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Enhancement of surface flow constructed wetlands performance at low temperature through seasonal plant collocation

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HIGHLIGHTS

- Seasonal plant collocation wetland system performed well at low temperature.
- Plant growth and plant uptake were sustainable during the year-round experiment.
- DO and ammonia oxidizing bacteria were enriched benefitting from plant collocation.

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ABSTRACT

In the present study, a novel seasonal plant collocation system (SPCS), specifically the *Potamogeton crispus* and *Phragmites australis* series system, was investigated to enhance the performance of surface flow constructed wetlands (SFCWs) at low temperature. Results of a year-round experiment showed that SPCS conquered the adverse effect of low temperature and achieved sustainable nutrients removal. In addition, during winter, removal efficiencies of NH_4-N, TP, COD, and TN in SPCS were 18.1%, 17.6%, 10.1% and 5.2% higher than that in the control, respectively. *P. crispus* and *P. australis* complemented each other in terms of plant growth and plant uptake during the experiment period. Furthermore, it emerged that *P. crispus* could increase the quantity of ammonia oxidizing bacteria by 10.2%, due to its high oxygen enrichment ability. It is suggested that seasonal plant collocation has a promising future in SFCWs of areas being affected by climate change, e.g. northern China.

1. Introduction

Constructed wetlands (CWs) are engineered systems that enable natural treatment processes to occur within a more controlled environment. They have been widely used for wastewater treatment because of their ability to remove nutrients, organic matter, pathogenic bacteria and other pollutants (Wu et al., 2016). Compared with conventional purification systems, CWs are economical, easy to operate and maintain (Li et al., 2014). Removal of contaminants in CWs is highly dependent on the combined effects of filtration, sedimentation, plant absorption and complex microbial processes. These include the biodegradation of organics, nitrification–denitrification of nitrogen, uptake of nitrogen and phosphorus and adsorption of phosphorus, etc. (Ávila et al., 2015; Wu et al., 2016).

Unlike other traditional wastewater treatment processes, CWs are man-made nature systems, which are subject to changes in seasonal temperature (Rai et al., 2015). Previous studies have shown that treatment performance of CWs clearly declined obviously at low temperature (Bojcevska and Tonderski, 2007; Wang and Li, 2015). Wang et al. (2012a,b) reported that removal efficiency of ammonia nitrogen (NH_4-N), total nitrogen (TN) and total phosphorus (TP) declined by 15%, 45% and 16%, respectively, in cold winter compared to that in warm seasons in a long-term study of a two-stage surface flow constructed wetland (SFCW). Common thermophile plants (e.g., *P. australis* and *Arundo donax*) in CWs are in a state of senescence at low temperature, which leads to weak metabolism (Van de Moortel et al., 2010). As a result, both plant nutrient uptake rates and the microbial quantities around plant roots declined. Moreover, microbial activities can also be

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depressed when at low temperature. Various studies on wastewater treatment reported that both nitrite and nitrate bacteria were strongly inhibited below 10 °C (Kim et al., 2006; Randall and Buth, 1984), which led to poor efficiency in nitrogen removal. Thus, in the regions like northern China, strategies should be studied and implemented to enhance treatment efficiency of CWs at low temperature. Doing so will make it possible to overcome the fluctuations in performance that are caused by climate change.

To date, strategies for improving CWs treatment efficiency at low temperature have mainly concentrated on optimizing hydraulic loading, psychrotrophic bacteria selection, and insulation. Zhang et al. (2006) reported that removal efficiencies of NH_4-N and COD of a wetland when treating polluted river water in winter increased from 14% to 39% and 20% to 31%, respectively, when hydraulic loading rate decreased by 50%. However, all the above methods have some disadvantages. Low hydraulic loading could improve wastewater treatment efficiency in winter, but at the cost of reduced treatment capability. Psychrotrophic bacteria have poor competitive ability in wetland, and insulation measurements can be costly. It is therefore critical and urgent to develop an efficient and economical method to improve CWs' performance at low temperature.

Plants are essential structural components of CWs, and play an important role in wastewater treatment because of their uptake, storage, and release processes. Koottatep and Polprasert (1997) reported that plant uptake contributed 43% of the TN removal in a study that explored the role of plant uptake in nitrogen removal in wetlands. Greenway and Woolley (2000) also reported that plant uptake accounted for 44%–65% of TP removal in a study on plant biomass and nutrient removal in a wetland. Wetland plants show significant differences in physiological properties. Many thermophilous plants (e.g. *P. australis* and *Acorus calamus*) decline in winter while many cold-resistant plants (e.g. *P. crispus* and *Ceratophyllum demersum*) are still growing. A submerged and emergent plants collocation system, which consisted of *P. australis* and *P. distinctus,* was proposed by Weisner et al. (1994) to study the characteristics of organic carbon release in the system. They found that the removal of nitrogen improved theoretically. Liang et al. (2011) compared monoculture and mixed wetlands, and observed that mixed wetlands had significant advantages in terms of treatment performance, adaptability for seasonal variations, and abundance of microbial populations compared to monoculture wetlands. However, no study has to date reported using seasonal submerged and emergent plants collocation to enhance the treatment performance of SFCWs at low temperature.

