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Influence of substrates on nutrient removal performance of organic channel barriers in drainage ditches

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SUMMARY

Pilot-scale field trials were performed to investigate the nutrient removal capacity of organic channel barriers (OCBs) with the objective of developing innovative technology for effectively reducing nutrient transport in simulated drainage ditches. The performance comparison of three OCBs, which were composed of rice straw (RS), pine sawdust (PD), and activated carbon with <1 mm quartz sand (AC), indicated that the RS OCBs produced the highest mean removal rate of 73% for ammonium-N (NH_4^+–N) and 96% for nitrate-N (NO_3^-–N). Performance of the RS OCBs with RS application rates at 0, 45, 75, and 120 kg dry weight showed the quantity of RS had a significant positive correlation with NH_4^+–N removal ($r = 0.754$, $p < 0.01$) and NO_3^-–N removal ($r = 0.969$, $p < 0.01$), but an insignificant negative correlation with phosphate-P (PO_4^{3-}–P) removal ($r = -0.492$, $p = 0.104$). Release of carbon (C) from the RS OCBs primarily occurred during the first three weeks. Total C loss accounted for less than 5% of the initial C mass. These findings indicated that RS OCBs can be used to construct a low-cost treatment system that requires minimal maintenance and can be easily integrated into drainage ditches to reduce nutrient export from agricultural areas.

1. Introduction

In agroecosystems, a large proportion of nutrients applied for crop production are transported to aquatic ecosystems due to low fertilizer utilization efficiency. This transport has become a key factor in nitrogen (N) and phosphorus (P) overloading in natural water bodies around the world (e.g., Chatterjee, 2009; Galloway et al., 2003). Diffuse agricultural pollution also results in more difficulties in preventing water pollution (e.g., Conley et al., 2009; Royer et al., 2006). The first national Chinese pollution census of 2007 listed agriculture as the main source of N and P pollution revealing that agriculture is responsible for 57% and 67% of the total national discharges of N and P, respectively (National Pollution Source Survey Staff, 2010). The control of agricultural pollution will be urgent in Chinese rural areas in the coming years (Qiu, 2011). Drainage ditches comprise the primary water conduits in agricultural lands; they also serve as the dominant pathways for nutrient transport from agricultural lands to downstream water bodies (Kröger et al., 2007). The use of drainage ditches to control nutrient loss from agricultural catchments would constitute a significant advancement. However, natural ditches and streams exhibit short-term nutrient retention times and low nutrient removal capacities (e.g., Merriam et al., 2002; Moore et al., 2010). Therefore, a number of field practices, such as aquatic plant vegetation, water-control structures, in-stream wetlands, and bioreactors, have been implemented in drainage ditches to tackle diffuse pollution from agriculture (e.g., Hunt et al., 1999; Leu et al., 1998; Liu et al., 2013; Needelman et al., 2007; Robertson and Merkley, 2009; Woli et al., 2010).

The cost of building and operating an agricultural wastewater treatment system is an important factor in the selection of a treatment technique (Ruane et al., 2011). Denitrification bioreactor designs, including barrier, wall, bed, layer, filter, and trench types, are selected in polluted agricultural areas because they are

Abbreviations: OCB, organic channel barrier; RS, rice straw; RS OCB, organic channel barrier composed of rice straw; PVC, polyvinyl chloride; PD, pine sawdust; AC, activated carbon with <1 mm quartz sand; DOC, dissolved organic carbon; CFUs, colony-forming units; NRR, nutrient removal rate; NMR, nutrient mass removal rate.

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low-cost options that require minimal maintenance and are effective strategies for nitrate-N (NO_3^-–N) removal (Schipper et al., 2010). In bioreactors, organic substances act as external carbon (C) sources and electron donors to stimulate heterotrophic denitrification, which causes permanent N removal (e.g., Schmidt and Clark, 2012; Woli et al., 2010). Solid organic substrates are convenient low-cost fillers for bioreactors. Wood media, which exhibit a high permeability and a high C-to-N (C:N) ratio, have been extensively used in field trials. Denitrification bioreactors filled with wood media are capable of providing consistent long-term NO_3^-–N removal without C replenishment. *In situ* investigations have indicated that wood media annually consumes less than 5% of the initial C mass within bioreactors (e.g., Robertson et al., 2000; Robertson and Merkley, 2009; Schipper and Vojvodic-Vukovic, 2001; Schmidt and Clark, 2012).

In addition to wood media, other natural organic media, such as cornstalks, wheat, maize cobs, barley straw, and rice husks, are used as alternative C substances for bioreactors, as noted by Schipper et al. (2010). Small-scale laboratory experiments demonstrate that alternative C substrates provide higher NO_3^-–N removal capacities than wood media and can be regarded as efficient C sources that rapidly release bioavailable C for the denitrification bacteria (Greenan et al., 2006). However, bioreactors with alternative C substrates also require frequent C replenishment due to rapid C depletion during processing. For example, filter bioreactors filled with wheat straw exhibit a substantial C loss of 37.7% of the initial mass during a 140-days experimental period. The time limitation of the bioreactor's working life must also be considered (Saliling et al., 2007). Denitrification bioreactors show mean NO_3^-–N mass removal rates in the range of 0.62–12.7 g N m^{-3} d^{-1} (Schipper et al., 2010). However, the occurrence of N-limiting situations under field conditions frequently limits the N mass removal capacity of denitrification bioreactors, which is reflected by rapid N depletion in bioreactors (e.g., Elgood et al., 2010; Schmidt and Clark, 2012). Although filling bioreactors with alternative C substrates for enhanced NO_3^-–N removal has been successful, the suitability of rice straw (RS) as an organic substrate in bioreactors for NO_3^-–N removal remains unknown. In addition, the potential ability of bioreactors to remove dissolved ammonium-N (NH_4^+–N) and phosphate-P (PO_4^{3-}–P) has not been addressed (e.g., Park et al., 2009; Ruane et al., 2011).

