The Sustainability of Tilapia Aquaponics: A Case Study

by

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Table of Contents

Abstract

As circular economy systems gain popularity with the environmental movement, the combination of raising fish (aquaculture) and growing crops outside of soil (hydroponics) appeals to many, especially in low-resource areas. But how environmentally friendly is it really, especially when compared to other farming technologies? This study aims to measure the energy, water, and nutrient inputs of a tilapia and tomato aquaponics system over a six-month growing season and compare those numbers to plant and fish biomass outputs. Then, the data is compared to traditional tomato farming, aquaculture, and hydroponics technologies to determine which has the best input to output ratios in each category. The system output 45.1 kg of plant biomass, 91.9 kg of tomatoes, and 21.6 kg of tilapia. Aquaponics is found to consume more water and energy than traditional and hydroponic tomato growth methods. Traditional farming was found to use 31.9 L water/kg tomato and produce 19.2 gCO2e/kg tomato. Hydroponics was found to consume 17 L water/kg tomato and produce 209 gCO2e/kg tomato. Aquaponics was found to utilize 186 L water/kg tomato and produce 28,300 gCO2e/kg tomato. However, aquaponics consumes less water and energy than traditional aquaculture. Aquaculture uses 1200 L water/kg tilapia and produces 62,100 gCO2e/kg tilapia while aquaponics uses 43.5 L water/kg tilapia and produces 28,200 gCO2e/kg tilapia.

Literature Review

General Overview

Aquaponics is a relatively new discipline within the scientific community. It is the concept of combining aquaculture and hydroponics systems into one cohesive closed-loop system that cycles nutrients and water to the mutual benefit of the plant and fish species within the system (Fox et al. 2010). The first scientific papers on aquaponics were published in the 1980s, but research on the subject only really became widespread around 2010 (Junge et al. 2017). As water and food scarcity became more widespread with climate change, aquaponics was one of the technologies that scientists began looking to as a potential solution for stable and sustainable food production with potential for reduced water usage as compared to traditional farming methods. Aquaponics systems are easier to implement within urban areas or as local food production because of the adaptable size of the system and its freedom from soil (Love et al. 2015), so it is possible to create an aquaponics system that requires less transportation energy than a traditional farm. The overall impact of energy use of the system can also be significantly decreased by the implementation of on site renewable energy generation technologies (Tokunaga et al. 2015, Forchino et al. 2017). However, despite the potential for increased sustainability in aquaponics in relation to traditional aquaculture and farming methods, the running of such a system can be quite labor intensive and costly in some cases. It is important to continuously monitor an aquaponics system to make sure that nutrients are in proper concentrations for plant growth so that adjustments can be made if necessary for the well-being of the plants and animals involved (Suhl et al. 2016). Therefore, labor costs for aquaponics systems can be up to ⅓ of the total costs of running the system (Tokunaga et al. 2015). Despite these high labor prices, aquaponics has been found to be profitable in Hawaii, where fresh produce costs tend to be higher than those in the continental United States (Tokunaga et al. 2015).

Different System Types

There are three commonly used types of aquaponics systems. These include nutrient film technique (NFT), floating raft/deep water culture, and media filled systems (Wongkiew 2017). Nutrient film technique systems circulate a shallow stream of water which contains nutrients from the fish along the bare roots of the plants in the system (Wongkiew 2017). This method requires no media for the plant to grow in other than the grow bed channel. Some of the difficulties of NFT systems are that only small vegetable species can be used, there needs to be some method for efficient solids removal to prevent clogging the system, and a biofilter is required for nitrification (Wongkiew 2017). Floating raft/deep water culture systems are the most common type of aquaponics system in the literature today. These systems consist of floating boards (typically made of polystyrene) that float on top of the water. Water from the fish tank circulates into the plant tank to provide nutrients. This type of system is popular because there is no thin channel of water flow to clog like in NFT systems (Wongkiew 2017). Floating systems, like NFT systems, require both solids removal and biofilters in their designs (Love et al. 2015). In a life cycle assessment, floating systems are typically the best system type of the three explored in this paragraph (Forchino et al. 2017). Finally, media filled systems are the simplest of the three types to build and implement. This is because media filled systems do not require biofilters because the media in the grow bed provides a space for nitrification (Zou et al. 2016). In these systems, water from the fish tank is pumped into grow beds filled with some type of media in intervals so that aerobic bacteria can convert nutrients into forms that plants can uptake (Fox et al. 2010). These intervals are often controlled by either a bell siphon or an automatic siphon with a timer (Fox et al. 2010).

In addition to the types of system design that can be used to categorize aquaponics systems, distinctions can also be made in terms of system size, location, and types of fish and plants that can be raised within systems. The sizes can be broken down into three categories: hobby, social/school, and commercial (Junge et al. 2017). However, there are no definitive size restrictions that have been documented for each size and this categorization is up to the interpretation of the observer and often based more on what the system is used for rather than the actual size. Systems can also be categorized by whether they are in rural or urban areas, as this distinction may impact the layout of the system as well as the energy use for transportation of products and supplies. Finally, there are many different types of fish and plants that can be used in aquaponics systems. Common types of fish utilized are trout (Buzby et al. 2016), tilapia (Delaide et al. 2017, Love et al. 2015, Ngo et al. 2017), and carp (Filep et al. 2016). Plant varieties included sage, chives, garlic, lovage, swiss chard, beets, kohlrabi, many different types of lettuce (Buzby et al. 2016), basil (Filep et al. 2016), tomato, and bok choy (Hu et al. 2015).

