Aquacultural Engineering 65 (2015) 37–45

Contents lists available at ScienceDirect

Aquacultural Engineering

journal homepage: www.elsevier.com/locate/aqua-online

Nitrification performance and robustness of fixed and moving bed biofilters having identical carrier elements

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ARTICLE INFO

Article history:
Available online 31 October 2014

Keywords:
Nitrite accumulation
Apparent nitrite removal
TAN
Hydrogen peroxide
Recirculating aquaculture system

ABSTRACT

This study compared moving bed (MB) and fixed bed (FB) biofilter performance. The experimental recirculating aquaculture system had four equal biofilters in parallel. Each of the two replicated FB biofilters (with heavy elements) and the two MB biofilters (with neutral elements) had 200 l carrier media with a surface specific area to volume ratio of 750 m^2/m^3. Total ammonia nitrogen (TAN) and apparent nitrite removal rates were measured during identical steady-state conditions and during a water treatment event where 50 mg/l hydrogen peroxide was applied. FB biofilters were found to perform equal to or better than MB biofilters during the experimental phases. The average ($n = 2$) surface specific TAN removal in the FB biofilters was significantly higher than the MB biofilters (0.20 vs. 0.14; g N/m^2/d) at steady state. The FB biofilters had a positive apparent nitrite removal (0.02 g N/m^2/d) at steady state in contrast to MB biofilters releasing nitrite (−0.02 g N/m^2/d). Application of H_2O_2 caused a transient five-fold TAN increase up to 1.05 mg N/l in the system. Prolonged elevated nitrite levels up to 2.85 mg N/l (>15 fold increase) was observed for one week due to reduced nitrite oxidation particularly in the MB biofilters. The findings indicate FB biofilters to be more resistant against the sanitizer applied, due to increased organic matter in the biofilters compared to MB biofilters. Aspects of the experimental setup are discussed in relation to other studies and commercial biofilter operations.

1. Introduction

Nitrification is a keystone process in recirculating aquaculture systems (RAS). The two-step microbial oxidation of ammonium via nitrite to nitrate is universal and vital to ensure that ammonia and nitrite do not accumulate in recirculating fish culture systems (Hagopian and Riley, 1998). Nitrifying bacterial colonization occurs as attached growth, either as activated sludge as bioflocs in suspension (Henze et al., 2000; Crab et al., 2007) or as fixed film on surfaces as utilized in bioreactors and biofilters (Gutierrez-Wing and Malone, 2006; Malone et al., 2006). Under aerobic conditions, biological filtration includes autotrophic ammonia and nitrite removal and heterotrophic degradation of dissolved and particulate organic matter. These processes consume oxygen and produce CO_2 resulting in a pH decrease in the biofilm and the water phase. The bacteria compete for dissolved substrates and available surface areas, therefore the microbial dynamic, succession and activity is strongly affected by the prevailing microenvironment.

Various bench scale experiments have described important factors of relevance to aquaculture biofiltration: chemical parameters (e.g. Chen et al., 2006; Lyssenko and Wheaton, 2006a,b), microbial interactions (Michaud et al., 2006; Schreier et al., 2010) and physical/hydraulic conditions (Zhu and Chen, 2001a; Prehn et al., 2012). The nitrification process itself is well described but *de facto* biofilter performance is complicated by the underlying biotic and abiotic variables (degrees of freedom) associated with commercial operation. Although the important biological processes are not fully controlled under all sets of conditions, biofiltration is still considered the best solution (effective and relatively inexpensive) for removing total ammonia nitrogen (TAN) and nitrite in RAS in favor of other processes (Ahn, 2006; Díaz et al., 2011; Gendel and Lahav, 2013).

Numerous biofilter designs have been developed and tested including ongoing research on optimizing carrier materials and configurations (Greiner and Timmons, 1998; Guerdat et al., 2010; Pfeiffer and Wills, 2011). Country specific traditions and preferences have led to numerous biofilter solutions, including trickling filters (Eding et al., 2006), moving bed biofilm reactors (Rusten et al., 2006) and fluidized bed sand filters (Summerfelt, 2006; Davidson et al., 2008). Danish water reuse systems, the so-called model trout

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http://dx.doi.org/10.1016/j.aquaeng.2014.10.005
0144-8609/

farms (MTF), and Danish designed RAS typically rely on a combination of submerged static/fixed bed biofilters, moving bed biofilters and/or trickling filters.

An ideal biofilter for all purposes does not exist (Summerfelt, 2006), and as all types of biofilters have their pros and cons, efforts have been made to set guidelines for reporting biofilter performance (Colt et al., 2006; Drennan et al., 2006; Malone and Pfeiffer, 2006; Guerdat et al., 2011). Biofilter studies are generally time consuming to allow for mature microbial colonization and to reach steady state conditions. Different pilot scale biofilter studies have tested effects on nitrification performance in different biofilter setups (Sandu et al., 2002; Ling and Chen, 2005; Lyssenko and Wheaton, 2006a) using synthetic substrate-enriched RAS water. Recently, Suhr and Pedersen (2010) compared nitrification performance in submerged fixed bed biofilters (FBB) and moving bed biofilters (MBB). The study showed that the fixed bed biofilters with high porosity and moderate specific surface area (200 m^2/m^3) were more robust to changes and had a superior surface specific TAN removal (0.46 $g/m^2/d$) compared to moving bed biofilters (0.27 $g/m^2/d$). However, calculated as a volumetric TAN removal, FBBs removed 92 $g/m^3/d$ compared to 231 $g/m^3/d$ in the moving bed biofilters (filling rate: 70%).