In this study, a pilot-scale field trial was performed to investigate the nutrient removal capability of organic channel barriers (OCBs) constructed in simulated drainage ditches. Objectives of this study were to: (i) compare N removal rates for the RS OCB and OCBs filled with two alternate C substrates—pine sawdust (PD) and activated C with sand (AC), (ii) analyze the performance of the RS OCB at different RS application rates in terms of nutrient removal efficiency of the channels and effects of hydraulic retention time on NH_4^+–N removal, and (iii) evaluate the amount of C loss by the RS OCB.

2. Materials and methods

2.1. Study site

This study was conducted at the Changsha Research Station for Agricultural and Environmental Monitoring (CRSAEM), located in the Jinjing catchment in Hunan Province of the PR China. The catchment covers an area of 105 km^2 and has a typical subtropical climate. A small meteorological station (InteliMet Advantage, Dynamax Inc., USA) at the CRSAEM was used to monitor the maximum and minimum temperatures and the total rainfall, which were 32.1 °C, 10.9 °C, and 1,141 mm, respectively, during the study period of April 2012–August 2012. The monitoring data from 2010 to 2012 showed that the stream NH_4^+–N, NO_3^-–N, and PO_4^{3-}–P concentrations in the Jinjing catchment were in the range of 0.01–8.05, 0.12–4.46, and 0.01–0.55 mg L^{-1}, respectively (Li et al., 2014a,b). These data prompted us to select 5 mg L^{-1} NH_4^+–N, 5 mg L^{-1} NO_3^-–N, and 0.5 mg L^{-1} PO_4^{3-}–P wastewater as influents for this study. In other way, mean base flow rate for a natural drainage ditch at the CRSAEM was 6.12 m^3 d^{-1} in 2011. Therefore, this observed rate of approximate 6.0 m^3 d^{-1} was used in the pilot-scale filed trial.

2.2. Set-up of the simulated drainage ditch system and the OCBs

The simulated drainage ditch system was constructed at the CRSAEM in 2011, which had three primary components: water supply unit, 20 ditch cells, and water distribution equipment. Through a polypropylene pipe (110 mm in diameter), the main water supply unit of a 100 m^3 tank can obtain adequate clean water with TN < 0.5 mg L^{-1} and TP < 0.1 mg L^{-1} from a reservoir surrounded by a hill. Artificial wastewater in the study was prepared in the 100 m^3 tank by adding the appropriate quantity of chemicals. Each of the 20 ditch cells were constructed with equivalent dimensions: 16 × 2.0 × 0.35 m (length × width × depth). Cells were placed in a paddy field after removal of topsoil (depths from 0 to 0.1 m). Water distribution equipment included the stainless steel flumes with dimensions of 2.0 × 0.1 × 0.1 m and a set of polyvinyl chloride (PVC) connection pipes. A flume was placed horizontally in the inlet of each ditch cell with a platform that was 0.4 m higher than the bottom level of the ditch to evenly distribute influents (Fig. 1). A set of PVC pipes was used to deliver water from the tank to the flumes. A tap and a water meter with a measuring precision of 0.1 L were installed in front of each flume to regulate and monitor flow flux. Two pipes were placed in the baffle wall at the end of each ditch cell; they were used as outlets to maintain a 0.1 m water depth in each ditch cell during the study period. In addition, effluents from the simulated drainage ditch were collected and delivered to an adjacent wetland with an area of approximately 0.2 ha to prevent the release of artificial wastewater into the natural aquatic environment.

A schematic of the OCBs in the ditch cells is shown in Fig. 1. OCBs were placed in the back of the ditch cells and a 3-m distance from the outlets was maintained. Stainless steel frame was used to construct OCBs with a width of 2 m and a thickness slightly less than 0.1 m to ensure that all OCBs were submerged. Lengths of the OCBs were not equivalent and were dependent on the quantity of C substrates in the study OCBs.

2.3. Experimental materials

Air-dried RS was collected from a paddy field near the simulated drainage ditches. RS samples had a total moisture content of 5.3%, a total organic C content of 396 g kg^{-1}, and a C:N of 31.3. PD was purchased from a local sawmill, and the activated C was purchased from Longkai Instrument Company (Changsha, China). Artificial wastewater with 5 mg L^{-1} NH_4^+–N, NO_3^-–N, and PO_4^{3-}–P were prepared by ammonium hydrogen carbonate (NH_4HCO_3, 95% purity), potassium nitrate (KNO_3, 96% purity), and potassium dihydrogen phosphate (KH_2PO_4, 95% purity), respectively, which were purchased from Changsha Minle Chemical Companies (Changsha, China).

2.4. OCB experiments to evaluate nutrient removal in the simulated drainage ditches

Two tests were performed to study nutrient removal by the OCBs. Test 1 compared NH_4^+–N removal and NO_3^-–N removal of the OCBs filled with three types of C substrates: RS, PD, and