Parameters of Aquaponics Systems

A lot of work has been done in the study of optimal parameters of the various nutrients and resources that flow through aquaponics systems. The most notable of these are nitrogen, ammonia, phosphorus, pH, water use, and energy use. Nitrogen utilization efficiency in an aquaponics system is typically best when the pH of the water is between 6.0 and 9.0 (Zou et al. 2016). In outdoor systems, seasonal variations may not affect nitrogen utilization efficiency, but they do affect the ratio of nitrification to plant growth (Zou et al. 2016). Nitrogen utilization efficiencies also vary by plant and should be researched for individual systems based on plant selection (Hu et al. 2015). Compared to traditional farming methods, only about half of the amount of nitrogen is required in aquaponics systems for comparable plant growth (Van Ginkel et al. 2017). Aquaponics is a complex biological system and levels of different forms of nitrogen and transformations of nitrogen should be closely monitored and systematically controlled (Wongkiew 2017). Ammonia levels were a large barrier in early aquaponics systems, as ammonia would build up in the system and could be toxic to fish, but are not as much of a problem in more modern systems (Bohl 1977, Collins et al. 1975, Love et al. 2015). In typical modern systems, nitrifying bacteria break down the ammonia (Zou et al. 2016). Phosphorus is highly utilized and produced by aquaponics systems as well (Cerozi et al. 2017). When plants are first planted, there tends to be more phosphorus than necessary in the system. In the middle stages of growth, there tends to be just enough. At the end growth stages, there tends to be a shortage of phosphorus (Cerozi et al. 2017). Phosphorus availability in aquaponics systems is also highly impacted by pH, much like nitrogen. The optimal pH range for keeping phosphorus available for plant uptake in the system is between 5.5 and 7.2 (Cerozi 2016).

Water use and energy use are important to document in order to determine how sustainable an aquaponics system is. On average, the water use required for 1 kg of vegetable growth is 244 L and the amount of water use required for a 1 kg increase in tilapia is 278 L (Delaide et al. 2017). In comparison, farming techniques on average require about 8 times more water than aquaponics techniques (Van Ginkel et al. 2017). It is also important to note that a recirculation rate of 200-400% per day of water is optimal for plant growth (Ngo et al. 2017). This should be water that is cycled through the system over and over. Water exchange can help with decreasing nutrient levels if they get too high, but this should be done cautiously as any amount of water exchange typically results in high levels of nutrient loss across all parameters (Delaide et al. 2017). Many forms of water losses in systems have been documented from leaks to evaporation to transpiration. As long as water losses are not too severe, in many areas of the United States, rainfall should be able to make up for most losses (Love et al. 2015). On average, energy use for 1 kg of vegetable production is 84.5 kWh and the amount of energy required for a 1 kg increase in tilapia is 96.2 kWh (Delaide et al. 2017). There seems to be little difference overall in energy consumption between aquaponically grown plants and traditionally grown plants (Van Ginkel et al. 2017).

As chemical controls such as pesticides and herbicides can harm fish, other methods of pest control in aquaponically grown plants need to be evaluated in order to have a successful system (Junge et al. 2017). Methods for pest control in aquaponics are not widely decided upon or accepted. However, many commercial aquaponics businesses believe that employees and owners need more education and information about fish diseases and plant pests as well as what they can do about them (Villarroel et al. 2016). The ability of aquaponic crops to be free of pesticides and herbicides (essentially organic) can be a huge boost to aquaponic farmers in terms of marketing and the ability to sell aquaponic produce at potentially higher prices (Miličić et al. 2017).

According to Love et al. (2015), the main factors that affect the profitability of an aquaponics system are whether the system is someone's primary source of income, geographic location, knowledge of aquaponics, and sales ability. In Villarroel et al. (2016)'s survey of European aquaponics systems, only 19% of respondents were commercial aquaponics producers and only 19.6% of total respondents listed aquaponics as their primary source of income. The largest users of aquaponics systems were schools and universities (43%) and a huge 91.7% of respondents had a postgraduate degree, showing that aquaponics seems to still be viewed as an educational pursuit that requires quite a bit of expertise and isn't widely commercialized yet. According to Miličić et al, customers of aquaponics systems seem to have a good opinion of the practice in general because most aquaponic-grown produce is organic, local, and environmentally friendly and is advertised as such (Miličić et al. 2017).

Major Challenges to Aquaponics

Despite benefits of using aquaponics technology, such as decreased water use, decreased organic waste, and local production of multiple types of food products (Love et al. 2015), there are still major challenges in the implementation of aquaponics technology. Some barriers to implementation include high start-up costs (Villarroel 2016), extensive knowledge requirements, high resource demand, daily maintenance requirements, and narrow ranges of nutrient and temperature requirements that leave little room for error (Love et al. 2015). These barriers will likely decrease or disappear as the field grows and time passes, but are still significant enough to exclude many people currently (Villarroel 2016). There are additionally some global impacts that aquaponics could have that could cause environmental issues such as water use (in potentially water scarce areas), nutrient release into the environment, and introduction of exotic species and diseases into the local ecosystem in the event of a fish escape (Samuel-Fitwi et al. 2012). Some of the major challenges that need to be addressed in order to create sustainable aquaponics systems are improved nutrient utilization, better pest management, reduction of water requirements, use of alternative energy sources to power the systems, and better pH stabilization measures (Goddek et al. 2015).

