2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

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Life cycle assessment (LCA) and Techno-economic analysis (TEA) of tilapia-basil aquaponics

Kun Xie, and Kurt Rosentrater

Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA 50011

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Abstract.
Aquaponics is the system combining hydroponic and aquaculture, in which fish and plants are raised together, and they can be beneficial from each other as well as to each other. When the system is maintained properly and is in a balance status, aquaponics will mimic the natural ecosystem, use much less water than traditional aquaculture, and have almost no effluent. As a result, it is thought more environmentally friendly and sustainable. In this study, both Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) of a tilapia and basil aquaponic system were conducted. Three scales, including a truly running system, pilot scale, and commercial scale of aquaponics were considered and analyzed. This study provided environmental impacts and profitability for operating aquaponics in the Midwest of U.S. It also showed that the operating scale and basil price had obvious effect on profits. When the scale was large enough, such as with the grow bed area of 75.6 m^2 and when the basil price equals to or is great than \$60/kg, operating aquaponics was profitable.

Keywords. *Aquaponics, Life cycle assessment (LCA), Techno-economic analysis (TEA), Tilapia, Basil, Greenhouse gas emission, cost, profit*

1.Introduction

The term sustainable agriculture was explained as integrated systems of combing plant and animal production using ecologic applications. The long term goals of sustainable agriculture include:1) meeting human food needs; be environmentally friendly; 2) making full use of nonrenewable resources; 3) sustaining both economy and ecology; 4) improving life quality for not only farmers, but for the community and the society (NALC, 1990).

Aquaponics is the system combining hydroponic and aquaculture, in which aquatic animals and plants are raised

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together, and is considered as a mutually beneficial system (Love et al, 2014). Hydroponic crop production is a technology that plant roots grow in nutrient solution instead of soil, with or without other mechanical support (Jensen, 1997). Due to the non-soil culture of plants, aquaponics on some extent involves much less pathogens than traditional agriculture (Lacheta et al, 2010). The aquatic waste can be used as fertilizer for plants, and biofilters can remove other toxic components to maintain proper living environment for fish. When the system is maintained properly and in a balanced status, aquaponics will mimic the natural ecosystem, use much less water than traditional aquaculture, and have minimal effluent, as a result, it is thought environmental friendly and as a sustainable agriculture (Blidariu and Grozea, 2011). For developing countries with limited fresh water, aquaponics has the potential to provide protein and vegetables in a sustainable way (Nichols and Savidov, 2012).

The operation of aquaponic systems provides the possibility and opportunity to produce fresh food in the backyard and building roof, which means urban people have more chance to consume local food. While some hobbyist operate small scale aquaponics outdoors, such as in the backyard or on the building roof, most commercial aquaponics operators, however, choose greenhouse or other indoor facility to control the environment (Licamele, 2009), in order to maintain food quality and safety, as well as to pursue maximum production yield, especially in areas with cold air temperatures. Greenhouse overcomes the short growing season in cold area; also it increases plant yield using supplementary light (Hamamoto and Yamazaki, 2011).

Although aquaponics is not a new technology, the popularity and development are still in their early age. According to a survey conducted by Love et al. in 2013, the median year for aquaponics operators began their practice is in 2010 and a large proportion of workers are volunteers and part-time workers (Love et al, 2015). The survey also reported that most operators design aquaponic systems by themselves rather than hiring specific engineer or consultant, which indicated there were large knowledge gaps for public and the increasing popularity of aquaponics may have large potential for creating job opportunities.

In terms of plant culture in aquaponics, there are various methods and media for plant support and production, and rafts are the most typical one (Love et al., 2015). Rafts are polystyrene or other synthetic aromatic polymer material which can float on the top of water. When used in aquaponics, according to the type of the plant, holes with different diameters and spacing will be made in the raft. The plants will be placed in net pots and the net pots will be inserted into the holes in the raft. Other common methods include media beds, which use clay pebbles or expanded shale to support plants; wicking beds, which use natural absorptive media such as coconut coir instead of other typical materials in media beds; nutrient film technique (NFT) is a system that shallow water with all the nutrients required by plants go through plant roots in a channel; vertical towers are facilities where plants are set in a vertical system and water is pumped at intervals to go through the roots; dutch buckets are another type of plant container filled with soilless media, and water with nutrients floods the system periodically (Love et al., 2015). According to the survey conducted by Love et al. in 2013, almost 70% of aquaponics operators chose two or more methods during the plant production (Love et al., 2015).

Tilapia (Oreochromis niloticus) and basil (Ocimum basilicum) are the two species that most operators chose in their aquaponics (Love et al, 2015), which can be considered as model species for aquaponics. Originally coming from Africa, the hardy tilapia are fast growing tropical fish, and now are raised in the U.S. in both outdoor and indoor environments (AGMRC, 2014). Tilapia is thought to be the model species for aquaponics due to several reasons. The most important reason is the popularity and market potential. According to the national fishery institute, tilapia was reported to become the fourth popular sea food in the United States in 2012 (NFI, 2012). The other reason of widely raised by aquaponics operators is that they have the ability of surviving in poor water quality so they are easy to deal with in tanks or ponds; besides, they have the potential to grow to high density in confinement (Popma et al, 1996). Other commonly raised fish include ornamental fish and catfish. Basil is a model aquaponics plants because it grows fast and it is resistant to insects, another more important reason is that it can be cultivated in a 28 days circle from transplanting to harvest (Rakocy, 2004), so it is convenient to do seeding, transplanting and harvesting. Besides, basil has the relatively higher retail prices than other crops, which makes it have the potential to make profit. Salad greens, other herbs except basil, tomato, and head lettuce are other popular plants (Love et al., 2015).

Originally arising from the mid of 1970s, aquaponics was first introduced to recirculating aquaculture systems using plants to help maintain water quality in fish culture (Lewis et al., 1978). How to maintain water quality is an inevitable problem when operating aquaponics and ammonia level is a major concern. Fish excrete ammonia, which is a metabolic product, through their gills and urine (Sace and Fitzsimmons, 2013). When Ammonia is accumulated to the level of above 0.05 mg/L, it is thought to be toxic for most fish (EDIS, 2012). During the aquaponics cycle, the process of nitrification is the conversion of ammonia to nitrite, and then to nitrate. The two groups of bacteria for fulfilling these two steps are Nitrosomonas and Nitrobacter (Rakocy 2006). While nitrite is toxic to fish, nitrate is considered non-toxic and can be utilized by plants as nutrient. pH is another daily monitoring indicator when operating aquaponics, and the suggested water pH to optimize nitrification is 7.5-8.0 (Tyson et al, 2011). Other concerned water quality items include alkalinity, chloride, hardness, CO_2, and temperature.

There were some studies on aquaponics operation and mechanism, but most of them focus on research scale (Rakocy et al., 2006; 2012). Some researches focused on the conversion from fish waste to nutrients and the utilization of nutrients. Villarroel et al. (2011) conducted a study of integrating fish feeding rates and ion waste production for strawberry tilapia aquaponics. Blidariu and Grozea (2011) suggested that the selection of plant species should be adapted to the fish stocking density and subsequent nutrient concentration: Herbs, lettuce and other greens, which have relatively low nutrient requirement compared with other plants, are more suitable to grow in aquaponics. Graber and Junge proved that a special design of trickling filters, which was called light-expanded clay aggregate (LECA), was able to prompt nutrient recycling in aquaponics (Graber and Junge, 2009). It was reported that most of the nutrients would be sufficient in the aquaculture effluent when ratio of daily feed input and plant growing area is maintained well (Rakocy et al., 2003). In the commercial-scale tilapia and basil aquaponics operated by the University of Virgin Island (UVI), those nutrients that need to be supplemented to batch cultured basil are calcium, potassium, and iron, and no nutrient needs to be supplemented to staggered production (Rakocy et al., 2004). It was considered that the nutrient demands of different age plants could counterbalance for each other.

Recently, researches mainly focused on how to optimize aquaponics operation. The study conducted by Petrea et al. in 2013 concluded that the nitrite and nitrate content of spinach could be affected by plant density, and they also stated that spinach-trout aquaponics met food safety requirement (Petrea et al., 2013). Some studies focused on the hydraulic loading rate and plant ratio (Endut et al, 2010); while others focused on calcium and phosphorous dynamic (Petrea et al, 2014). A study conducted by Liang and Chien in 2013 suggested that increasing feeding frequency and extending photo period would increase fish and plant yield, and decrease water nitrogen and phosphorus accumulation (Liang and Chien, 2013). It was also reported that the introduction of freshwater prawn to vegetable tilapia aquaponics increased system stability, diversity and yield (Sace and Fitzsimmons, 2013).

There were a handful studies related to the cost and profit for commercial scale aquaponics (Bailey et al., 1997; Tokunaga et al., 2013; Bunyaviroch et al., 2013), but these studies were conducted in tropical area and without the consideration of harsh winter weather like the mid-west U.S. The study conducted by Bailey et al. in 1997 was in the U.S. Virgin Islands, so neither greenhouse nor equipment designed to heat the greenhouse was considered in the analysis, and there were no supplemental lights, either. Besides, this study was not a complete TEA, and did not consider cost and profit on a base of a functional unit. The study conducted by Tokunaga et al. was in Hawaii and it concluded that the economic performance for commercial scale aquaponics had some potential, even though the potential might be not as promising as former studies suggested. The study conducted by Bunyaviroch et al. (2013) investigated a commercial case in Puerto Rico and indicated that aquaponics was viable there but the profitability was limited. Palm et al. conducted a study focusing on factors affecting economic sustainability of closed ebb flow aquaponics in Germany (Palm et al, 2014). Based on a techno-economic study of aquaponics in South Africa, Lapere concluded that high capital and operating cost made it difficult to make profit (Lapere, 2010); however, the natural and economic environments are quite different in South Africa and in the mainland of U.S.

In 2013, Love et al. conducted a relatively comprehensive international survey on aquaponics production and profitability (Love et al., 2015). It indicated that energy, water, and fish feed were the three major physical inputs in aquaponics. The sizes of aquaponics varied from tens to thousands of US gallon water volume according to different operating purpose. Small scale aquaponics could be operated in the backyard as hobby while commercial scale aquaponics was considered as agriculture which could make profit. It was reported that the average size of commercial aquaponics was using 10,300 L water and was occupying 0.01 ha field. Less than half operators also reported that they used supplemental light to help plant production. The survey also stated that electricity was the primary energy source for aquaponics.

Aquaponics is supposed to have large potential in development and expansion, and as reported by Love et al. in 2013, even for commercial operators, 55% of them harvested less than 45 kg fish and 52% of them harvested less than 226 kg plants in the previous year. The survey also showed that more commercial aquaponics producers sold products through direct markets, such as at aquaponics facility, farm market, and restaurant, other than indirect markets, such as via grocery store and wholesale; which also indicated that aquaponics was still not a mature agriculture. The survey also showed that only 31% of operators made profits during the previous year, and many of them were not only selling fish and plants, but also selling aquaponics materials and services (Love et al., 2015).

In our study, both Life cycle assessment (LCA) and Techno-economic analysis (TEA) of tilapia and basil aquaponics were conducted. Three scales, including a truly running system on Iowa State University campus, pilot scale, and commercial scale of aquaponics were considered and analyzed. This study aimed to provide environmental impacts and profitability for operating aquaponics in the Midwest U.S.A.

2. Methodology

An Italian large leaf basil (Ocimum basilicum) and Nile tilapia (Oreochomis niloticus) aquaponic system was operated on Iowa State University (ISU) campus, which was located in the Forestry Greenhouse, Ames, Iowa. Ames is a city classified with humid continental climate, type Dfa (CDO, 2014). The average amount of annual precipitation is 837 mm (CDO, 2014); and the average low temperature in January is -11.3 ^{o}C, while the average high temperature in July is 29.1 ^{o}C (USCD, 2014). As a result, in order to keep plants and fish alive in the winter, as well as to make profit, ISU aquaponics had to be operated indoor.

