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Intensified organics and nitrogen removal in the intermittent-aerated constructed wetland using a novel sludge-ceramsite as substrate

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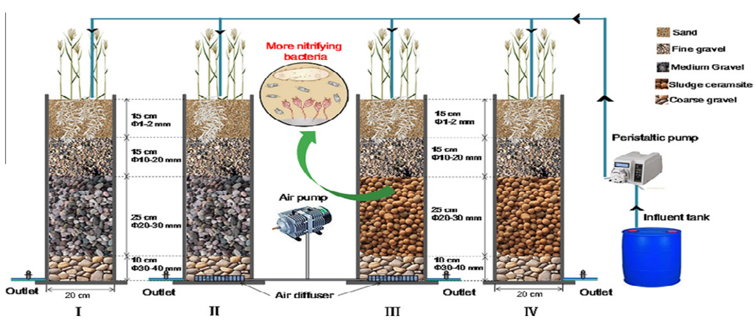
HIGHLIGHTS

- A novel sludge-ceramsite was integrated with intermittently aerated SSF CWs.
- Intermittent aeration and sludge-ceramsite enhanced organics and nitrogen removal.
- High removal of COD (97.2%), NH_4^+-N (98.9%) and TN (85.8%) were achieved.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, a novel sludge-ceramsite was applied as main substrate in intermittent-aerated subsurface flow constructed wetlands (SSF CWs) for treating decentralized domestic wastewater, and intensified organics and nitrogen removal in different SSF CWs (with and without intermittent aeration, with and without sludge-ceramsite substrate) were evaluated. High removal of 97.2% COD, 98.9% NH_4^+-N and 85.8% TN were obtained simultaneously in the intermittent-aerated CW system using sludge-ceramsite substrate compared with non-aerated CWs. Moreover, results from fluorescence in situ hybridization (FISH) analysis revealed that the growth of ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB) in the intermittent-aerated CW system with sludge-ceramsite substrate was enhanced, thus indicating that the application of intermittent aeration and sludge-ceramsite plays an important role in nitrogen transformations. These results suggest that a combination of intermittent aeration and sludge-ceramsite substrate is reliable to enhance the treatment performance in SSF CWs.

1. Introduction

With globally increasing world population, urbanization and industrialization, environmental problems such as water shortages and pollution have become a serious concern, and thus the pervasive issue of inadequate access to clean drinking water is expected to worsen in coming decades (Shannon et al., 2008). Due to less construction and management in wastewater treatment infrastructures, discharging directly large volumes of untreated wastewater into surface water bodies is a common practice in many cities and small towns especially in developing

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countries (Wu et al., 2015a). Consequently, unmanaged wastewater such as the decentralized domestic wastewaters can be a source of pollution (mainly organics and nitrogen), resulting in negative health and environmental consequences such as deterioration of water quality and eutrophication of the lake (Chen et al., 2011; Saeed and Sun, 2012; Wu et al., 2011a). Therefore, besides sewage treatment facilities, ecological treatment technologies have been attracted more attention in these years when facing the strict wastewater discharge standards and the growing environmental legislation (Rai et al., 2013; Li et al., 2014; Ju et al., 2014).

Constructed wetland (CW) as a typical and optimal ecological wastewater treatment, has low costs and can easily be operated and maintained. Thus, CWs have been extensively used to treat a variety of wastewaters such as domestic sewage, agricultural wastewater, industrial effluent, mine drainage, landfill leachate, urban runoff, and polluted river water (Wu et al., 2014; Coban et al., 2015; Doherty et al., 2015). Among the various types of CWs, free water surface (FWS) and subsurface-flow (SSF) CWs are the most commonly used types for wastewater treatment. According to the flow direction the SSF CWs can further be classified into vertical-flow (VF) and horizontal-flow (HF) types (Wu et al., 2015a). It was also reported in numerous studies that CWs could be efficient for removing various pollutants (organic matter, nutrients, heavy metals, pharmaceutical contaminants, etc.) from wastewater (Saeed and Sun, 2012; Tromp et al., 2012; Verlicchi and Zambello, 2014). Among the different types of pollutants, the removal of organics and nitrogen is enormously important because the organics-rich wastewater often depletes dissolved oxygen (DO) concentration in water bodies, leading to the death of aquatic life in freshwater ecosystems.

