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Denitrifying bioreactor clogging potential during wastewater treatment

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ABSTRACT

Chemoheterotrophic denitrification technologies using woodchips as a solid carbon source (i.e., woodchip bioreactors) have been widely trialed for treatment of diffuse-source agricultural nitrogen pollution. There is growing interest in the use of this simple, relatively low-cost biological wastewater treatment option in waters with relatively higher total suspended solids (TSS) and chemical oxygen demand (COD) such as aquaculture wastewater. This work: (1) evaluated hydraulic retention time (HRT) impacts on COD/TSS removal, and (2) assessed the potential for woodchip clogging under this wastewater chemistry. Four pilot-scale woodchip denitrification bioreactors operated for 267 d showed excellent TSS removal (>90%) which occurred primarily near the inlet, and that COD removal was maximized at lower HRTs (e.g., 56% removal efficiency and 25 g of COD removed per m^3 of bioreactor per d at a 24 h HRT). However, influent wastewater took progressively longer to move into the woodchips likely due to a combination of (1) woodchip settling, (2) clogging due to removed wastewater solids and/or accumulated bacterial growth, and (3) the pulsed flow system pushing the chips away from the inlet. The bioreactor that received the highest loading rate experienced the most altered hydraulics. Statistically significant increases in woodchip P content over time in woodchip bags placed near the bioreactor outlets (0.03 vs 0.10%P_2O_5) and along the bioreactor floor (0.04 vs. 0.12%P_2O_5) confirmed wastewater solids were being removed and may pose a concern for subsequent nutrient mineralization and release. Nevertheless, the excellent nitrate-nitrogen and TSS removal along with notable COD removal indicated woodchip bioreactors are a viable water treatment technology for these types of wastewaters given they are used downstream of a filtration device.

1. Introduction

Chemoheterotrophic denitrification is the most widely used nitrogen (N) removal process in wastewater treatment (Lu et al., 2014). Addition of a soluble carbon (C) source (e.g., methanol, acetate, ethanol, glycerol) fuels this anoxic step-wise microbial reduction of nitrate (NO_3^-) to dinitrogen (Tchobanoglous et al., 2003). Recent increasing concern about nutrient pollution from non-point sources and other non-regulated N streams has resulted in the expansion of denitrification technologies to include simple reactors filled with inexpensive and readily available solid organic C sources such as woodchips (Schipper et al., 2010). In agricultural settings, these woodchip denitrification bioreactors offer a targeted approach for passive N treatment from subsurface drainage, runoff, and greenhouse effluents (generally > 25% N removal, 2–20 g N removed per m^3 bioreactor per d; Christianson et al., 2012; Warneke et al., 2011; Woli et al., 2010).

Woodchip bioreactors are being examined in applications such as aquaculture facilities that have more controlled flow rates than non-point source N streams that have been the major application of bioreactors to date (Lepine et al., 2016; von Ahnen et al., 2016). Flushing of chemical oxygen demand (COD) and nutrients upon woodchip bioreactor start-up is a well-established phenomenon (Healy et al., 2012), but the opportunity to design these systems for more controlled flow rates (e.g., wastewater versus tile drainage water) raises the new question of how to minimize flushing impacts through design (i.e., through hydraulic retention time (HRT)). Moreover, because woodchip bioreactors have most widely been

Abbreviations: $CBOD_5$, carbonaceous biochemical oxygen demand; COD, chemical oxygen demand; HRT, hydraulic retention time; TSS, total suspended solids.

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used in the treatment of relatively low total suspended solids (TSS) and COD agricultural N sources (e.g., agricultural tile drainage), it is now vital to evaluate the impact of design flow rates on TSS and COD removal in woodchip bioreactor treatment of wastewater. Efficient filtration of wastewater TSS would be widely expected due to the rough surface area of the woodchips (Choudhury et al., 2016). However, conventional knowledge indicates that frequent woodchip replacement due to either C media exhaustion or media clogging potentially changes the economics of this low-cost denitrification option. Increasing interest from the aquaculture industry, in particular, necessitates better understanding of the potential for woodchip clogging as well as design HRT guidance for TSS and COD removal in woodchip denitrification bioreactors. The objectives of this work were to: (1) evaluate the HRT impacts on COD and TSS production or removal under start-up or longer-term operation, respectively, and (2) assess the potential for woodchip clogging to occur under this wastewater chemistry. Previous findings from this study include the first ever evaluation of woodchip bioreactor HRT for NO_3^- removal from aquaculture wastewater (Lepine et al., 2016) and assessment of phosphorus dynamics in the woodchips and wastewater (Sharrer et al., 2016).

2. Methods and materials

2.1. Bioreactor design and operation

Four pilot-scale woodchip denitrification bioreactors (Fig. 1; L × W × D:3.8 × 0.76 × 0.76 m; ≈1:10 scale based on surface foot print) were constructed of plywood, lined with plastic, and operated for 267 d at The Conservation Fund's Freshwater Institute research campus (Shepherdstown, WV, USA; May 2014 to February 2015; previously described by Lepine et al., 2016 and Sharrer et al., 2016). The woodchips were classified as a "3 inch, hardwood blend" by the local supplier (Lowe Products, Shepherdstown, WV), and had a D_{50} (median diameter) of 1.2 cm, porosity of 70%, and bulk density of 217 ± 11 kg/m^3 (mean ± SD).