There were five main components in our aquaponics: fish culture tank, where the fish stayed from fingerling until harvest; mechanical and biological biofilter, which transferred fish waste to nitrite and nitrate that could be used as fertilizer by plants; plant grow bed, where plants grew from two weeks after being sowed until harvest; sump tank with pump, where water from plant grow bed recirculated back to the fish tank; and air blower, which provided air to both fish and plant roots.

There were three independent systems in our greenhouse, which could be thought as replications during experiments. For each system, the rectangular fish culture tank was of 74-cm long, 50-cm wide, and 65-cm high. Generally there would be 158 L water in the fish tank. Plastic mesh cover was used to prevent the escape of fish, and air stones were set inside the tank to provide enough oxygen. With the aeration provided by air stones, the maximum stock density of tilapia could reach up to 120 kg/m^3 (Rakocy, 1989). Typically it took 6 to 7 month for tilapia to grow from hatchery to 450-680 g size which is ready to harvest (GAA, 2003). The feed conversion ratio (FCR) for tilapia was between 1.6 and 2.0 (Rakocy, 2004).

The dimension of the filter tank was of 56 cm long, 40 cm wide, and 35 cm high. The water in the filter tank was about 3 cm deep. About 200 of 3.81 cm pronged balls and 0.0283 m^3 PVC ribbon bio fills provide bacteria attached area. Solid filter pad was set above the bio balls and bio fills to pre-filter solid waste and materials. Once the system was set up and in balance, the bio balls and bio fills did not need to be specially treated, while the solid filter pad needed to be cleaned periodically to remove extra materials.

For the hydroponic unit, there were four plant trays in our system, and four age stages of plants were planted separately: the youngest ones needed the least nutrients, and were planted at the far end of the outflow from fish tank; while the oldest ones requiring most nutrients were planted at the near end of the outflow. The area of each tray was about 0.63 m^2, and 16 basils were planted in a tray. Basil was sowed into the holes of starting plug sheets which were made from molten rocks and stayed in the sheets for two weeks. Then basils were transplanted into the rafts floating on the trays which were at the far end of the outflow from fish tank. Basils at the same age were then moved closer toward the near end of the outflow every week. After four weeks' growing in the grow beds, which equaled six weeks after being sowed, basils were ready to harvest.

The analysis was based on the assumption that the system was stable and run at ideal situation, which meant that there was no large-scale of fish or plant disease, and no extra fertilizer was required. Both TEA and LCA were directly conducted with the information from our ISU aquaponics. The ISU aquaponics was used as a baseline and then the results were scaled up to 10 and 300 times of the baseline. Based on the survey conducted by Love et al. (Love et al., 2014), the water volumes varied from 3 to 600,000 gallon (about 11 to 2,271,247 L), and our 300 times of the baseline system had a water volume of 216,900 L, which was a reasonable commercial-scale. For the baseline, most of the information of building materials and aquaponics equipment was the same with those we used in ISU aquaponics , and only a small part of them were substituted with alternative brands, but still with the same major character. All the facility and equipment information came from retail merchandise website.

2.1 System Boundary and Fractionation Flowchart

Since the study was based on the assumption that an existing aquaponics was running ideal, the system boundaries had to adapt to this purpose. In this study we only considered LCA and TEA within the two processes of fish culture and plant growing. The system boundary and flowchart were shown in Figure 1, and the system characters were shown in Figure 2.

2.2 Functional Unit

Both TEA and LCA were analyzed based on a functional unit of 1 kg tilapia and 1 kg basil. Total annual impact, and impact per kg tilapia and impact per kg basil were calculated. Since the price of basil varied and influenced the profit much more than the price of tilapia, the system unit profit was calculated only on the base of 1 kg basil.

2.3 Main Assumptions

2.3.1 Main assumptions for baseline (grow bed area 7.56 m^2)

In the baseline, one greenhouse with the size of 26.76 m^2 was the facility to set up the aquaponics system. Three 50 gallon (189 L) fish tanks were used for fish culture, and the total grow bed area was 7.56 m^2. The total water volume in the system was about 723 L.

2.3.2 Main assumptions for 10 times of baseline (grow bed area 75.6 m^2)

In the 10 times of baseline, one greenhouse with the size of 140.47 m^2 was the facility to set up the aquaponics system. Three 500 gallon (1890 L) fish tanks were used for fish culture, and the total grow bed area was 75.60 m^2. The total water volume in the system was about 7230 L.

2.3.3 Main assumptions for 300 times of baseline (grow bed area 2041.2 m^2)

In the 300 times of baseline, three greenhouses with the size of 802.68 m^2 was the facility to set up the aquaponics system. Thirty 500 gallon (1890 L) fish tanks were used for fish culture, and the total grow bed area was 2041.20 m^2. The total water volume in the system was about 216900 L.

2.4 Assumptions for LCA

(1) The environmental impacts we considered contain energy use and greenhouse gas emissions. Based on our aquaponics experience, electricity and natural gas were the two types of energy consumed; water was also a large input. The electricity loss during transportation was negligible. The three greenhouse gas emissions we considered were carbon dioxide, methane, and NO_x.

(2) The electricity came from a coal-fired plant. The greenhouse gas emissions of producing electricity from coal and producing natural gas were shown in Table 1 (Spath et al., 1999; Riva et al., 2004).

2.5 Assumptions for TEA

(1) Based on our operation, the weekly water loss was 10%.

(2) The effective volume of each fish tank was 84%, and the maximum fish biomass was 120 kg/m^3.

(3) The surviving rate of fish from fingerlings to harvest was 90%, and the harvest cycle was 6 month.

(4) There were 16 basils in one tray and there were 12 trays in total for the baseline. 25% basils would be ready for harvest each week.

(5) Both fish and basil yield in the two larger scales were 10 times and 300 times of the baseline, respectively.

(6) The average wet weight of basil was 27.3 g/plant, and the basil price was considered at $10, $15, $20, $40, $60, $80, and $100/kg.

(7) The average weight of tilapia was 0.68 kg (1.5 lb) per fish, and fresh tilapia price was $ 9.00/kg (FishChoice, 2014).

(8) The fish feed conversion rate was 1.6.

(9) According to Ames municipal utilities, the winter for water and electricity started from Nov.1 and lasted till Jun 30, and the summer started from Jul 1 and lasted till Oct 30.The average electricity price was $0.10/ kWh; and the average water price was $0.02/ft^3.

(10) The operating time of fans, water pump, air pump, UV clarifier was 24 h/d, and 365 d/y.

(11) In the winter, in order to provide supplemental light, the operating time of timer for light supplementation was 24 h/d, and 22 weeks, and the operating time of light was 4 h/d, and 22 weeks. No light supplementation was needed in summer.

(12) The operating time of heater was 24 h/d, and 198 d/y.

(13) The required labor was 52 week/y for all three scales, and 10 h/week, 20 h/week, and 120 h/week for the baseline, 10 times of baseline, and 300 times of baseline, respectively.

(14) The hourly labor payment was $12/h.

(15) The yearly interest rate was 5.5%, insurance rate was 0.462% and tax rate was 0.35%.

(16) The yearly maintenance cost was 1% of total capital cost.

(17) Since the greenhouse was free shipping, the freight was 1% of the costs of all other initial equipment.

(18) Both the types and numbers of the equipment varied according to different scale sizes.

(19) For the 10 times of baseline and 300 times of baseline, the proportions of wood were less because 500 gallon tanks were supposed to set on the ground.

(20) Due to large amount of purchase, most prices of the items in the 10 times of baseline were 90% of that in Baseline; and 80% for the 300 times of baseline.

(21) No extra fertilizer was used.

(22) The depreciation and salvage value at the end of service life were assumed to be 0.

3. Results and Discussion

The LCA results showed that all of the annual total environmental impact categories increased as the scale expanded. The details were shown in Tables 2 and 3, and Figures 3-5 and 9-11. For annual water use, which was shown in Figure 3, the regression line was linear trend between water use and grow bed area. It was because of specific maximum fish biomass production in unit water volume. And this also was the reason that unit water use remained the same, which was shown in Figure 6. In Figure 4, 5, and 9-11, the annual environmental impacts and grow bed area could be regressed as both linear and exponential trend lines, and both those two type regressions had reasonable R^2. In real aquaponics operation, the shaded region referred to the flexibility caused by different operation efficiency, such as the variance of fish feed nutrient, variance of plant growing time, variance of equipment performance, etc. The unit environmental impact categories decreased as the scale expanded, which were shown in Tables 4 and 5. The regression lines were shown power or logarithmic relationship between unit environmental impact categories and grow bed area, which were shown in Figures 7, 8, and 12-14.

For each scale, the annualized cost was considered including capital cost and operating cost, which were shown in Tables 6-11. As shown in Figure 15, the annualized total cost increased as the scale expanded, and the relationship of annualized total cost and grow bed area could be regressed as both linear and exponential, and both those two type regressions had reasonable R^2. Similar to LCA, the shaded region referred to the flexibility caused by different operation efficiency. The annualized unit cost was considered on the base of per kg tilapia and per kg basil, and the trend lines could be regressed as a power relationship between unit cost and grow bed area. The details of annualized total cost and unit cost for three scales were shown in Table 12 and Figures 15 and 16.

Since the price of basil varied a lot in different markets, both the annual total profit and system unit profit were influenced strongly by the price of basil. The basil price we considered were $10/kg, $15/kg, $20/kg, $40/kg, $60/kg, $80/kg, and $100/kg. When basil price was lower or equaled to $20/kg, none of the three scales could make positive profit; when basil price was $40/kg, only the 300 times of baseline could make positive profit; and when basil price was greater or equaled to $60/kg, both 10 times of baseline and 300 times of baseline could make positive profit. The details of the total annual profit and unit profit for three scales were shown in Tables 13 and 14 and Figures 17 and 18.

There were some studies focusing on the cost and profit for commercial-scale aquaponics (Bailey et al, 1997; Tokunaga et al, 2013; Bunyaviroch et al., 2013), but these studies were conducted in a tropical area and without the consideration of winter with low temperature like the Midwest U.S.A. Bunyaviroch et al. investigated a commercial aquaponics in Puerto Rico and concluded that aquaponics was viable there but the profitability was limited. Based on a techno-economic study of aquaponics in South Africa, Lapere indicated that high capital and operating cost made it difficult to make profit (Lapere, 2010). The present work filled the data gap for aquaponics operating on U.S. mainland, and both supplement light and heating were included in our calculations. Compared to the tropical area, it was harder for small aquaponics operated in Midwest U.S.A. to make profit; and even for those commercial scales, the basil price was the most important indicator to predict whether aquaponics was profitable. Our work was also consistent with the investigation conducted by Love et al., which showed that only 31% of operators made profits during the year between 2012 and 2013 (Love et al., 2015).

Based on our TEA, how to sell basil for a relatively high price was the key issue to profitability. It was an ideal option to sell basil via farmers market, or sell them to local restaurant, other than sell basil via wholesale. In general, the basil price sold via farmers market and local restaurant was much higher than via wholesale.

While our work focused on a tilapia-basil aquaponic system, more work needs to be done to explore aquaponics with other fish and plants. Besides, our model was based on the assumption that fish are raised in plastic tanks and plants grow using rafts. More work needs to be done to explore aquaponics using other system components.

For better understanding the Iowa State University aquaponics, more pictures could be found in Figures 19- 24.

4. Conclusions

Compared with previous work, the present study was the first LCA and TEA model for aquaponics operated in mainland in U.S.A., where the winter is cold and both supplement light and heating are required to maintain all year round operation.

Based on our LCA and TEA analyses, both unit environmental impacts and unit cost of tilapia-basil aquaponic system decreased as the operation scale expanded. This study provided useful information for basil and tilapia aquaponics at different scales. The results indicated that when the scale was large enough, such as with the grow bed area of 75.6 m^2, aquaponic prediction was profitable when the basil price equaled to or was great than $60/kg. More work is required to conduct LCA and TEA for other types of aquaponics in the future.

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References

AGMRC. 2014 b. Tilapia Profile. Agricultural Marketing Resource Center. Available at http://www.agmrc.org/commodities__products/aquaculture/tilapia-profile/. Accessed 17 December 2014.

