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Co-cultivation of microalgae in aquaponic systems

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ABSTRACT

Aquaponics is a sustainable system for the future farming. In aquaponic systems, the nutrient-rich wastewater generated by the fish provides nutrients needed for vegetable growth. In the present study, the role of microalgae of *Chlorella* sp. in the floating-raft aquaponic system was evaluated for ammonia control. The yields of algal biomass, vegetable, and removal of the key nutrients from the systems were monitored during the operation of the aquaponic systems. When the systems were in full operation, the algae production was about 4.15 ± 0.19 g/m^2·day (dry basis) which is considered low because the growth conditions are primarily tailored to fish and vegetable production. However, it was found that algae had a positive effect on balancing pH drop caused by nitrifying bacteria, and the ammonia could be controlled by algae since algae prefer for ammonia nitrogen over nitrate nitrogen. The algae are more efficient for overall nitrogen removal than vegetables.

1. Introduction

Aquaponics, synergistically integrated aquaculture and hydroponics, is considered as a sustainable system for the future urban farming. In an aquaponic system, wastewater generated by fish is converted to high-value vegetable products (Love et al., 2015). Aquaponic systems have many advantages and are targeted solving world facing problems including population surge, soil degradation, water shortage, and food security. Comparing with traditional agriculture that uses 70% of the fresh water for irrigation, aquaponics recirculates water within the system that reduces water evaporation and infiltration. A report shows that aquaponics consumes only 1/7 of conventional agriculture water usage (Goddek et al., 2015). Furthermore, since there is no soil involved in the system, the problems associated with soil contamination and soil degradation are eliminated. Due to the controlled environment that reduces the diurnal temperature and light illumination swing, the vegetable productivity is higher than conventional in field cultivation. Using lettuce as an example, it only takes about 32–35 day for lettuce to be harvested in aquaponics while for the conventional agriculture, it usually takes 45 days for it to reach the same weight. With proper management and by following organic practice, the vegetables produced could be sold as an organic product that could potentially bring 50–100% more income than conventional products (Consumer Reports, 2015). Moreover, aquaponics offers a complete food plate on table that covers both vegetable and meat products. The aquaponic systems are especially suitable for the urban area, small islands, as well as arid places that have water shortage. However, since aquaponics needs to balance the growth condition for both fish and vegetables, the overlap of the two sets of conditions often leaves a thin margin for the system to succeed. Ammonia overshoot can be one of the multiple 'single points of failure' that cause death of fish.

Microalgae, as a naturally occurring microorganism in the aquaponic system, are commonly considered a nuisance because they often plug the water pipes, consume oxygen, attract insects and worsen the water quality. The decomposition of accumulated algae leads to excessive consumption of dissolved oxygen and results in a low level of dissolved oxygen (DO) that is dangerous to fish life. Algae could also cause diurnal pH swings and DO variation due to photoautotrophic growth under daytime light and respiration during the night (Storey, 2013) which shows algae have a great impact in an ecological system.

However in this study, instead of eliminating algae in the aquaponics, the beneficial aspects of the algae were intended to be utilized when algae were properly managed. Under a controlled circumstance, the algae may be used to 1) further remove nutrients and improve water quality in the aquaponic system, 2) control pH drop caused by nitrification process, 3) generate dissolved oxygen in the system, 4) produce polyunsaturated fatty acid as a value-added fish feed, and 5) add diversity and improve resilience to the system.

It is known that in the fish waste, ammonia nitrogen is the main form of nitrogen pollutant (90%) in the exit water (Wongkiew et al.,

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2017). According to the nitrogen cycle in the aquaponic system, the ammonia is firstly converted to nitrite (NO_2^-) by ammonia oxidizing bacteria that are represented by the "nitrosomonas" genus and then nitrite-oxidizing bacteria, represented by the "nitrobacter" genus, convert nitrite further to nitrate (NO_3^-) (Goddek et al., 2015). Although some fish species can detoxify ammonia to urea through the ornithine-urea cycle (Ip and Chew, 2010), high levels of ammonia/ammonium are still very toxic to fish due to the accumulated NH^{4+} displaces K^+ and depolarizes neurons and the excessive Ca^{2+} influx finally leads to cell death in the fish's central nervous system (Randall and Tsui, 2002). In general, the total ammonia/ammonium level should be controlled less than 3 ppm (Rakocy and Brunson, 1989). For tilapia fish, the unionized ammonia, which is a temperature and pH related parameter, is recommended to be less than 0.04 ppm (Nelson and Pade, 2008). Once the nitrogen is converted to nitrate nitrogen, it will be far less toxic to fish population and ready to be utilized by the vegetables.

Differing from most of the aquaponics vegetable that could only use nitrate nitrogen, algae can utilize both nitrate and ammonia nitrogen (Shi et al., 2000; Xin et al., 2010). In many studies, algae were used for aquaculture wastewater treatment (Sfez et al., 2015; Kuo et al., 2016). Studies indicate that some algal species even prefer ammonia uptake when both ammonia and nitrate are presented that nitrate use is suppressed at even low level of ammonium with 0.018 mg/L (Raven et al., 1992; Syrett and Morris, 1963). It can be very beneficial for ammonia reduction in the aquaponic system. Differing from pH sensitive nitrification process that is optimized at pH of 7–8, algae can adapt to a wider range of pH variation from 5.5 to 9. In case that the nitrification process fails, algae can still act as a backup system for ammonia removal.

