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Integrated constructed wetland systems employing alum sludge and oyster shells as filter media for P removal

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ABSTRACT

This research aimed to investigate the technical feasibility of integrated constructed wetland system consisting of a pre-filter unit and a constructed wetland (CW), in series; packed with alum sludge (AS) and oyster shells (OS) as the filter media, respectively, for nitrogen and phosphorus removal from domestic wastewater. Based on the 240 days of operation from January to August 2007, this integrated system was highly effective in removing BOD, N, P and TSS compounds which were found to be 89.5%, 68.8%, 99.4% and 89.9%, respectively. After this period, the integrated system was modified as the CW and post-filter unit, in series. The post-filter of this modified integrated system was operated during 60 days with cover for light shield and during another 60 days with no cover from September to December 2007. The treatment performance of modified integrated system was effective in removing BOD_5, N, P and TSS compounds which were found to be 91.4%, 86.8%, 99.7% and 73%, respectively, during which the post-filter had operated with no cover. To simulate high rainfall conditions, the integrated system was tested under hydraulic shock loading at the overall hydraulic retention time of 0.7 day during one day. This hydraulic shock loading conditions made BOD_5, TN, TSS concentration increase, but made no effect on P concentration. Integrated system combined a pre-filter and a CW unit or a CW unit followed by a post-filter is recommended for use in domestic wastewater which should result in high treatment performance, especially on P removal.

1. Introduction

The United Nations (UN) Millennium Development Goals aim to improve the quality of life in developing countries, including the provision of improved sanitation facilities to at least 2.4 billion people who do not have access to suitable sanitation (WHO/UNICEF/WSSCC, 2000). In this respect, decentralized wastewater treatment systems are being considered as an attractive option to treat wastewater in developing countries and remote areas where centralized wastewater systems are technically inappropriate and not affordable. Even in some developed countries such as the USA, decentralized wastewater treatment systems serve about 25% of the population or over 60 million people (UNEP, 2002).

There have been many attempts to develop decentralized wastewater treatment systems that are economical and ecologically sustainable. Among the various decentralized wastewater treatment systems, the interest in constructed wetland (CW) has been increasing over the past three decades because CW has a flexible design and operational features that can be customized for the treatment of domestic, agricultural and industrial wastewaters (IWA, 2000; US EPA, 2000). On the other hand, many research results pointed out the low efficiency of P removal compared to other parameters such as BOD_5 and TSS in CW systems. Investigations performed on 20 wastewater treatment plants employing CW systems in France found the P removal efficiencies to be 31% in the 1st-stage reed beds and 5% in the 2nd-stage vertical sand filter (Paing and Voisin, 2005). Behrends et al. (2007) reported P removal efficiencies of CW units of 66–93% during the initial operation periods, but these P removal efficiencies were later reduced to less than 10%, due to the saturation of P adsorption capacities of the CW media. Since high P contents in the CW effluent can cause eutrophication problems in the receiving water, there is a strong need to maximize P removal efficiency or to lengthen the effective period of P removal in the CW systems to make them suitable for decentralized wastewater treatment.

Adsorption process is applied to reduce P in CW system for decentralized wastewater treatment. A number of media have been tested as adsorbents such as sands (Arias et al., 2001), slag (Lee et al., 1997), zeolite (Sakadevan and Bavor, 1998), fly ash (Cheung and Venkitachalam, 2000), iron oxide tailings (Zeng et al., 2004), alum sludge (Yang et al., 2006a), oyster shells (Park and Polprasert, 2008a,b) and coagulant precipitates from drinking water treatment

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Table 1
Characteristics of OS and AS after sieving.

	Oyster shells	Alum sludge
	0.6–1.3 mm	0.6–1.3 mm
Bulk density (g/cm^3)	1.01	0.74
Particle density (g/cm^3)	2.13	1.90
Porosity (%)	52.3	60.7
Specific surface area (g/m^2)	1	33

plants (Leader et al., 2005). Alum sludge (AS) which contains high concentration of aluminum is a by-product from drinking water treatment where aluminum sulfate is used as coagulant. Babatunde and Zhao (2007) reported that the content of aluminum in AS was 29.7 ± 13.3% based on dry weight. In several countries, AS is dewatered and disposed of as wastes to landfill sites. Oyster shells (OS), available in abundance on the seashore of some countries; contain high content of calcium (approximately 96% as $CaCO_3$) and P adsorption capacity of 16 g/kg (Yoon et al., 2003; Seo et al., 2005). In case of Korea, shell fish farms cover 4100 ha of coastal ocean and produce approximately 300,000 Mg (Million grams) of OS every year (KDI, 2002). Shell fish farms have been faced with the problems of OS disposal. Crushed OS could be used as an alternative liming material to restore the soil and microbial properties in upland areas and to increase crop productivity (Lee et al., 2008). Using these materials, which are considered as wastes, as P adsorption media in an integrated wastewater treatment system, would be beneficial in saving disposal costs and avoiding the purchase of conventional/commercial media for P adsorption.

