

Nitrogen recovery and nitrous oxide (N₂O) emissions from aquaponic systems: Influence of plant species and dissolved oxygen

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ARTICLE INFO

Keywords:

Aquaponic
Nitrogen recovery
Nitrogen loss
Nitrous oxide
Nitrogen use efficiency
Denitrification

ABSTRACT

Aquaponics recycles nitrogen from nitrogen-rich aquaculture effluent into organic crops (fish and vegetables/fruits) in hydroponic grow beds. Fundamental understanding of nitrogen transformations in aquaponics is critically important to improve nitrogen use efficiency (NUE) within aquaponics systems and to reduce release of environmentally harmful effluent and gases. This study elucidated nitrogen transformations in floating-raft aquaponic systems using four plant species, namely lettuce (*Lactuca sativa longifolia* cv. *Jericho*), pak choi (*Brassica rapa* L. *Chinensis*), tomato (*Lycopersicon esculentum*), and chive (*Allium schoenoprasum* L.). Using nitrogen mass balance and ¹⁵N labeled nitrogen species, it was found that nitrate was the primary form of nitrogen assimilated by plants. Nitrification and denitrification occurred simultaneously in the aquaponic system, resulting in an inevitable nitrogen loss (22.3–29.3% of nitrogen input). Nitrogen loss via nitrifier denitrification (33.7–55.3%), which was stimulated by low dissolved oxygen (DO) levels (~3.8 mg/L), and denitrification occurred simultaneously. Moreover, nitrogen loss from the aquaponic system in the form of nitrous oxide (N₂O), a potent greenhouse gas, accounted up to 0.72–1.03% of the nitrogen input. Aerating biofilters to prevent the formation of anoxic zones reduced total nitrogen loss but did not affect N₂O emission. This study suggests that increasing DO concentrations only by aeration does not improve NUE and reduce N₂O emission simultaneously.

1. Introduction

Anthropogenic nitrogen losses from food production can have significant impacts on the environments. The excessive use of reactive nitrogen (e.g., urea) in food production was responsible for 68–93% of total anthropogenic nitrogen loss in the past decade (Shibata et al., 2017). Furthermore, nitrogen loss from food production is expected to increase drastically due to the increase in the world population, which is estimated to increase by two to three billion people in the next 30 years (Zhang et al., 2015). In the absence of a proper treatment system, over 50% of applied nitrogen is lost to natural environments and can result in eutrophication, nitrate contamination of groundwater, and nitrous oxide (N₂O) emissions (Galloway et al., 2003; Lassaletta et al., 2014; Pikaar et al., 2017). N₂O, a potent greenhouse gas, is also one of the most dominant ozone-depleting substances and has a global warming potential 298 times higher than that of CO₂ under 100-year time horizon (Forster et al., 2007; Ravishankara et al., 2009). Approximately 2.0–2.5% of nitrogen applied as fertilizer to agricultural fields ends up as N₂O emissions, and N₂O emissions from soil-based agriculture are responsible for ~50% of global anthropogenic N₂O

emission (Davidson, 2009; IPCC, 2007).

Several strategies such as improving nitrogen use efficiency (NUE), implementing nitrogen recovery, and reducing wastes from food production systems have been suggested to reduce the effects of nitrogen loss (Galloway et al., 2003; Shibata et al., 2017; Zhang et al., 2015). For example, to meet the demand for food with currently available nitrogen (as chemical fertilizer), the NUE in crop production needs to be improved from 40% in 2015 to 70% by 2050 (Zhang et al., 2015). In addition to environmental issues, higher nitrogen loss requires more fertilizer and ultimately reduces overall profit (Shelton et al., 2018).