The bioreactors were operated under a start-up phase which consisted of wastewater application on hourly pumping cycles (Phase I: d 1–162) and a phase with double the hydraulic loading rate (HLR) as Phase I with bioreactors dosed with the same volume of wastewater as during Phase I except twice per hour (Phase II: d 169–267). The four bioreactors were each operated under a different HRT and HLR, and the retention times during Phase II were approximately half that of Phase I (Phase I: 12, 24, 42, and 55 h HRT; Phase II: 6.6, 12, 20, and 29 h HRT). Hydraulic retention time (τ) for woodchip bioreactors is described as:

$$\tau = \frac{V_r * \rho}{Q} = \frac{Pore\ Volume}{Q} \quad (1)$$

where Q is the reactor flow rate, V_r is the saturated volume of the reactor (3.8 × 0.76 × 0.61 m; Fig. 1), and ρ was woodchip porosity (70%) (Tchobanoglous et al., 2003). Lepine et al. (2016) previously reported N removal rates for these pilot-scale denitrification bioreactors were a function of HRT (g N removed per m^3 bioreactor per d = 17.3 + (111.2 * $e^{(-0.22 * HRT)}$)).

Wastewater (i.e., overflow from gravity thickening settlers used to dewater and capture waste biosolids) generated via the production of rainbow trout (*Oncorhynchus mykiss*) and Atlantic salmon (*Salmo salar*) in on-site recirculating aquaculture systems was pumped to a mixing tank where it was dosed with sodium nitrate to achieve bioreactor inflow of 25–80 mg NO_3^--N/L. The context for this study was treatment of aquaculture wastewater, thus it was most realistic to use effluent from the on-site fish culture system (e.g., wastewater microbiology, temperature, etc., consistent with a production fish culture system), but N dosing was required to produce realistic NO_3^- levels due to the efficiency of upstream N-removal unit processes at this research facility. The mixing tank solution was circulated to four individually calibrated treatment vessels located directly before the four bioreactors (Fig. 1). A pump in each treatment vessel fed the associated downstream bioreactor over a period of less than five minutes on an electronically-controlled schedule either once every hour (Phase I) or twice every hour (Phase II). Inlet and outlet manifolds (5.1 and 10.2 cm diameter PVC, respectively, with drilled holes) spanned the width of each bioreactor at the base of each system. Each outlet manifold connected through the bioreactor downstream wall to a 0.61 m standpipe, which directed outflow into a common sump for the four bioreactors. Flow rates were measured weekly by filling containers of a known volume over a period of one pumping cycle.

2.2. Water quality

Water samples were collected at the influent mixing tank and the four bioreactor outlets. Sample collection timing was initially based on cumulative pore volumes eluted (or, flow volume treated) to normalize between the four HRT treatments. Thus, over the first 47 d (or approximately 20 cumulative pore volumes for the slowest flow rate treatment that was operating under a 55 h HRT), samples were collected relatively frequently but not necessarily at the same time for all four bioreactors. Beyond this day, samples were collected concurrently every week. All samples were analyzed on-site for COD, carbonaceous biochemical oxygen demand ($cBOD_5$), and TSS following standard methods (APHA, 2005; Hach, 2003). Removal efficiencies (%) for COD, $cBOD_5$, TSS, and NO_3^--N were calculated as the influent concentration minus the effluent concentration divided by the influent concentration (see Table 1 for mean influent concentrations). Removal rates for COD and TSS (g COD or TSS removed m^{-3} bioreactor d^{-1}) were calculated as the difference in influent and effluent concentrations times the bioreactor flow rate divided by the total bioreactor volume (length × width × depth of woodchips; 2.21 m^3).

Water samples were also collected from 5 cm diameter PVC monitoring wells located 0.18, 1.74, and 3.57 m from the bioreactor upstream wall in each bioreactor (Fig. 1) on d 120 and 188, which provided information for Phases I and II, respectively. The depth to water was measured in each well (Geotech Environmental Equipment, Keck Water Level Meter) before and after purging a volume of no less than approximately three times the monitoring well volume (or, no less than 3000 mL) using a peristaltic pump (MasterFlex L/S Model 7018-20). Well samples were analyzed for TSS, NO_3^--N, and sulfate (SO_4^{2-}) following standard methods (APHA, 2005; Hach, 2003).

2.3. Flow dynamics

A pressure transducer suspended in the inlet pipe just above the bioreactor floor in each bioreactor logged the depth of water in this pipe every minute (Fig. 1; Solinst Levelogger Model 3001). Data from the four transducers were downloaded weekly and a representative 7 h period was selected for analysis for each bioreactor for each week. Data were corrected for barometric pressure (Solinst Barologger Edge, Model 3001; Solinst Levelogger Software 4.0) and normalized to the outlet standpipe elevation (i.e., 60 cm saturated depth). The pressure transducers were cleaned weekly per manufacturer's instructions to remove bacterial growth. One way analysis of variance (ANOVA) testing was used to evaluate changes in the time required for the pumped volume to move from this inlet pipe into the woodchips across the first 24 wk of operation (Sigma Plot 12.5).