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Nitrogen removal from sewage and septage in constructed wetland mesocosms using sand media amended with biochar

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ABSTRACT

Biochar has been identified as a media amendment to improve nutrient removal from wastewater, and N retention and plant growth in agroforestry. It therefore has the potential for treating domestic wastewater. The aim of this research was to compare nitrogen removal and plant growth in pure sand and sand amended with biochar, in wetland mesocosms (240 L) receiving sewage. There were seven media treatments based on the proportions of biochar in the sand media (100% sand, sand and coir peat, 5, 10, 15, 20, 25% biochar). The plant species were Paperback tree (*Melaleuca quinquenervia*) and Lemongrass (*Cymbopogon citratus*). The mesocosms were continuously loaded for 8 months with secondary clarified wastewater (SCW) (16 L/day). Septage was then intermittently loaded (20 L/2 days) for a further 8 months. Inflow and outflow samples were monitored for TN, NH_4-N, and NO_x-N.

All treatments showed good nitrogen removal efficiency. Average removal efficiencies of TN, NO_x-N and NH_4-N in the mesocosms loaded with SCW ranged from 71 to 87%, 81 to 93% and 65 to 79%, for 100% Sand to 25% Biochar respectively. For septage, the removal efficiencies ranged from 63 to 81%, 69 to 87% and 66 to 81%, for 100% Sand to 25% Biochar respectively. Significant differences of nitrogen outflow concentrations were observed between pure sand and sand amended with biochar. Physical chemical properties of the biochar would have facilitated microbial processes and adsorption. Strong positive correlations were observed between biochar content in the media and nitrogen removal rates. The increased nitrogen removal may be attributed to higher mineralisation of organic nitrogen and NH_4-N, especially in the case of septage where strong correlation was observed between BOD_5 and TN removal. Total N biomass in the plants harvested after 21 months ranged from 13.4–14.0 g N. The addition of biochar did not increase plant N biomass in either species.

1. Introduction

Constructed wetlands (CWs) are an efficient eco-technology for wastewater treatment with the advantages of low cost, simple operation and maintenance (Kadlec and Wallace, 2008). CWs can be used to treat domestic wastewater to reduce biological oxygen demand, total suspended solids, coliforms and nutrients (Abou-Elela et al., 2013; De Rozari et al., 2015, 2016; Wu et al., 2015). They can be constructed using local materials which reduce construction cost considerably (Lucas and Greenway, 2011a; Zurita et al., 2009). The challenges in this technology are to find local materials which can effectively remove nutrients for a long term application.

Media is an important component of the CWs. It is used to control either the rate of water infiltration or retention time, filter sediments and particulates, provide sorption surfaces for nutrients, provide surface biofilms, and provide a nutrient source for microbes (bacteria, fungi, protozoan, algae) and macrophytes (Kadlec and Wallace, 2008). The majority of nitrogen removal takes place in the media via sorption, and microbial processes including ammonification, nitrification, denitrification, and anaerobic ammonium oxidation (anammox) (Saeed and Sun, 2012). Media also influences the hydraulic conductivity (K_{sat}) and hydraulic retention time (HRT) which are important factors affecting nitrogen removal efficiency (Lucas and Greenway, 2011b; Zhang et al., 2015). Better removal efficiency of nitrogen is correlated with low infiltration and/or slow hydraulic conductivity (Davis et al., 2006; Lucas and Greenway, 2011a).

Several studies have focused on nitrogen (N) removal using different media (e.g., Millot et al., 2016; Wu et al., 2015; Zhang et al., 2012; Zurita et al., 2009). Zhang et al. (2015) reviewed the performance of CWs in tropical and sub-tropical regions and concluded that the media

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significantly affected the removal efficiencies of TN, NH_4-N, and NO_3-N in vertical flow constructed wetland (VFCW) systems.

Removal efficiency may be enhanced by augmenting sand or gravel media with other material that may facilitate nitrogen removal. Since biochar has high organic carbon content, this material can serve as a soil conditioner to improve the physicochemical and biological properties of the soil. Mohan et al. (2014) reported that biochar added into the soil could increase nutrient availability, microbial activity, soil organic matter, water retention and crop production. In laboratory scale, Gupta et al. (2015) compared the efficiency of biochar media made from Oak tree (*Quercus sp*) and gravel in CWs planted with *Canna sp* for nitrogen removal from synthetic wastewater. The results showed that nitrogen removal was higher in the CW with biochar media. Kizito et al. (2017) compared the nitrogen removal efficiency in vertical flow (VF) columns loaded with anaerobic digested effluent. They reported that columns packed with biochar media (from corn cob and wood biochar) performed significantly better than those packed with gravel media. Zhou et al. (2017) also reported that biochar made from bamboo enhanced the nitrogen removal efficiency in aerated VFCW systems compared to gravel systems. Therefore, biochar may be a suitable amendment to enhance nitrogen removal in CWs. However, the findings reported in the literature are mainly based on laboratory scale experiments under laboratory controlled conditions and in many cases used synthetic wastewater (Kizito et al., 2017; Sarkhot et al., 2012; Yao et al., 2012; Gupta et al., 2015; Zhou et al., 2017). Our study investigated the nitrogen removal efficiency in vertical flow mesocosms using sand media augmented with biochar planted with two plant species *(Melaleuca quinquenervia* and *Cymbopogon citratus*) under field environmental conditions and using domestic wastewater from both secondary clarified wastewater (SCW) and septage. This paper compares (1) hydraulic conductivity, (2) nitrogen removal (TN, NH_4-N and NO_x-N), and (3) N uptake in 2 plant species *(Melaleuca quinquenervia* and *Cymbopogon citratus*) in pure sand media and sand media augmented with biochar.

