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Optimizing nitrate removal in woodchip beds treating aquaculture effluents

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ABSTRACT

Nitrate is typically removed from aquaculture effluents using heterotrophic denitrification reactors. Heterotrophic denitrification reactors, however, require a constant input of readily available organic carbon (C) sources which limits their application in many aquaculture systems for practical and/or economic reasons.
A potential alternative technology for removing nitrate currently applied for treating surface and drainage water is based on using wood by-products as a carbon source for denitrification.
Using lab-scale horizontal-flow woodchip filters, the current study investigated the potential of optimizing woodchip reactors for treating aquaculture effluent. A central composite design (CCD) was applied to assess the effects of simultaneously changing the empty bed contact time (EBCTs of 5.0–15.0 h; corresponding to theoretical hydraulic retention times of 3.3–9.9 h) and bicarbonate (HCO_3^-) inlet concentration (0.50–1.59 g HCO_3^-/l) on the removal rate of NO_3^- N, and additional organic and inorganic nutrients, in effluent deriving from an experimental recirculating aquaculture system (RAS).
Volumetric NO_3^- N removal rates ranged from 5.20 ± 0.02 to 8.96 ± 0.19 g/m^3/day and were enhanced by adding bicarbonate, suggesting that parts of the removal was due to autotrophic denitrification. The highest N removal rate (8.96 ± 0.05 g/m^3/day) was achieved at an EBCT and HCO_3^- combination of 15 h and 1.59 g HCO_3^-/l. Bicarbonate inlet concentration as a single factor had the strongest effect on N removal rates followed by the interaction with EBCT, and EBCT^2 (quadratic term).
The study thus indicates that woodchip beds may be applied and optimized for removing nitrate from aquaculture effluents.
Statement of relevance: This study is a relevant contribution to research in aquaculture as it presents an alternative method for removing nitrates from aquaculture effluents especially for less intensive fish farms. Furthermore, it shows how this method can be optimized to yield higher removal rates of nitrate.

1. Introduction

Cost-effective removal of nitrogen (N) from fish farm effluents is a primary limiting factor for the expansion of the aquaculture industry in many regions (Directive 2000/60/EC). In-line or end-of-pipe removal of nitrogen is commonly facilitated by denitrification reactors. Denitrification reactors, however, require a constant input of readily available endogenous or exogenous organic carbon (C), and delicate process control is necessary to maintain an optimal C/N ratio (~3–6) in the reactors (van Rijn et al., 2006; Suhr et al., 2013). Implementation of such reactors is therefore largely limited to intensive recirculating aquaculture systems (RAS) where they may aid to reduce water intake rates and save heating costs, control pH, and reduce environmental discharge fees (van Rijn et al., 2006). For the majority of less intensive farms characterized by relatively high flow rates of dilute discharges application of denitrification reactors for end-of-pipe treatment is typically restricted by the large demand for exogenous carbon, and there is a need to find alternative, cost-effective technologies.

Since the 1990's, removal of nitrogen from surface and drainage waters with high N concentrations has been facilitated by the use of wood by-products in denitrifying bioreactors (reviewed by Schipper et al., 2010b and Christianson et al., 2012). As the water flows passively through these reactors packed with woody material, oxygen is removed due to bacterial metabolism creating an anoxic environment. In addition to removal of oxygen, wood has C/N ratios in the range of several hundred (Greenan et al., 2006; McLaughlan and Al-Mashaqbeh, 2009), and acts as a solid C-source for microbial denitrification under the anoxic conditions (Shipper et al., 2005; Warneke et al., 2011a).

The hydraulic retention time (HRT), typically ranging from hours to days, is an important parameter in these systems (Lepine et al., 2015) and has been shown to correlate positively with NO_3^- N removal (Chun et al., 2009; Greenan et al., 2009). Furthermore, NO_3^- N removal rates in woodchip bioreactors treating ground or drainage waters may

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be limited by low nitrate loadings (Shipper et al., 2005). At high nitrate loadings, on the other hand, removal rates may be restricted by temperature (Warneke et al., 2011a) and/or the availability of carbon rather than nitrate concentration (Gibert et al., 2008; Robertson, 2010; Schipper et al., 2010b). Among various natural organic substrates tested (Gibert et al., 2008), woodchips are most commonly used in field-scale denitrification systems because of their availability at low costs, good hydraulic permeability, and high C/N ratio (Schipper et al., 2010b). Furthermore, woodchip denitrifying bioreactors require minimum maintenance and have a high longevity (5–15 years) given that wood is degraded more slowly under anoxic compared to aerobic conditions (Schipper et al., 2010b).

Pre-trials with laboratory scale, horizontal woodchip reactors at DTU Aqua, Denmark, showed that the reactors were instantly effective in removing nitrate from RAS effluents, and that the removal depended on the empty bed contact time (EBCT; i.e. HRT in reactor without woodchips). The pre-trials further showed that there was a concomitant decrease in pH from the inlet to the outlet of the reactors, and that this decrease was larger when the EBCT was increased. Similar observations have been noted by others working with drainage water, synthetic wastewaters, and septic systems (Van Driel et al., 2006b; Robertson et al., 2005b; Robertson and Merkley, 2009; Warneke et al., 2011a; Ghane et al., 2015; Lepine et al., 2015). The observations, however, seem to contradict with the belief that heterotrophic denitrification is the primary process that takes place in the reactors as this process releases hydroxyl ions (OH^-) which ought to raise pH along the woodchip beds, as also observed in a single study by Warneke et al. (2011b). A decline in pH is commonly considered to be a result of leaching of dissolved organic substances, inferred from a concurrent decrease in pH and high release of dissolved organics typically observed in the initial period after woodchip bioreactor start-up (Cameron and Schipper, 2010; Lepine et al., 2015).We, however, further speculated that a continued drop in pH from reactor inlet to outlet typically observed during prolonged bioreactor operation could in part also be due to autotrophic denitrification, and that overall N removal rates therefore would be enhanced by adding an inorganic carbon source.

