Science of the Total Environment 628–629 (2018) 603–610

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Nitrous oxide emissions from near-zero water exchange brackish recirculating aquaculture systems

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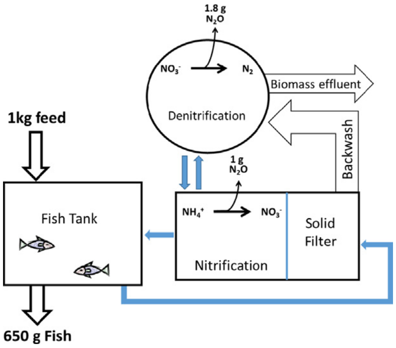
HIGHLIGHTS

- Nitrification and denitrification in RAS water may cause significant N_2O emissions.
- Direct and potential N_2O emissions from RAS compartments were quantified.
- Overall N_2O emissions of 885 mg/kg feed or 1.36 g/kg fish production were recorded.
- Aquaculture N_2O emittance account for 0.5% of global anthropogenic N_2O emission

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 28 December 2017
Received in revised form 7 February 2018
Accepted 8 February 2018
Available online xxxx

Editor: D. Barcelo

Keywords:
Aquaculture
Recirculating aquaculture system (RAS)
Nitrous oxide (N_2O)
Nitrification
Denitrification

ABSTRACT

The development of intensive recirculating aquaculture systems (RAS) with low water exchange has accelerated in recent years as a result of environmental, economic and other concerns. In these systems, fish are commonly grown at high density, 50 to 150 kg/m^3, using high-protein (30%–60%) feeds. Typically, the RAS consists of a solid treatment and a nitrification unit; in more advanced RAS, there is an additional denitrification step. Nitrous oxide (N_2O), a byproduct during nitrification and denitrification processes, is a potent greenhouse gas that destroys the ozone layer. The aim of this study was to measure and assess N_2O emissions from a near-zero discharge land-based saline RAS. N_2O flux was monitored from the RAS's fish tank, and moving-bed nitrification and activated-sludge (with intrinsic C source) denitrification reactors. N_2O emission potential was also analyzed in the laboratory.

N_2O flux from the denitrification reactors ranged between 6.5 and 48 mg/day, equivalent to 1.27 ± 1.01% of the removed nitrate-N. Direct analysis from the fish tank and nitrification reactors could not be performed due to high aeration, which diluted the N_2O concentration to below detection limits. Thus, its potential emission was estimated in the laboratory: from the fishponds, it was negligible; from the nitrification reactor, it ranged between 0.4 and 2.8% of the total ammonia-N oxidized. The potential N_2O emission from the denitrification reactor was 3.72 ± 2.75% of the reduced nitrate-N, within the range found in the direct measurement. Overall, N_2O emission during N transformation in a RAS was evaluated to be 885 mg/kg feed or 1.36 g/kg fish production, accounting for 1.23% of total N application. Consequently, it is estimated that N_2O emission from aquaculture currently accounts for 2.4% of the total agricultural N_2O emission, but will decrease to 1.7% by 2030.

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https://doi.org/10.1016/j.scitotenv.2018.02.089
0048-9697/

1. Introduction

In the last few decades, aquaculture has become the fastest growing agricultural sector due to increasing demand for fish and aquatic products on the one hand, and dwindling fish populations due to overfishing on the other (FAO, 2016; Pauly et al., 2002). Indeed, the last FAO report from 2016 estimated that aquaculture production had exceeded, for the first time, the capture of wild fish, and that it was the only means of supplying an ever-growing demand. To date, most freshwater aquaculture is performed in extensive or semi-intensive ponds, and marine aquaculture in offshore cages (Boyd and McNevin, 2015; FAO, 2016; Hall et al., 2011). However, these methods suffer from several economic and environmental problems, such as high water use and pollution of water bodies, destruction of various ecosystems, insufficient production per area and others (Boyd and McNevin, 2015; Bush et al., 2013; Tovar et al., 2000). The use of inland intensive recirculating aquaculture systems (RAS) has been suggested as an efficient way to produce fish intensively (e.g., 30–150 kg fish/m^3 of water). The RAS is a relatively small and controlled system; water treatment with various reactors (Fig. 1) allows for its recirculation to the fish tank, thereby reducing water use (Ebeling, 2000). The recirculation rate is usually a function of the treatment level. Typically, with better solids and N treatment, less water is exchanged and less chemicals and heat are needed (van Rijn, 1996; van Rijn et al., 2006). This concept enhances control over water quality, fish performance, biosecurity and energy use (Ebeling, 2000; Tal et al., 2009; Timmons and Ebeling, 2013).

Use of RAS can therefore mitigate many of the environmental problems associated with pond and cage aquaculture (Avenue and Kong, 1995; Tal et al., 2009; Timmons and Ebeling, 2013). Interestingly, RAS still account for <5% of aquaculture practice; however, this number is predicted to rise to about 40% by 2030 (Bostock et al., 2016; Essery, 2015; FAO, 2016). Moreover, these systems constitute a good research platform for studying biogeochemical processes in aquatic systems in general and aquaculture in particular.