Empirical observations at some Danish MTF indicate that nitrite accumulation can be more pronounced in systems having MBBs only. It remains to be tested whether this relates to a specific type of biofilter, preferably under steady state conditions, reflecting water quality of commercial systems. Furthermore, issues of robustness due to realistic changes in operation also need to be addressed, since stable operation is essential in commercial farming.

The robustness of a given biofilter is therefore a valuable rating characteristic, as it determines potential consequences of a given change in operation on the resulting water quality. Examples of such changes might include changes in feed composition, increased feed loading or use of sanitizing chemicals to control parasites. The latter has previously been shown to affect the nitrifying bacteria communities in biofilters (Collins et al., 1975; Noble and Summerfelt, 1996; Schwartz et al., 2000; Pedersen et al., 2009). To prevent this, measures can be taken to protect the biofilters, i.e. by bypassing the units during application of hydrogen peroxide as described in Pedersen and Pedersen (2012). As biofilters are highly diverse, it may be speculated whether different biofilter types and modes of operation respond in a similar manner to acute exposure of an aquaculture disinfectant.

To examine this hypothesis a controlled experiment was made in a RAS having four identical biofilters in parallel, comprising of each of two replicates of FBB and MBB. The amount of bioelements and total surface specific area was identical in all four biofilters; the carrier elements only differing in density. Constant input in terms of fish feed and ammonium chloride and fixed water exchange reflected realistic RAS water concentrations of organic matter and nitrogenous compounds. All four filters received the same type and amount of RAS water from the common fish tank for a prolonged experimental period. The purpose of the study was thus to assess and compare specific nitrification performance in the filters at steady state. The study also included a deliberate disruption in terms of water sanitation to evaluate the specific response of the filters and to compare the recovery and robustness of them.

2. Materials and methods

2.1. Experimental setup

The experiment was conducted in a 8.5 m^3 RAS (Fig. 1). The system included four identical, separate upflow biofilters connected in parallel. Each of the 0.40 m^3 biofilters was filled with 0.20 m^3 identical carrier media (RK BioElements®, RK Plast, Denmark) sharing the same detailed specifications (shape and surface specific area) except for differences in the density of the PP-material used (Table 1). Two of the filters contained RK BioElements Heavy (density 1.20 g/cm^3) which functioned as a sub-merged, static/fixed bed biofilter (FBB). The other two biofilters contained RK BioElements Medium (density 1.00 g/cm^3) that was kept agitated by the injection of compressed air at the bottom of the filter creating moving bed biofilter conditions (MBB; Table 1). The biofilters received a similar, constant water flow and were hence equal in terms of hydraulic loading and elevation velocity. The RAS also included a trickling filter unit receiving the biofilter effluents and a drumfilter (40 μm mesh; HydroTech, Sweden) constantly receiving a separate side stream from the rearing tank. Oxygen levels were maintained above 8 mg O_2/l by two diffusors at the bottom of the rearing tank providing air and oxygen, respectively.

Table 1
Specifications of the experimental RAS.

	Value
Experimental setup characteristics	
System volume (m^3)	8.5
Tank volume (m^3)	5.5
Make-up water (m^3/d)	1.4
Hydraulic retention time (d)	6
Feed loading (kg/m^3)	0.72
Fish density (kg/m^3)	23–30
Feed[a] quantity (g/d)	1000
Feeding duration (hrs.)	6
NH_4Cl supplement (g/d)	250
Biofilter characteristics (n = 4)	
V_{media} (m^3) Media volume	0.20
A_{media} (m^2) Total active surface area of media	150
Cross-sectional area of filter (m^2)	0.5
Hydraulic loading rate ($m^3/m^2/d$)	340
Flow to each biofilter (l/min)	120
Aeration in MBB (l/min)	40
Elevation velocity (cm/min)	24
Media characteristics[b]	
Specific surface area (m^2/m^3)(Neutral vs. heavy)	750/750
Specific media gravity (g/cm^3)	1.00/1.20

[a] Biomar EFICO Enviro 920A, 3 mm; Biomar, Brande, Denmark.
[b] Manufacture info and specifications of the two distinct types of carrier at www.rkplast.dk; RK Bioelements Neutral and Heavy; RK Plast, Skive, Denmark.

2.2. Management and operating conditions

During the experiment, the rearing tank held 120 (beginning) to 160 (end) kg rainbow trout averaging 150 g/pcs at the beginning of the trial. A fixed amount of 1000 g feed was delivered daily to the fish in the rearing tank from 8 a.m. to 2 p.m. by use of a belt-feeder.

Prior to this experiment the RAS had been operating at similar conditions for more than two months. Following backwash of all four biofilters, constant operating conditions, according to Table 1, were resumed. A conditioning period was again kept for several weeks to ensure achievement of steady-state conditions, evidenced by stable TAN (<0.4 mg N/l), nitrite (<0.3 mg N/l) and nitrate (~150 mg N/l) concentrations in the RAS.

The RAS was operated to meet a number of criteria in order to test and compare biofilter performance. The criteria included controlled conditions in terms of constant feed input and fixed make-up water, water quality and operating conditions, stocking densities, feeding rates, and a high feed loading (kg feed/m^3 make-up water) resembling commercial RAS conditions and having organic matter input almost entirely originating from feed. Supplementary TAN was provided by continuous NH_4Cl dosage (Table 1) to increase N-loading of the system without excessively increasing fish biomass. A constant amount of make-up water, equivalent to 1.4 m^3/d was established using municipal tap water.