The algae growth under autotrophic growth condition generally increases pH value in the water; however the nitrification process in the aquaponic system lowers the water pH value due to the nitric acid generated. The pH value should be controlled at 7.0 or slightly above 7.0 because the nitrification slows down when pH drops below 7 and stops when pH is less than 6.0 (Nelson and Pade, 2008). The algae component turns out to be the counterpart of the nitrification process for the pH adjustment.

Algae produce oxygen under photoautotrophic condition. According to the simplified photosynthesis equation $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$, for every one mole of carbon dioxide fixed from the atmosphere, one mole of oxygen will be released. Since there is barely organic carbon in the water, all carbons accumulated in the algae biomass primarily come from the atmosphere. Assuming the carbon content in microalgae is 50%, for every gram of algae produced there will be 1.3 g of oxygen generated. Although decomposition of dead algae cells consumes oxygen, this problem could be mitigated if the algae cells are harvested from the system periodically.

Microalgae are known for high lipid content with enriched omega-3 fatty acids which are uncommon in many aquaponics vegetables. It was reported that many algal species contain about 20% of lipids and among them many fatty acids were essential fatty acid (Li et al., 2011; Zhou et al., 2012). Adding suitable algae to the fish feed could improve both fish health and their nutritional value (Cheunbarn and Cheunbarn, 2015; Tocher, 2010). Furthermore, the algae production might add additional economic value for the feed because the market values of algae are high, e.g., *Spirulina* is about $10/Lb and *Chlorella* is nearly $20/Lb which is more expensive than vegetable.

However, the presence of algae can be contradictory since algae are in a competing position with in-system vegetable for nutrition, space and sunlight. On one hand, too many algae may indicate the nutrients in the water body are not well consumed by vegetables that the water quality might in a poor quality and affect the fish health. On the other hand, too little algae would diminish the benefits mentioned above. In addition, algae growth in the system will rely mainly on photosynthesis that requires light. If the surface area that could be used for growing vegetable is replaced by microalgae, it will inevitably reduce the vegetable productivity. However if the microalgae productivity could surplus vegetable production, due to higher market value and nutritional benefit, it might be worthwhile to grow algae instead of growing vegetables. The question of how to use the algae in a beneficial way without consuming too much resource in the system has not been addressed before and remain unclear. Therefore, the objective of this research was to evaluate the algae effect on the aquaponic system and to determine if algae were worthwhile to be added into the system.

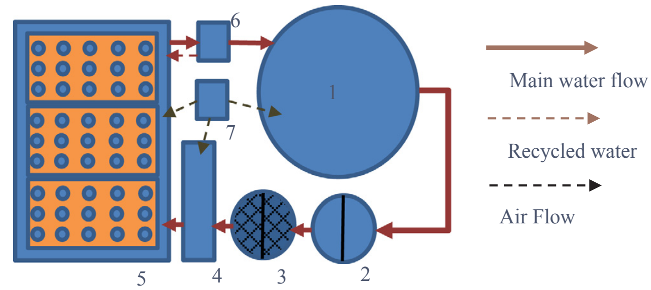

Fig. 1. The aquaponic system (80″ × 100″) from Nelson and Pade Inc. (1) fish tank (110 gallon), (2) clarification tank (30 gallon) with central baffle, (3) mineralization tank (15 gallon) with central baffle and net, (4) degassing tank (5 gallon), (5) vegetable tray (42″ × 67″), (6) water pump, (7) air pumps.

2. Material and methods

2.1. The aquaponic system

Two aquaponic systems (F-5 Fantastically Fun Fresh Food Factory, Nelson and Pade Inc.) were purchased from Nelson and Pade Inc. and set up in a greenhouse on Saint Paul campus at the University of Minnesota. The overall dimension of the system is 80″ × 100″ (Fig. 1). The water discharged from the fish tank (110 gallon) enters the clarification tank (30 gallon) where the fish solid waste can be separated out. The central baffle forces the water to flow downwards and then upwards so that the solid deposits at the bottom of the tank. The mineralization tank (15 gallon) is filled with plastic orchard netting used for attaching bacteria and filtering solids. In mineralization tank, undigested solids are converted to ammonia and other micronutrients needed by the plant. Due to anaerobic condition developed in the mineralization tank, nitrogen and N_2O gas resulted from denitrification process and other harmful gasses such as hydrogen sulfide and methane could be formed that in the degassing tank (5 gallon), vigorous aeration is used to blow these gasses out of the system.

The vegetable tray (42″ × 67″) has three floating rafts with 15 holes in each raft where a total of 45 plants could be planted in one tray. A water pump is used to circulate the water in the system and part of the water will return to the vegetable tray. An air pump is used to aerate the water in the fish tank, degassing tank and the vegetable tank.

2.2. Experiment setup

The experiments were conducted in two different stages. The first study was in September 2016 when the system was newly started and run for several weeks. After the first study the system was maintained with regular effort including changing water, feeding fish, harvesting vegetables, adjusting pH if needed. It was expected that the nitrate level would be higher in a later stage that algae might have higher productivity, therefore the second study was in February and March 2017 when the systems were in a more matured stage.

2.2.1. Algae species

The algae used in this study are naturally occurring algal species in which *Chlorella* sp. is the dominant strain. It is characterized as a robust and fast growing specie and superior for wastewater treatment. Because