In RAS, fish feed is virtually the only organic matter input, accounting for about 40–50% carbon (C) (Boyd and McNevin, 2015; Boyd and Tucker, 2014). It contains 25–65% protein (Lovell, 1988; Pillay and Kutty, 2005), corresponding to 4.1–10.7% organic nitrogen (N). Only about 20–30% of the N from the applied feed is recovered by the fish as biomass (Sandu and Hallerman, 2013; Yogev et al., 2017), while the rest is excreted into the water, mainly as total ammonia N (TAN) and organic N (dissolved and particulate) (Ebeling et al., 2006). Ammonia is toxic to most fish, even at low concentrations of a few milligrams per liter (Randall and Tsui, 2002; Timmons and Ebeling, 2013), and it therefore has to be removed from the fish tank. Nitrification is the major method used to remove ammonia in RAS resulting in accumulation of the less toxic nitrate in the system (Guerdat et al., 2010; van Rijn, 1996). Nitrate concentration is typically kept at non-toxic levels through water exchange or, if the water needs to be conserved, by introduction of a denitrification unit (Martins et al., 2010; van Rijn, 2013). Denitrification refers to the anoxic biological reduction of nitrate to dinitrogen gas (N_2), and it was used to remove nitrate from the studied system.

During these bioprocesses of N transformation (nitrification and denitrification), the byproduct nitrous oxide (N_2O) is produced (Fig. 2) (Guo et al., 2013; Schreiber et al., 2012). Although N_2O is not an intermediate in the main nitrification pathway, nitrifying bacteria produce it. The mechanism is not completely understood, but two different pathways have been considered. The first is associated to the oxidation of hydroxylamine to nitrite and the second to the nitrifier/denitrification pathway under oxygen-limiting conditions (Guo et al., 2013).

N_2O is a potent greenhouse gas which has a global warming potential 265 times that of carbon dioxide over its 100-year lifespan, and it is considered the single most important ozone-depleting gas (Ravishankara et al., 2009). Moreover, its concentration in the atmosphere has increased by 20% since the 1880s, from 270 ppb to 322.4 ppb in 2011 (Hartmann et al., 2013). Agriculture is considered to be a primary anthropogenic source of N_2O emission (McCarl and Schneider, 2001). However, most studies have focused on natural or fertilized soil, whereas only a handful of studies have been conducted on N_2O emission from aquaculture. Theoretical calculation estimated the annual global N_2O emission from aquaculture in 2008 to be 9×10^{10} g, representing 0.51% of the global N_2O emission (Williams and Crutzen, 2010). Hu et al. (2012) further estimated that by 2030, emission will have increased to 3.83×10^{11} g, accounting for 5.72% of anthropogenic N_2O-N emission, assuming that the aquaculture industry continues to grow at the present annual rate of about 7–10%. A few recent studies have considered N_2O emissions from nitrification units in freshwater RAS without a denitrification unit (Hu et al., 2013, 2014, 2015; Paudel et al., 2015). In those studies, the dissolved N_2O concentration in the

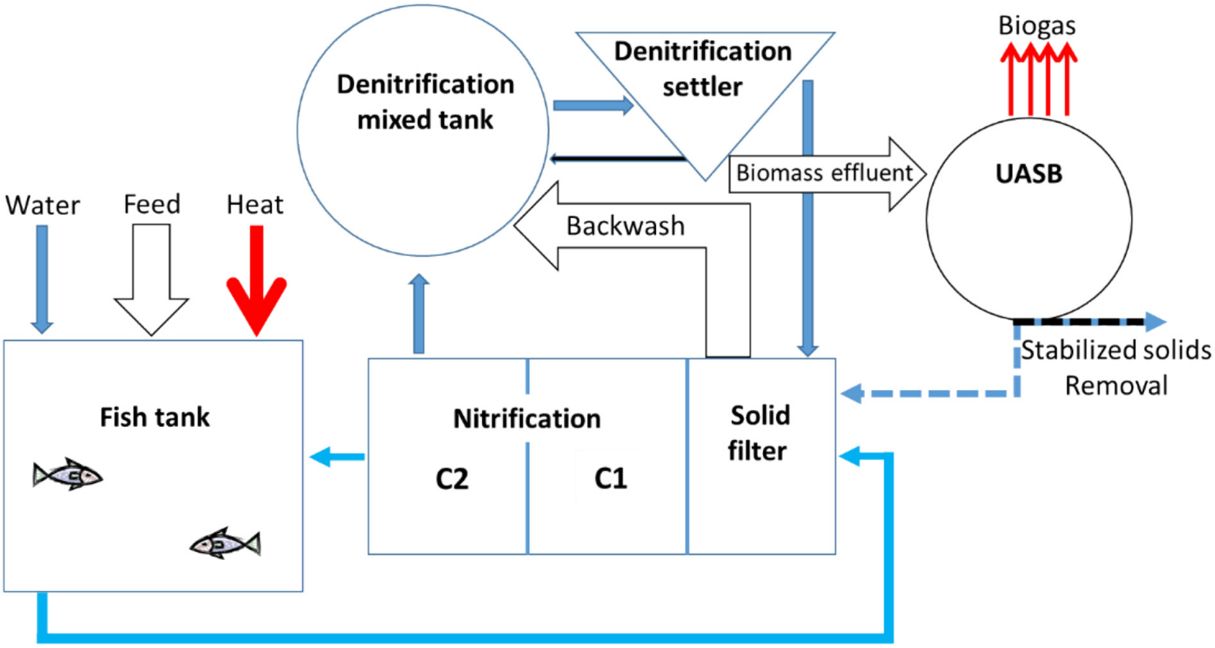

Fig. 1. Schematic diagram of the near-zero exchange recirculating aquaculture system that was used in the current study (after Yogev et al., 2017).