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Removal of low concentration nutrients in hydroponic wetlands integrated with zeolite and calcium silicate hydrate functional substrates

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ABSTRACT

Nutrient pollution in surface and ground water is one of the world's most widespread, costly and challenging environmental problems, resulting in serious environmental and health issues. This study investigated the removal of low concentration nutrients from synthetic solution simulating slightly nutrient polluted water. Continuous-flow filtration column and hydroponic wetland experiments were conducted to investigate the impact of operating conditions and using zeolite and calcium silicate hydrate (CSH) as functional filtration substrates. The interactions between phosphorus (PO_4^{3-}-P) and nitrogen (NH_4^+-N and total nitrogen) with hydroponic plants, CSH and zeolite at different hydraulic loading rates (HLR) were found to have significant impacts on nutrient removal. During filtration column experiments, CSH was highly effective for PO_4^{3-}-P removal and achieved an average removal efficiency greater than 90%. Zeolite removed more NH_4^+-N than CSH, achieving an average removal of 77%. Longer filtration time improved nutrient removal, and the optimal retention time was found to be 12 h. The wetland testing demonstrated nutrient uptake by hydroponic plants played a major role in removal of PO_4^{3-}-P and NH_4^+-N during plant growth season. Installation of CSH and zeolite functional substrates was critical to ensure stable overall nutrient removal in hydroponic wetlands. The functional substrates provided complementary physical–chemical sorption capacity for PO_4^{3-}-P and NH_4^+-N, especially when the plants uptake varied between growth and harvest seasons. Higher HLR reduced slightly the overall nutrient removal in wetlands. Throughout the testing period of 70 days, hydroponic wetlands showed no advantage in organic nitrogen removal compared to subsurface flow constructed wetlands. The total nitrogen percent removal was below 30% in both wetland units probably due to lack of microbiological activities in the wetlands resulting from low organic matter in synthetic influent water.

1. Introduction

Water quality deterioration has become a significant challenge due to population growth combined with increasing industrialization of land use. Many major rivers in the world have been polluted due to discharge of domestic, agricultural, and industrial wastewaters. Surface water contamination is more severe in developing countries due to intensive agriculture and less stringent discharge regulations. According to the 2013 China Environmental State Bulletin (MEPPRC, 2014), water qualities of seven major water systems, namely the Yangtze River, the Yellow River, the Pearl River, the Songhua River, the Huai River, and the Liao River, were rated as slightly polluted. Some sections of these rivers were rated as highly polluted. In addition, 11.5% of the major freshwater lakes and reservoirs in China were rated as highly polluted, and 26.2% as slightly polluted. Because these rivers and lakes are the primary drinking water sources for nearby towns and municipalities, many water treatment plants cannot provide the product water quality meeting the drinking water standards due to inadequacy of conventional water treatment processes. Total phosphorus and ammonia nitrogen are the major pollutants

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causing compliance challenges (MEPPRC, 2014). There is a pressing need to improve surface water quality and develop cost-effective technologies to remove nutrients in polluted surface water systems.

Ecological technologies such as constructed wetlands represent an innovative and emerging solution for environmental protection and restoration (Zhang et al., 2014). Constructed wetlands have become attractive engineered water treatment systems due to low to moderate cost, simple operation and maintenance, and environmental friendliness. The removal mechanisms in wetlands are complex, involving sedimentation, filtration, precipitation, volatilization, adsorption, plant uptake, and microbial processes (Wu et al., 2014). Contaminant removal efficiency is highly variable and dependent upon wetlands design, configuration, loading rate, temperature, soil or bed substrate types, operation regimes, and redox conditions.

