Journal of Environmental Management 228 (2018) 466–474

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Nitrogen removal efficiencies and pathways from unsaturated and saturated zones in a laboratory-scale vertical flow constructed wetland

Rasha Al-Saedi[a,b,c,*], Keith Smettem[a,c], Kadambot H.M. Siddique[c]

[a] School of Civil, Environmental, and Mining Engineering, The University of Western Australia, Perth, WA 6001, Australia
[b] Department of Environmental Engineering, Al- Mustansiriya University, Baghdad, Iraq
[c] The UWA Institute of Agriculture, The University of Western Australia, Perth, WA 6001, Australia

ARTICLE INFO

Keywords:
Vertical flow constructed wetland
Nitrogen removal
Unsaturated zone
Saturated zone
Bacterial composition

ABSTRACT

A laboratory-scale vertical flow constructed wetland system was designed and monitored to compare nitrogen removal rates and pathways from both saturated and unsaturated zones under a hydraulic loading rate and influent total nitrogen concentration of 1.5 m^3/m^2.d and 508 mg/L respectively. Weekly measurements of the concentrations of nitrogen compounds, chemical oxygen demand, temperature, dissolved oxygen, oxidation-reduction potential, and hydrogen ion concentration were taken throughout the study. At the end of the experiments, PCR analysis of 16S rRNA gene sequencing was performed to identify microbial communities in the unsaturated and saturated parts of the system. The nitrogen compounds were removed from the system after 182 days, with similar total nitrogen removal efficiencies (94% and 93%) for the unsaturated and saturated zones respectively. Heterotrophic nitrification/aerobic denitrification was the major pathway responsible for the removal of nitrogen compounds. Adsorption into the gravel bed also contributed to ammonium removal. Proteobacteria were the dominant bacterial strains involved in nitrogen transformation and accounted for 80% of the total bacteria in the unsaturated zone and 60% in the saturated zone. With little difference in the concentration removal efficiencies of the unsaturated and saturated zones, a more effective design would be an entirely saturated wetland as the total mass removal of nitrogen depends on the water volume stored, which at full saturation in this design was seven times greater per unit wetland volume than the unsaturated zone.

1. Introduction

The removal of high nitrogen (N) loads generated from domestic effluents, animal farms, and food production industries is of particular concern due to negative impacts on receiving water bodies such as eutrophication, algal blooms, and groundwater contamination (Kantawanichkula et al., 2009; Terada et al., 2003). Dissolved inorganic N forms, including nitrate (NO_3), nitrite (NO_2) and ammonia (NH_3) or ammonium (NH_4) can impact aquatic systems because they are immediately available for uptake by microorganisms (Lee et al., 2009; Sun et al., 2012). Constructed wetlands (CWs) have been widely used to efficiently treat high nitrogen wastewater (Kantawanichkula et al., 2009; Tanner et al., 1995). In this study, we focused on vertical flow constructed wetlands (VFCW), being state of the art wetland technologies (Sani et al., 2013) with minimal space requirements, higher oxygen transfer capacity, highly effective organic matter removal, and simple hydraulics (Saeed and Sun, 2012) compared to other treatment systems.

In VFCWs, the removal of N often depends on the efficiency of essential biological processes such as ammonification, nitrification, and denitrification (Stefanakis et al., 2014). Nitrification is the aerobic oxidation of NH_4 to NO_2 by ammonium oxidizing bacteria (AOB) and then to NO_3 by nitrite oxidizing bacteria (NOB). Denitrification is the reduction of nitrate to N gas by heterotrophic denitrifiers under anoxic conditions (Saeed and Sun, 2012). The biological degradation of N in CWs is usually accomplished by aerobic nitrification and anoxic denitrification (Lee et al., 2009; Nielsen et al., 2005; Wang et al., 2005). However, heterotrophic nitrifying-aerobic denitrifying microorganisms may contribute significantly to nitrogen removal in wetlands (Adrados et al., 2014). These microorganisms are able to nitrify and denitrify simultaneously under aerobic conditions, by oxidizing ammonium to nitrite or nitrate and immediately denitrify these compounds to N_2 gas (Yao et al., 2013).

Effective TN removal can be achieved by sustaining a variety of microbial communities that perform simultaneously under a typical environmental habitat (Sun et al., 2012). The content, diversity, and

* Corresponding author. School of Civil, Environmental, and Mining Engineering, The University of Western Australia, Perth, WA 6001, Australia.
E-mail address: 21456205@student.uwa.edu.au (R. Al-Saedi).

https://doi.org/10.1016/j.jenvman.2018.09.048
Received 28 June 2018; Received in revised form 8 September 2018; Accepted 13 September 2018

dynamics of microbes impact the performance, robustness, and balance of wastewater treatment facilities (Naz et al., 2016). However, The final feature of the microbial community can be influenced by factors such as, organic load, the design of treatment systems, the type of substrate used, composition of the influent wastewater, and the operational conditions of the system (Adrados et al., 2014). Knowledge of the microbial population involved in treatment wetlands is therefore essential for understanding and enhancing process efficiencies.