Methodology

Overview of Study

The purpose of this study is to build and run an aquaponics system for a term of 6 months and document the nutrient, water, and energy inputs to the system. At the end of running the system, fish and biomass (fruits and plants) were harvested and weighed as outputs of the system. Blue tilapia (oreochromis aureus) and semi-determinate tomatoes were chosen as the fish and plant species respectively to be used in the system. The blue tilapia were chosen because of prevalence in aquaponics literature as well as their increased hardiness in colder water conditions than other tilapia species. This trait was important because despite the system being inside a greenhouse, it was also located in Michigan, USA, which can get quite cold in the fall and winter, resulting in cooler greenhouse temperatures. Semi-determinate tomatoes were chosen because the system was located in a greenhouse with limited space for growing out plants. Tomatoes were chosen above leafy green plants (which have higher prevalence in literature) because of a perceived social stigma of eating the part of the plant that had touched “fish water”. More research may have to be done to show if this concern was valid. A period of 6 months was decided on based on information from Aquaponics USA which suggested that blue tilapia would reach maturity over a six to nine month period.

System Design

The design of the system was determined by materials available. Some materials were donated which included wood, HDPE tubs, PVC pipe in various shapes and sizes, various waterproof tarps, stone grow media, and three pumps (one 1.3 amp and two 0.85

amp). Based on this, it was decided to construct a media-filled system because of the availability of the materials. The fish pond and one large grow bed of equal size were constructed out of wood, which was then lined with tarps to prevent leaks. The dimensions of these are shown in figure 1 below. Then four HDPE tubs were used as another set of grow beds, approximately equal in combined volume to the first large grow bed. A ratio of 2:1 grow beds to fish pond volume was decided on based on recommendations from various hobbyist literature. An area next to the pond and grow beds was cut out of the greenhouse floor and lined with another tarp to act as a sump tank for the system. This sump tank was important because the system was designed so that if any water level changes occurred (due to leaks, evaporation, etc.), they would only occur in the sump tank. This kept the fish safe from any disasters that could result in changing water levels. The sump tank was approximately twice the volume of the fish tank. A 1.5 kW heater was attached to the pump between the sump tank and the fish pond.

Because of inconsistencies in operation and difficulties with implementation of siphons, it was decided to convert to a continuous flow system. In a continuous flow system, water is distributed over the media and the outflow is set a level some 3 inches below the surface to create space for the bacteria to grow.

When fully constructed, the system operated as such (see Figure 2):

1. Water from the sump tank was pumped to the fish pond via a 1.3 amp pump. Water passed through the heater as it was pumped between tanks.
2. From there, the water either flowed by gravity or by a 0.85 amp pump to one of the grow beds. The small grow beds were connected to the fish pond via PVC pipes which water flowed out of via gravity when a certain water level was

reached. The large grow bed was fed by the pump as it was further away from the fish pond than the smaller grow beds and also at a higher elevation than them.

3. Once in the grow beds, water was filtered through the plants which uptake various nutrients and then exited the grow beds through the continuous flow system which led back into the sump tank.