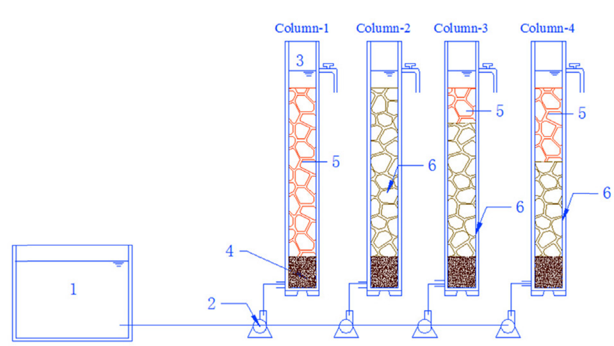
In recent years, subsurface flow constructed wetlands have been used to treat waters with high flow and low concentrations of nitrogen and phosphorus, such as effluent from municipal wastewater treatment plants (Greenway, 2005; Wu et al., 2014; Zhang et al., 2014), and slightly contaminated in-lake river waters (Li et al., 2008; Wang et al., 2012; Wu et al., 2011; Yang et al., 2014). However, the shortcomings of constructed wetlands are gradually revealed during practical applications. Constructed wetlands often show poor removal of nutrients, and the conventional wetland bed substrates such as sand and gravel have limited nutrient sorption capacity (Babatunde et al., 2008; Huett et al., 2005; Iamchaturapatr et al., 2007; Vohla et al., 2011). Thus wetlands often have large environmental footprint. Total nitrogen (TN) removal in constructed wetlands was reported to vary between 40% and 55%, and the removed TN loading rate ranged between 250 and 630 g N m^{-2} per year depending on the type of wetlands and inflow loading rate (Vymazal, 2007). Subsurface flow constructed wetlands often lack improved hydraulic characteristics, thus clogging occurs frequently especially at high loading rates (Hua et al., 2010; Huang et al., 2012).

Recent studies have been focused on understanding wetland bed substrates, plants, and hydraulic characteristics to overcome the limitations of conventional constructed wetlands. Adding functional substrates in constructed wetlands can sorb nutrients and remove suspended solids from water. For example, calcium silicate hydrate (CSH) is an effective sorbent for phosphorus removal (Chen et al., 2009; Li et al., 2011), while zeolite shows excellent removal capacity for ammonium nitrogen (NH_4^+-N) (Jha and Hayashi, 2009; Saeed and Sun 2012; Wu et al., 2006). By utilizing N, P, and other nutrients, plants can uptake these contaminants for plant growth, thereby reducing their concentrations in wetlands (Pan et al., 2007; Shelef et al., 2013; Yang et al., 2008). Some plants can also accumulate salts and phytotoxic elements such as heavy metals in plant tissues. Plants can therefore be used for phytoremediation of salts and toxic heavy metals in saline and polluted waters (Freedman et al., 2014; Salt et al., 1995; Shelef et al., 2012, 2013; Weis and Weis, 2004).

Hydroponic cultivation, the most intensive and effective production method of soilless culture, has developed rapidly to increase agricultural products in today's industry (Putra and Yuliando, 2015). The plant roots are partially or completely dipped in nutrient solution, which is formed by dissolving fertilizers in the irrigation water with an appropriate concentration (Savvas et al., 2013). Recently, hydroponic cultivation has attracted substantial interests for phytoremediation of eutrophic lakes in China, such as DianChi Lake, ChaoHu Lake, and Erhai Lake. Hydroponic cultivation in these lakes facilitates resources recovery due to the high productivity and nutrient removal capability of economic plants (Li et al., 2014).

Although previous batch experiments using CSH as functional substrate demonstrated improved nutrient removal and promoted plant growth by sorption of phosphorus, phosphorus removal did not achieve the same efficiency during continuous-flow constructed wetlands testing (Li et al., 2011). The average phosphorus removal efficiency achieved 97% during bench-scale sorption testing, whereas the removal decreased to approximately 65% during continuous-flow wetland experiments (Li et al., 2011). The main reason for the decline of phosphorus removal in wetland was found due to the negative effect of plants metabolisms on phosphate crystallization. Wetland plants roots release organic acids, which affects phosphate crystallization and precipitation onto CSH. Therefore, CSH should be installed separately from plant roots to avoid negative influence.

In this study, an innovative hydroponic wetland combined with zeolite and CSH as multi-functional substrates was studied to treat synthetic water that simulates surface water with low nutrients concentration. Zeolite, CSH, and hydroponic plants were placed in separate zones to minimize the negative interactions among them, and to improve hydraulic characteristics of the wetland. The study was initiated with bench-scale filter column experiments to investigate the sorption of PO_4^{3-}-P and NH_4^+-N by CSH and zeolite under different filter loading rates. Then the nutrient removal was investigated in two continuous-flow hydroponic wetland (HW) units, HW1 with plant-CSH zones, and HW2 with plant-zeolite-CSH zones, at hydraulic loading rates (HLR) of 0.4 and 0.8 $m^3 m^{-2} d^{-1}$. The study aimed to understand the functions of plants, zeolite



1- influent water tank，2- peristaltic pump，3- filter column，4- graded gravel layer，

5- calcium silicate hydrate，6- natural zeolite

Fig. 1. Schematic of continuous-flow filter column experiments.