum sinese* Roxb, System B planting with *Pennisetum purpureum* Schum., and System C without planting) were designed to evaluate total nitrogen (TN) and total phosphorus (TP) removal efficiency from wastewater. Results showed that the removal efficiency of TP from both System A and System B were significantly higher than that of System C, but there are no significant differences of the removal of TN among the three CW systems. After a five-month CW operation, System C was clogged and the TP removal efficiency was negative due to desorption of TP from the substrate. Our study demonstrated that the two newly selected plant species had a positive effect on removing TN and TP from wastewater and reducing clogging in the CW systems.

1. Introduction

Constructed wetlands (CWs) are an effective ecological engineering technology, which rely on biological, physical and chemical processes to remove organic pollutants, nutrients, trace elements, pathogens and other pollutants from wastewaters (Cui et al., 2010; Du et al., 2014). Generally, there are 2 typical types of CWs: (a) surface flow CW and (b) subsurface flow CW, which can be divided into vertical-flow and horizontal-flow. The vertical-flow constructed wetland (VFCW) provides an attractive alternative for treating sewage (Du et al., 2014). Many previous studies have shown that wetland plants (Fu et al., 2013), hydraulic load (Cooper, 2005), temperature, climate (Huang et al., 2009) and microbial activity (Cui et al., 2013) could significantly affect the purification efficiency of wastewater in VFCWs. Nutrient (especially N and P) enrichment of water bodies has become a hot issue in China.

Plants play both direct and indirect roles in removal of pollutants from wastewater in CW systems. Some scientists believe that CWs plants play an important role mainly because plants take up N and P (Xiong et al., 2011; Fan et al., 2013). Plant roots can increase the porosity of the substrate, mitigate clogging, and further increase hydraulic conductivity (Brix, 1997; Hua et al., 2014). However, other studies showed that there is a negative correlation between the plant roots and the hydraulic conductivity of substrate. Tanner (1994) attributed the CW clogging to plant residues. Growing plants in wetlands can take up pollutants as nutrients to supply their growth, but they also release nutrients into soil and water as residuals (Dzakpasu et al., 2014). CW plants typically include cattails, cedar, bamboo, reeds, iris, canna, rushes, and water hyacinth lotus in Chinese inland (Wang et al., 2008). Reeds, wild rice and cattails are more suitable for cold areas, while other species such as water hyacinth showed better performance in warm climates (Wang et al., 2008). The right CW plant species are chosen based on the characteristics of plant growth, their nutrients uptake capacity, and their suitability to local climate conditions.

In our previous study, we have used *Cyperus alternifolius* and *Canna indica* L. as CW vegetation and evaluated their ability for removing nutrients from wastewater (Cui et al., 2009; Cui et al., 2010, 2011). In this study, we selected two new energy plant species, i.e., *Pennisetum sinese* Roxb and *Pennisetum purpureum* Schum. as CW bioenergy plants to examine the uptake and removal efficiency of N and P from wastewater. The *Pennisetum sinese* Roxb, also called grain bamboo grass, is an efficiently economic energy crop, whereas the *Pennisetum purpureum* Schum.,

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also named elephant grass, is one of the good forage plants in tropical and subtropical regions. *Pennisetum* species, as bioenergy plants, can transform CO_2 and H_2O into non-oxygenated hydrocarbons through photosynthesis, which can be applied for reduction of methanogenesis (Rodríguez et al., 2011). In our preliminary study, we compared the growth status of these two plants, examined the different nutrients uptake by stems and leaves between the different plants, and monitored the N and P removal and porosity of the CW substrate. This study will provide better insights into the effect of the two selected bioenergy plants for nutrients removal and CW clogging reduction.

2. Material and methods

2.1. Vertical-flow CWs setup and operation

Vertical-flow CW systems were set up in mid-March 2014, located at College of Natural Resources and Environment, the 20th test area room, South China Agricultural University (SCAU), Guangzhou, China. Three systems were set up as follows: A System planting with *Pennisetum sinese* Roxb, B System planting with *Pennisetum purpureum* Schum., and C System without planting. *Pennisetum sinese* Roxb and *Pennisetum purpureum* Schum. were selected as CW plants because their growth habits are suitable for subtropical climate, and the plants possess a high yield, short growth cycle, low management costs, eco-effective and high energy return rate (Gao and Zhang, 2013; Ma and Liu, 2012). The schematic diagram of the CW systems and their top surface water distribution pipes system are as shown in Fig. A1 (Supplementary information, Appendix A). The plant samples (more than 100 days of plant growth, stout and without disease) of *Pennisetum sinese* Roxb and *Pennisetum purpureum* Schum. were transplanted into A and B Systems, respectively, with a density of 10 plant/m^2.

