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Phosphorus dynamics modeling and mass balance in an aquaponics system

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ABSTRACT

Aquacultural effluents are rich in P, a growing concern worldwide for potential environmental pollution. Thus integrating aquaculture with agriculture, e.g. aquaponics, shows promise to enhance nutrient and water use efficiency and overall environmental sustainability. The present study was carried out to quantify a P flow, P mass balance, and evaluate P removal efficiency by hydroponic lettuce integrated with tilapia aquaculture. Also, a phosphorus dynamics simulation model was developed to be a decision support system for phosphorus management. 15 tilapia juveniles (20 g) and four 15-day-old lettuce seedlings comprised each aquaponics experimental unit ($n = 3$). At days 0, 7, 14, 21 and 28 after transplanting, water samples were taken from each aquaponics biofilter to determine the reactive and total concentration of phosphorus. The P dynamics model was validated by comparing predicted to observed values of dissolved P over time. The linear regression equations between predicted and measured values were compared with the 1:1 line for statistically significant differences ($p < 0.05$) in slope and intercept values. The adequacy of the model was determined by testing if intercept equals zero and slope equals one separately using the one sample Student *t*-test. Comparison of simulated and measured values of dissolved P dynamics showed a good fit around the 1:1 line with the slope ($b = 1.005$) and intercept values ($a = 0.0189$) being not statistically different ($p > 0.05$) from 1.0 and 0, respectively. The assimilation of P in the fish and plant components comprised 71.7% of the total P input, indicating high P utilization by the system. The P dynamics model predicted the behavior of dissolved phosphorus in aquaponics systems, which can be used to determine adequate fish:plant ratios, maximize P use efficiency and minimize waste. The overall high P utilization by fish and plants identified in this study showed that aquaponics is an excellent tool for recycling phosphorus while yielding a high-quality crop.

1. Introduction

With the prospects of an increasing world population and the necessity to raise food production, phosphorus (P) represents a critical nutrient to a growing agriculture industry. Phosphate rock has been the exclusively viable source of phosphorus in the manufacturing of phosphate fertilizers (Morawicki, 2012). Mining and processing phosphate rock are highly energy intensive processes requiring energy worth > 70,000 BTU per ton of ore (U.S. DOE, 2002) that potentially result in a broad range of adverse environmental effects. P fertilizer supplies will be affected by rising feedstock prices, and by challenges to access to more fossil fuel and phosphate rock reserves. In the future, the extraction of low-grade phosphate ores will necessitate additional beneficiation processes, which might increase production costs (Heffer and Prud'homme, 2013) and greenhouse gasses emissions (Bojarski et al., 2008).

The use of agricultural wastes as an alternative to the overdependence of synthetic fertilizer production for a worldwide supply of P shows promise and is being re-examined (Cordell et al., 2009). Aquacultural effluents are known to be rich in dissolved and suspended solids that contain mainly phosphorus (P) and nitrogen (N), generated from fish excretion, feces and uneaten feed (Summerfelt and Clayton, 2003). These P wastes released by aquaculture operations are a growing concern worldwide due to their potential of environmental pollution (Chowdhury et al., 2013). Hence, integrating aquaculture with existing irrigated farming systems has the potential to enhance productivity, water use efficiency and overall environmental sustainability (Ingram et al., 2000), reduce use of pesticides and chemical fertilizers (Rejesus et al., 2013), promote ecological and social benefits (Halwart et al., 2003), and maximize farm production without increasing water consumption (McIntosh and Fitzsimmons, 2003).

Aquaponics, an example of integrated aquaculture-agriculture, is the combination of recirculating aquaculture and soilless vegetable production in a closed-loop system. Aquaponics has received considerable attention due to system's capability to raise fish at high density, sustain adequate water quality, minimize water exchange, and produce a

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profitable vegetable that is responsible for the direct assimilation of dissolved fish wastes and products of microbial breakdown (Danaher et al., 2013). Hence, there is potential for aquaponics systems to become an alternative way of recycling P and enhancing overall P utilization. However, the P dynamics and budget in aquaponics systems remain unclear. The dynamics of phosphorus has been reported in one study involving aquaponics systems, but the overall P budget showed that the total amount of P recovered in fish, plants, and solids exceeded the quantity provided in the diet (Seawright et al., 1998). No study so far has attempted to model the dynamics of P in aquaponics systems. Most studies have focused in describing nitrogen dynamics and budget in aquaponics. For instance, the carrying capacity of aquaponics systems have been determined based on nitrogen removal by plants (Endut et al., 2014; Seawright et al., 1998) while other nutrients are usually neglected. Aquacultural effluents contain disproportionate amounts the nutrients required by plants. In general, aquaponics nutrient solutions lack micronutrients (Rakocy, 2012) and potassium (Graber and Junge, 2009). The changes in concentrations of different nutrients in integrated systems differ because of the disparity between the relative proportions of available nutrients generated by fish and nutrients absorbed by plants (Seawright et al., 1998). Thus, when designing aquaponics systems based only on the nitrogen budget, there is no guarantee other nutrients like P are lacking or exceeding plant's requirements. Phosphorus deficiency causes stunted plant growth, whereas phosphorus excess may lead to antagonistic interactions with micronutrients, especially zinc (Barben et al., 2010).

