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Start-up performance of a woodchip bioreactor operated end-of-pipe at a commercial fish farm—A case study

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ABSTRACT

There is a need for simple, maintenance-free technologies for removing nitrogen (N) from aquaculture effluents. Denitrifying woodchip bioreactors have been used successfully to remove nitrate-N (NO_3-N) from ground and surface waters and may potentially be applied to dilute aquaculture effluents as well. Real-life applicability in commercial, outdoor fish farms including practical start-up issues such as e.g. time till stable performance and potential leaching are, however, unknown to the industry.

This case study consequently investigated the temporal performance of a woodchip bioreactor (12.5 m^3) during start-up. The bioreactor was operated end-of-pipe at a commercial, outdoor rainbow trout (*Oncorhynchus mykiss*) farm in Denmark operated at low recirculation intensity. Applying an empty bed contact time (EBCT) of 5 h, the specific objectives of the study were to resolve: i) how fast the bioreactor would start to remove NO_3-N; ii) how fast steady state was achieved; iii) which NO_3-N removal rates could be attained at the relatively low effluent temperature (~8 °C) and iv) to which extent any concomitant leaching of phosphorous (P), ammonia or organic matter would occur.

In- and outlet grab samples were obtained every 6 h until the bioreactor was in steady state (2 weeks) followed by weekly 24 h pooled samples for another 3 weeks (5 weeks in total). Additional grab samples were obtained from 9 sampling ports within the bioreactor on 3 consecutive days during steady state. Samples were analyzed for dissolved nutrients (total N, nitrate, nitrite, ammonium, total phosphorous, ortho-phosphorous, BOD_5 and COD). In addition, oxygen, temperature and pH were logged every 30 min while sampling and alkalinity were measured once a week.

Removal of NO_3-N started immediately and remained stable at 7.06 ± 0.81 g NO_3-N/m^3/d ($n = 6$) throughout the sampling period. Increased effluent NO_2-N concentrations (peaking at 1.14 mg NO_2-N/l after 4–5 days) were transiently observed during the initial 11 days. After that, the woodchip bioreactor was largely in steady state with respect to N-balances corroborated by a close match between filtered total-N (TN_{diss}) and NO_3-N removal rates. Measurements within the bed showed that the majority of the influent dissolved oxygen (DO) was consumed within the first part of the bioreactor and that NO_3-N removal thereafter proceeded gradually with distance within the bed. Leaching of non-structural, dissolved organic compounds were observed just after startup, causing a short-term (1 week) increase in effluent concentrations of COD, BOD_5, P and ammonium.

Additional measurements carried out until 147 days after start-up showed that the woodchip bioreactor continued to remove TN_{diss} at an average removal rate of 7.81 ± 0.82 g N/m^3/d, and that the initial leakage of P stopped altogether.

In summary, the study demonstrated that woodchip bioreactors can effectively remove NO_3-N from dilute aquacultural effluents at low temperatures and commercial conditions and that stable performance is achieved within a few weeks.

1. Introduction

Fish farming generates excess nitrogen (N) that is often discharged to the environment. In many regions surplus N causes environmental concerns and the production in land-based aquaculture systems is therefore often limited by their ability to remove N.

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While biofilters converting ammonia to nitrate are widely used on commercial farms, generally only few outdoor farms apply specific measures to remove nitrate. This is particularly true for smaller and less intense farming systems characterized by low effluent temperatures, high flow rates and dilute wastewater. These farms need an inexpensive, easy-to-operate treatment method for removal of nitrate.

Woodchip bioreactors are simple, low-cost technologies which have been used to remove nitrate from ground and surface waters successfully for more than 20 years (Schipper et al., 2010). Their treatment performance is considered to be based on woodchips providing organic carbon (C) as C- and energy source for heterotrophic denitrification in the anoxic conditions within the reactors (Schipper et al., 2005; Warneke et al., 2011a). However, woodchip bioreactors may potentially also provide sites for autotrophic denitrification (Yamashita and Yamamoto-Ikemoto, 2006, 2008; Yamashita et al., 2011; Von Ahnen et al., 2016).

Woodchip bioreactors are typically packed-bed reactors operated at hydraulic retention times (HRTs) of several hours to days (Christianson et al., 2011; Greenan et al., 2009). Installation and operation of the passive treatment systems is simple with expected lifetimes of more than 10 years without media replenishment when operated properly (Robertson et al., 2008).

Despite their potential use in aquaculture, woodchip bioreactors have to our knowledge not yet been applied to treat outdoor aquaculture effluents on a commercial scale. A considerable amount of research has been carried out on woodchip bioreactors treating ground and surface waters (Schipper et al., 2010; Christianson et al., 2012), but the results may not be directly transferrable to aquaculture settings given the differences in wastewater composition and flow regimes. A recent study by Lepine et al. (2015) showed that pilot-scale woodchip bioreactors treating the effluent from a semi-commercial recirculating aquaculture system (RAS) were able to remove up to 39 g N/m^3/d. The relatively warm (~19 °C) RAS effluent was, however, rich in chemical oxygen demand (COD) and was dosed with sodium nitrate to obtain bioreactor inflow nitrate concentrations of 20–80 mg NO_3-N/l.

