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Research Paper

Removal of water nutrients by different aquatic plant species: An alternative way to remediate polluted rural rivers

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ABSTRACT

This study was designed to determine the efficiencies and mechanisms of water nutrient removal via different aquatic plant species as a potential remediation strategy for polluted rural rivers. The results showed that water hyacinth achieved the highest removal efficiency for TN (89.4%) and NH_4^+-N (99.0%), whereas water lettuce exhibited the highest removal efficiency for total phosphorus (93.6%) during the static experiment when water temperature ranged from 28 °C to 36 °C. In the dynamic experiment, the removal efficiency of nutrients by water hyacinth and water lettuce was better than that of *Myriophyllum spicatum*, when the water temperature was in the range of 14–20 °C. In addition, nutrient removal efficiency in ponds with all three aquatic plant species was enhanced by increased hydraulic retention time. Regarding removal mechanisms, the removal of nitrogen and phosphorus by all three aquatic plants primarily depended on plant adsorption. However, the increased removal of nitrogen by water hyacinth and water lettuce was also closely linked to microbial nitrification/denitrification because of the rich root systems of these species compared to that of *Myriophyllum spicatum*. Therefore, this paper presents a promising technology for *in situ* remediation of severely polluted rural rivers in developing countries, and will serve as a reference for the use of a combination of aquatic plants to mitigate different water quality conditions.

1. Introduction

As the economy rapidly develops, the speed of the integration of urban and rural areas continues to increase, leading to unprecedented inputs of inorganic and organic pollutants into rural rivers (Conley et al., 2009). In particular, to improve the living conditions of residents of the Yangtze River countryside, flushing toilets have been widely promoted. However, most rural areas lack a complete drainage system and sewage treatment facilities; thus, large volumes of domestic wastewater and fecal sewage treated simply by septic tanks have been discharged directly into rural rivers (Ye and Ying, 2009). Most of the Yangtze River water has been severely polluted because of this mode sewage drainage because of the slow and relatively sealed rural rivers in the southern region of this river (Zhen et al., 2011). Grade V and worse describes the water quality for 14.5% of 62 key lakes (reservoirs), 16% were grade IV, 61% were in grades II–III, and only 8% were grade I (Shao et al., 2014).

Over the past decades, various technologies, including aeration (Xu et al., 2004), water diversion (Zhou et al., 2010), sediment dredging (Koussouris et al., 1989), chemical flocculation (Pan, 2007), chemical algaecide addition (Umphres et al., 2012), and *in situ* chemical reaction techniques (Kanan and Nocera 2008) have been developed for the remediation of rivers polluted by various impurities. However, the deficiencies of these physicochemical methods were obvious, although river pollution could be alleviated to a certain extent. For example, the cost was high for aeration and water diversion, and sediment dredging required numerous workers, in addition to destroying the river ecosystem (Bona et al., 2000). Moreover, secondary pollution brought by chemical agents was inevitable, even though treatment efficiency of the polluted river by adding chemical reagents was obvious (Kanan and Nocera 2008; Umphres et al., 2012). To protect rivers from further deterioration and to improve the environment of rural areas, the need for cost-effective technologies that are suitable for developing countries is urgent.

In recent years, phytoremediation technology has been well studied because of its high efficiency and ecofriendly properties compared to conventional remediation techniques (Wang et al., 2010; Rahman and Hasegawa, 2011; Zhang et al., 2007). Phytoremediation refers to the use of plants to remove and accumulate contaminants from the environment (Ojoawo et al., 2015). It includes the utilization of plants to mitigate, transfer, stabilize, or degrade pollutants in soil, sediment, and water. According to recent studies on biomass of selected plants,

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particularly macrophytes and their rhizomes, offer initial clues on the means of improving the quality of wastewater (Aremu et al., 2012; Mohammed, 2014). According to one study (Brix, 1997), the photosynthetic capacity of aquatic plants to transform molecules, and thus make them available to rhizospheric microorganisms, thereby benefiting from the self-purification of the impacted environment is the basis of phytoremediation. Along with uptake of nutrients and removal of suspended solids in the rooting zone, rhizospheric oxidation by aquatic plants promotes the process of water purification. Oxygen is released by aquatic plants through their stems and leaves into their rhizosphere. The types and mechanisms of oxygen transport are specific to different aquatic plants (Stottmeister et al., 2003). Rhizospheric oxidation drives biochemical reactions, including decomposition of organic compounds and nitrification/denitrification by rhizospheric bacteria, *i.e.*, rhizodegradation/rhizotransformation (Bankston et al., 2002; Schwab and Burney, 1989).