Bailey, D. S., Rakocy, J. E., Cole, W. M., Shultz, K. A., and St Croix, U. S. 1997. Economic analysis of a commercial-scale aquaponic system for the production of tilapia and lettuce. In Tilapia Aquaculture: Proceedings of the Fourth International Symposium on Tilapia in Aquaculture, Orlando, Florida (pp. 603-612).

Blidariu, F., and Grozea, A. 2011. Increasing the Economical Efficiency and Sustainability of Indoor Fish Farming by Means of Aquaponics Review. Scientific Papers Animal Science and Biotechnologies, 44(2), 1-8.

Bunyaviroch, C., Ding, X., Mamayek, S., and Manning, B. 2013. Aquaponic Systems in Puerto Rico: Assessing Their Economic Viability BS thesis. Worcester Massachusetts Worecester Polytechnic Institute.

CDO. 2014. Climate: Ames. Climate-Data.ORG. Available at: http://en.climate-data.org/location/17149/ Accessed 17 December 2014.

EDIS. 2012 Ammonia in Aquatic System. Electronic Data Information Source of UF/IFAS Extension. Available at: http://edis.ifas.ufl.edu/fa031. Accessed 17 December 2014.

Endut, A., Jusoh, A., Ali, N., Wan Nik, W. B., and Hassan, A. 2010. A study on the optimal hydraulic loading rate and plant ratios in recirculation aquaponic system. Bioresource technology, 101(5), 1511-1517.

FishChoice. 2014 Tilapia: Market Report Updated September 2014. Available at: http://www.fishchoice.com/buying-guide/tilapia#Market_Report. Accessed 17 December 2014.

GAA. (2003) Prison Aquaculture Program. The Global Aquaculture Alliance. Available at:http://www.gaalliance.org/newsroom/aquasolutions-detail.php?Prison-Aquaculture-Program-11. Accessed 17 December 2014.

Graber, A., and Junge, R. 2009. Aquaponic Systems: Nutrient recycling from fish wastewater by vegetable production. Desalination, 246(1), 147-156.

Hamamoto, H., and Yamazaki, K. 2011. Supplemental Lighting inside the Plant Canopy Increased the Yield and Quality of Three-Truss-Ordered Tomato. Acta Horticulturae, (907), 283-286.

Jensen, M. H 1997. Hydroponics. HortScience. 32(6), 1018-1021.

Lacheta A. 2010 The future of food, Well Being Natural Health and Living News, Available at: http://www.wellbeing.com.au/article/Greenliving/Natural-Skincare/The-future-of-food_863. Accessed 17 December 2014.

Lapere, P. 2010. A techno-economic feasibility study into aquaponics in South Africa MS thesis, Stellenbosch, South Africa: University of Stellenbosch, Department of Industrial Engineering.

Lewis, W.M., Yopp, J.H, Schramm JR, H. L., and Brandenburga, A. M. 1978.Use of hydroponics to maintain quality of recirculated water in a fish culture system. Transactions of the American Fisheries Society. 107(1), 92–99.

Liang, J. Y., and Chien, Y. H 2013. Effects of feeding frequency and photoperiod on water quality and crop production in a tilapia–water spinach raft aquaponics system. International Biodeterioration and Biodegradation, 85, 693-700.

Licamele, J. D. 2009. Biomass production and nutrient dynamics in an aquaponics system. PhD diss, Tucson, Arizona: The University of Arizona, Department of Agricultural and Biosystems Engineering.

Love, D. C., Fry, J. P., Genello, L., Hill, E. S., Frederick, J. A., Li, X., and Semmens, K. 2014. An international survey of aquaponics practitioners. PLoS One. 9(7), e102662.

Love, D. C., Fry, J. P., Li, X., Hill, E. S., Genello, L., Semmens, K., and Thompson, R. E. 2015. Commercial Aquaponics Production and Profitability: Findings from an International Survey. Aquaculture (435)67-94.

NALC. 1990. Food Agriculture Conservation and Trade Act of 1990. The National Agriculture Law Center. Available at: http://nationalaglawcenter.org/wp-content/uploads/assets/farmbills/1990-1.pdf. Accessed 17 December, 2014.

NFI 2012. Top 10 Consumed Seafoods National Fisheries Institute Website. Available at: http://www.aboutseafood.com/about/about-seafood/top-10-consumed-seafoods. Accessed 17 December, 2014.

Nichols, M. A., and Savidov, N. A. 2012. Aquaponics: Protein and vegetables for developing countries. Acta Hort. (ISHS) 958:189-193.

Palm, H W., Bissa, K., and Knaus, U. 2014. Significant factors affecting the economic sustainability of closed aquaponic systems. Part II: Fish and plant growth AACL Bioflux, 7(3), 162-175.

Petrea, S. M., Cristea, V., Dediu, L., Contoman, M., Ion, S. P., Mocanu, M. C., and Antache, A. 2013. A Study of Nitrogen Cycle in an Integrated Aquaponic System with Different Plant Densities. Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca. Animal Science and Biotechnologies, 70(1), 55-64.

Petrea, S. M., Cristea, V., Dediu, L., Contoman, M., Cretu, M., Antache, A., and Bandi, A. C. 2014. A Study of Phosphorus and Calcium Dynamics in an Integrated Rainbow Trout and Spinach (Nores variety) Aquaponic System with Different Crop Densities. Scientific Papers Animal Science and Biotechnologies, 47(2), 196-206.

Popma, T. J., and Lovshin, L. L. 1996. Worldwide prospects for commercial production of tilapia. International Center for Aquaculture and Aquatic Environments.

Rakocy, J. E., and Brunson, M. W. 1989.Tank culture of tilapia. College Station, Texas: Southern Regional Aquaculture Center. SRAC Publication No. 282

Rakocy, J., Shultz, R. C., Bailey, D. S. and Thoman, E. S. 2003. Aquaponic production of tilapia and basil: comparing a batch and staggered cropping system. In South Pacific Soilless Culture Conference-SPSCC 648 (pp. 63-69).

Rakocy, J. E., Bailey, D. S., Shultz, R. C., and Thoman, E. S. 2004. Update on tilapia and vegetable production in the UVI aquaponic system. Proceedings of the Sixth International Symposium on Tilapia in Aquaculture. (pp. 12-16).

Rakocy, J.E., Masser, M.P., and Losordo, T.M. 2006. Recirculating Aquaculture Tank Production Systems: Aquaponics—Integrating Fish and Plant Culture. SRAC Publication. No: 454.

Rakocy, J.E., 2012.Aquaponics-Integrating Fish and Plant Culture. Aquaculture Production Systems. 344-386.

Riva, A., D'Angelosante, S., and Trebeschi, C. 2004. Natural gas and the environmental results of life cycle assessment. Energy. 31(1), 138-148.

Sace, C. F., and Fitzsimmons, K. M. 2013. Vegetable production in a recirculating aquaponic system using Nile tilapia (Oreochomis niloticus) with and without freshwater prawn (Macrobrachium rosenbergii). Academia Journal of Agricultural Research, 1(12), 236-250.

Spath, P. L., Mann, M. K., and Kerr, D. R. (1999). Life cycle assessment of coal-fired power production (No. NREL/TP-570-25119). National Renewable Energy Lab., Golden, CO (US). Available at: http://web.anl.gov/PCS/acsfuel/preprint%20archive/Files/44_1_ANAHEIM_03-99_0090.pdf. Accessed 17 December 2014.

Tokunaga, K., Tamaru, C., Ako, H, and Leung, P. 2013. Economics of Commercial Aquaponics in Hawaii. Aquaponics in Hawaii Conference.

Tyson, R. V., Treadwell, D. D., and Simonne, E. H. 2011. Opportunities and challenges to sustainability in aquaponic systems. Horttechnology, 21(1), 6-13.

USCD. 2014. Climate Ames-Iowa U.S. climate data. Available at: http://www.usclimatedata.com/climate/ames/iowa/united-states/usia0026 Accessed 17 December 2014.

Villarroel, M., Rodriguez Alvariño, J. M., and Duran Altisent, J. M. 2011. Aquaponics: integrating fish feeding rates and ion waste production for strawberry hydroponics in Spain. journal of agricultural research, 9(2), 537-545.

Table 1. Air emission of producing electricity from coal and producing natural gas.

Emission category	Electricity g/kWh	Natural gas g/m^3
CO_2	1,022[a]	1,248.000[b]
CH_4	0.91[a]	247.600[b]
NO_x	3.35[a]	5.158[b]

a: Spath, P. L., and Mann, M. K. (1999). Environmental Aspects of Producing Electricity from a Coal-Fired Power Generation System-A Life Cycle Assessment. National Renewable Energy Laboratory, USA.

b: Riva, A., D'Angelosante, S., and Trebeschi, C. (2006). Natural gas and the environmental results of life cycle assessment. Energy, 31(1), 138-148.

Table 2. Annual water and energy use of tilapia-basil aquaponic systems with various grow bed areas.

Grow bed area (m^2)	Annual water use (m^3/y)	Annual electricity use (kWh/y)	Annual natural gas use (m^3)
7.56	3.74	11,052.93	7,403.97
75.6	37.40	23,836.98	43,077.62
2041.2	1,121.87	641,830.89	387,698.58

Table 3. Annual greenhouse gas emission of tilapia-basil aquaponic systems with various grow bed areas.

Grow beds area (m^2)	Annual CO_2 emission (g/y)	Annual CH_4 emission (g/y)	Annual NO_x emission (g/y)
7.56	20,536,243.01	1,843,280.15	75,216.97
75.6	78,122,261.77	10,687,710.46	302,048.24
2041.2	1,139,799,004.33	96,578,235.40	4,149,882.78

Table 4. Unit water and energy use of tilapia-basil aquaponic systems with various grow bed areas.

Grow bed area	Unit water use		Unit electricity use		Unit natural gas use	
(m^2)	m^3/ kg basil/y	m^3/ kg tilapia/y	kWh / kg basil/y	kWh / kg tilapia/y	m^3/ kg basil/y	m^3/ kg tilapia/y
7.56	0.05	0.03	162.10	96.57	108.58	64.69
75.6	0.05	0.03	34.96	20.83	63.18	37.64
2041.2	0.05	0.03	31.38	18.69	18.95	11.29

Table 5. Unit greenhouse gas emission of tilapia-basil aquaponic systems with various grow bed areas.

Grow bed area (m^2)	Unit CO_2 emission		Unit CH_4 emission		Unit NO_x emission	
	g/ kg basil/y	g/ kg tilapia/y	g/ kg basil/y	g/ kg tilapia/y	g/ kg basil/y	g/ kg tilapia/y
7.56	301,172.69	179,421.02	27,032.48	16,104.37	1,103.09	657.16
75.6	114,569.60	68,253.85	15,673.98	9,337.64	442.97	263.89
2041.2	55,718.78	33,193.98	4,721.20	2,812.62	202.87	120.86

Table 6. Capital cost of tilapia-basil aquaponics with grow bed area 7.56 m^2.

Component	Type	Price ($/each)	Quantity	Total cost ($)
Greenhouse	16' x 18'	11,250.00	1	11,250.00
Fan	ValuTek™ 12" - 3 Speed	215.00	2	430.00
Heater	Modine™ Effinity 55K BTU Nat Gas	1,399.00	1	1,399.00
Lumber				614.44
Hardware				530.96
PVC				591.44
Water pump	Simer Portable 2305	50.37	3	151.11
Blower	Aquatic Eco-systems SL22	272.65	3	817.95
UV clarifier	TetraPond 9W UVC 9	103.11	3	309.33
Light	400W Fixture w/HPS Lamp - 120V	209.95	8	1,679.60
Tanks				1,416.22
Rubber liner	Smartpond 1,100-Gallon Rubber	159.00	1	159.00
pH/ ORP meter	HQ11d Portable pH/ORP Meter	514.00	1	514.00
Others				1,085.67
Equipment initial costs ($)				**20,948.72**
Electrical wiring and controls				837.95
equipment installation				1,920.00
equipment freight				96.99
Total equipment initial costs ($)				**23,803.66**
Engineering and design				1,666.26
Total capital costs ($)				**25,469.92**
Capital costs per year ($)				**3,379.04**

Table 7. Operating cost of tilapia-basil aquaponics with grow bed area 7.56 m^2.

