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Nutrient removal capability and growth characteristics of *Iris sibirica* in subsurface vertical flow constructed wetlands in winter

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ABSTRACT

Aquatic plants easily wither and go into dormancy in winter when temperature is extremely low. Little is known about nitrogen and phosphorus uptake by plants and its role in removing nutrient in constructed wetlands (CWs). Investigating the performance of CWs planted with overwintering plants and selecting out which plants will support an effective CW over the winter period are important. In this study, microcosmic subsurface vertical flow constructed wetlands (MVFCWs) were planted with *Iris sibirica* for treating simulated polluted river water and evaluated for nutrient removal, plant growth characteristics and plant nutrient uptake under different nutrient concentrations. Treatment performances indicated that the highest average total nitrogen (TN), ammonia nitrogen ($NH_4{}^+$-N), total phosphorus (TP), soluble reactive phosphorus (SRP), and chemical oxygen demand (COD) removal efficiencies were obtained in MVFCW units with medium nutrient (10–16 mg/L TN, 7–10 mg/L $NH_4{}^+$-N, 1.8–2.5 mg/L TP, and 80–120 mg/L COD); the removal efficiencies were 45.8 ± 15.4%, 62.1 ± 8.8%, 57.7 ± 8.3%, 59.1 ± 10.1%, and 39.3 ± 12.1%, respectively. MVFCW units with low nutrient (5–8 mg/L TN, 3.5–5 mg/L $NH_4{}^+$-N, 0.9–1.25 mg/L TP, and 40–60 mg/L COD) exhibited the worst treatment effects. Plant nutrient uptake in the different MVFCW units ranged from 19.86% to 50.19% of N removal and from 13.19% to 22.32% of P removal at the end of experiment. The N and P accumulation ability of the below-ground part of plants was better than that of the above-ground part. The *I. sibirica* plants demonstrated high nutrient uptake in winter, and MVFCWs facilitated a certain degree of nutrient removal. Thus, *I. sibirica* can be considered an effective overwintering plant selection in CWs for restoring polluted river water and potentially be suitable for generalizing elsewhere, especially over the winter period.

1. Introduction

Point and non-point pollution of nitrogen and phosphorous from agricultural, fishing, industrial and municipal drainage have become an increasing concern in many countries, especially developing countries. Excessive release of nitrogen and phosphorus may enter water bodies such as lakes, rivers and lead to undesirable eutrophication of surface waters, which is the most widespread problem to water environment quality around the world (Wu et al., 2011), resulting in serious algal blooms, oxygen depletion and bringing about widespread degradation of freshwater ecosystems. So it is obvious that some appropriate measures should be taken to significantly lower the impacts of nutrient pollution. Although multifarious methods can be utilized to repair polluted rivers and lakes, however, a cost-effective and reliable eco-friendly system of controlling point and non-point pollution can be an alternative (Vymazal, 2005).

The constructed wetland (CW) system is a reasonable option for treating wastewater by simulating natural wetlands, owing to the little reliance on energy inputs, lower cost, and fewer operation and maintenance requirements (Jing and Lin, 2004; Wang et al., 2012). CWs have been widely utilized to treat various types of wastewater, such as domestic, industrial and agricultural wastewater and landfill leachate. Moreover, CWs have been utilized to treat municipal or domestic wastewater for more than four decades (Vymazal, 2009; Vymazal and Kröpfelová, 2009).

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Macrophytes are considered to be the main biological component of CWs and play an important role in wetland succession and nutrient removal. Not only do they remove nutrients from wastewater and substrates (Mitsch et al., 2005; Hadad et al., 2006; Vymazal, 2011), but they also serve as an intermedium for purification reactions. Macrophytes act as an intermedium for purification reactions by increasing environmental diversity in the rhizosphere and by enhancing a variety of chemical and microbial processes that promote purification efficiency in CWs (Tanner, 2001; Wu et al., 2011). However, reports have indicated that nutrient removal and plant growth are directly or indirectly affected by the climatic conditions and temperature (Jing and Lin, 2004; Vymazal, 2007). Aquatic plants easily wither and go into dormancy in winter when temperature is extremely low (Taylor et al., 2011). Information on the importance of macrophytes and their role in removing nitrogen and phosphorous from polluted rivers water by CWs during winter is limited. Furthermore, little is known about nitrogen and phosphorus uptake by plants over the winter period. Another problem is the uncertain performance of CWs in northern areas, where the temperature is low in winter and high in summer, and varies greatly from season to season, also between day and night. Therefore, research on the performance of CWs planted with overwintering plants, nitrogen and phosphorus uptake by plants during winter and which plants will support an effective CW over the winter period are crucial for the improvement of treatment effects.

CWs have four main types: free water surface flow wetlands, horizontal subsurface flow constructed wetlands (HFCWs), vertical subsurface flow constructed wetlands (VFCWs), and hybrid systems that incorporate surface and subsurface flow constructed wetlands (Vymazal, 2002, 2007; Hijosa-Valsero et al., 2011). Compared with HFCW systems, VFCW systems usually require smaller footprint. VFCWs with unsaturated flow demonstrate better oxygen transport ability than HFCWs (Liu et al., 2012). Zhang et al. (2009) also indicated that in a VFCW system, mostly aerobic conditions provide the ideal environment for oxygen-requiring nitrifying bacteria and nitrification can be achieved in these systems. In addition, VCFWs have high hydraulic load rates, are good in removing nutrients in any season (Brix and Arias, 2005).

