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Growth characteristics of six wetland plants and their influences on domestic wastewater treatment efficiency

Li Li[a], Yang Yang[a,b,*], Nora F.Y. Tam[c,**], Lei Yang[d], Xiu-Qin Mei[a], Feng-Juan Yang[e]

[a] Research Center of Hydrobiology, Jinan University, 510632 Guangzhou, PR China
[b] Ministry of Education, Engineering Research Center of Tropical and Subtropical Aquatic Ecological Engineering, Jinan University, 510632 Guangzhou, PR China
[c] Department of Biology and Chemistry, City University of Hong Kong, Kowloon Tong, Hong Kong Special Administrative Region
[d] Department of Marine Environment and Engineering, National Sun Yat-Sen University, 80424 Kaohsiung, Taiwan
[e] China Water Resources Pearl River Planning Surveying and Designing Co. Ltd., 510610 Guangzhou, PR China

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ABSTRACT

Plants are an indispensable component of a constructed wetland; however, the eco-physiological characteristics of wetland plants and their influences on wastewater treatment efficiency are still unclear. In this study, we investigated the growth features of six commonly used wetland plants, namely, *Canna indica* (Ci), *Iris pseudacorus* (Ip), *Pontederia cordata* (Pc), *Cyperus alternifolius* (Ca), *Vetiveria zizanioides* (Vz), and *Pennisetum purpureum* (Pp) that were treated with sewage. After 50 days of treatment, plants treated with diluted sewage, especially Ci and Ip, had a better growth rate than those receiving undiluted sewage. The abilities of different wetland plants to directly take up nitrogen (9.28–17.26 mg g^{-1} DW) and phosphorus (0.89–2.18 mg g^{-1} DW) were species-specific, but within each species, uptake was similar between diluted and undiluted sewage. Total biomass determined the total accumulation of N and P in plant tissues. The removal of pollutants, except nitrate and organic matter, was dependent on both plant species and sewage dilution. The first-order rate constants (K) for nitrate and organic matter were similar between diluted and undiluted sewage. Differences in the removal of nitrate and biochemical oxygen demand among plant species were due to differences in chlorophyll fluorescence, a photosynthetic characteristic, leading to different root lengths. The amounts of oxygen release to the rhizosphere (radial oxygen loss [ROL]) by wetland plant was directly governed by total root biomass and significantly influenced the removal of ammonia and total dissolved phosphorus via processes such as plant uptake and nitrification. The removal of total phosphorus and chemical oxygen demand resulted from the filtration by root systems. A non-species-specific significant positive correlation was found between ROL (12.50–205.25 μmol O_2 d^{-1} g^{-1} DW_{root}) and root porosity (9.95–32.49%). These results suggest that the root features and photosynthetic characteristic of wetland plants are important determinants of sewage treatment efficiency and could be used to select appropriate plants for constructed wetland systems.

1. Introduction

Constructed wetlands are alternative wastewater treatment systems that are low-cost, easy to operate, and require less maintenance than conventional technologies, such as activated sludge processes (Stefanakis et al., 2011). Plants are indispensable components of a constructed wetland treatment system, and the presence or absence of plants is one of the characteristics used to define wetlands. Stottmeister et al. (2003) demonstrated that wetland plants were important for adsorbing and absorbing nutrients from wastewater and substrates, and providing large surfaces for microbial colonization, which enhance the purification ability of the rhizosphere. However, physical-chemical and microbial processes have been considered more important than the presence of plants in constructed wetlands for the removal of pollutants (Brix, 1997). The positive effects of plants in sewage treatment shown in previous studies were mainly based on comparisons between the performance of planted wetland systems and that of unplanted constructed wetland systems (Iamchaturapatr et al., 2007; Gagnon et al., 2012). The role of wetland plants and their significance in wastewater treatment are still under debate.