Component	Total cost ($/y)
Fixed costs	
Interest	1,400.85
Insurance	117.67
Tax	89.14
Subtotal ($/y)	**1,607.66**
Variable costs	
Yearly use materials	1,399.36
Chemicals	26.47
Basil seeds	9.60
Fish feed	996.20
Fish fingerlings	278.63
Water	3.01
Electricity	1,121.50
Natural gas	718.74
Labor	6,240.00
Maintenance and repair	254.70
Subtotal ($/y)	**11,048.21**
Total fixed costs ($/y)	**12,655.88**

Table 8. Capital cost of tilapia-basil aquaponics with grow bed area 75.6 m^2.

Component	Type	Price ($/each)	Quantity	Total cost ($)
Greenhouse	21'x72'	15,674.00	1	15,674.00
Fan	ValuTek™ 12" - 3 Speed	215.00	2	430.00
Heater	Modine™ Power 320 K BTU Nat Gas	1,899.00	1	1,899.00
Lumber				2,006.82
Hardware				2,841.46
PVC				2,111.15
Water pump	Simer ½ HP	159.99	3	479.97
Blower	Aquatic Eco-systems SL22	272.65	3	817.95
UV clarifier	TetraPond 9W UVC 9	103.11	3	309.33
Light	400W Fixture w/HPS Lamp - 120V	188.96	40	7,558.20
Tanks				4,802.23
Rubber liner	Smartpond 1,100-Gallon Rubber	143.10	6	858.60
pH/ ORP meter	HQ11d Portable pH/ORP Meter	514.00	1	514.00
Others				1,508.45
Equipment initial costs ($)				**47,811.15**
Electrical wiring and controls				1,672.45
equipment installation				3,600.00
equipment freight				261.37
Total equipment initial costs ($)				**47,344.97**
Engineering and design				3,314.15
Total capital costs ($)				**50,659.12**
Capital costs per year ($)				**6,720.83**

Table 9. Operating cost of tilapia-basil aquaponics with grow bed area 75.6 m^2.

Component	Total cost ($/y)
Fixed costs	
Interest	2,786.25
Insurance	234.05
Tax	177.31
Subtotal ($/y)	**3,197.60**
Variable costs	
Yearly use materials	4,582.99
Chemicals	122.86
Basil seeds	56.20
Fish feed	8,965.80
Fish fingerlings	2,507.67
Water	30.12
Electricity	2,418.66
Natural gas	4,181.76
Labor	12,480.00
Maintenance and repair	506.59
Subtotal ($/y)	**35,852.65**
Total fixed costs ($/y)	**39,050.25**

Table 10. Capital cost of tilapia-basil aquaponics with grow bed area 2041.2 m^2.

Component	Type	Price ($/each)	Quantity	Total cost ($)
Greenhouse	90'x 96'	59,466.60	3	178,399.80
Fan	ValuTek™ 12" - 3 Speed	172.00	9	1,548.00
Heater	Modine™ Power 320 K BTU Nat Gas	1,519.20	9	13,672.80
Lumber				53,515.20
Hardware				75,647.04
PVC				56,041.20
Water pump	Simer ½ HP	127.99	90	11,519.28
Blower	Aquatic Eco-systems SL22	218.12	90	19,630.80
UV clarifier	TetraPond 9W UVC 9	82.49	90	7,423.92
Light	400W Fixture w/HPS Lamp - 120V	167.96	1200	201,552.00
Tanks				109,136.40
Rubber liner	Smartpond 1,100-Gallon Rubber	127.20	180	22,896.00
pH/ ORP meter	HQ11d Portable pH/ORP Meter	514.00	3	1,542.00
Others				33,567.15
Equipment initial costs ($)				**786,091.59**
Electrical wiring and controls				31,443.66
equipment installation				54,000.00
equipment freight				6,076.92
Total equipment initial costs ($)				**877,612.17**
Engineering and design				61,432.85
Total capital costs ($)				**939,045.02**
Capital costs per year ($)				**124,581.01**

Table 11. Operating cost of tilapia-basil aquaponics with grow bed area 2041.2 m^2.

Component	Total cost ($/y)
Fixed costs	
Interest	51,647.48
Insurance	4,338.39
Tax	3,286.66
Subtotal ($/y)	**59,272.52**
Variable costs	
Yearly use materials	87,482.64
Chemicals	1,460.34
Basil seeds	368.64
Fish feed	239,088.00
Fish fingerlings	66,841.40
Water	903.53
Electricity	55,047.70
Natural gas	37,635.84
Labor	74,880.00
Maintenance and repair	9,390.45
Subtotal ($/y)	**573,098.54**
Total fixed costs ($/y)	**632,371.06**

Table 12. Annualized total cost and system unit cost of tilapia-basil aquaponic systems with various grow bed areas.

Grow bed area (m^2)	Annualized total cost ($/y)	Biomass quantity (kg) Tilapia	Basil	Annualized unit cost $/kg tilapia /y	$/kg basil /y
7.56	$16,034.91	114.46	68.19	140.09	235.16
75.6	$45,771.08	1,144.58	681.88	39.99	67.13
2041.2	$756,952.07	34,337.52	20,456.28	22.04	37.00

Table 13. Annual total profit with various basil prices and tilapia price at $9/kg.

Grow bed	Annual total profit with various basil price ($/y)						
area (m^2)	$10/kg	$15/kg	$20/kg	$40/kg	$60/kg	$80/kg	$100/kg
7.56	-$14,322.91	-$13,981.97	-$13,641.04	-$12,277.28	-$10,913.53	-$9,549.78	-$8,186.03
75.6	-$28,651.07	-$25,241.69	-$21,832.31	-$8,194.79	$5,442.73	$19,080.25	$32,717.77
2041.2	$243,351.59	-$141,070.19	-$38,788.79	$370,336.81	$779,462.41	$1,188,588.01	$1,597,713.61

Table 14. System unit profit of tilapia-basil aquaponic systems with various grow bed areas.

Grow bed	System unit profit with various basil price ($/y)						
area (m^2)	$10/kg	$15/kg	$20/kg	$40/kg	$60/kg	$80/kg	$100/kg
7.56	-$210.05	-$205.05	-$200.05	-$180.05	-$160.05	-$140.05	-$120.05
75.6	-$42.02	-$37.02	-$32.02	-$12.02	$7.98	$27.98	$47.98
2041.2	-$11.90	-$6.90	-$1.90	$18.10	$38.10	$58.10	$78.10

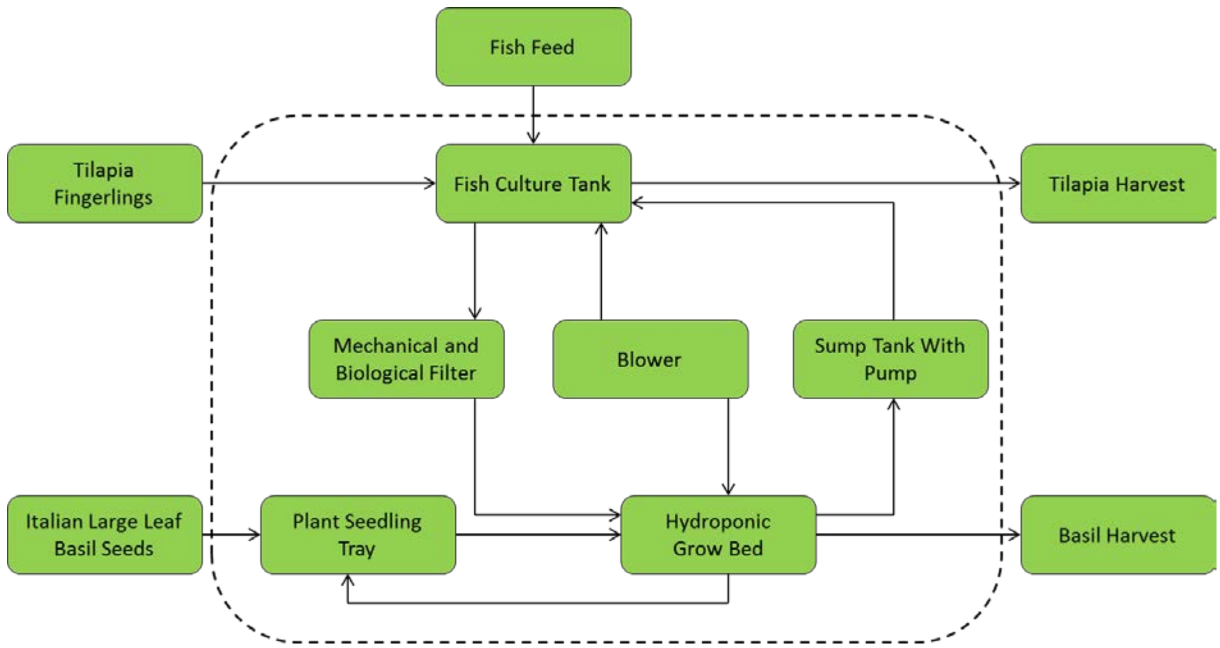

Figure 1. Aquaponics system boundary and flowchart.

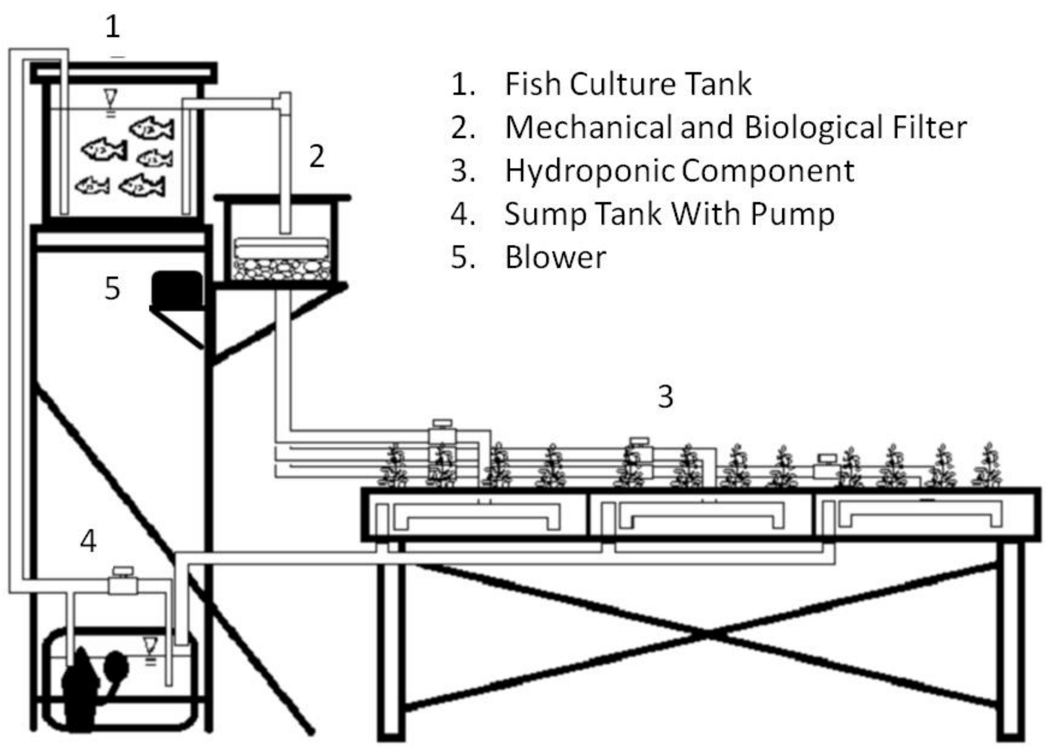

Figure 2. Iowa State University Aquaponics character (courtesy of Allen Pattillo).