Aquaponics is a combination of aquaculture and hydroponics. Aquaponics has a high potential to recycle waste nitrogen from aquaculture effluent and increase NUE in crop productions (Wongkiew et al., 2017b). Aquaponics produces organic crops in a recirculating system, thereby preventing nitrogen losses via infiltration and surface leaching, which are the dominant pathways for nitrogen losses in a soil-based agriculture (Shelton et al., 2018; Wongkiew et al., 2017a). The nitrogen transformations in an aquaponics rely on the symbiotic relationships among bacteria, fish, and plants. Fish in the aquaculture tanks excrete total ammonia nitrogen (TAN). Bacteria in biofilters and plant roots

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<https://doi.org/10.1016/j.ibiod.2018.08.008>

Received 19 July 2018; Received in revised form 28 August 2018; Accepted 28 August 2018

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maintain good water quality for fish by oxidizing toxic TAN to nitrite and ultimately to non-toxic nitrate via aerobic nitrification (Tanikawa et al., 2018; Wongkiew et al., 2017a). Plants in the hydroponic grow bed assimilate the nitrogen from the aquaponic systems, thus increasing NUE. NUE in an aquaponic system depends on the amounts of nitrogen uptake by the plants and fish relative to nitrogen input in fish feed (Hu et al., 2015). Although nitrogen discharge from aquaculture effluent can be managed in an aquaponics, nitrogen loss in gaseous forms (20–60% nitrogen loss relative to fish feed input) is inevitable resulting in an incomplete nitrogen recovery (NUE of 40–60%) and high N_2O emissions (0.6–2.0% of N_2O relative to N in fish feed input) (Hu et al., 2015; Wongkiew et al., 2017b; Zou et al., 2016b).

Similar to natural systems, nitrogen loss in aquaponic systems can occur via denitrification (reduction of nitrate) and nitrifier denitrification (nitrite reduction via autotrophic nitrification) (Klotz and Stein, 2008; Kuypers et al., 2018; Wragge et al., 2001; Zhu et al., 2013). Due to low nitrite concentration ($< 1 \text{ mg N/L}$) in aquaponic systems, chemo-denitrification (chemical decomposition of hydroxylamine) and anammox are not significant pathways of nitrogen loss (Hu et al., 2012; Wongkiew et al., 2017b). Nitrifier denitrification occurs under the presence of oxygen at high nitrite and low chemical oxygen demand (COD), and near neutral pH levels (6.5–8.5) (Rathnayake et al., 2015; Wunderlin et al., 2012). Denitrification occurs in the absence of oxygen and high COD at near neutral pH levels (6.0–8.0) (Lu et al., 2014). N_2O is also released from aquaponics as other agricultural systems to the atmosphere with dinitrogen gas (N_2) during the nitrogen losses via denitrification and nitrifier denitrification (Hu et al., 2015; Jia et al., 2013; Kool et al., 2010; Zou et al., 2016b). N_2O emissions from aquaponic systems can be affected by several parameters such as feeding rate, pH, DO levels, and plant species (Goto et al., 1996; Hu et al., 2012, 2015; Zou et al., 2016b).

Among the parameters that affect nitrogen loss and N_2O emissions, DO is the most critical parameter in aquaponic systems. Maintaining high DO levels in aquaponic systems by aeration is a simple operating technique. A high DO level not only increases fish and plant growth, but it also can directly regulate nitrification, denitrification, and nitrifier denitrification pathways in aquaponic systems. However, studies on the fundamental understanding of the nitrogen loss pathways, especially reducing nitrogen loss and N_2O emissions, relating to DO levels and plant types are limited (Hu et al., 2015; Jia et al., 2013; Zou et al., 2016b). For example, Zou et al. (2016b) and Fang et al. (2017) focused on the optimum pH and aeration pattern for reducing N_2O emission in media-based aquaponics. However, there is still need for better understanding of the effects of DO levels on the nitrogen loss pathways and N_2O emission in order to improve NUE and reduce N_2O emissions from aquaponic systems. For example, if nitrogen loss occurs via nitrifier denitrification, maintaining an aerobic environment using high

DO levels may not be an effective strategy to minimize nitrogen loss and N_2O emissions.

In this study, nitrogen loss pathways and N_2O emissions in a floating-raft aquaponic system were examined using four plant types and two DO levels. The overall objectives were to examine the effects of plant species and DO levels on nitrogen recovery, nitrogen loss, and N_2O emissions from aquaponic systems. The findings could be helpful in managing an efficient nitrogen recovery from aquaculture effluent using aquaponic systems.