Nutrient compositions and loadings in effluents from less intensive, cold water aquaculture units are quite different from this, and the purpose of the current case study was—to examine: i) if and how fast a woodchip bioreactor operated end-of-pipe at a partly recirculated fish farm would start working under commercial scale loading conditions; ii) how fast steady state would be reached with respect to effluent concentrations of dissolved nutrients including N, phosphorous (P), and organic matter compounds; and iii) which NO_3-N removal rates could be attained on-farm at the relatively low temperature (~8 °C) when applying a relatively short empty bed contact time (EBCT) (5 h).

2. Materials and methods

2.1. Case study site

A 12.5 m^3 woodchip bioreactor was installed at a commercial rainbow trout farm (Lundby Fish Farm) in the North Jutland Region of Denmark in mid-October 2015. The farm took in make-up water (ground water, 6–8 °C) at a constant flow rate of 90 m^3/h. The make-up-water entered an indoor hatchery and was subsequently reused and partly recirculated (return flow of ~252 m^3/h) in an outdoor, pond raceway system consisting of earthen ponds connected in parallel and stocked with mainly broodstock rainbow trout (*Oncorhynchus mykiss*). Twenty five kg feed/d (Aller Gold, Emsland Aller Aqua GmbH, Germany) was applied in the hatchery throughout the study period, while 75 kg feed/d (Aller REP EX, Emsland Aller Aqua GmbH, Germany) was administered to the broodstock outdoors. The recirculated water in the pond system was treated by in-farm sludge cones for settling and removal of solids, followed by a fixed bed biofilter (13 m^3 biomedia, Bio-Blok® 200 m^2/m^3, Expo-net A/S, Hjoerring, Denmark). Effluent water (corresponding in volume to the make-up water) passed another biofilter (40 m^3 Bio-Blok® 200 m^2/m^3) before entering into a free water surface constructed wetland, polishing the water before it was finally discharged into the local stream.

2.2. Woodchip bed system and operation

A trench (10 m × 3.2 m × 1.1 m) with banks approximately 0.5 m above the ground was dug next to the constructed wetland (Fig. 1) and sealed with an impermeable polyvinyl chloride (PVC) liner. Vertically inserted polyethylene (PE) grids (mesh size = 2 cm) were fitted at both ends of the lined basin and supported by cuboid frame constructions (199 × 60 × 100 cm) made from galvanized steel pipes. The space between the two grids was filled with woodchips (crossed clones of *Salix viminalis* × *Salix schwerinii)* obtained from existing stockpiles (Ny Vraa Bioenergy I/S, Tylstrup, Denmark). The woodchips ranged from 1 to 5 cm in length and from 0.2 to 1.5 cm in width. Total woodchip porosity was 65 ± 1% calculated by submerging air-dried woodchips in 1 l bottles (closed with a lid), adding any absorbed water after 24 h and calculating the total porosity from the total volume of water used (Christianson et al., 2010). Woodchips were packed up to about 30 cm above the water level within the bioreactor and the volume of the submerged woodchips was 12.5 m^3. Sample ports were installed at 9 points within the woodchip bioreactor forming a 3 × 3 grid (Fig. 1). The sample ports were made from perforated tubes (ϕ = 4.5 cm, h = 140 cm, BioBlok 250, Expo-net A/S, Hjoerring, Denmark) inserted vertically in the bed to create permeable columns with free water volume between the woodchip bed bottom and the water surface.

An inlet and outlet zone (~1.5 m^3 each) at either end of the packed woodchip bed allowed an even distribution of water at both ends of the gravity-fed system. A pump (Unilift KP250A, Grundfos A/S, Denmark) mounted in a PE basket was placed near the bank of the constructed wetland in 2 m distance from the biofilter discharge to the wetland, constantly pumping and lifting water from the wetland to the woodchip filter inlet zone via a hose. The intake flow (2.5 m^3/h, measured at the hose outlet) was controlled via a connected ball valve and frequently monitored. From the inlet zone, water flowed by gravity as a horizontal subsurface flow through the woodchip packing into the outlet zone. From the outlet zone the water overflowed into a stand-pipe which directed the water back into the constructed wetland about 8 m downstream the intake pump (Fig. 1).

During the start-up sampling period, the woodchip bioreactor was operated at a constant EBCT of 5 h (i.e., calculated as 12.5 m^3 of submerged woodchip packing receiving a constant intake flow rate of 2.5 m^3/h), which, accounting for the woodchip porosity, corresponds to a theoretical HRT of 3.25 h. A short EBCT was chosen to reduce the anticipated period of nutrient washout/leaching from the fresh woodchips. When putting in operation, the woodchip bioreactor was filled with water at the same flow rate as operated during the subsequent start-up phase.

2.3. Sample collection

Grab samples were obtained every 6 h from the inlet and outlet zones until the bioreactor was in steady state. The frequent sampling schedule was accompanied by weekly 24 h pooled samples which succeeded for another three weeks. All samples were collected via refrigerated (3 °C) auto samplers (Glacier® Portable; Teledyne ISCO, USA) sampling water from the inside of the inlet