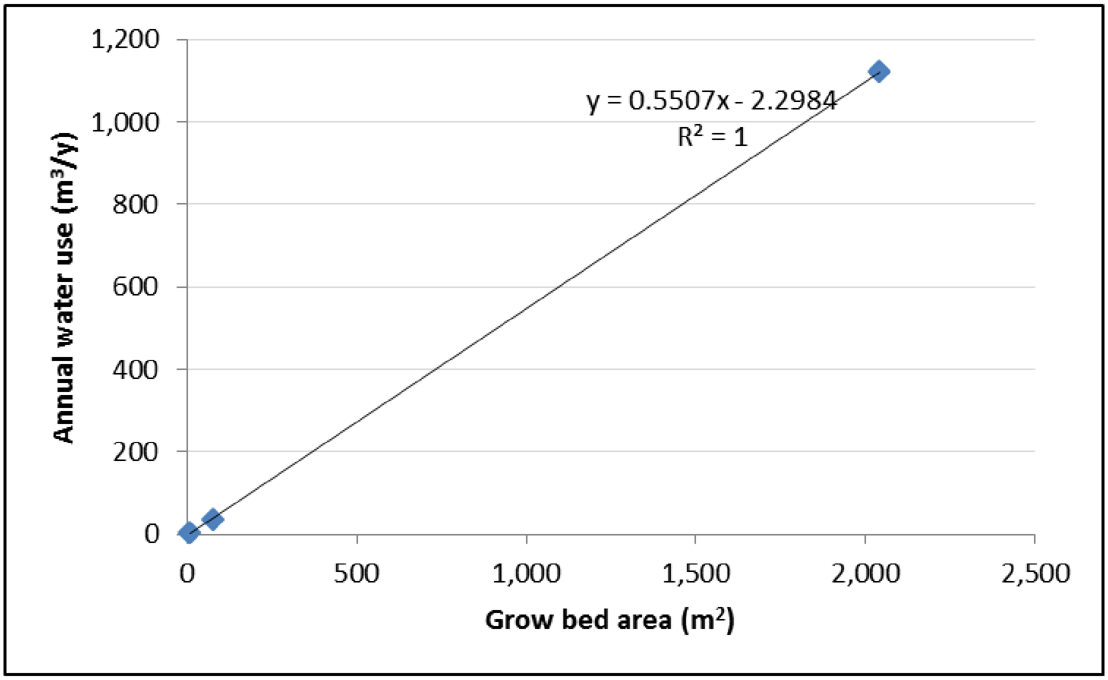

Figure 3. Annual water use of tilapia-basil aquaponic systems with various grow bed areas.

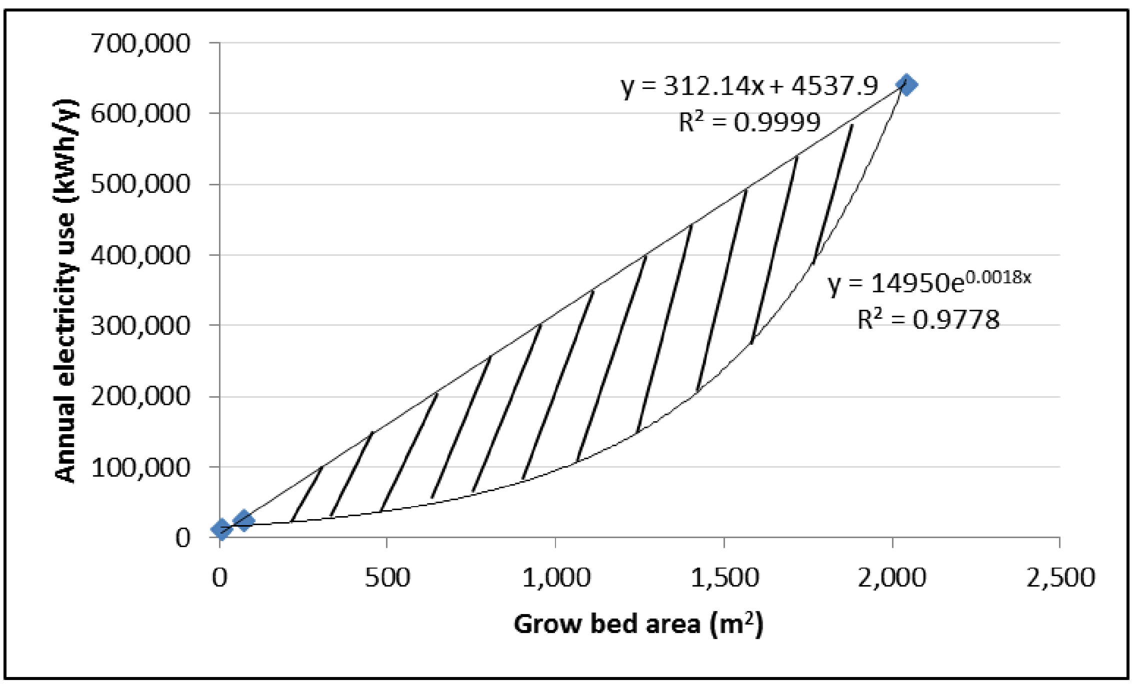

Figure 4. Annual electricity use of tilapia-basil aquaponic systems with various grow bed areas (shaded region refers to the flexibility caused by different operation efficiency).

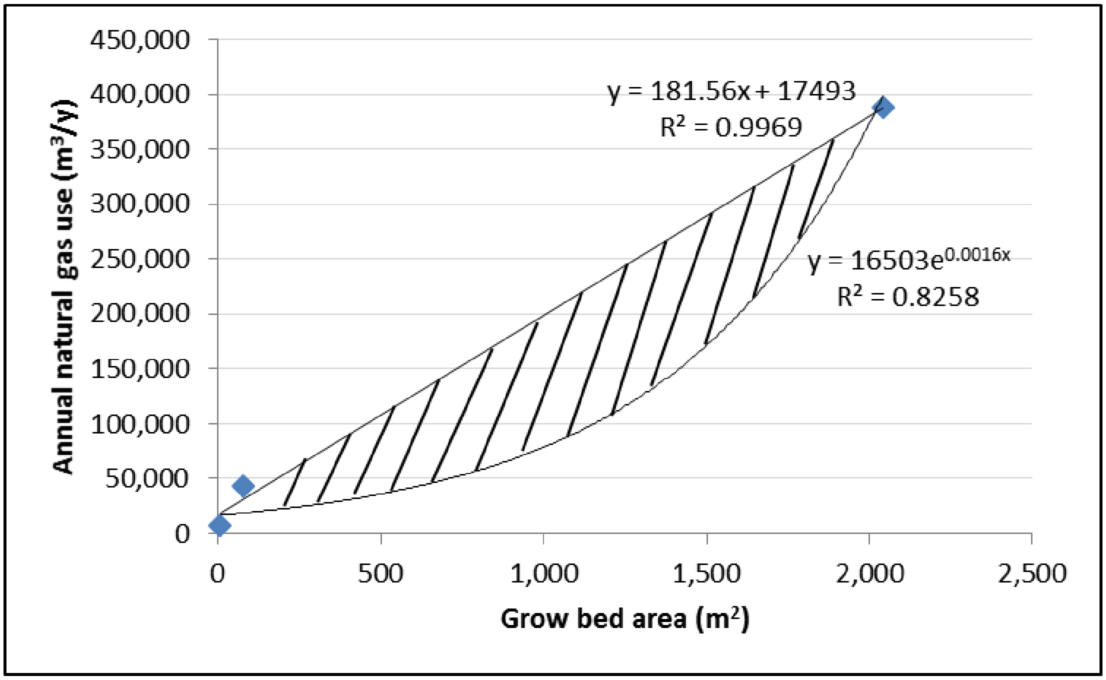

Figure 5. Annual natural gas use of tilapia-basil aquaponic systems with various grow bed areas (shaded region refers to the flexibility caused by different operation efficiency).

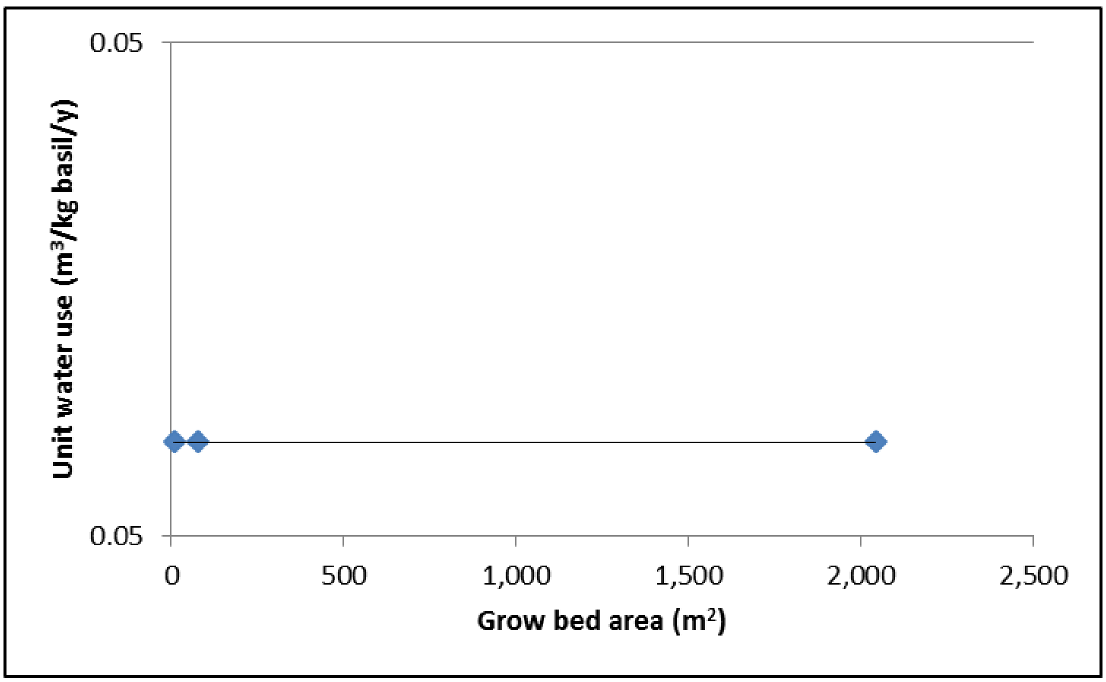

Figure 6. Unit water use of tilapia-basil aquaponic systems with various grow bed areas.

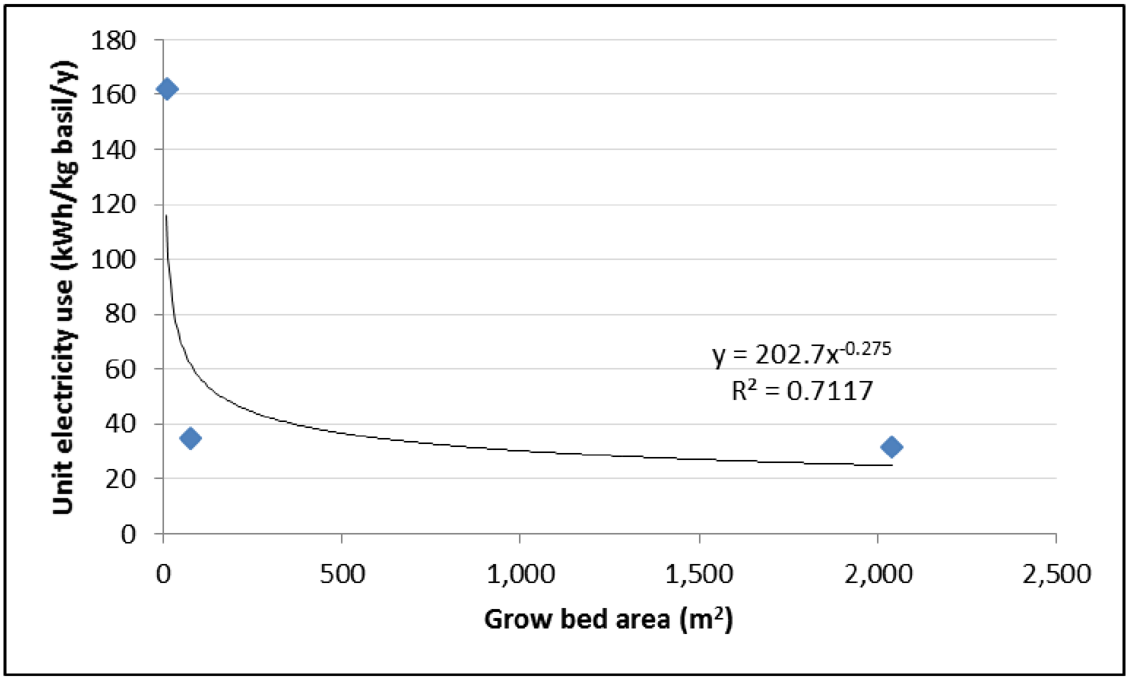

Figure 7. Unit electricity use of tilapia-basil aquaponic systems with various grow bed areas.

