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Environmental Sustainability Assessment of a Media Based Aquaponics System in Thailand

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Abstract: This study evaluates an Aquaponics system operated in Bangkok, Thailand for the duration of 15 months from a life cycle assessment perspective. The scoped boundaries include system infrastructure, energy usage, water usage, fish feed, and sludge discharge from water filtration. The functional unit of this analysis was the composite of fish (65 kg), vegetable production (323 kg) and sludge discharge (252 kg) for 15 months.

The sustainability of this urban aquaponics system is highly influenced by the resulting life of the infrastructure, crop selection and scalability. The revenue values of the vegetables always exceed the fish because the aquaculture stocking density is a bound ratio to the vegetable harvest. In a stable continuous operating system of tilapia and vegetables, the system will on average produce approximately 1:5 (65 kg:323 kg) by weight ratio. Because the fish excrete the composition of matter that becomes the nutrients for the vegetables and the vegetables are in fact the uptake mechanism resulting in the water's filtration, the two components cannot be scaled independently.

The results of the study indicated total system impacts to be: Global Warming Potential 881 kg CO_2-eq, Acidification 4.67 kg SO_2-eq, Fresh Water Eutrophication 0.01 kg P-eq, and Marine Water Eutrophication 4.18 kg N-eq. The case indicated feed and electrical provisions to be the highest contributor to environmental impacts. While the results varied based on the method of allocation applied to the final results, the comparisons with other LCA studies producing fish showed Aquaponics to have lesser environmental impacts due to the added benefit of extra vegetable food production.

Keywords: Aquaponics, Aquaculture, Recirculating, Life Cycle Assessment, Sustainability.

1. Introduction

Recirculating aquaculture systems are designed to raise large quantities of fish in relatively small volumes of water by treating the water to remove toxic waste products and then to allow for its reuse. In the process of recirculating the water, non-toxic nutrients and organic matter accumulate. The effluent produced from fish culture is rich in ammonia. Ammonia in its un-ionized form is toxic to fish at low levels. Nitrifying bacteria in the water column oxidize ammonia to nitrite via the *Nitrosomonas* species of bacteria and nitrite to nitrate via the *Nitrobacter* species. Nitrate is not toxic to fish except at high levels (>1000 mg L NO_3-N) [1] but is the dominant source of nitrogen for hydroponic plant production [2]. These metabolic by-products do not need to be wasted if they are channeled into an infrastructure of secondary crops (hydroponics) that have economic value or benefit the production system. In essence, vegetation uptakes nitrates from system water which allows for the continuous recycling back to the aquaculture without the need for exchange. The only requirement with water replacement comes from negligible losses due to plant evapo-transpiration and atmospheric evaporation [3]. Tank culture of tilapia is a good alternative to pond or cage culture if sufficient water or land is not available and the economics are favorable. Tilapia grow well at high densities in the confinement of tanks when good water quality is maintained. This is accomplished by aeration and continuous water exchange to renew dissolved oxygen (DO) and remove toxic bio-wastes [4]. Typical Aquaponics designs are referred to as recirculating aquaculture systems (RAS). Intensive tank culture offers several advantages over pond culture. High fish density in tanks disrupts breeding behavior and allows male and female tilapia to be grown together to marketable size. In ponds, populations breed to the point where parents and offspring compete for food and become stunted. Tanks allow the culturist easy management over fish stocks and to exert a relatively high degree of environmental control over parameters (e.g., water temperature, DO, pH, waste) that can be adjusted for maximum production. With tanks, feeding and harvesting operations require much less time and labor compared to ponds. Intensive tank culture can produce very high yields on small land footprints.

Tank culture also has some disadvantages. Since tilapia have limited access to natural foods in tanks, they must be fed a complete diet containing vitamins and minerals [5]. The filtration technology of recirculating systems can be fairly complex and expensive and requires constant and close attention. Any tank culture system that relies on continuous aeration or water pumping is at risk of mechanical or electrical failure and significant fish mortality.

Aquaponics may play an important role in water conservation, globally a major concern for food production [6]. As little as $0.25 m^3$ of water is required to produce 1 kg of tilapia (*Oreochromis niloticus)* [6] compared to 2 m^3 for similar biomass in intensive pond systems [7]. The largest single user of water in the world is the land based agricultural industry [8] where massive portions of irrigated water are lost via percolation into the soil [9]. Because hydroponically produced plants use recycled water, opportunities for water conservation are significant utilizing the aquaponics methodology. Another benefit of aquaponics is that organic fish effluent replaces the need for inorganic commercial chemical fertilizers. In addition, because pesticides and antibiotics cannot be used, the system provides potentially chemical free, more nutritious produce. Intensive food production systems are often criticized by their discharge of solid wastes into the environment [10], however aquaponics minimizes the need for discharge due to its recirculating nature [11].

As such, a system that grows additional crops utilizing by-products from the fish production system of the primary species is called an integrated system. It can be considered an eco-system approach to food production building upon the resilience of nature. Aquaponics, as an integrated system designed and scaled appropriately to meet production thresholds, has the potential to be an environmentally friendly and sustainable organic food production methodology as it combines culture of fish and plants in a recirculating system of water without incorporating soil or use of pesticides or fertilizers. The main objective of this study was to identify environmental hotspots of an aquaponics system in Thailand using the LCA method and to substantiate the statement of its sustainability.