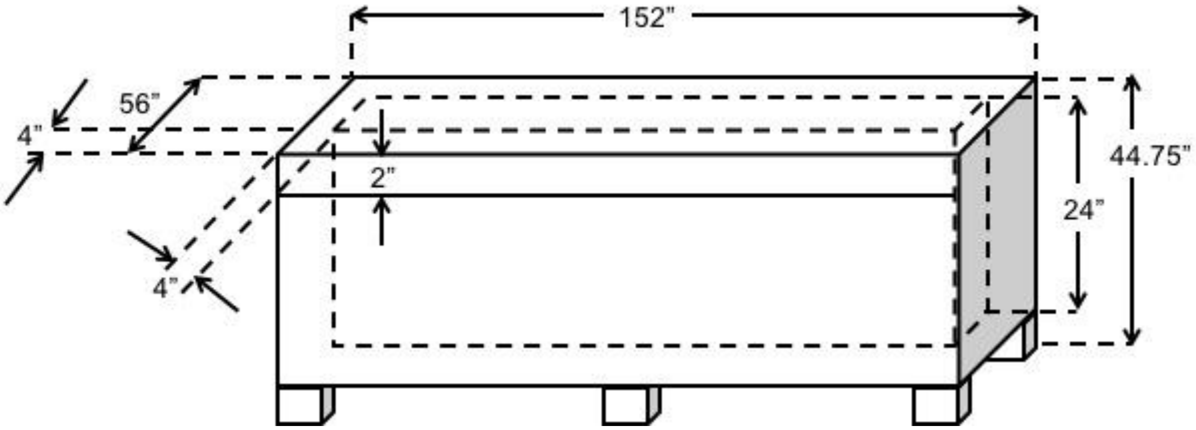

Figure 1: Fish Tank and Large Grow Bed Dimensions

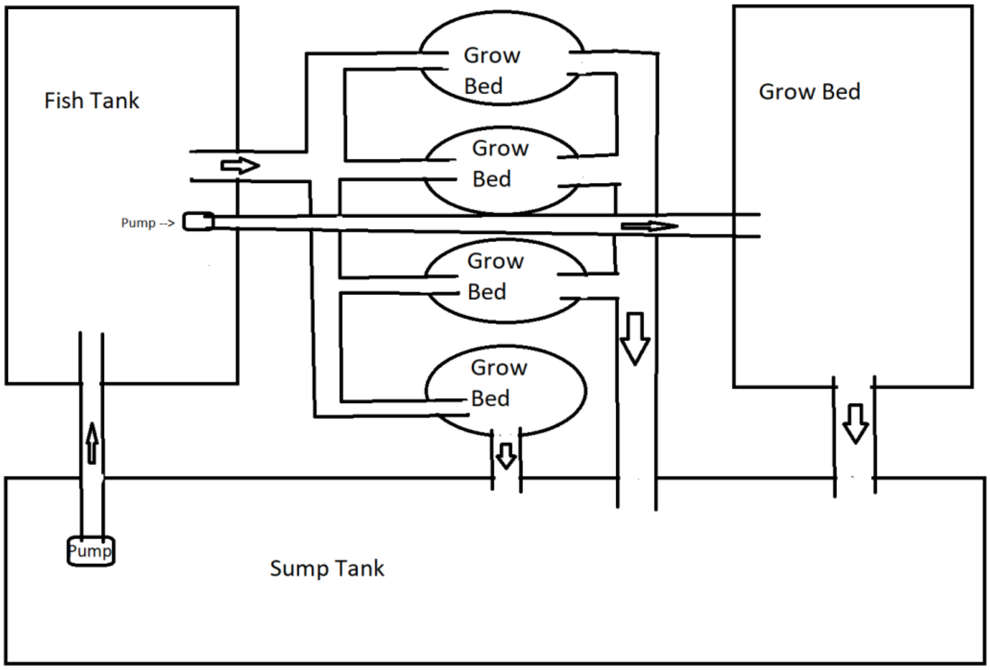

Figure 2: A diagram of the direction of flows throughout the aquaponics system.

Data Logs

As required by the Institutional Animal Care and Use Committee (IACUC) at the University of Michigan, a daily log was conducted for the system which included the date, time, health of fish, water temperature, feedings, and any other fish-related notes. For the purposes of this research, columns were also added for water additions to the system and any tomato harvests or biomass removals. Fish were fed and observed for any health issues twice daily. An additional weekly log was kept at the request of IACUC of water quality parameters to ensure safe conditions for the fish. Water quality analysis testing was also conducted weekly for Dissolved Oxygen (mg/L O_2), Phosphate (mg/L PO_4^{2-}), Nitrate (mg/L NO_3^-), Ammonia (mg/L NH_3-N), and Nitrite (μg/L NO_2-N) using a Hanna Instruments multiparameter benchtop photometer and pH meter.

Water Use

Any water additions were recorded in the daily log and measured using a save-a-drop water meter connected to a hose. Measured water additions began following the initial fill and cycling of the system, after fish were added. A total water input, average daily water input, and water input per kilogram of tomatoes produced were calculated for comparison with other technologies.

Electricity Use

Electricity use was initially measured by P3 International P4460 Kill A Watt EZ Electricity Usage Monitors, which plug into standard wall outlets and devices then are plugged into them. However, the measurements of electricity use were found to match the specs of the devices provided by the manufacturers almost exactly, so use of the monitors was discontinued due to operational convenience. As an alternative, electricity use was calculated based on equipment specifications and time of use. Of the total 185 days of the experiment, the pumps (0.2568 kW total) operated constantly and the heater (1.5 kW) ran for 93 days. There was also a mini fridge that was used to keep food on-site that was operated for all 185 days. The mini fridge was rated at 180 Watts. Grow lights were considered, but since the system was operated during May to November in the northern hemisphere, they were not needed.

Carbon dioxide equivalent emissions for electricity use of the system were calculated using total electricity use of the system, the fuel mix of the local utility (Detroit Edison) for 2018, and carbon intensity values for each fuel source provided by the U.S. Energy Information Administration (EIA) from June 2018. Emissions were calculated as a total, on a per kilogram of tomato basis, on a per kilogram of food produced basis, and on a per day basis to be compared with numbers for different farming technologies.

Nutrient Inputs

Fish food was ordered from Aquaponics USA as a bundle. This bundle included food for each stage of growth of the tilapia. “Fingerling crumble” was provided in an amount of 10 lbs (approx. 4.5 kg) which was rated as containing 50% protein and 17% fat. The ingredients were listed as fish meal, fish oil, wheat flour, brewer’s yeast, and vitamin mix (A, C, D, E). After the “fingerling crumble” was the “fingerling pellet”, which was slightly larger and provided in the amount of 20 lbs (approx. 9 kg). It contained 50% protein and 16% fat. The ingredients of the “fingerling pellet” were fish meal, dehulled soybean meal, ground corn, fish oil, corn gluten meal, and vitamin mix (A, C, D, E). Twenty pounds were also provided of the “intermediate pellet”, which was even larger and contained 45% protein and 16% fat. “Intermediate pellets” contained fish meal, dehulled soybean meal, ground wheat, fish oil, wheat flour, and vitamin mix (A, C, D, E). Finally, 40 pounds were provided of the “growout pellet”. This was the largest pellet and contained 36% protein and 6% fat. The listed ingredients of the “growout pellet” were dehulled soybean meal, ground corn, wheat middlings, fish meal, brewer’s dried yeast, and vitamin mix (A, C, D, E). All but the last 10 lbs of the “growout pellet” were used. Values were calculated for total food inputs and total protein inputs based on the data above.