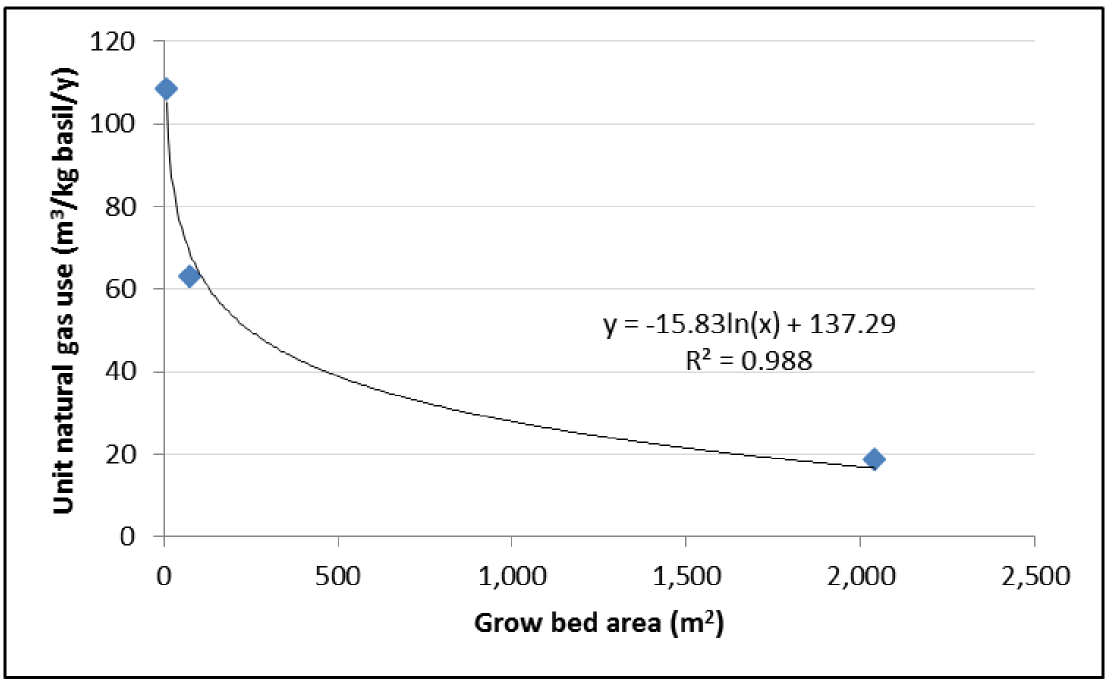

Figure 8. Unit natural gas use of tilapia-basil aquaponic systems with various grow bed areas.

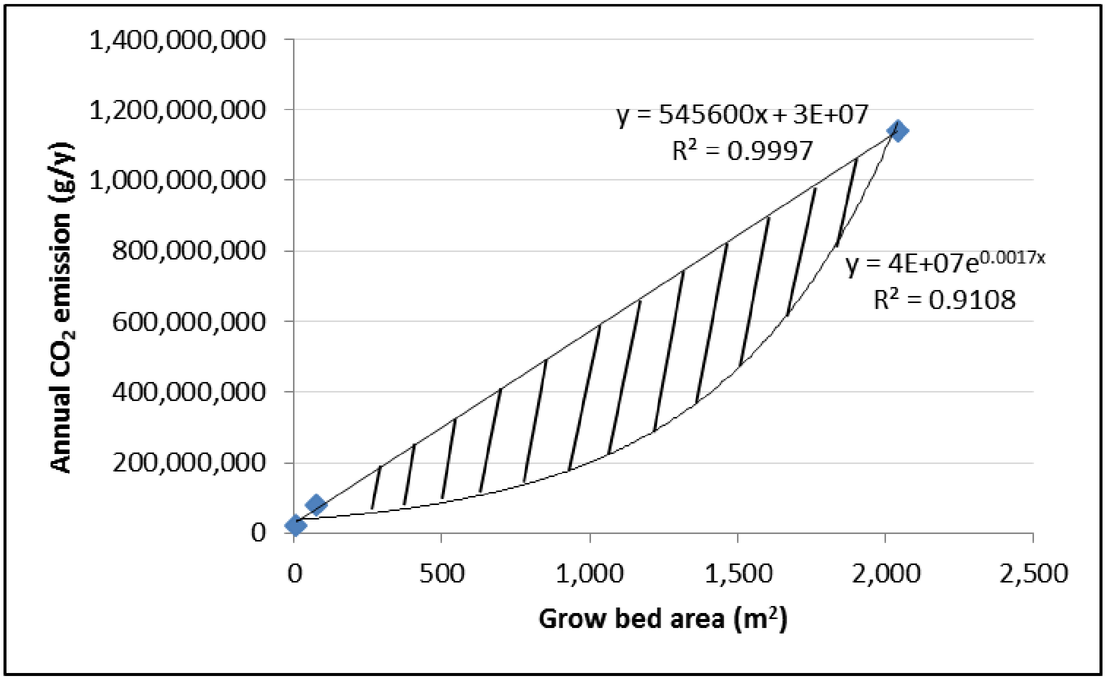

Figure 9. Annual CO_2 emission of tilapia-basil aquaponic systems with various grow bed areas (shaded region refers to the flexibility caused by different operation efficiency).

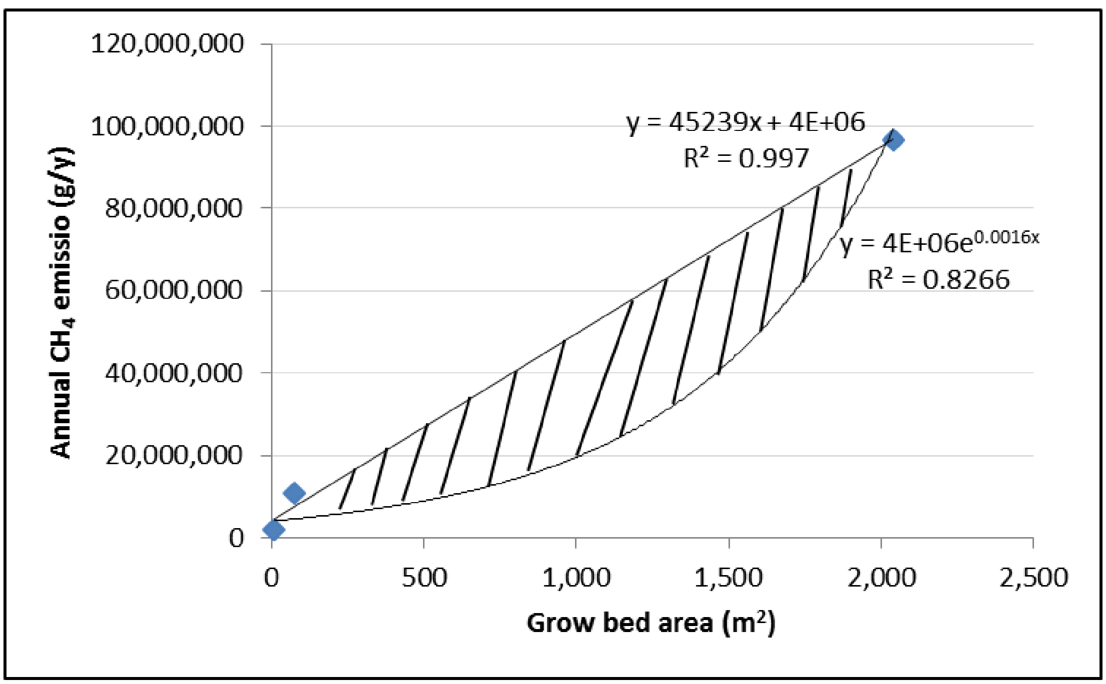

Figure 10. Annual CH_4 emission of tilapia-basil aquaponic systems with various grow bed areas (shaded region refers to the flexibility caused by different operation efficiency).

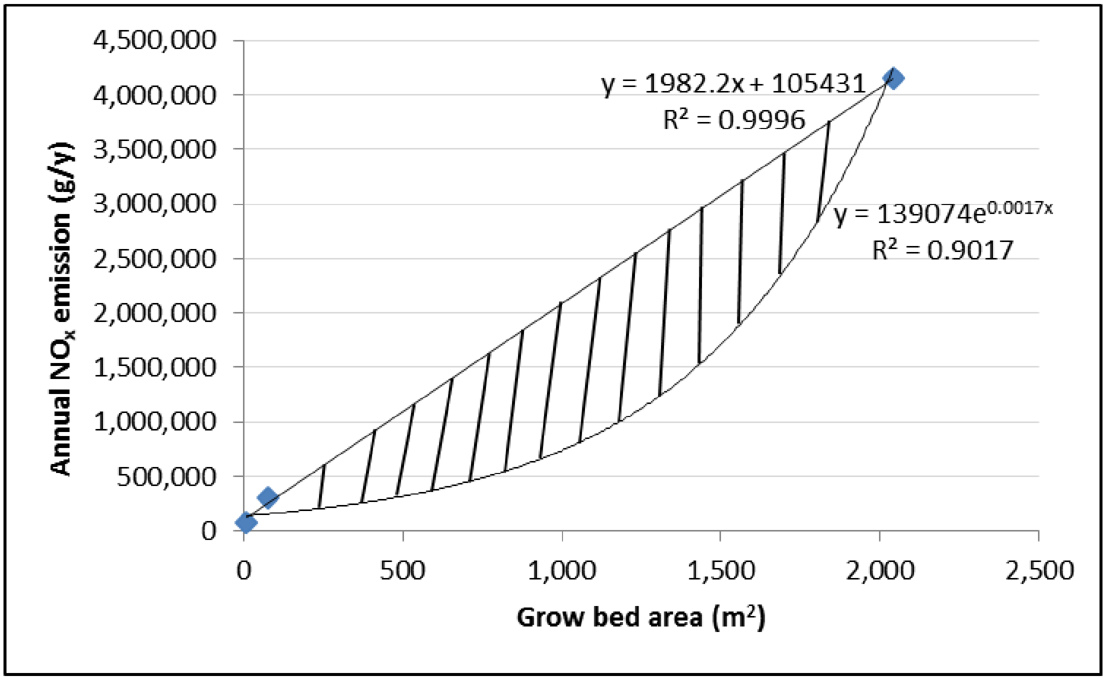

Figure 11. Annual NO_x emission of tilapia-basil aquaponic systems with various grow bed areas (shaded region refers to the flexibility caused by different operation efficiency).