2. Materials and methods

2.1. Pilot-scale floating-raft aquaponics and operation

Six floating-raft aquaponic systems were operated in parallel in a greenhouse at the Magoon facility, University of Hawaii at Manoa. Each aquaponic system (working volume = 650 L) consisted of a fish tank, an upflow biofilter, a cascade aeration tank, and a grow bed (hydroponic bed) (Fig. 1). Water from each fish tank was pumped to the upflow biofilter. The upflow biofilter containing Kaldnes plastic media (surface area $\geq 800 \text{ m}^2/\text{m}^3$) for attached-growth of microbes was designed to perform nitrification, capture, and accumulate fish feces and suspended solids from the fish tank. The required surface area of the media was calculated based on TAN conversion rate of $1.0 \text{ g/m}^2\text{-day}$ as described in Wongkiew et al. (2017b). The aquaculture effluent from the cascade aeration entered the grow bed and finally to the fish tank (Fig. 1). Fish tanks were continuously aerated via coarse bubble diffusers at a constant air flow rate of 10 L/min to maintain DO levels above 6.0 mg/L . Gas from the aquaponic systems was ventilated via air outlet points 1 and 2 (outlet 3 was closed) (Fig. 1). For an efficient nitrification, the aquaponic systems were operated at a constant water recirculation rate of $2.25 \text{ m}^3/\text{day}$ (Wongkiew et al., 2017b).

Tilapia (*Oreochromis* spp.), a warm-water species, was used in this study due to their tolerance to low DO levels (Popma and Masser, 1999). Tilapia (an average stocking density of $15.2 \pm 4.6 \text{ kg/m}^3$) were fed with a commercial fish feed (Classic Trout, 3.5 mm diameter, Skretting, UT, USA) once a day at a constant feeding rate of 35 g/day . Four plant species namely pak choi (*Brassica rapa* L. *Chinensis*), lettuce (*Lactuca sativa* longifolia cv. *Jericho*), chive (*Allium schoenoprasum* L.) and tomato (*Lycopersicon esculentum*) were used in this study due to their growth performance in soilless systems in tropical regions (Kratky, 2010). Each grow bed contained a single raft for growing one plant species at a time (24 plants per raft for pak choi, lettuce and chive, and 6 plants per raft for tomato). The vegetable seeds were germinated for about two weeks before being transplanted into the grow beds.

DO, pH and temperature were monitored daily in fish tanks and grow beds (see section 2.4 for analytical methods). Throughout the

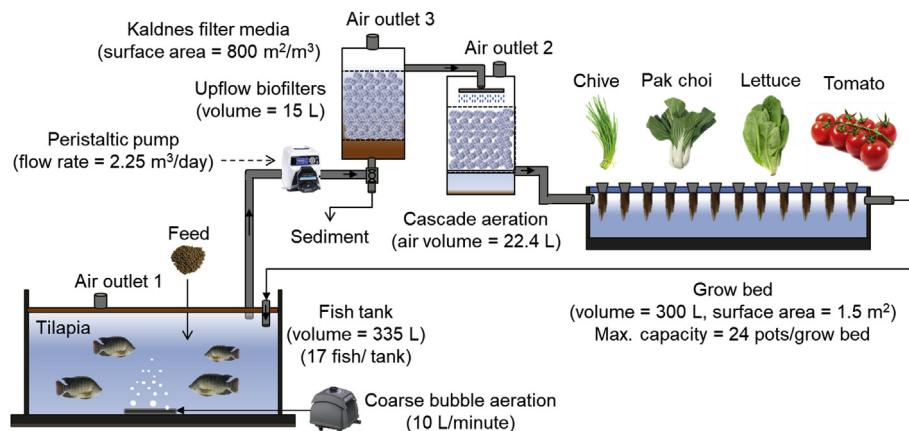


Fig. 1. Schematics of a floating-raft aquaponic system.

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