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# Performance of integrated ecological treatment system for decentralized rural wastewater and significance of plant harvest management

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ABSTRACT

A full-scale integrated ecological treatment system (IETS) comprising, in series from inlet to outlet: two biofilters, one surface flow wetland (SFW), and two stabilization ponds, was constructed to treat rural decentralized domestic sewage and swine wastewater. The results showed the IETS had high removal efficiencies for ammonia nitrogen ($NH_4^+$-N), total nitrogen (TN), total phosphorus (TP), and chemical oxygen demand (COD) with average values of 95.7%, 93.0%, 94.6%, and 82.0%, respectively. Incorporation in the IETS of the SFW, vegetated with *Myriophyllum aquaticum*, was found essential in enhancing the wastewater treatment. The abundances of the *amoA* gene of ammonia-oxidizing archaea (AOA) and ammonia-oxidizing bacteria (AOB) within the SFW sediment ranged from $1.69 \times 10^8$ to $2.46 \times 10^9$ copies $g^{-1}$ and from $2.63 \times 10^7$ to $6.90 \times 10^7$ copies $g^{-1}$ dry sediment, respectively. The greatest AOA and AOB abundances, which were observed at the outlet of the SFW, were found to be related to the decreasing $NH_4^+$-N concentrations along the water flow path. The abundance of the *narG* gene was approximately two orders of magnitude greater than that of *nosZ*. Multiple harvests of *M. aquaticum* contributed to 23.7–33.7% of TN removal and 34.2–49.5% of TP removal in the SFW. A plant management practice with a harvesting frequency of once every 20 days yielded the largest amounts of plant biomass and nutrient uptakes. These findings indicated that the vegetation of fast-growing macrophytes such as *M. aquaticum* in IETS was demonstrated to be an effective way for increasing plant uptake of N and P and enhancing microbial nitrogen-transforming activities, which contributed to improve IETS performance in decentralized rural wastewater treatment.

## 1. Introduction

Recently, ecological engineering technologies (EETs) that include constructed wetlands (CWs), soil infiltration treatment systems, and biofilm technology have attracted attention in relation to the treatment of industrial wastewater, storm water runoff, hospital wastewater, domestic sewage, and swine wastewater (Ávila et al., 2013; Liu et al., 2018; Vymazal, 2014). The outstanding advantages offered by EETs, such as efficient removal, low cost, and simple operation management, have stimulated widespread application, especially in rural areas of developing countries (Belmont et al., 2004; Zhou et al., 2009). Considering the substantial variation in pollution intensity of decentralized wastewater, the integration of other treatment practices into CWs is supposed to be necessary for the enhancement of nutrient and organic pollutants removal (Wu et al., 2015; Zhang et al., 2017b).

The selection of appropriate plant species is crucial to the design of CWs because plants contribute vital functions, e.g., direct nutrient uptake, provision of substrates for the growth of attached microbes, release of oxygen and exudates, and reduction of water flow velocity (Tanner, 2001). However, the contributions made by various plant species to both nutrient uptake and nitrogen (N) and phosphorus (P) removal vary markedly. Plant uptake has been observed to contribute significantly to high levels of total nitrogen (TN) and total phosphorus (TP) removal, i.e., 69.5% and 88.8%, respectively (Kyambadde et al., 2004). However, further results have shown that the amounts of N and P removed via harvesting were low and that they did not exceed 10% (Vymazal, 2007). Therefore, plant harvest management could be beneficial for nutrient removal because multiple harvests might be more

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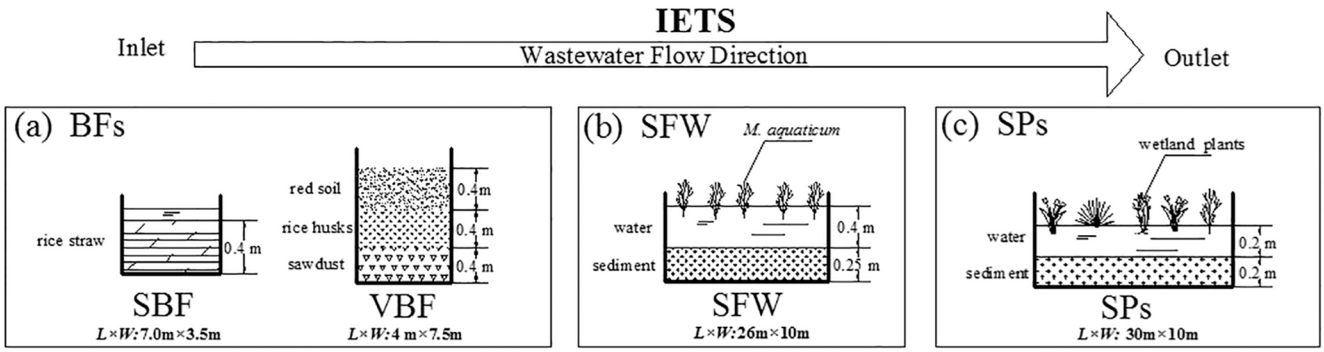


**Fig. 1.** Schematic of the IETS. Each treatment unit is designed in series as follows: two biofilters (BFs) comprising a surface-flow BF (SBF) and a vertical-flow BF (VBF), one surface flow wetland (SFW), and two stabilization ponds (SPs).

effective than single harvesting in removing N and P (Březinová and Vymazal, 2015). Conversely, some studies have suggested that repeated harvesting could reduce long-term nutrient removal efficiency because of the inhibition of plant regrowth caused by excessive harvesting (Tanaka et al., 2016).