2.2. Wastewater irrigation

The wastewater used in this study is the simulated domestic sewage by mixing the follwing components in 400 L tap water: milk powder 70 g, soluble starch 60 g, urea 18 g, $(NH_4)_2SO_4$ 10 g, $MgSO_4$ 6 g, KH_2PO_4 6 g, $NaHCO_3$ 60 g, and the water quality parameters values are as followed: the average values of TN, TP and COD were 40, 4 and 330 mg/L respectively; the variation range of pH and DO values were 6.4–6.7 and 4–6 mg/L. The variation range of suspended solid was 80–100 mg/L.

2.3. Operation and management

Constructed wetlands were set up in mid-March 2014 and started operated on March 28 and ended on September 26. Each system operated at the same hydraulic loading (20 cm/d). The method of wastewater feeding was: From March 28, CWs were pumped continuously with simulated wastewater for 8 h every day, and each system were irrigated at 400 L/d. From April 11, water samples were collected and analyzed once a week. The above-ground biomass (stems and leaves) of CW plants was harvested once a month. The deposition of organic and inorganic solids at the wetland surface leads to a clogging mat (outer blockage) and deposition of solids within pores results in substrate clogging (inner blockage). We conclude that the phenomenon "banked-up water" is from clogging.

2.4. Quality analysis

The wastewater samples of effluent were collected weekly from April to September, 2014. Triplications of effluent samples for each system were stored in polyethylene bottles (500 mL) to measure TN and TP using standard methods (APHA, 1998), and N and P uptake by CW plants were calculated by the formulas showed in Supplementary information, Appendix A. Organic matter in CW substrate is determined by external heating method and potassium dichromate volumetric method. Soil organic matters were oxidized by H_2SO_4 and K_2CrO_4 solution under heating conditions. The rest of the K_2CrO_4 was titrated with $FeSO_4$. The amount of soil organic matters was calculated according to the amount of K_2CrO_4 consumed.

3. Results and discussion

3.1. Growth rate and biomass

Total biomass and average monthly growth rate of *Pennisetum sinese* Roxb and *Pennisetum purpureum* Schum. are shown in Fig. 1. The total biomass and average growth rate of *Pennisetum sinese* Roxb were higher than those of *Pennisetum purpureum* Schum. in May and June. From the beginning of July, the biomass and the growth rates of *Pennisetum purpureum* Schum. were gradually higher than those of *Pennisetum sinese* Roxb. The biomass of two plants in September was decreased as compared to August. This occurred because the temperature and humidity in September were relatively lower. Monthly harvesting can effectively separate the nutrients from the CW systems and promote the development the CW plants.

3.2. N and P uptake by wetland plants

The nutrients distribution patterns can be summarized as follows: leaf N concentration > stem N concentration and stem P concentration > leaf P concentration (Table 1). There were significant differences in N and P concentrations of different plant tissues. These two CW plants sustain their own growth by taking up N and P in CWs. Table 1 compares the N and P uptake by the

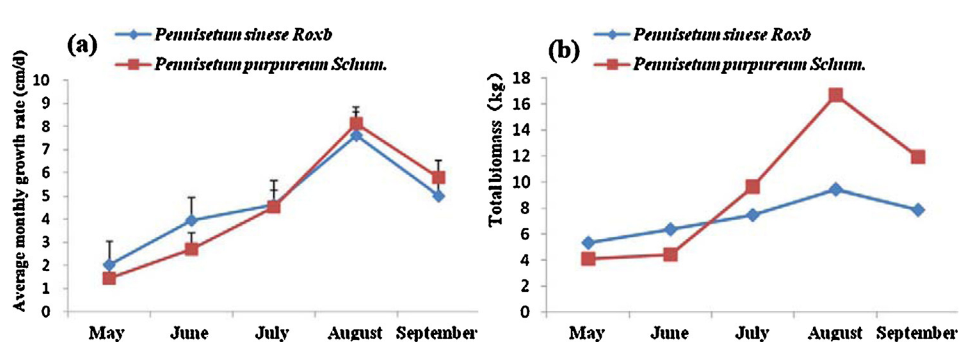

Fig. 1. Two selected wetland vegetation growth rates (a) and biomasses (b).

Table 1
Comparison of the N and P uptake by *Pennisetum* species and other CW plants.