System Outputs

Seventy-five blue tilapia fingerlings were ordered from Aquaponics USA at a 50/50 male to female ratio. Eighty fish were delivered with only two casualties (uncertainty due to living fish partially eating any dead fish). As the fish grew, it became apparent that there was at least one red tilapia and at least one black Mozambique tilapia in the mix. There were also some tilapia that looked like they were potentially a mix between blue and red tilapia. What appeared to be the red tilapia and black Mozambique tilapia grew much more slowly than the blue tilapia and were still quite small by the end of the experiment. One fish was taken and euthanized by a veterinarian early in the experiment to do a necroscopy to check for parasites in the mix and ensure fish health. The veterinarian found nothing unusual.

Seventy-eight fish were harvested at the end of the term. Fish were weighed as whole fish and also as fillets. Fillets were cut, after euthenasia, by several experienced fishermen to ensure that they were cut properly without losing any edible parts. The fishermen were used to fish native to Michigan and remarked that tilapia had an additional bone structure in their underbellies that Michigan-native fish did not have which made it difficult to salvage meat from that area. This may be something to consider in future projects, as different fish species or special fillet techniques may create opportunities for increased viable meat outputs.

Tomato harvests and biomass trimmings throughout the experiment were weighed and recorded in a daily log. At the end of the experiment, any remaining fruits and biomass were removed from the system and weighed.

Other Farming Technologies

The data collected in this experiment were meant to be compared with reported aquaponics data (as seen in the background section) as well as data for hydroponic tomatoes and traditional tomato farming. Data for carbon footprint and water use were collected for each farming technology. The scope of this comparison only involves electricity, nutrient, and water inputs as well as food outputs of the various farming technologies so that a fair comparison can be made between them and with the built aquaponics system. This means that this analysis does not include any shipping of tomato product for retail, packaging of the product for sale, or any end of life analysis of materials consumed or product produced. In terms of water use, the outputs are relatively simple already, but for energy and nutrient use, the scope had to be limited. For the more complicated categories, data was consolidated to find an overall CO_2e measurement for all the inputs.

In terms of traditional methods, three different irrigation systems were compared. The first was ditch irrigation, in which water is delivered to a field through a ditch or pipe and is spread over the ground to crops. The second method was sprinkle irrigation, in which water is delivered by sprinkler to crops. The third method was drip irrigation, in which water is delivered by some kind of system of pipes and/or pumps that slowly drips water to crops. This delivery system can be above ground and drip onto the plants directly, or it can be below ground and drip straight to the roots of the plants.

For hydroponic methods, two different methods were compared. The first method was open hydroponics, in which water flows through the system and then dumps into a nearby body of water or drainage pipe when through. The second method was closed hydroponics, in which the water flows through the system and then is cycled back to the beginning of the system where additional nutrients are added before the water goes through the system again.

In order to determine what data to use in calculations, various studies on water use and carbon footprint for variations on traditional farming and hydroponics were found. Numbers among the studies were averaged to find a good value to use for comparison. Sources for these numbers included various scientific journals, national labs, the Simapro database, the EIA, and the IPCC (see sources and appendix). The data came from sources both inside and outside of the US. Sources from within the United States were preferred since this experiment was conducted in the US, but there seemed to be somewhat of a literature gap in the US in terms of measuring farming inputs, so outside sources were also used.

For water use, traditional farming was consolidated to one value. This is because it was difficult to find information on different water use measurements for the different methods of traditional farming. Many papers were not clear about what kind of irrigation system they were using, which made comparison difficult, so all traditional methods were combined into a single average. Water use was measured in terms of liters of water used per kilogram of tomatoes produced.

It is assumed for the CO_2e assessment that all farming methods take place in the US, however it does not make sense to choose a single location in the US to base all calculations on because different system setups are required in different climates throughout the US. For example, in colder climates, greenhouses and/or heaters are more cost effective generally than in warmer climates because of the increase in growing season that they provide. For this reason, it was important to do an analysis of the differences in CO_2e outputs for each method when accounting for location. A Monte Carlo analysis was done in Excel that varied the CO_2e emissions based on the different inputs to the US power grid in different locations.

Results

Nutrients

	System Output (kg)
Plant Biomass	45.1
Tomatoes	91.9
Fish	21.6
Fillets	6.1
Protein	1.6

The aquaponics system yielded a total of 45.1 kg of plant biomass and 91.9 kg of tomatoes. The initial fish harvest showed that the 78 fish had a mass of 21.6 kg. After being filleted, the edible fish biomass came out to 6.1 kg (approx. 13.4 lbs). At a protein output of 120 g/lb of fillet, the protein output of the system was 1.6 kg. The system was only run for six months, which is the minimum recommended amount for blue tilapia to reach maturity according to Aquaponics USA. If the system could be run for nine months, which was the higher end of the estimate, outputs could be increased. This may be something to consider in the future.

Water

	Water Use (L/kg tomato)
Aquaponics	186
Hydroponics	17.0
Traditional Farming	31.9

	Water Use (L/kg tilapia)
Aquaponics	43.5
Aquaculture	1200

Following the initial fill of the system, water use was calculated to be about 30 gal/day (approx. 114 L/day). Given this, water use comes out to an overall figure of 229 L/kg of product (tomatoes and tilapia together). This was divided up by biomass proportion into 186 L/kg of tomatoes produced and 43.5 L/kg of tilapia produced. In the aquaponics literature it was found that on average, the water use required for 1 kg of vegetable growth was 244 L and the amount of water use required for a 1 kg increase in tilapia was 278 L (Delaide et al. 2017). Using this figure gives an estimate of the total water use for the system to be 28,434 L, which is slightly more than the actual water use of 21,009 L.