A number of previous papers indicate SSF CWs can achieve higher organics removal performances compared with FWS CWs. Oxygen is a crucial environmental parameter that controls nitrification and organics biodegradation in CWs, and classical microbiological nitrogen removal reactions are also often restricted by lack of organic carbon in wetland systems (Saeed and Sun, 2012). However, SSF CWs often exhibit limited and fluctuating nitrogen removal efficiency because of insufficient oxygen supply and lack of biodegradable organics (Saeed and Sun, 2012; Wu et al., 2014). Therefore, in order to obtain effective nitrification or to increase the applied wastewater loads, artificial aeration wetland systems have been designed and operated as an alternative of supplement oxygen (Boog et al., 2014; Li et al., 2014). However, some common drawbacks such as increasingly energy inputs, excessive oxygenation and inefficient oxygen diffusion can limit the successful and sustainable application of aeration CWs (Fan et al., 2013a; Wu et al., 2015b). Currently, based on numerous studies on laboratory and pilot scale SSF CWs, intermittent aeration CWs have been proved to be a more cost-effective strategies (Fan et al., 2013b; Boog et al., 2014), because it not only saved operating cost but also greatly increased nitrogen removal efficiency by creating favorable conditions for nitrification and denitrification simultaneously (Foladori et al., 2013; Fan et al., 2013c; Meng et al., 2014). Additionally, compared with the commonly used gravel medium in CWs, researchers have paid considerable attention to other substrates mainly including natural material, artificial media and industrial by-product, and these optional substrates were frequently used for optimizing the removal of nitrogen and organics in CWs in recent years (Wu et al., 2015b). These mixed substrates, such as organic wood-mulch, alum sludge, bentonite, dolomite, wollastonite, activated carbon and light weight aggregates, not only have reactive surfaces for microbial attachment, but also could provide a high hydraulic conductivity and higher porosity associated with better aeration in CWs (Saeed and Sun, 2012). Recently, several investigations have successfully made the porous sludge-ceramsite from drinking-water treatment sludge and wastewater treatment sludge (Xu et al., 2008; Qi et al., 2010), and it has also been demonstrated that sludge-ceramsite can be used in biological wastewater treatment (Zou et al., 2012; Wu et al., 2015c). For example, a novel sludge ceramsite was prepared and employed in the up-flow biological aerated filter for soy protein secondary wastewater treatment, and the results showed that COD and NH_4^+-N removal could be 91% and 90%, respectively (Wu et al., 2015c). However, very little research focuses on the application of sludge-ceramsite substrate for enhancing treatment performance in intermittent-aerated SSF CWs treating decentralized domestic wastewater.

Therefore, the aim of this study was to evaluate the effectiveness of intermittent-aerated SSF CWs with a novel sludge-ceramsite (prepared from dehydrated sewage sludge and clay) for intensifying organics and nitrogen removal simultaneously. Specific objectives of this study are: (i) to evaluate the removal performance of organics and nitrogen in intermittent aeration SSF CWs with sludge-ceramsite substrate for treating decentralized domestic wastewater; (ii) to identify the contribution of intermittent aeration and sludge-ceramsite on enhancing the pollutants removal efficiency in SSF CWs by comparing with common SSF CWs; and (iii) to investigate the influence of intermittent aeration and sludge-ceramsite substrate on the growth of wetland microorganisms, as well as to analyze mechanisms of nitrogen removal in the SSF CWs.

2. Methods

2.1. Characterization of microcosm wetlands

The experiment work was carried out under the transparent rain shelter in Baihua Park in Jinan, northern China (36°40′36″N, 117°03′42″E). Four parallel laboratory-scale SSF CWs designed in a vertical-flow (VF) style (System I: Non-aerated CW; System II: intermittent aeration CW; System III: intermittent aeration CW with sludge-ceramsite substrate; System IV: Non-aerated CW with sludge-ceramsite substrate) were developed (Fig. 1). CW systems, each with a height of 65 cm and an inner diameter of 20 cm, were constructed from a perspex tube with an outlet at the bottom. Multi-dimensional gradation of the substrate was adopted in this study: a 10 cm bottom layer of coarse gravel (3–4 cm in diameter) in each wetland was served as the supporting layer; the following medium gravel or sludge-ceramsite layer (2–3 cm in diameter) as the main substrate layer was filled in each wetland with a depth of 25 cm, above which was a 15 cm fine gravel layer (1–2 cm in diameter); a 15 cm top layer of washed river sand (1–2 mm in diameter) was added for facilitating the dispersion of wastewater and the growth of plants. Specifically, sludge-ceramsite employed in the system III and system IV was made from dried sewage sludge and clay obtained from wastewater treatment plant according to our previous study (Qi et al., 2010; Wu et al., 2011b). Preparation of sludge-ceramsite mainly included the following steps: crushing and screening of raw materials, mixing, dosage, pelletizing and drying, preheating and sintering treatment, and cooling treatment. This sludge-ceramsite had the good physical properties with low bulk, grain density (350 kg m^{-3} and 931 kg m^{-3}) and water absorption (8.2%), and had no potential environmental risks. In addition, the appearance and microstructure (numerous apertures of about 30–60 μm in diameter) of the sludge-ceramsite indicated that it was suitable for the attached growth of microorganisms (Wu et al., 2015c). In CW system II and system III, in order to supply oxygen, the porous air sparger was installed in the bottom supporting layer of each system. Each wetland tub had an average gravel bed porosity of 35% with an average void volume of 6.5 L. In this study, *Phragmites australis* was selected