Therefore, the aim of this study was to evaluate the efficiencies of seasonal plant collocation system (SPCS) for intensifying pollutants removal, focusing on low temperature condition. In addition, the mechanisms of nutrients removal in the SPCS were studied as well.

2. Materials and methods

2.1. Experiment setup

The experiment was conducted under a transparent rain shelter in Baihua Park in Jinan, northern China (36°40′36″N, 117°03′42″E). The climate is characterized by annual precipitation of 670.7 mm, and the highest temperature is above 35 °C in summer while the lowest temperature can reach below 0 °C in winter. The experiment period lasted from March 2, 2015 to January 31, 2016. In February 2016, which is generally known as the freeze-up period, the experiment was stopped.

P. crispus, one of the common submerged plant species found in north China, was used for this study. Ye and Guo (2011) constructed a series of water purification wetlands with winter vegetation, and *P. crispus* indicated a continuously purification effect in winter. The SPCS comprised *P. crispus* and *P. australis* in a series, while normal plant composition system (NPCS), acting as the control was planted using only the *P. australis* species. Each system was composed of two units in a series, and each unit was constructed by plexiglass with the following dimensions: 100 cm height, 90 cm length and 60 cm width (Fig. 1a). Dimensional gradation substrate was used in the treated units: a 10 cm bottom layer of gravel (1–2 mm in diameter) and a 30 cm top layer of washed river sands (1–2 mm in diameter). In SPCS, the first treated unit (FTU) was planted with *P. crispus* and the second treated unit (STU) was planted with *P. australis*, while both treated units were planted with *P. australis* in NPCS (Fig. 1b). *P. crispus* and *P. australis* were planted at a density of 120 rhizomes per square meter and 45 rhizomes per square meter, respectively. All plants were transferred from Xiaomei River wetland, Liaocheng, China. After planting, the systems were fed with low concentration of wastewater and stabilized for two weeks before the experiment began. *P. crispus* did not survive the summer, so the wilted *P. crispus* was removed in September 9, 2015, and was reseed in September 15, 2015. The systems' influent was met for the water quality: 50 mg/L COD, 5 mg/L NH_4-N, 20 mg/L TN and 1 mg/L TP. All systems were fed continuously with a hydraulic retention time (HRT) of 5d.

2.2. Plant physiology

Plant heights of the *P. crispus* and *P. australis* were monitored every month during the experiment period. In the middle of April, July, October and January, mature leaves of the plants were collected to measure chlorophyll content according to the method reported by Wellburn (1994). Results of the four months represented for the chlorophyll content in spring, summer, autumn and winter, respectively. *P. crispus*'s absorbing capacity for NH_4-N and NO_3-N were tested using hydroponic *P. crispus*, which were cultivated in basins accompanying the purification systems. The experiment parameters and ambient conditions were kept consistent with the purification systems except the static inflow form. On the fifteenth day of each month, 5 plants of *P. crispus* in the basin were taken to the laboratory and tested for absorption rates for NH_4-N and NO_3-N. *P. crispus* was put into a beaker filled with artificial wastewater, and the NH_4-N and NO_3-N concentrations were 5 and 15 mg/L, respectively. A series of solution samples were taken at 5 min intervals for 20 min to estimate NH_4-N and NO_3-N absorption rates, which could be calculated by linear regression analyses of the concentration versus time (Romero et al., 1999).

2.3. Water sampling and analysis

In each system, water samples were collected from the influent and effluent of the treated units every 5 days. After sampling, all samples were then taken to the laboratory immediately and analyzed for NH_4-N, TP, COD and TN following the standard methods (APHA, 2005). Dissolved oxygen (DO) and water temperature were measured at the mid-water depth in situ using a DO meter (HQ 30d 53LED™ HACH USA).

2.4. Microbial analysis

At the end of each season, microbial samples in every unit were collected by collecting sand samples from the top layer (5–10 cm) in five spots in every unit (Wang et al., 2015). MOBIO PowerSand™ DNA Isolation Kits were used to extract the DNA of the mixed substrate of the five sand samples. To characterize the amount of ammonia oxidation bacteria (AOB), the *amoA* genes were detected