Different applications of phytoremediation have been investigated, and the efficiency of this technology in water treatment (Maggioni et al., 2009; Petrucio and Esteves, 2000; Wang et al., 2002), metal phytoremediation (Mant et al., 2006; Santos et al., 2007), xenobiotic phytoremediation (Rock et al., 2004), and herbicide phytoremediation (Knauer et al., 2008) has been confirmed. Different plant species, such as water hyacinth (*Eichhornia crassipes*), duckweed (water lemna, *Lemna* spp.), water lettuce (*Pistia stratiotes*), vetiver grass (*Chrysopogon zizanioides*), and common reed (*Phragmites australis*), have been used for remediation of polluted river water (Jamuna and Noorjahan, 2009; Lu et al., 2010; Valipour et al., 2011). For example, it was reported that water hyacinth could improve the quality of water surrounding water hyacinth mats (Wang et al., 2012). Moreover, reductions in total dissolved solids (26%), phosphate (33%), and total hardness (37%) were obtained through remediation of polluted water using water hyacinth (Moyo et al., 2013). The great potential of water lettuce to uptake N and P from numerous types of water quality properties has been reported (Lu et al., 2010). A floating aquatic macrophyte system (FAMS) was evaluated in small raceways in central Florida, USA (Desmet et al., 1990). It was found that mean biochemical oxygen demand (BOD) and total suspended solid (TSS) removal performance of the FAMS was 141 kg BOD and 44 kg TSS ha^{-1} day^{-1}. In addition, it was pointed out that nitrogen uptake by mature plants was significantly less than that of young growing plants in full-sized and mature operating systems (Rogers et al., 1991).

Most studies have investigated the remediation efficiency of polluted rivers or wastewater by single plant species; however, researches to understand of the removal mechanisms of water nutrients by different aquatic plant species and remediation of polluted water in rural areas by aquatic plants are needed.

In this study, three kinds of common aquatic plants—water hyacinth, water lettuce, and *Myriophyllum spicatum*—found in the southern region of the Yangtze and possessing a high nutrient removal capacity and rapid growth rate were selected as the experimental subjects. The purification efficiency of water hyacinth, water lettuce, and *Myriophyllum spicatum* was investigated through static and dynamic experiments. Furthermore, the removal mechanisms for major pollutants by the three aquatic species were investigated. The potential of river remediation through small-scale reformation of the existing rivers and ditches in the southern region of the Yangtze River in China was explored, and a reference for the effect of combining aquatic plant species on water quality conditions is provided.

2. Materials and methods

2.1. Experimental aquatic plant system

2.1.1. Experimental location and facility

The experiment performed in Shanghai, China (latitude 31°34.5′N, longitude 121°58′E, altitude 4 m). Shanghai is a typical water town with dense waterways and is part of a subtropical plain, which has a maritime monsoon climate, with a mean annual air temperature of 16 °C. The highest monthly average temperature obtained from many years of observation in Shanghai is 28 °C in July and August, and the lowest is 0 °C in January.

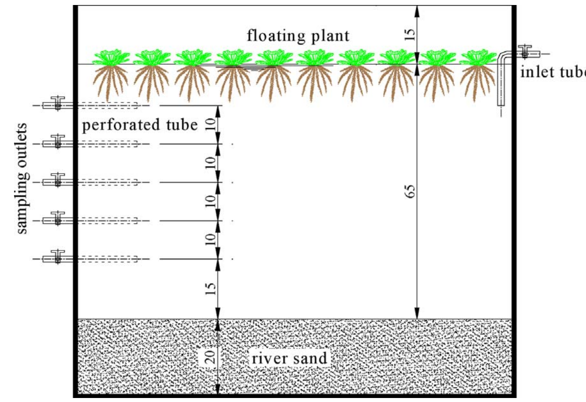

Fig. 1. Setup of the experimental equipment.

The main experimental apparatus consisted of four uncovered PVC water tanks (dimension: length × width × height = 100 × 60 × 100 cm), each with a series of sampling heads set on the side and 20 cm river sand laying on the bottom (Fig. 1). The experimental groups were established by introducing water hyacinth, water lettuce, and *Myriophyllum spicatum* into three separate water tanks, with the fourth tank as the control group, which lacked floating plants.

2.1.2. Plant materials

The water tanks were outdoors with good ventilation and light transmission to mimic the natural conditions of ponds with aquatic plants. Water hyacinth, water lettuce, and *Myriophyllum spicatum* used in this study were taken from a nursery base in Xiaoshan County in Zhejiang Province.

Water hyacinth (*Eichhornia crassipes*) is a typical tropical and subtropical free-floating plant with broad, thick, ovate leaves approximately 15 cm long. Its stem and leaves are emergent, hanging above the surface of the water. It grows well in hot, humid climates and the optimal growth temperature is between 25 and 35 °C. The growth of water hyacinth would be inhibited if the temperature was above 39 °C, and the plant would enter a dormant state if the temperature was in the range of 7–10 °C.

Water lettuce (*Pistia stratiotes*) is a perennial monocotyledon, whose thick, soft leaves form a rosette. It is a floating plant with submersed roots. The leaves are approximately 14 cm long, excluding the stem. The flowers are dioecious and concealed by the leaves. Water lettuce grows in places with a hot, humid climate. It has strong fecundity and is not resistant to cold climates.

Myriophyllum spicatum is a submerged aquatic plant with a creeping stem base and spreading upper section. This plant has branches, and its flowers form in the leaf axils. It prefers hot or low temperatures in humid climates. *Myriophyllum spicatum* can survive winters that lack icing conditions because of its strong cold-resistance capacity.

2.1.3. Experimental setup and sampling methods

The experiments began in May 2016 and ended in November 2016. The operational phases of the experiments were:

I) The static experiment began on May 19, 2016 and was completed on August 10, 2016. The average water temperature was 25–36 °C. The standard plant coverage was 80% of the water surface at startup. The initial amounts of water hyacinth, water lettuce, and *Myriophyllum spicatum* were 50, 50, and 100 strains, respectively, with corresponding plant heights of 15, 10, and 50 cm. The