Plants	Stem			Leaf		N uptake (g/m^2)	P uptake (g/m^2)
	N (g/kg)	P (g/kg)		N (g/kg)	P (g/kg)		
Pennisetum sinese Roxb	17.38 ± 3.64	2.4 ± 0.52		34.01 ± 5.66	2.1 ± 0.10	104	7.6
Pennisetum purpureum Schum.	20.3 ± 4.04	2.5 ± 0.79		36.98 ± 2.22	1.9 ± 0.09	144	8.71
Phragmites communis	13.66	3.32	–	29.14	4.55		
Sparganium stoloniferum	–	–	–	22.99	5.07		
Typha orientalis Presl	11.66	3.59	–	25	4.97		

Pennisetum species with other CW plants (Liu et al., 2012). It is apparent that the N uptake by the stem and leaf of *Pennisetum* species is higher than the other three CW plants, while the P uptake is relatively lower. Planting *Pennisetum sinese* Roxb and *Pennisetum purpureum* Schum. as CW plants can uptake the nutrients from wastewater to promote their growth. The total net nutrient accumulation by CW plants was 104 g N/m^2 and 7.6 g P/m^2 for *Pennisetum sinese* Roxb, 144 g N/m^2 and 8.71 g P/m^2 for *Pennisetum purpureum* Schum. The N and P uptake by *Pennisetum purpureum* Schum. were higher than that of *Pennisetum sinese* Roxb due to the fact that the biomass of *Pennisetum purpureum* Schum. was larger than that of *Pennisetum sinese* Roxb, which can be observed in Fig. 1b.

3.3. N and P removal by vertical-flow CWs

The removal efficiencies of N and P in different CW systems are shown in Fig. 2. As shown in Fig. 2a, the three CW systems showed a similar trend on TN removal and no significant difference was found between the systems with planting and without planting. Generally, N removal was mainly attributed to the effect of CW substrate, and the effect of the CW plants on removal was negligible. The main pathway of N removal in CW substrate was occurred through nitrification–denitrification (Hu et al., 2012). The N removal efficiency in these three CW systems was about 50–70%. The high removal efficiency of TN in this experiment might be attributed to the higher temperature in summer, resulting in higher microbial activities. Temperature indeed has a great effect on the nutrients removal efficiency of CWs (Fan et al., 2013).

Phosphorus removal efficiency from the three CW systems is shown in Fig. 2b. The P removal of the three CW systems showed a consistent decreasing trend at the initial stage (from April 11 to June 13) and different trends after June 13. After August 15, the P removal efficiency patterns from the three CW systems were in the following order: B > A > C, and showed a significant difference in September 12 ($p = < 0.01$). It was in about September that C system was suffered clogging, and the P removal efficiency appeared to be negative. That is, the TP value in effluent was larger than that in influent water, and some soluble P would release from the substrate. Clogging did not occurred in planting systems (A and B), indicating that CW plants played a critical role in reducing clogging. The expansion of plant roots can enhance the effective porosity of the substrate and benefit to avoid clogging. It is suggested that *Pennisetum purpureum* Schum. and *Pennisetum*

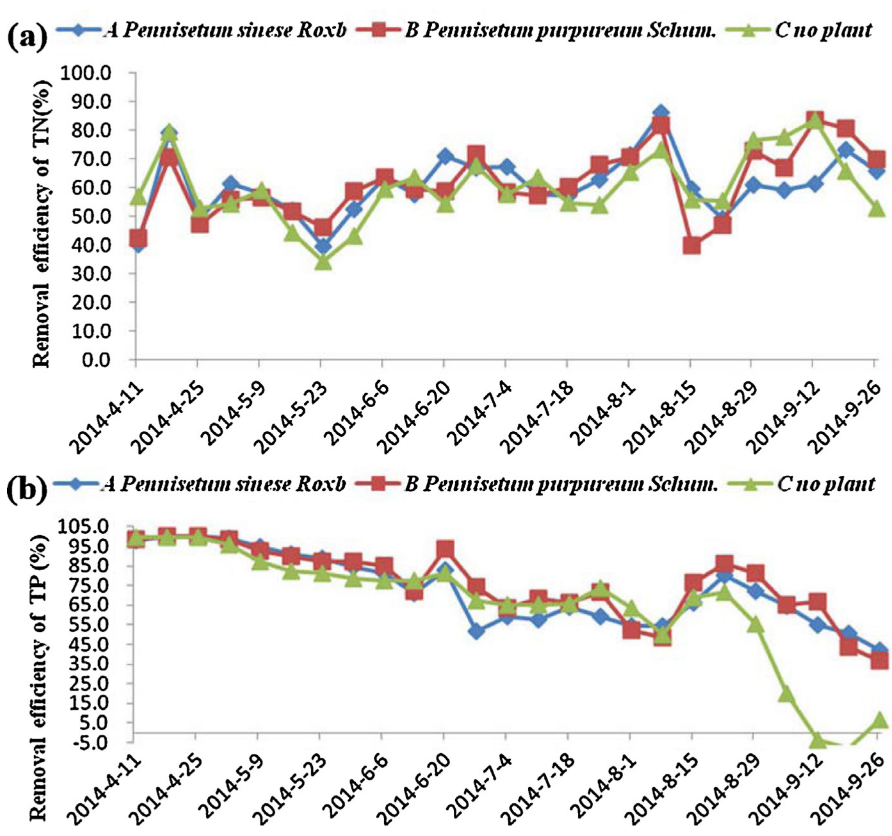

Fig. 2. N (a) and P (b) removal efficiencies by vertical-flow constructed wetlands.