Further pre-trials in the laboratory showed that increasing EBCT and adding bicarbonate (an inorganic carbon source with pH buffering capacity) in the form of sodium hydrogen carbonate ($NaHCO_3$) affected effluent pH in opposite directions. We therefore hypothesized that nitrate removal rates could be enhanced by optimizing pH and inorganic carbon supply through simultaneously changing EBCT and bicarbonate addition. Consistent with this, the current study investigated the relationship between EBCT and bicarbonate dosage on the removal rate of nitrate and additional inorganic and organic nutrients deriving from RAS effluents in a lab-scale woodchip bed setup.

2. Materials and methods

2.1. Experimental design

The interaction between EBCT and bicarbonate inlet concentration on the removal rate of NO_3^- N and additional inorganic and organic nutrients in lab-scale woodchip bioreactors was examined by applying a central composite design (CCD) and response surface methodology (RSM) using the Design-Expert version 9 software (Stat-Ease, Inc., Minneapolis, USA). Consistent with the CCD, the two variables were each fixed at five coded levels: $-\alpha$, -1 (low), 0 (central), $+1$ (high), $+\alpha$; where alpha (α) is the relative distance of the axial points from the center point (α was fixed at 1.41 in the current study as 2 variables were investigated making the model rotatable). The center point combination was replicated five times (i.e., five separate reactors), while four factorial points in single determinations covered all combinations of low and high values of the two factors. Furthermore, four axial points were included, each point including one variable at either of the two alpha levels (± 1.41) and a midpoint of the other variable. The experimental set-up consequently comprised a total of 13 separate horizontal flow filters (Fig. 1), each run at a specific combination of the two variables (Table 1).

The low and high levels of the two factors were determined based on pre-trial observations. Accordingly, the EBCT was set at 5 and 15 h, respectively, observed to be long enough to establish anoxic conditions and still short enough to ensure that NO_3^- N concentrations did not limit N removal rates. Including the four axial points, EBCTs were set at 2.9, 5.0, 10.0, 15.0 and 17.1 h. Accounting for the total woodchip porosity (66 ± 2%; Section 2.2) the EBCTs correspond to theoretical HRTs of 1.9, 3.3, 6.6, 9.9 and 11.3 h, respectively.

Similarly, the low and high bicarbonate inlet concentrations, comprising the sum of background HCO_3^- in the RAS effluent to be treated and the amount of HCO_3^- added in the form of $NaHCO_3$, were set at

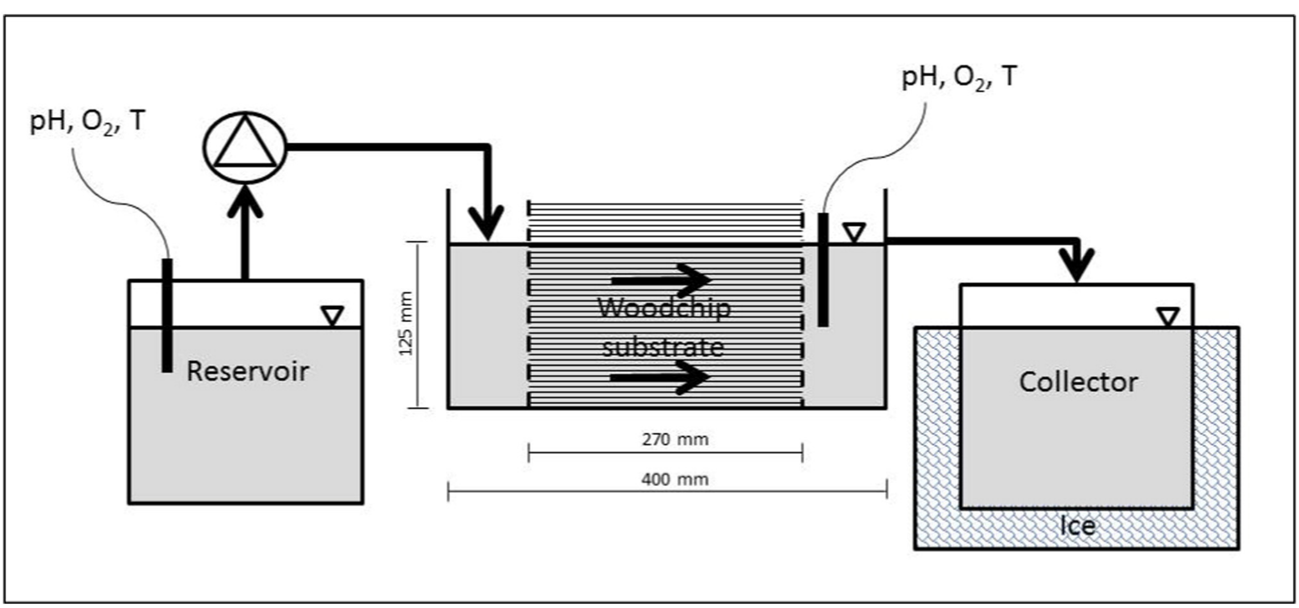

Fig. 1. Experimental horizontal flow woodchip filter (n = 13 in full set-up) connected to a reservoir (n = 5 in full set-up) and a 24 h-pooled sample collector kept on ice. Arrows display the direction of water flow. Location of sensors for measurement of pH, oxygen and temperature are indicated.