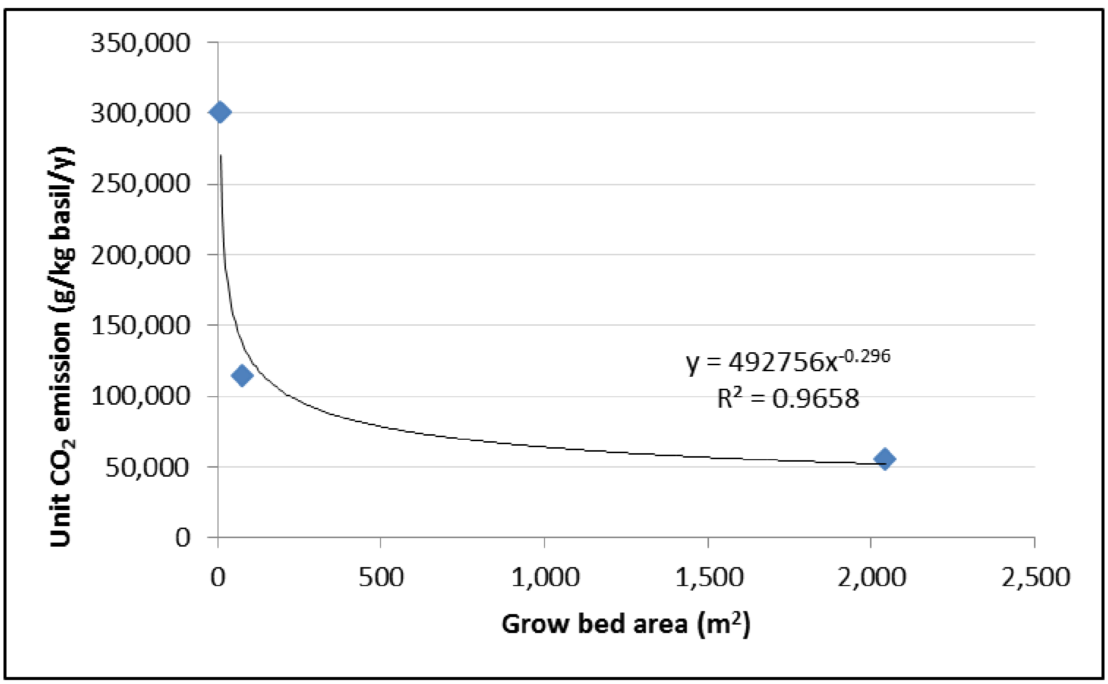

Figure 12. Unit CO_2 emission of tilapia-basil aquaponic systems with various grow bed areas.

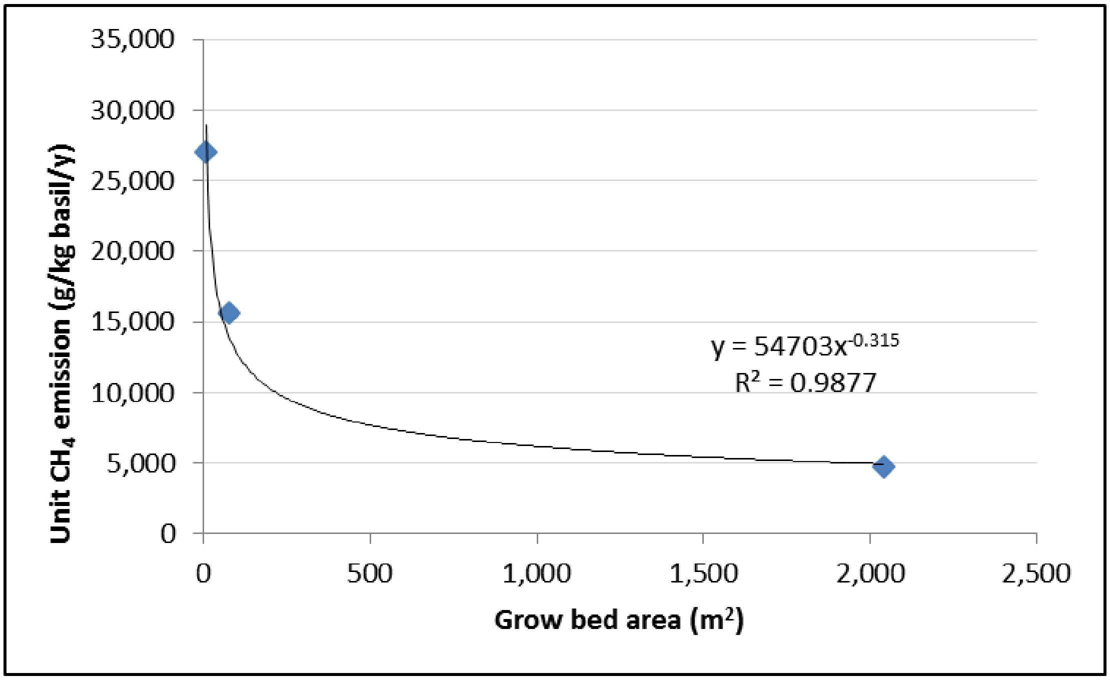

Figure 13. Unit CH_4 emission of tilapia-basil aquaponic systems with various grow bed areas.

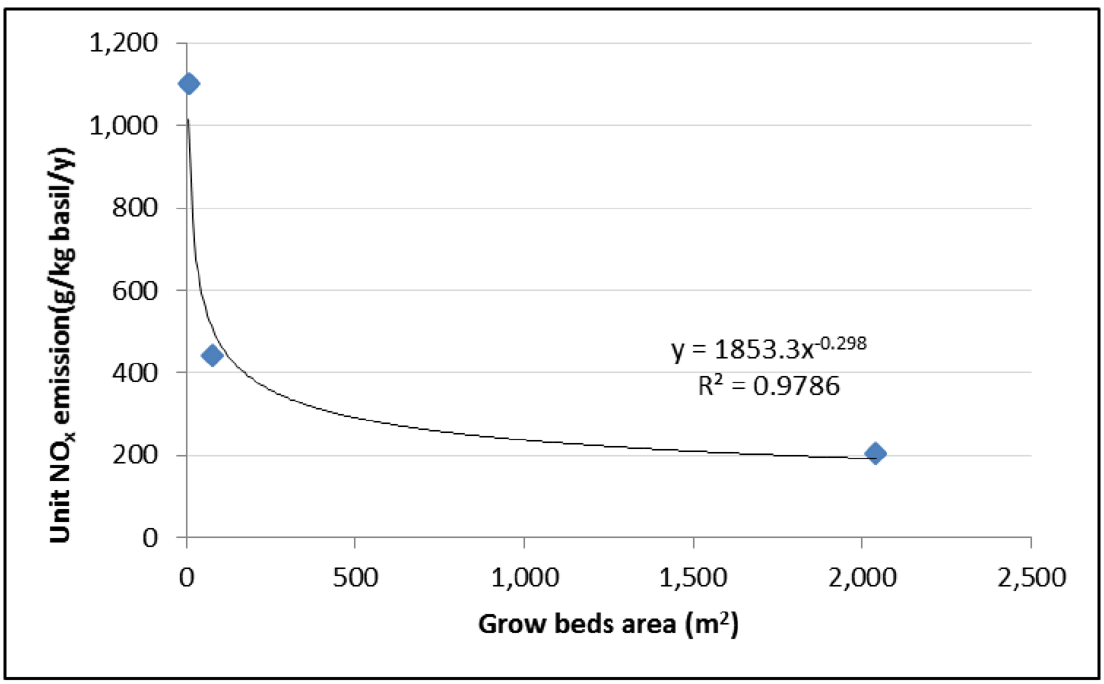

Figure 14. Unit NO_x emission of tilapia-basil aquaponic systems with various grow bed areas.

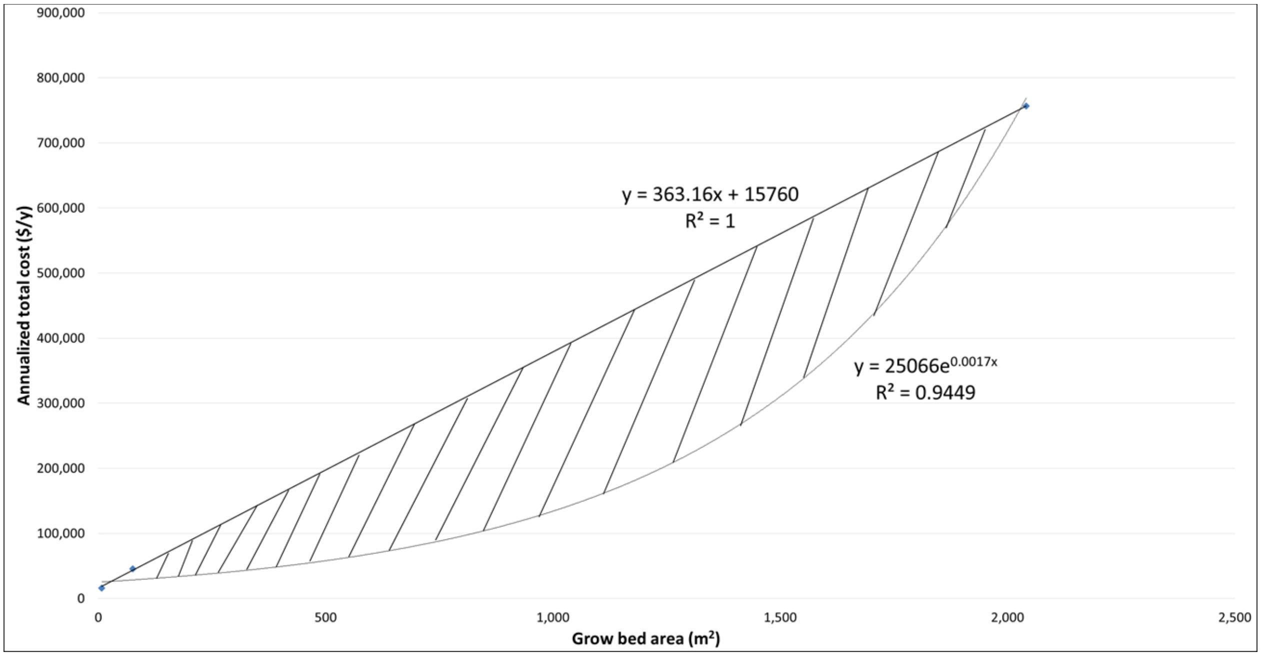

Figure 15. Annualized total cost (fish and plants) of tilapia-basil aquaponic systems with various grow bed areas (shaded region refers to the flexibility caused by different operation efficiency).

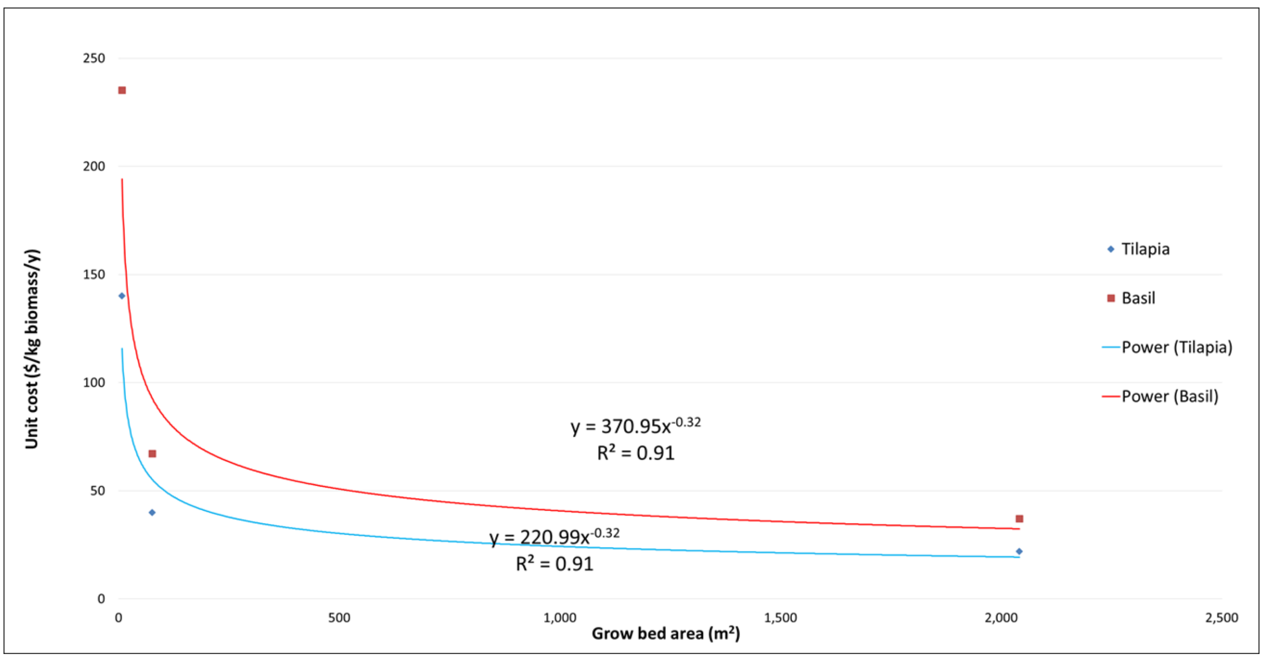

Figure 16. System unit cost of tilapia-basil aquaponic systems with various grow bed areas (total cost per unit of biomass produced).