Microbial processes in sediments are well known to be major removal mechanisms for N and organic pollutants, and plant vegetation providing a high surface area and carbon substrate for good growth of microbes in CWs can certainly affect the processes such as nitrification and denitrification (Angeloni et al., 2006; Ruiz-Rueda et al., 2009). However, different plant species resulted in the variance of abundance and community structure of nitrifiers and denitrifiers. Higher ammonia-oxidizing archaea (AOA) richness and diversity but lower ammonia-oxidizing bacteria (AOB) abundance is observed with *Iris pseudacorus* compared to *Typha orientalis* (Zhang et al., 2015). To gain further insight into the detailed microbial species involved in microbial N transformations, it was found that *Phragmites australis* with higher relative abundances of *Nitrospira* and *I. pseudacorus* with higher *Denitratisoma* respectively resulted in high nitrification and denitrification intensity (Liu et al., 2016a). Although *Myriophyllum aquaticum* has been improved to have significant effects on ammonia oxidizers and denitrifiers for three strengths swine wastewater treatment in the pilot-scale surface flow constructed wetlands (Luo et al., 2018; Li et al., 2018), the analysis of distribution of functional microorganisms is needed to better understand the N turnover processes for treating rural decentralized swine wastewater in a full-scale integrated constructed wetlands.

Influent loads affect the pollutant removal performance of ecological treatment systems and they should be considered carefully in design/construction of treatment projects (Saeed and Sun, 2012). Livestock farm wastewater is characterized by high concentrations of organic substances, N, and P (Knight et al., 2000), whereas domestic wastewater contains lower concentrations of these key pollutants. It could be an opportune way to reduce pollution intensity and to improve pollution removal efficiencies if livestock sewage were mixed with decentralized domestic wastewater. However, the on-site performance of an integrated ecological treatment system (IETS) to treat the mixed and decentralized domestic and livestock sewage in rural areas requires investigation.

It has been reported that CWs planted with fast-growing *Myriophyllum aquaticum* are effective in treating high-strength swine wastewater (Luo et al., 2017; Zhang et al., 2017b); however, detailed information on maximization of the contribution of *M. aquaticum* to nutrient removal and to distribution of microbial N transformation in the sediment within CWs has rarely been reported. In this study, a full-scale IETS comprising, in series from inlet to outlet, two biofilters (BFs), one surface flow wetland (SFW), and two stabilization ponds (SPs) was constructed to treat rural decentralized domestic sewage and swine wastewater. The present study had three primary objectives: (1) to evaluate the performance of a full-scale IETS during a three-year operating period, (2) to investigate the abundance and distribution of the microbial community within the sediment of an SFW planted with *M. aquaticum*, and (3) to evaluate the effects of different frequencies of harvesting of *M. aquaticum* on the overall performance of the SFW with consideration of the implications regarding CW management.

## 2. Materials and methods

### 2.1. Integrated ecological treatment system setup

In January 2013, an IETS was constructed to treat rural decentralized domestic sewage and effluent from a small livestock farm in a village in Changsha County of Hunan Province (P. R. China). The study site has a subtropical monsoon climate with an average annual temperature of 17.1 °C and average annual rainfall of 1434 mm.

The wastewater was collected and transferred under gravity flow via pipelines into a 19.2 $m^3$ anaerobic lagoon, from which it was allowed to overflow directly into the adjacent IETS. From inlet to outlet, the IETS comprised two BFs, one SFW, and two SPs (Fig. 1). The first wastewater treatment unit comprised two BFs: a surface-flow BF (SBF) with a total water volume of 14.7 $m^3$ and a vertical-flow BF (VBF) with a total water volume of 45 $m^3$. The dimensions of the SFW and of the two SPs were 26.0 × 10.0 × 0.4 m and 30.0 × 10.0 × 0.2 m (length × width × depth), respectively. The SBF was filled with rice straw to a depth of 40 cm, and the VBF was filled with sawdust, rice husks, and red soil from bottom to top each to a depth of 40 cm. These fillers were used to provide a large surface area and a source of carbon for the attachment and growth of microbes (Liang et al., 2015; Liu et al., 2015). The SFW was designed as the core treatment unit for advanced wastewater treatment and reclamation, and it was constructed on a paddy field with 25-cm-deep soil as the substrate. The SFW was planted with *M. aquaticum*, which can grow robustly and rapidly from March to December in subtropical China. With consideration of the local climatic conditions, the first SP was planted with *Ipomoea aquatica*, *Zizania latifolia*, and *Nasturtium officinale*, which are types of aquatic vegetation that have some economic benefits. With consideration of environmental friendliness and aesthetics, the second SP was constructed with *Menyantehes trifolia* and it was used to culture fish. The operational flow regime of the IETS was 10.9 $m^3 d^{-1}$ wastewater at a ratio of about 3:1 domestic to livestock sewage. The theoretical hydraulic retention times were 7, 10, and 11 d in the BFs, SFW, and SPs, respectively.

### 2.2. Water sampling and analysis

From March 2013 to December 2015, the samples in influent and effluent of BFs, SFW, and SPs were collected once per month. The water samples were analyzed for $NH_4^+$-N, TN, TP, and COD. $NH_4^+$-N was measured using an automated flow-injection system (AA3, SEAL, Germany) after the water samples had been filtered through a 0.45-μm

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