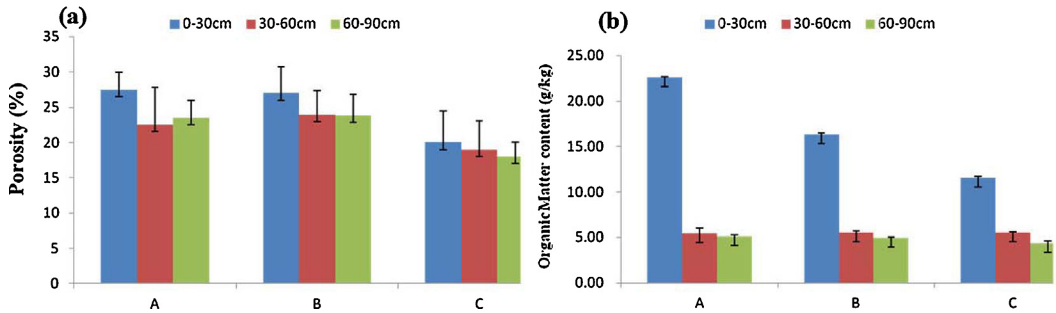

Fig. 3. Porosity (a) and organic matter content (b) in the different layers of the three systems Overall, A System and B System are better than C System on pollutant removal and clogging reduction. No CW clogging occurred for A and B systems during the experiment, while C System suffered clogging in early September. Therefore, the CW plants used in this study played a crucial role in the reduction of pore clogging.

sinese Roxb as CW plants had significant benefits in treating wastewater. The finding in this study was consistent with the literature report (Menon and Holland, 2013).

This occurred because N was removed through nitrification and denitrification in the CW substrate, which is conducive to the N removal. The P was mainly removed by substrate adsorption and microorganisms consumption. In addition, the ammoniation of organic N would produce NH_4^+, and NH_4^+ can affect the electrolyte concentration in substrate, which will further affect P adsorption and desorption through the surface potentials of the substrate particles (Xia and Gao, 1993). The CW plants played a significant role in promoting N removal. The efficient P removal is not attributed to the uptake by CW plants. Presumably P was mainly removed by substrate adsorption, in the process of which the CW plant played an important role by loosening the substrate with their roots, thus promoting the adsorption of P by CW substrate.

3.4. Porosity and organic matters in CW systems

Substrate porosity variation after a six-month (from March 28 to September 26) CW operation are shown in Fig. 3. Clogging occurred in C System in early September and the three CW systems showed a general porosity variation trend with CW substrate depth as: 0–30 cm > 30–60 cm > 60–90 cm. The reasons for this variation are that the microbial activity decreased as CW substrate depth increased. Porosity of planting systems (A and B) was higher than that of no planting system (C) due to the extension of plant roots. The roots loosed substrate and created increased porosity, and reduced clogging. This finding was consistent with the previous literature reports (Brix, 1997; Hua et al., 2014).

Fig. 3 shows the organic matter change in the three CW systems. At the end of the experiment, the organic matter content in A system was higher than that of the other two systems. The organic matter content in the substrate decreased as substrate depth increased and was in the following order: A System > B System > C System. These results showed energy plants can improve the accumulation of organic matter, and the *Pennisetum sinese* Roxb root system may be beneficial for organic matter retaining.

Overall, A System and B System are better than C System on pollutant removal and clogging reduction. No CW clogging occurred for A and B systems during the experiment, while C System suffered clogging in early September. Therefore, the CW plants used in this study played a crucial role in the reduction of pore clogging.

4. Conclusions

This study aimed at evaluating the ability of *Pennisetum sinese* Roxb and *Pennisetum purpureum* Schum. as CW vegetation to improve removal of TN and TP from wastewater and reducing clogging. The total net nutrient accumulation by the two CW plants showed a potential for the uptake of N and P in the wetland system. The porosity performance of substrate in the planting systems is better than those without planting system. The two newly selected plant species had a positive effect on removing TN and TP from wastewater and easing the porosity reduction in the CW systems. Overall, *Pennisetum sinese* Roxb and *Pennisetum purpureum* Schum. are the promising constructed wetland plants for treatment nutritive water.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2015.06.011.

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