The figure for water use in aquaponics is quite high compared to other tomato producing technologies whether this system's or the literature's total is used. For traditional farming methods, water use averages to 31.9 L/kg of tomatoes. In hydroponics technologies, water use averages out to 17 L/kg of tomatoes. This discrepancy in water use could come down to several factors. First, the addition of fish to the system requires a lot more water initially as the fish pond must be filled and kept filled for the duration of the system. There is also the requirement of keeping a sump tank with water in it as a safety measure for the fish. Keeping large, open pools of water on site for aquaponics can lead to much more evaporation than in the other technologies where this is not required.

However, water use is much less in aquaponics than in traditional aquaculture (Verdegem et al. 2006).

Energy

	Carbon Footprint (gCO_2e/kg tomato)
Aquaponics	28,300
Hydroponics	208
Traditional Farming	19.2

	Carbon Footprint (gCO_2e/kg tilapia)
Aquaponics	28,200
Aquaculture	62,100

For electricity, a total of 5,287 kWh was used over the 185 day run of the system, or about 28.6 kWh/day. Of that, 63.3% came from the heater, 21.6% came from the pumps, and 15.1% came from the mini fridge. In the literature review on aquaponics, it was previously noted that on average, energy use for 1 kg of vegetable production is 84.5 kWh and the amount of energy required for a 1 kg increase in tilapia is 96.2 kWh (Delaide et al. 2017). This figure would estimate that about 9,845 kWh would be used for the system described in this study (assuming that “vegetable” and tomato energy use is equivalent), which means that energy use was quite a bit lower than expected. This may be due to not using grow lights for the system. For tomatoes, 46.6 kWh/kg tomato produced was consumed. For fish, 46.5 kWh/kg of fish produced was consumed. When using the fuel mix of the local utility and carbon intensities of different energy sources from the EIA, carbon emissions over the course of running the system come out to 3.21 tons CO_2e. This is about 28,300 gCO_2e emitted per kilogram of tomato produced in this system in Southeast Michigan.

In comparison to traditional aquaculture, aquaponics was found to utilize only about 45% of the energy to produce the same amount of fish (Kim et al. 2018). This may be due to the reduced filter, water change, and aeration needs in aquaponics. These reductions are due to the use of plant grow beds as filters and quick circulation of water to provide aeration. This is a sizable improvement.

The carbon footprint of aquaponics from energy use is much higher than that of either traditional farming of tomatoes or hydroponics. The Monte Carlo analysis of traditional farming (figures 3 and 4) showed a mean of 19.2 gCO_2e/kg tomato produced while the analysis of hydroponics showed a mean of 208 gCO_2e/kg tomato produced. For aquaponics, the mean in the Monte Carlo analysis was 43,500 gCO_2e/kg tomato produced. This discrepancy between the other tomato producing technologies and aquaponics is likely due to the increased use of electrical equipment required for the fish. The heater used most of the electricity, which would not be required in technologies that do not include fish. It would also not be a factor in warmer climates, where a heater is not required to keep the fish alive or with fish species that can withstand colder temperatures. Additionally, the mini fridge, which was kept running at all times to keep the fish food fresh, used quite a bit of energy that the other technologies would not when it was added up over the course of the experiment. The entirety of electricity use from traditional farming of tomatoes came from building electricity while most of the energy used in hydroponically grown tomatoes came from pump systems similar to the ones in the aquaponics setup.