2. Methods

2.1. Experimental design

The experiments were conducted from November 2013 to July 2015 using 240 L vertical flow (VF) mesocosms. Sand sourced from river sand was the media while biochar produced from hardwood using fast pyrolysis processes at 500 °C was the amendment. There were seven different media treatments augmented with biochar content of 0–25% with 5% increments of biochar. The treatments contained 12% coir peat to enhance moisture retention (during intermittent loading) except in a control treatment that used 100% sand with no added coir peat, labelled as S100. The physical and chemical characteristics of the seven media treatments were presented in a previous paper (De Rozari et al., 2016). All treatments were triplicated. Each mesocosm was planted with one Melaleuca tree (*Melaleuca quinquenervia*) and one Lemongrass plant (*Cymbopogon citratus*).

Wastewater was stored in three 5,000 L tanks and each tank fed the seven treatment mesocoms (Fig. 1). The outlet was located at the bottom of mesocosm and elevated with a hose to approximately 5 cm below the media surface. Wastewater was replenished monthly. The experiment was divided into three phases: establishment phase – the mesocosms intermittently received tertiary wastewater effluent (November 2013–February 2014)-; continuous secondary clarified wastewater load phase (March–October 2014) with a hydraulic loading rate 16 L/day; and intermittent septage load phase (November 2014–July 2015) with 20 L of septage effluent loaded every two days. The removal of TSS, BOD_5, and coliforms has previously been reported in De Rozari et al. (2015). Phosphorus removal, microbial P biomass and plant-P biomass has been reported in De Rozari et al. (2016). This paper focuses on N removal and plant-N biomass.

2.2. Hydraulic conductivity

Hydraulic conductivity measurements were determined by falling head measurements and were carried out in February 2014, August 2014 and March 2015 for each mesocosm. The reading at the lip (max ponding depth) and distance from lip to the top of the outlet (outlet depth) were measured. The wastewater was added into the mesocoms when they were still draining. The depths were determined from the soil surface to water height. The elevation was measured in each mesocosm by reading the estimated depth at the middle of the meniscus. The measurements were carried out in 5-min intervals for at least 45 min (until the wastewater had drained).

The determination of saturated hydraulic conductivity (K_{sat}) was calculated based on the equation adapted from Bedient and Huber (1988):

$$K_{sat} = \frac{A_t L}{A_m (t_2 - t_1)} \ln\left(\frac{h_1}{h_2}\right)$$

A_t = average ponding area (m^2)
A_m = average media cross-sectional area (m^2)
L = media depth (m)
h_1 = initial head (m)
h_2 = final head (m)
t = elapse time (hours)

2.3. Water sample collection

The inflows and outflows were sampled every two weeks for the first four months (March–June 2014) and then monthly from August 2014 to July 2015. The inflows were collected from the inlet hose which was connected to the tank and the outflows were collected from a 135 L collection chamber connected to the mesocosm (Fig. 1). The collection chamber stored the outflow from the mesocosm for approximately two weeks. After collection, samples were refrigerated at 4 °C, then frozen until analysed. For NH_4-N and NO_x-N, the samples were filtered using 0.45 μm Millipore filters. The filtered solutions were then analysed using colorimetric methods with a Discrete Chemistry Analyser (Westco Smartchem 200, Danbury CT, USA) according to USEPA 350.1, USEPA 353.2 (USEPA, 1983). To determine TN, the standards and samples were first digested using standard persulphate methods according to standard methods 4500-P (APHA, 2005) and analysed using colorimetric methods with a Discrete Chemistry Analyser (Westco Smartchem 200, Danbury CT, USA) according to the methods for chemical analysis of water and waste (USEPA, 1983).

2.4. Plant samples

Determination of biomass was carried out by harvesting aboveground and belowground biomass. The Melaleuca trees were separated into stems, branches, leaves, bark and roots while the Lemongrass plants were separated into shoots, rhizome and roots. These samples were oven dried for 48 h at 70 °C to obtain a constant dry weight. Representative samples of oven dried plants from each plant part were ground and pelletised, then analysed for TN in a mass spectrometer (Sercon Hydra 20–22) according to Gautam and Greenway (2014). Plants in treatments BC5, BC10, BC15 and BC25 were harvested in March 2015 and the remaining plants (S100, SCP and BC20) were harvested in July 2015.

2.5. Statistical and data analysis

All statistical analyses were carried out using SPSS 21 software. The mean and standard deviation of saturated hydraulic conductivity (K_{sat}) were determined and One-way ANOVA test was applied to determine the significant differences K_{sat} among the treatments. A Tukey post-hoc