Understanding nutrient absorption dynamics is imperative to adapt adequately inputs to extraction rates, which vary through the production cycle and are influenced by the climate conditions, especially temperature and solar radiation (Castilla, 2012). The development of design criteria for aquaponics systems requires estimates of nutrient uptake and a deeper understanding of culture water nutrient dynamics (Rakocy and Hargreaves, 1993). Nutrient balance calculations are widely used to increase nutrient efficiency and reduce losses from agricultural systems (Modin-Edman et al., 2007). Thus, the present study was carried out to quantify a phosphorus flow, a phosphorus mass balance, and evaluate phosphorus removal efficiency by hydroponic lettuce integrated with tilapia aquaculture. Also, a phosphorus dynamics simulation model was developed to be a decision support system for phosphorus management in aquaponics systems.

2. Material and methods

2.1. System setup and operation

The trial was carried out in a controlled environment greenhouse to provide uniform environmental conditions. Three experimental aquaponics units, each consisting of a 20-L fish tank, 20-L sump filled with 10 L of biofilter medium (Biospheres, Amiracle) and a hydroponics channel were used to conduct the study (Fig. 1).

The sump contained a water pump (EcoPlus 185, 26.5 W) to deliver water to fish tanks at a rate of 600 L h^{-1}. An additional pump (2 W, 200 L h^{-1}) delivered water to the hydroponics NFT-channels and was controlled by a timer that maintained a cycle of 50 s on/1:40 min off. Aeration in the fish tanks and biofilters was provided by airstones. Three separate hydroponics units (Fig. 1) were used as the control for lettuce growth and phosphorus content comparison. Each hydroponics unit had a 20-L reservoir filled with a half-strength hydroponic solution (1.25 g L^{-1}, MaxiGro, Green Hydroponics), which was entirely replaced every week during the first two weeks; for the remaining two weeks, a full-strength nutrient solution (2.5 g L^{-1} MaxiGro, Green Hydroponics) was used and also completely replaced on a weekly basis until the end of the experiment. Water lost through evapotranspiration in all systems was replenished with deionized water.

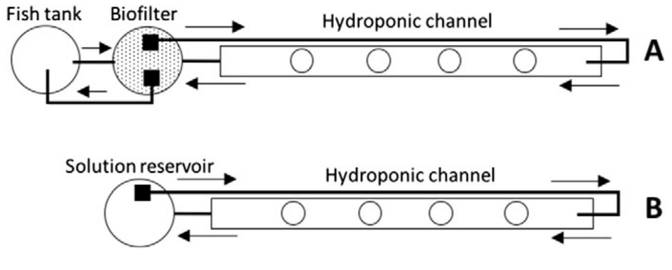

Fig. 1. Top view diagram of the experimental units. A represents the aquaponics unit, B the hydroponics unit, and the black squares are the pumps.

Aquaponics nutrient solutions are known to contain small amounts of potassium, magnesium, and micronutrients. In the present study, potassium was supplemented directly in the water with potassium chloride (Muriate Potash, Hi-Yield®) in all aquaponics systems on a weekly basis to maintain K^+ concentration at 50 mg L^{-1}. Magnesium was supplemented by foliar spraying twice a week using a 1.5% solution of magnesium sulfate salt. Micronutrients (Fe, Cu, Zn, Bo, Mn and Mo) were also supplemented by foliar spraying with a 0.15 g L^{-1} solution of a micronutrient blend product (S.T.E.M, soluble trace element mix, Peters Professional, Everris) every two days during the first two weeks and twice a week during the last two weeks after transplanting. The foliar applications of referred nutrients were chosen over dissolution in the aquaponics nutrient solution to prevent interaction of these supplements with dissolved phosphorus, such as the formation of insoluble salts, like magnesium and iron phosphates, which could precipitate phosphorus out of solution and affect the nutrient dynamics analysis.

Air temperature, relative humidity, and solar radiation were monitored and controlled using a controller and data logger (Campbell Scientific CR23X). Given that each aquaponics unit had a relatively small volume of water, the water temperature fluctuated according to air temperature. Dissolved oxygen in fish tanks was checked on a daily basis using a YSI Pro20 handheld meter and remained constant above 5.0 mg L^{-1} in all units. The pH in aquaponics systems was adjusted to be at 6.8 on the day plants were transplanted using a 5.0 M sulfuric acid solution, and monitored on a weekly basis using a handheld pH meter (HACH Hq40d multi). The pH in aquaponics systems decreased over the weeks, and it was adjusted with sodium bicarbonate accordingly; since experimental trials were of short duration, sodium buildup was not considered a significant concern. The pH of the hydroponics nutrient solution was adjusted at 5.5 on the day it was prepared but not adjusted after that.

2.2. Fish and plants culture conditions

Fifteen tilapia juveniles with an average initial body weight of approximately 20 g were obtained from spawning broodstock at the site. Fish were transferred to their respective tanks five days prior to lettuce transplanting for acclimation. Red Cherokee lettuce pelleted seeds (Johnny's Seeds) were sown in Rockwool cubes and kept in the greenhouse under natural light and photoperiod. Four lettuce seedlings were transplanted to each NFT-channel 15 days after sowing, with the appearance of the first extended leaf. Ten additional lettuce seedlings with similar characteristics to the ones transplanted were oven-dried for two days at 65 °C for initial dry biomass determination.

Fish were fed a commercial diet (35% crude protein, Star Milling California) at approximately 1.0% of body weight per day, twice a day (8:00 am and 4:00 pm). Feeding rate based on fish biomass was not corrected over time and was maintained constant during the entire experiment. Each fish tank contained approximately 300 g of total biomass, resulting in a feeding rate of 3 g of feed per day. The initial total fish biomass, total feed input and, consequently daily feeding rate were determined based on the calculated carrying capacity of the system to remove close to 100% of the excreted phosphorus in the dissolved form by uptake and accumulation in plant biomass.