* Corresponding author at: Research Center of Hydrobiology, Jinan University, 510632 Guangzhou, PR China. Tel.: +86 20 85223445; fax: +86 20 85222101.
** Corresponding author. Tel.: +852 34427793; fax: +852 34420522.
E-mail addresses: muzi_lilly@hotmail.com (L. Li), yangyang@scies.org (Y. Yang), bhntam@cityu.edu.hk (N.F.Y. Tam).

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It is well known that wetland plants can transport large amounts of oxygen to their roots. Most of the oxygen is consumed by respiration within the plant or by microorganisms supported by carbon compounds derived from the plant. Excess oxygen released into plant surroundings is called radial oxygen loss (ROL) (Bedford et al., 1991). ROL is an important feature of the adaptation of wetland plants to anoxic habitats and provides suitable habitats for aerobic, anaerobic, and facultative microorganisms to colonize around the rhizosphere, thereby stimulating aerobic decomposition (Reddy et al., 1989; Chen et al., 2007). Dong et al. (2011) reported that roots utilized 35% and 9% of the released oxygen in the degradation of organic matters and the nitrification of ammonium nitrogen, respectively, while 56% of the released oxygen was used for root respiration. The amount of oxygen released to the rhizosphere is governed by above-ground biomass, rather than the total size of the root system (Wießner et al., 2002). The photosynthetic characteristics of wetland plants also significantly influence oxygen release, which ultimately affects the removal and degradation of contaminants by constructed wetland treatment systems (Huang et al., 2010). The removal rate of total phosphorus (TP), chemical oxygen demand (COD), and the removal rate of total nitrogen (TN) are positively related to photosynthetic rate, ROL, and biomass, respectively (Lai et al., 2012). Root anatomy and physiology, to a certain extent, influences ROL. Previous studies have shown that increases in root diameter are associated with increases in cross-sectional area of internal air spaces, which leads to increases in oxygen transport (Visser et al., 2000; Bezbaruah and Zhang, 2004). Wetland plants that have constitutive aerenchyma tissues in their root systems can increase their root porosity in stagnant, oxygen-deficient conditions, which allows them to increase oxygen transfer (Colmer, 2003). However, plants with fibrous roots that are relatively thin (diameter $\leq$3 mm), such as *Canna indica*, *Pontederia cordata*, and *Vetiveria zizanioides*, have significantly higher ROL, root activity, photosynthetic rate, transpiration rate, and removal rates of TN and TP than plants with thick root (Chen et al., 2007; Lai et al., 2011). It is still unclear whether ROL is an active or passive process in wetland plants, as is the relationship between ROL and photosynthesis, how ROL varies among plant species and how ROL is related to sewage treatment efficiency.

The goals of the present study were to (i) investigate the growth and eco-physiological characteristics of different wetland plants receiving diluted or undiluted sewage; (ii) determine the relationship between ROL and chlorophyll fluorescence (a photosynthetic characteristic), and their roles in wastewater treatment; and (iii) compare the growth characteristics and abilities of different wetland plants in removing pollutants from diluted or undiluted sewage. Six fibrous-root wetland plants, including *C. indica*, *Iris pseudacorus*, *P. cordata*, *Cyperus alternifolius*, *V. zizanioides*, and *Pennisetum purpureum*, were selected. These plants commonly colonize wet areas, such as bogs, ponds and shallow rivers, and widely distribute in tropical and subtropical regions. They are also the most commonly used wetland plants in constructed wetland wastewater treatment systems.