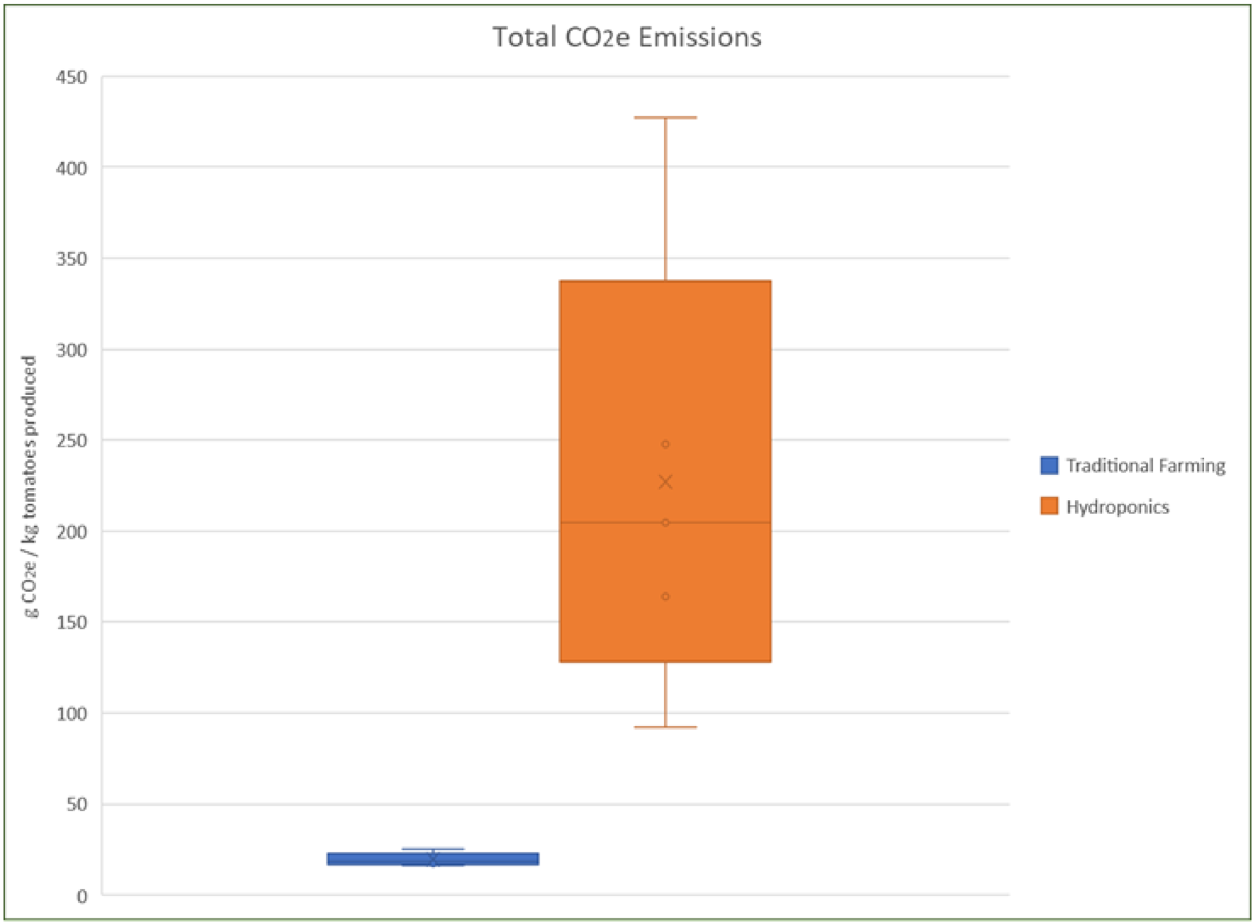

Figure 3: Monte Carlo Analysis results for Total CO2e Emissions for Traditional Farming and Hydroponics from electricity across the United States

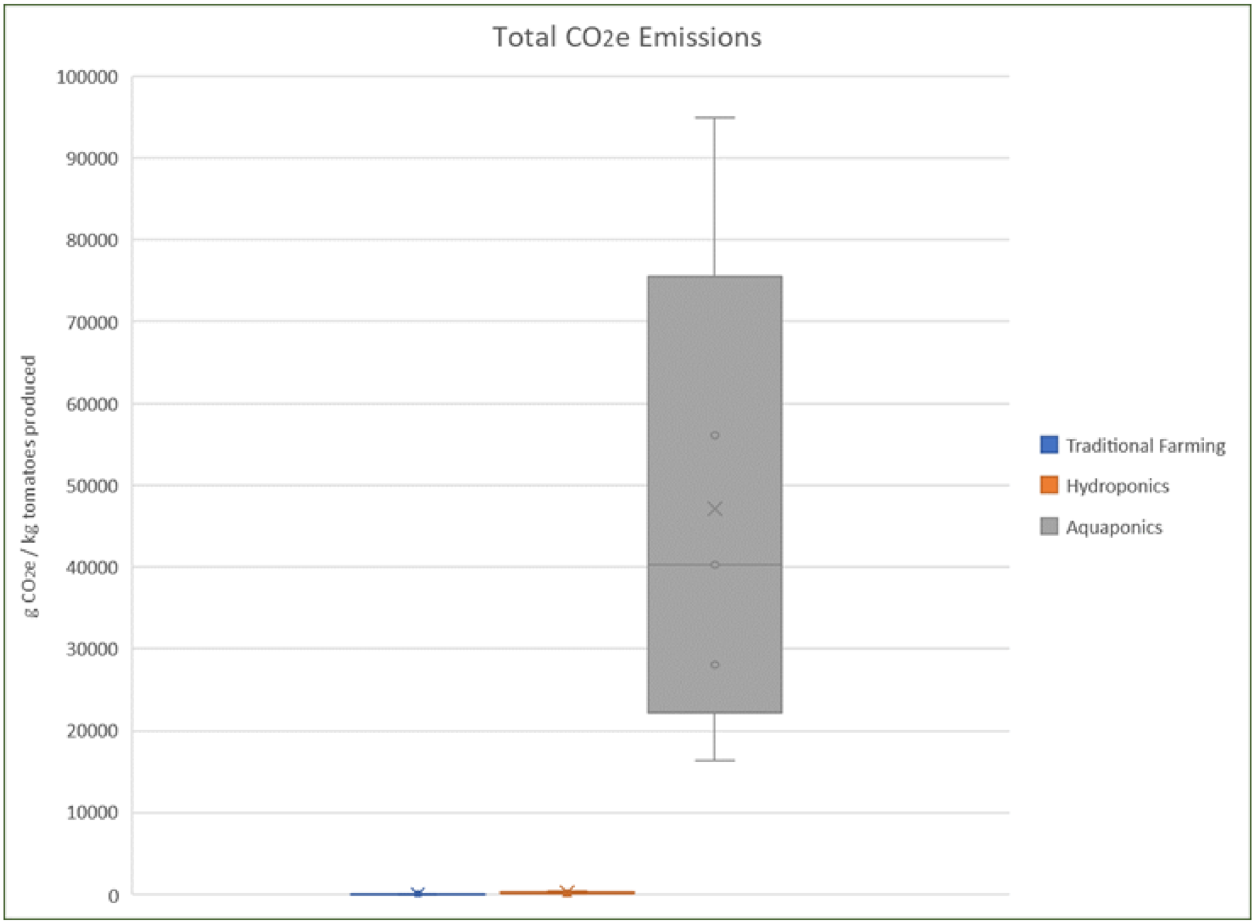

Figure 4: Monte Carlo Analysis results for Total CO2e Emissions for Traditional Farming and Hydroponics from electricity across the United States