To improve the treatment performance, integrated systems which consist of various types of constructed wetlands staged in series have been introduced (Vymazal, 2005). An integrated constructed wetland system employing light weight aggregates (LWA) was to purify a school house wastewater, which has resulted in the BOD removal of 91%, total suspended solids (TSS) removal of 78%, total P (TP) removal of 89%, total N (TN) removal of 63% and ammonia nitrogen (NH_4-N) removal of 77% (Oovela et al., 2007). Seo et al. (2008) reported that an integrated CW system consisting of a horizontal flow (HF), vertical flow (VF) and horizontal flow (HF) units, in series, could remove 95.1%, 68.4%, and 94.3% of COD, TN and TP, respectively.

In this study carried out with a pilot-plant scale, an integrated CW system consisted of pre-filter and CW units, in series, and designed for P removal (called ICONWEP) was developed for use in decentralized wastewater treatment. The objectives of this study were: (a) to investigate performance of the ICONWEP system in treating a domestic wastewater, especially on P removal efficiency; (b) to conduct mass balance analysis of P removal by the ICONWEP; and (c) to test the applicability of CW and filter unit employing OS and AS media, respectively, for integrated wastewater treatment system.

2. Materials and methods

2.1. Adsorption media

OS were collected from an oyster farm near Pathaya city, 150 km east of Bangkok, Thailand. AS was collected from water purification plant of Phathumthani province, 40 km north of Bangkok. These materials were dried, crushed by grinder (Wiley Mills, USA) and sieved to obtain media sizes of 0.6–1.3 mm. Characteristics of sieved OS and AS are shown in Table 1. Bulk and particle density of each media was determined by the method of Blake (1965a,b) and the porosity of each media was calculated from bulk and particle density of each media (Vomicil, 1965). Specific surface area of each media was measured by the ethylene glycol monoethyl method (Heilman et al., 1965a,b).

2.2. Integrated constructed wetland systems of P removal enhancement

A pilot-plant scale ICONWEP unit was constructed at the research station of the Asian Institute of Technology (AIT) campus, located at 40 km north of Bangkok, Thailand. Fig. 1 illustrates the conceptual diagram of system which was operated and monitored for 240 days from November 2006 to August 2007 with a vertical flow pre-filter and a constructed wetland, in series, packed with AS with diameter 0.6–1.3 mm and OS with diameter 0.6–1.3 mm, respectively (called ICONWEP I). The plants growth of this integrated system was poor because of the low concentrations of P in the influent of CW unit due to the P removal by AS pre-filter. Avoiding this problem, this system arrangement was changed as a vertical flow CW unit and a post-filter unit packed with OS with diameter 0.6–1.3 mm and AS 0.6–1.3 mm, respectively (called ICONWEP II). The post-filter unit of this ICONWEP II was operated for 60 days with wood-panel cover for light shield and, after that period, that unit was operated for another 60 days without cover to investigate the difference of treatment performance between those two.

The pre- or post-filter unit, made of polyethylene tank, had a dimension of 63 cm × 45 cm × 40 cm (length × width × depth) and was packed with 20 cm of AS (0.6–1.3 mm) media (equivalent to 42 kg by weight) as the top layer, 10 cm of gravel (4–15 mm) as the bottom underdrainage layer. The AS media with the sizes of 0.6–1.3 mm installed in the filter unit was expected to remove the P mainly through adsorption.

The CW unit, made of polyethylene tank with a diameter of 63 cm and depth of 60 cm (or the volume of 187 L), was filled with 15 cm of coarse sand (0.6–2 mm) as the top layer, 30 cm of OS media with the sizes of 0.6–1.3 mm (equivalent to 94 kg by weight) as the intermediate layer and 15 cm of gravel (4–15 mm) as the bottom underdrainage layer. Cattail plants (*Typha angustifolia* L.) were planted at a density of 16 stems/m^2 in the CW unit. The cattail plants became mature and fully grown with the height of over 2 m after 4 weeks of wastewater feeding. The OS media size of 0.6–1.3 mm were installed in the CW unit to help minimize clogging problems and to enable better contact between the wastewater, plant roots and the OS media. The CW unit was operated as subsurface flow in which there was no free water surface maintained in the CW unit (Fig. 1). A previous study by Park and Polprasert (2008a,b) found the P adsorption capacities of the >0.6 mm AS and OS media to be 12 and 24.5 g/kg media, respectively; hence the amounts of P that could be adsorbed by AS and OS media in the filter and CW units were calculated to be 504 and 2303 g, respectively.

To compare the CW performance, another CW unit packed with OS similar to that of ICONWEP was operated in parallel for 1 year from January to December 2007 and used as control. The control CW unit was fed with the same influent wastewater and subjected to the same operating conditions.

In order to observe the P removal efficiencies and to analyze mass balance of P removal, wastewater of the AIT campus which had the P concentration of 3–4 mg/L and was spiked with KH_2PO_4 at P concentrations of 10–27 mg/L before feeding continuously to the ICONWEP unit at an average loading rate of 26 mL/min, equivalent to the hydraulic retention times (HRT) of 1 day and 2.5 days in the filter and CW unit, respectively, or the overall HRT of 3.5 days (Table 2). The HRT of 2.5 days maintained in the CW unit was slightly lower than the commonly recommended values, but, due to the low-strength characteristics of the AIT wastewater (average BOD_5 concentration of 35 mg/L), resulted in the organic