2. Materials and methods

2.1. Experimental design

Six plant species, namely *C. indica* Linn. (Ci), *I. pseudacorus* Linn. (Ip), *P. cordata* Linn. (Pc), *C. alternifolius* Rottb. (Ca), *V. zizanioides* (Linn.) Nash (Vz) and *P. purpureum* Schum (Pp), were collected from a nursery in Guangzhou, China. Each species was planted in a hydroponic culture for three weeks. Tap water was used as the culture medium for the first week. For the following two weeks, the tap water was replaced by 50% Hoagland nutrient solution. The Hoagland solution had the following composition: 2.5 mM $Ca(NO_3)_2 \cdot 4H_2O$, 2.5 mM KNO_3, 1.0 mM $MgSO_4 \cdot 7H_2O$, 0.5 mM KH_2PO_4, 25 μM Fe(II)-EDTA, 22.5 μM H_3BO_4, 0.5 μM $ZnSO_4 \cdot 7H_2O$, 0.25 μM $CuSO_4 \cdot 5H_2O$, 5.0 μM $MnSO_4 \cdot H_2O$, 0.05 μM $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$ (Hoagland and Arnon, 1938). After three weeks of growth, healthy and uniformly sized plants, with an average height of around 20 cm, were transferred to another hydroponic system. In addition, another three plants of each species were dried to a constant weight at 70 °C to determine the initial dry weight.

Twelve square plastic boxes, each with dimensions of 25 cm × 40 cm × 30 cm ($L \times W \times H$), were used as hydroponic systems. In each system, 10 healthy young plants of the same species were transplanted to each box and fixed with a square cystosepiment, the dimensions of which were 25 cm × 40 cm × 0.5 cm ($L \times W \times H$). Each box was filled with 20 L of undiluted or diluted domestic sewage. In addition, two blank controls (BK), without plants but with a square of cystosepiment floating on the water, were irrigated with diluted or undiluted sewage to minimize the impact factors for water purification, such as the mineralization of organic N. The hydraulic retention time was five days, after which the sewage was replaced with another batch of fresh sewage, i.e. the water was completely exchanged every five days. Undiluted domestic sewage was collected from the campus of Jinan University, Guangzhou, China, and contained 22.53 ± 2.81 mg L^{-1} TN, 1.09 ± 0.57 mg L^{-1} nitrate nitrogen (NO_3^--N), 18.26 ± 1.34 mg L^{-1} ammonium nitrogen (NH_4^+-N), 2.31 ± 0.36 mg L^{-1} TP, 1.56 ± 0.26 mg L^{-1} total dissolved phosphorus (TDP), 219.10 ± 17.49 mg L^{-1} COD_{cr}, and 84.12 ± 23.33 mg L^{-1} biochemical oxygen demand (BOD_5). Diluted domestic sewage was prepared by diluting domestic sewage with tap water at 1:1 (v/v) ratio. The measured pollutant concentrations were 14.20 ± 2.68 mg L^{-1} TN, 0.31 ± 0.07 mg L^{-1} NO_3^--N, 10.27 ± 1.79 mg L^{-1} NH_4^+-N, 1.25 ± 0.17 mg L^{-1} TP, 0.76 ± 0.17 mg L^{-1} TDP, 110.44 ± 25.42 mg L^{-1} COD_{cr}, and 36.94 ± 12.54 mg L^{-1} BOD_5. All pollution concentration values represent the mean and standard deviation of 10 sets of undiluted and diluted sewage obtained at 5-day intervals. The plants were kept in a greenhouse receiving natural sunlight, and the mean air temperature during the study was 28.0 °C. Tap water, without any removal of chlorine, was added to hydroponic systems to compensate for evaporation during each 5-day hydraulic retention period. No aeration was used in any of the hydroponic systems. The DO in water was not measured during the experiment but the wastewater containing high concentrations of organic C and nitrogen was smelly and black in color, suggesting that DO in the reactor was maintained at low levels throughout the study.

2.2. Water quality

A 500 mL sewage sample was collected from each system at the end of each five-day retention period. The concentrations of TN, NO_3^--N, NH_4^+-N, TP, TDP, COD_{cr}, and BOD_5 in the samples were measured according to the standard methods for water and wastewater analysis (SEPA, 2002). The root exudates in water was not measured as the concentrations of organic carbon in the present study was much higher than the amounts of dissolved organic carbon (DOC) in the root exudates (Zhai et al., 2013), the effects due to the release of root exudates by plants could be insignificant.

First-order kinetic equations, commonly used to describe the rate of change in nutrient parameters (Sooknah and Wilkie, 2004), were used in this study. First-order rate constants were calculated