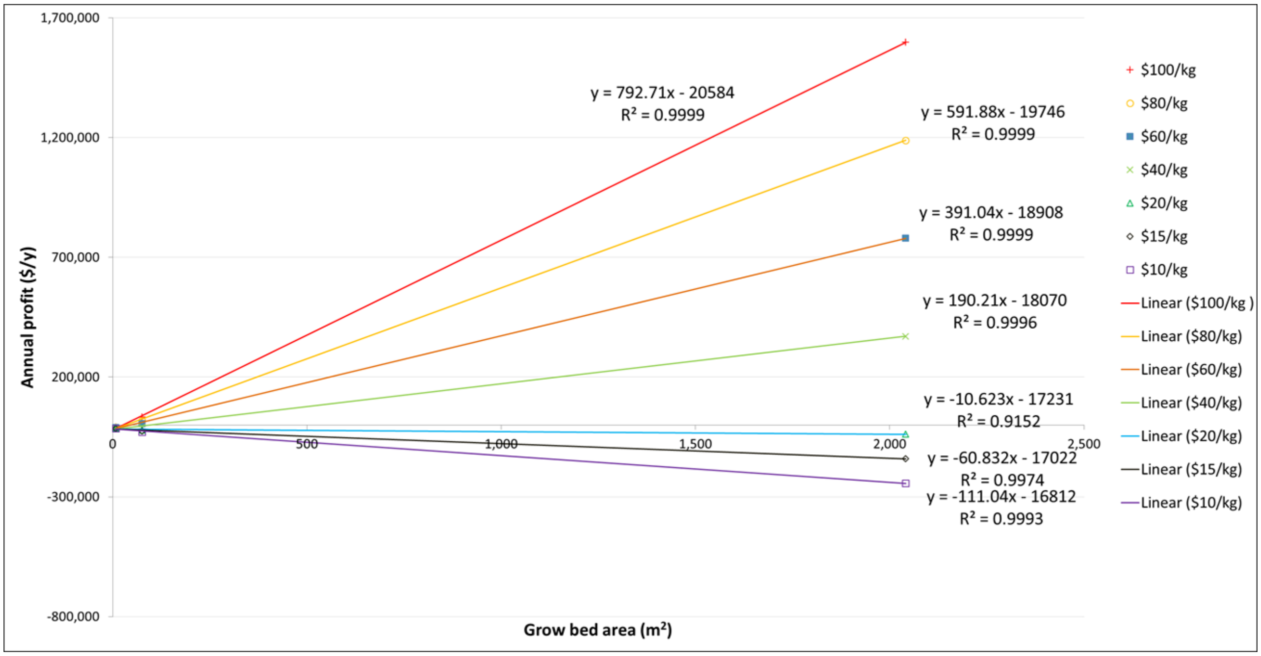

Figure 17. Annual total profits with various basil prices of tilapia-basil aquaponic systems with various grow bed areas (for a given tilapia sales price: $9 /kg).

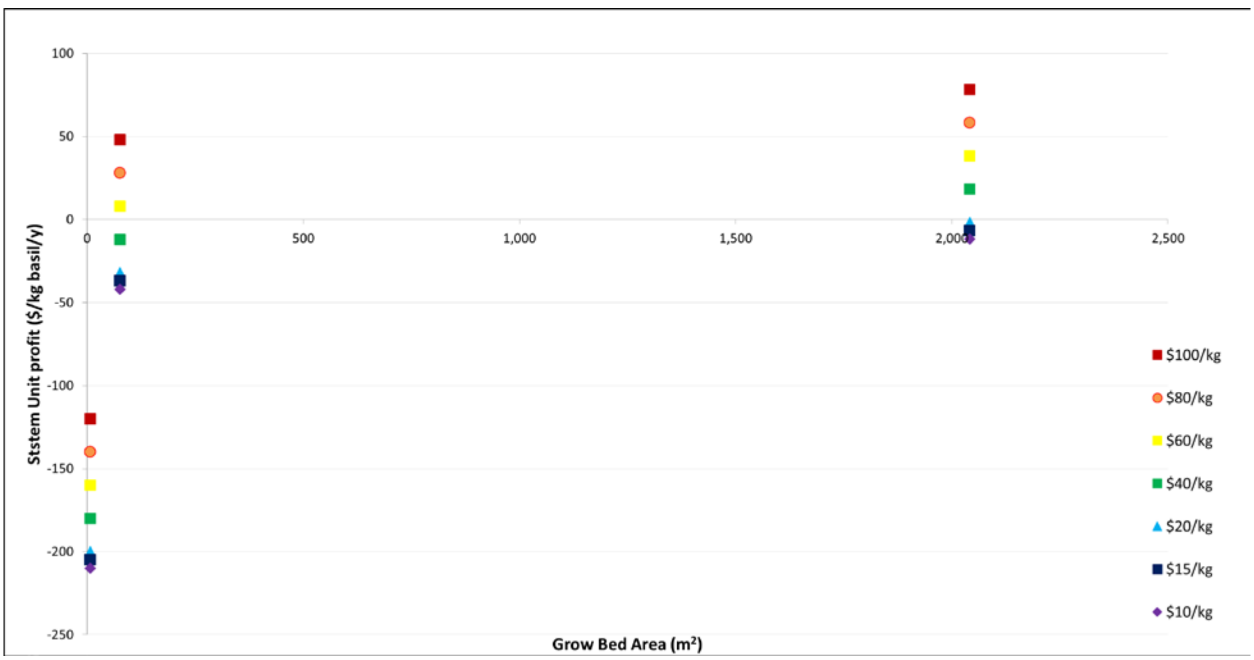

Figure 18. System unit profits with various basil prices of tilapia-basil aquaponic systems with various grow bed areas (for a given tilapia sales price: $9 /kg).

Figure 19. The Iowa State University tilapia-basil aquaponics (courtesy of Allen Pattillo).

Figure 20. Basil in the Iowa State University tilapia-basil aquaponics (courtesy of Allen Pattillo).

Figure 21. Tilapia in the Iowa State University tilapia-basil aquaponics (courtesy of Allen Pattillo).

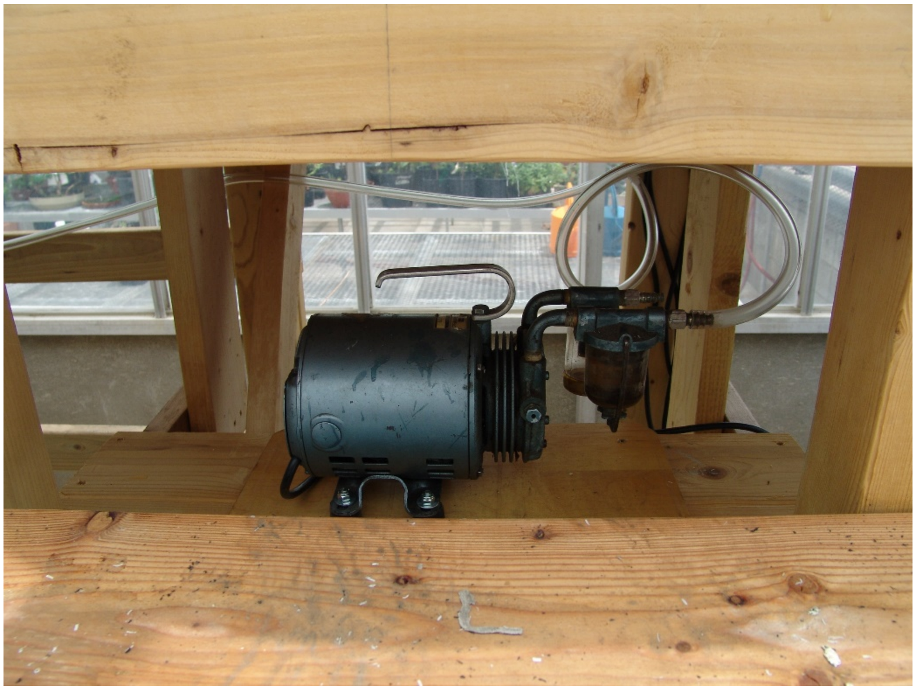

Figure 22. Blower in the Iowa State University tilapia-basil aquaponics (courtesy of Allen Pattillo).

Figure 23. Fish tank and filter tank in the Iowa State University tilapia-basil aquaponics (courtesy of Allen Pattillo).

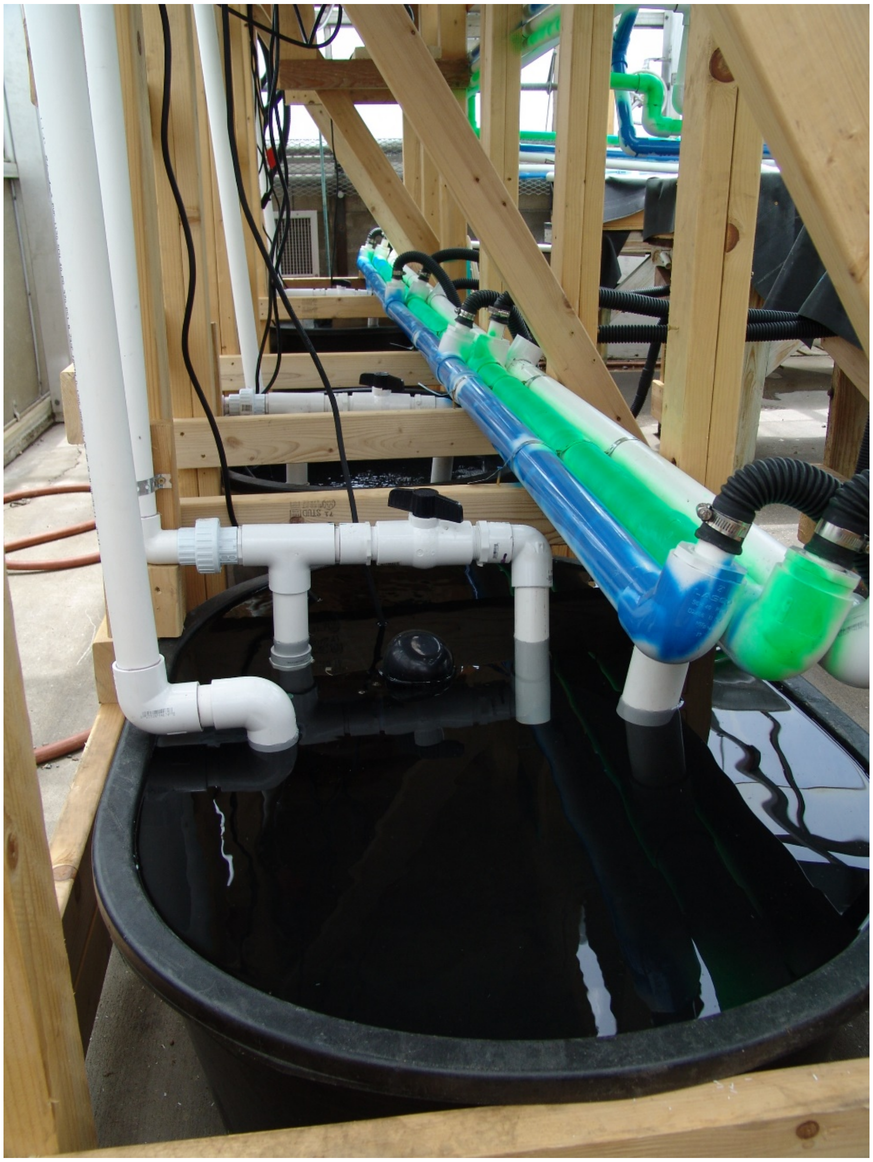

Figure 24. Stock tank in the Iowa State University tilapia-basil aquaponics (courtesy of Allen Pattillo).