The *Iris sibirica* is a flowering plant species in the family Iridaceae. It is native to Northeast Turkey, Russia, and Eastern and Central Europe. *I. sibirica* is a rhizomatous herbaceous perennial that can grow from 50 to 120 cm (20–47 in.) tall. Its glaucous green, blade-shaped, narrow and fairly rigid leaves are 40–80 cm (16–31 in.) long and 2–4 cm broad. Its flowers are typical of an iris; they bloom in late spring or early summer on unbranched or sparsely branched stems above the leaves. Each flower measures 4–7 cm in diameter and is mid-blue to purple-blue in color, often with a pale whitish or yellowish center (http://en.wikipedia.org/wiki/Iris_sibirica). The *I. sibirica* is the four season's evergreen plant and more resistant to low temperature than other species of iris (e.g. *Iris pseudacorus*) (Wang et al., 2012). It has well root systems and high survival rate, and can be applied to CWs treating polluted water.

In this paper, microcosmic (lab-scale) subsurface vertical flow constructed wetland systems (MVFCWs) were constructed and planted with *I. sibirica* to treat simulated polluted river water with different nutrient concentrations in winter. The main objectives of this study are (1) to assess the performance of VFCWs planted with *I. sibirica* in the treatment of nutrients, such as nitrogen and phosphorous; (2) to evaluate the growth characteristics, biomass, and nitrogen and phosphorous accumulation of the *I. sibirica* at different nutrient concentrations; and (3) to provide information on which plants will support an effective CW over the winter period and provide reference for plant selection in CWs at northern areas, where the temperature is low in winter and high in summer.

2. Materials and methods

2.1. Experimental wetland system

2.1.1. Experimental setup and design

The experimental site is located in a transparent rain shelter at the Institute of Environmental Sciences of Zhengzhou University, Northern China (112°42′–114°14′ E, 34°16′–34°58′ N). The microcosmic wetland systems were designed in a subsurface vertical flow style. MVFCWs were divided into two groups to better investigate the efficiencies of nutrient removal and plant growth characteristics. The first group (U1–U3) was utilized to study the treatment effects of water quality at different influent concentrations (U1: high nutrient; U2: medium nutrient; U3: low nutrient). The second group (U4–U6) included the corresponding MVFCW units for the study of the growth characteristics and nitrogen and phosphorous accumulation ability of the plant (U4: high nutrient; U5: medium nutrient; U6: low nutrient). The MVFCW units were constructed with plastic reactors. Each treatment unit had three replicates. Fig. 1a and b presents a general layout of the experimental facility and a schematic cross section of the VFCW unit. The treatment units were 50 cm long, 36 cm wide and 25 cm deep (45 L capacity, surface area of 0.18 m^2). Fig. 2a and b shows the treatment unit and *I. sibirica* plants. Two PVC tubes (D_{10} = 18 mm) with many small holes on one side were placed at the bottom of the treatment units to collect water. Water was directed to the outlet, which is an open valve placed at the bottom of the side to collect water samples. The MVFCW units were filled with fine gravel (D_{10} = 15 mm) at a depth of 4 cm to prevent the clogging of PVC tubes at the bottom. The MVFCW units were then filled with composite filling as the substrate at a depth of 20 cm.

The composite filling consisted of round ceramsite (round ceramsite is used to adsorb N and P), blast furnace-granulated slag (blast-furnace slag is known to adsorb P), soil, and sawdust (sawdust is a carbon source for bacteria) at a proportion of 3:3:2:1. Such a composite filling had good adsorption capacity and demonstrated high effect on the nutrient removal in our practical project as reported in our previous study (Gao et al., 2012). Round ceramsite has an effective size (D_{10}) of 8–15 mm, uniformity coefficient (C_u) of 1.21, and porosity of 31.1%. The parameters of the blast furnace-granulated slag were 1.5–37 mm effective size, 6.44 uniformity coefficient, and 48.2% porosity. Water depth was maintained on the substrate surface. Each filled wetland plastic reactor contained 17.5 L of water. The theoretical hydraulic retention time was approximately 30 h, and approximately 14 L of simulated river water was added every day.

2.1.2. Composition of polluted river water

In order to minimize variability in the experiment, simulated polluted river water was used in the experiment, which was designed and utilized to simulate the characteristics of polluted river water based on Chinese environmental quality standards for different grades of surface water (MEPC, 2002). Table 1 shows the composition and range of the different pollutant concentrations of the influents. The key pollutants of polluted river water were organic matter, ammonia nitrogen, phosphorus, and nitrogen. The "test solution" of simulated polluted river water was prepared with tap water composed of glucose, starch, ammonium chloride, peptone, beef extract, ammonium sulfate, potassium dihydrogen phosphate, sodium carbonate, and microelement solution. All other micronutrients for the normal growth and development of the plant (mg/L): 21Ca, 10Mg, 14S, 0.8P, 0.3Fe, 0.03Zn, 0.01Cu, 0.03Mn, 0.03B, and 0.002Mo were kept at the same level in all the treatments by adding $MgCl_2{\cdot}6H_2O$, $CaCl_2{\cdot}2H_2O$, $CoCl_2{\cdot}6H_2O$, $NiCl_2{\cdot}6H_2O$, $FeCl_2{\cdot}6H_2O$, $Na_2S{\cdot}9H_2O$, H_3BO_3, H_2MoO_4, and $MnCl_2$