Conclusions

Based on the results outlined above, aquaponics uses more energy and more water than both traditional methods of farming and hydroponics for every kilogram of tomatoes produced. So why would anyone use aquaponics? The biggest draw of aquaponics that none of the other tomato producing methods can provide is a protein source. Aquaponics is the only method that involves both plants and meat as food sources. As a technology that can be applied in low resource areas and in somewhat small spaces like rooftops or empty lots, being able to raise animals for meat can be quite appealing. This is hard to do with traditional methods, where large areas of land or bodies of water are typically required. However, aquaponics has reduced energy and water use compared to traditional aquaculture. This means that it is a more environmentally friendly meat production method, which makes it valuable to communities that want to produce their own protein at any scale.

With some improvements to the system, it may be possible for aquaponics to become competitive with other tomato production methods in the future. Setting up a system in a way that has fewer leaks and less surface area of water could lead to less evaporation, less daily water use, and a reduced need for top-offs to the system. This could bring down overall water use somewhat and maybe make aquaponics more competitive with other technologies. However, due to the needs of fish in the system, it may be difficult for aquaponics to outcompete the others even with reduced losses. In terms of energy use, the biggest draw was from heating the system. This result may suggest that aquaponics is more competitive with the other technologies in warmer areas where heaters are not needed. In addition, running the system only once as a case study did not allow for perfection of the stocking rate of tilapia. At the end of the process, it seemed as if more tilapia could happily fit in the system, which could improve figures reported for water and energy use per kilogram. Future runs of the system will hopefully show improvements on these fronts and make aquaponics progressively more sustainable.

Appendix

Water Additions Log	Gallons Added
First Addition	52
Day 5	56
Day 6	100
Day 7	51
Day 8	57
Day 10	205
Day 13	100
Day 15	197
Day 23	100
Day 25	100
Day 31	245
Day 41	100
Day 45	100
Day 50	115
Day 53	55
Day 56	50
Day 58	105
Day 60	208
Day 64	50
Day 65	170
Day 66	50
Day 68	100
Day 73	50
Day 75	100
Day 77	100
Day 83	100
Day 87	50
Day 91	100
Day 96	60
Day 98	300
Day 108	100

Data Summary for Comparison			
Technology	**Water Use**	**Energy Use - electricity**	**Energy Use - fuel**
Hydroponics	17 L/kg tomato	0.244 kWh/kg tomato	28.9 MJ/kg tomato
Traditional Farming	31.9 L/kg tomato	0.1408 MJ/kg tomato	0.0735 MJ/kg tomato
Aquaculture	1200 L/kg fish	538.8 kWh/kg fish	N/A
Aquaponics	43.5 L/kg tomato	46.6 kWh/kg tomato and 46.5 kWh/kg fish	N/A

Sources Used in Averages: AlShrouf et al. 2017, Barbossa et al. 2015, Bribián et al. 2011, Czaplicka-Kolarz et al. 2010, Del Borghi et al. 2014, Dias et al. 2017, Greenhouse Gas Protocol 2014, Hasanbeigi et al. 2014, Hogberg 2010, Kim et al. 2018, Krey et al. 2014, Moomaw et al. 2011, Schlömer et al. 2014, Schmitz et al. 2011, Verdegem et al. 2006, Worrell et al. 2000, Worrell et al. 2007

Life Cycle gCO_2e/kWh for various technologies			
Source	**Min**	**Med**	**Max**
Coal – PC	740	820	910
Biomass – Cofiring with coal	620	740	890
Gas – combined cycle	410	490	650
Biomass – Dedicated	130	230	420
Solar PV – Utility scale	18	48	180
Solar PV – rooftop	26	41	60
Geothermal	6	38	79
Concentrated solar power	8.8	27	63
Hydropower	1	24	22001
Wind Offshore	8	12	35
Nuclear	3.7	12	110
Wind Onshore	7	11	56

Energy Source	**2018 US Generation Amount (billion kWh)**
Total – All Sources	4178
Fossil Fuels (total)	2651
Natural Gas	1468

Coal	1146
Petroleum (total)	25
Petroleum Liquids	16
Petroleum Coke	9
Other Gases	12
Nuclear	807
Renewables (total)	713
Hydropower	292
Wind	275
Biomass (total)	63
Wood	41
Landfill Gas	11
Municipal Solid Waste (biogenic)	7
Other Biomass Waste	3
Solar (total)	67
Photovoltaic	63
Solar Thermal	4
Geothermal	17
Pumped Storage Hydropower	-6
Other	13

Fuel Source	**DTE Energy's Fuel Mix for Electricity in 2018**
Coal	64.19%
Nuclear	18.68%
Gas	8.67%

Oil	0.23%
Hydroelectric	0.17%
Biofuel	0.13%
Biomass	1.06%
Solid Waste Incineration	0.32%
Solar	0.21%
Wind	6.28%
Wood	0.07%

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