High treatment efficiency of single-stage VFCWs for N compounds, has been widely reported (Haoa and Martinezb, 1998; Helmer and Kunst, 1998; Menoud et al., 1999; Munch et al., 1996; Saeed and Sun, 2012; Sun et al., 2012; Tanner and Kadlec, 2002; Tanner et al., 2002). In VFCWs with gravel fill, Connolly et al. (2004) found effective nitrogen removal under fully saturated conditions. Dong and Sun (2007); Silveira et al. (2015) Huang et al. (2017) and Hu et al. (2014) improved N removal efficiency by dividing the bed into saturated and unsaturated layers.

In this study, we design and monitor a mixed saturated/unsaturated VFCW system under ambient temperatures and high N loading rate to: (1) compare the efficiency of transformation and removal of N products under unsaturated and saturated conditions in inorganic wastewater characterized by low organic constituents; (2) identify the microbial communities coating the VFCW gravel in the unsaturated and saturated zones to identify the most likely N removal pathways.

2. Materials and methods

2.1. Experimental and sampling procedure

Three replicate laboratory-scale polyvinyl chloride (PVC) columns were set up in the laboratory and packed with gravel as the main filter medium under an ambient temperature regime (Fig. 1). The design and sampling protocol are similar to Dong and Sun (2007) and summarized in Table 1. Before commencing the experiment, a mixed liquor activated sludge (ML) collected from a wastewater treatment plant was recirculated twice weekly for two weeks in the columns (4 g ML/L of tap water) in order to stimulate the growth of microorganisms. During the recirculation period, the water table height was set at 27 cm above the gravel base. The recirculated ML was then flushed from the columns. The columns were then saturated with a synthetic wastewater from a header tank at an influent flow rate and hydraulic loading rate 0.0088 m^3/d and 1.5 m^3/m^2.d respectively. The columns were then partially drained to establish the unsaturated zone over the saturated zone (Fig. 1). For each new preparation of 1 L synthetic wastewater; 4 mL of ML was added along with 2 mL and 1 mL of mine salt solution and trace element solution respectively. The synthetic wastewater recipe, along with the mine salt solution and trace element solution were prepared according to Zhang et al. (2010) (Table 2). Small spikes of NaCl were added to the synthetic wastewater after each new wastewater preparation to maintain pH values within the required range. The

Table 1
Characteristics of the experimental VFCW column.

Parameters	Values and units
Total height of column	50 cm (10 cm free board)
Height of gravel	40 cm (27 cm saturated + 13 cm unsaturated)
Internal diameter	8.5 cm
Column surface area	56.7 cm^2
Volume of gravel bed	2268 cm^3 (1531 cm^3 saturated + 737 cm^3 unsaturated)
Pore volume for saturated zone	730 cm^3
Gravel diameter range	7–14 mm
Dry bulk density	1.31 gm/cm^3
Average gravel bed porosity	0.48 cm^3/cm^3
Water content	0.456 cm^3/cm^3 (saturated), 0.064 cm^3/cm^3 (unsaturated)

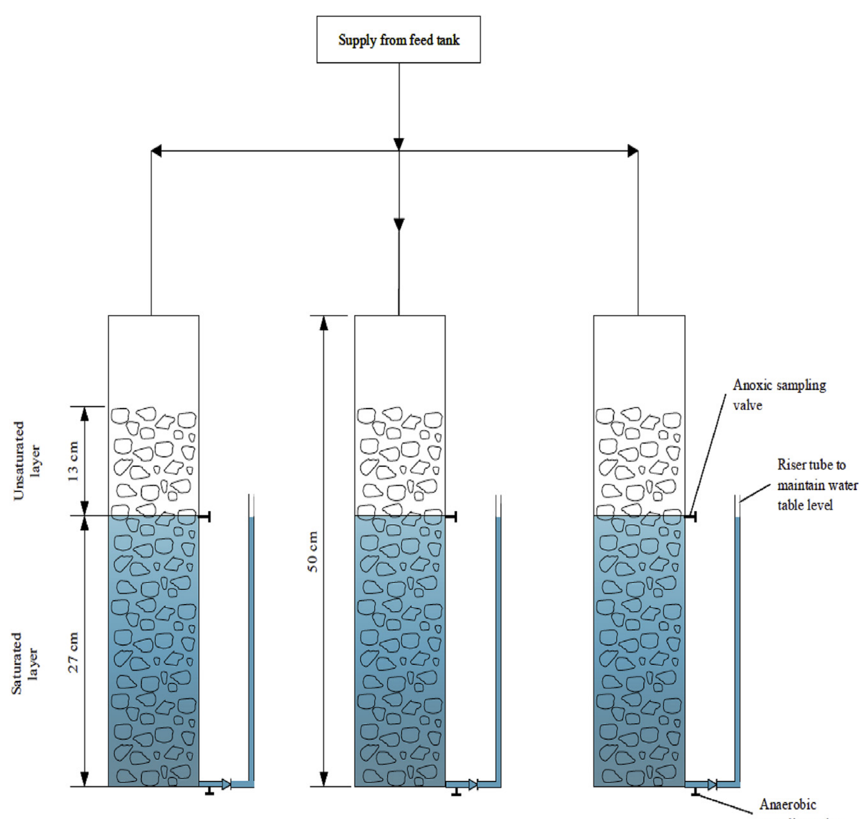

Fig. 1. Schematic diagram of the experimental wetland columns.