2 Methodology

Goal and Scope Definition

The purpose of this study was to make an assessment of environmental sustainability using LCA of an urban aquaponics system operating for 15 months in Thailand. Analysis was done to identify environmental impact hotspots to suggest ways to improve sustainability. The three relevant impact categories are Global Warming (CO_2-eq), Eutrophication as Nitrogen (N-eq) and Phosphorus (P-eq), and Acidification as Sulfur Dioxide (SO_2-eq) using the ReCiPe 1.08v Midpoint Method. These categories are appropriate to study a recirculating aquaculture system for food production due to the following: materials used in classic construction of aquaponics systems such as PVC, HDPE and other components are expected to contribute significant burdens. Electrical consumption is required for operation and thus power generation will likely contribute heavily to CO_2 emissions. The release of industrial fertilizers in upstream inventory construction processes may be significant. Lastly, the avoidance of downstream operations emissions of an aquaponics system in comparison with traditional systems of agriculture where waste streams are likely to be more impactful due to industrial petro-based fertilizer production and intensive use on land may be significant. One advantage of this type of system is the non-use of agrichemicals such as pesticides, herbicides and fungicides. In this case, the use of these chemicals are avoided, thus eliminated from entering the environment. In addition, a system output-nutrient aquaculture sludge is considered to be a credit to the total impact performance of system as the resulting sludge is a viable and affordable alternative to imported manufactured inorganic fertilizers which can be used in traditional soil based agriculture [12]. The sludge can also be used as feedstock for composting, vermiculture [13] or other biotransformation processes, such as biogas recovery [14].

System Boundaries

System boundaries for the experiment are shown in Figure 1. Actual production (of fish and vegetables) begin at harvest time, however inputs to the daily operations are what were inventoried and will be discussed. Fish (Nile tilapia) batch culture were initially stocked as fingerlings for ramp up of system and to allow colonies of bacteria to become establish to cycle ammonia and nitrogen. Two tanks held different size fish for grow out. A variety of vegetables noted in Table 3 were selected and harvested in batches at different times for the experiment.

All impact potentials were calculated based on the actual operation and performance of the system during 15 months. SimaPro 7.1 software and the ReCiPe 1.08v midpoint assessment method were used to identify impact potentials. Actual system configuration is displayed in Figure 2 and components in Table 1.

Table 1. Specifications of system infrastructure components.

Component description	Technical specifications	Quantity used
Fish Tanks Total Volume	375.5 (L) 751 (L)	2
Sump Tanks Total Volume	375.5 (L) 751 (L)	2
Swirl Filter	208 (L)	1
Grow Beds Total m^2 Grow Bed Hydroton Media	539 (L), 300 (mm) deep, 1.54 m^2 (each) 10.78 m^2 (Total)	7
Water Pump	Flow Rate: 2800 (L/h) Power: 40 W	1
Air Pump	Flow Rate: 70 (L/min) Power 58 W	1
Rain Water Catch Basin	550 L	1

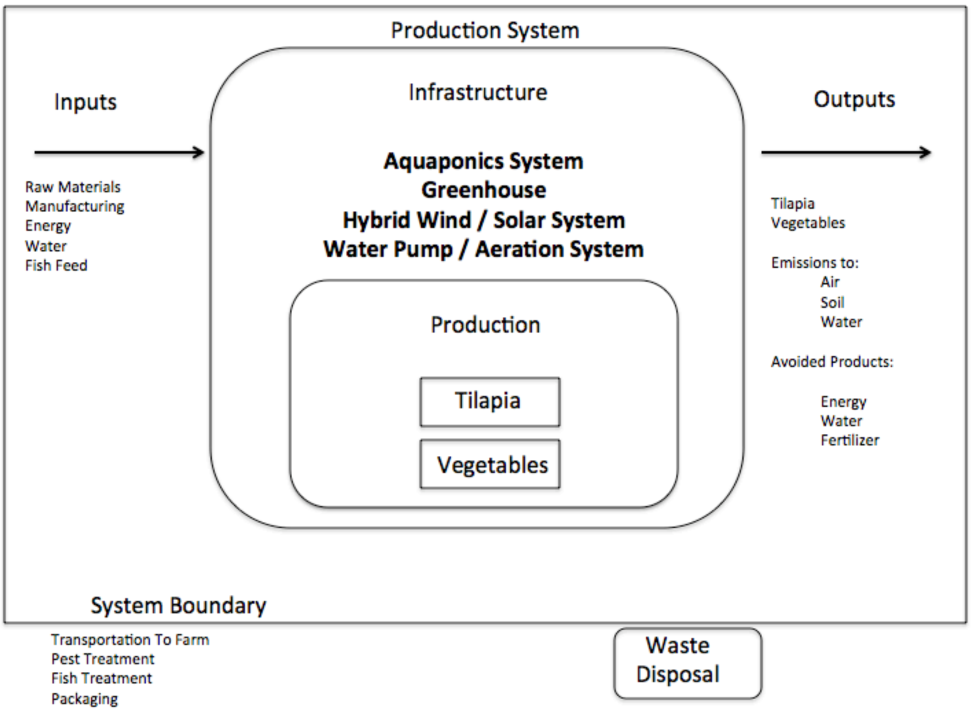

Figure 1. Simplified system boundaries of the study.

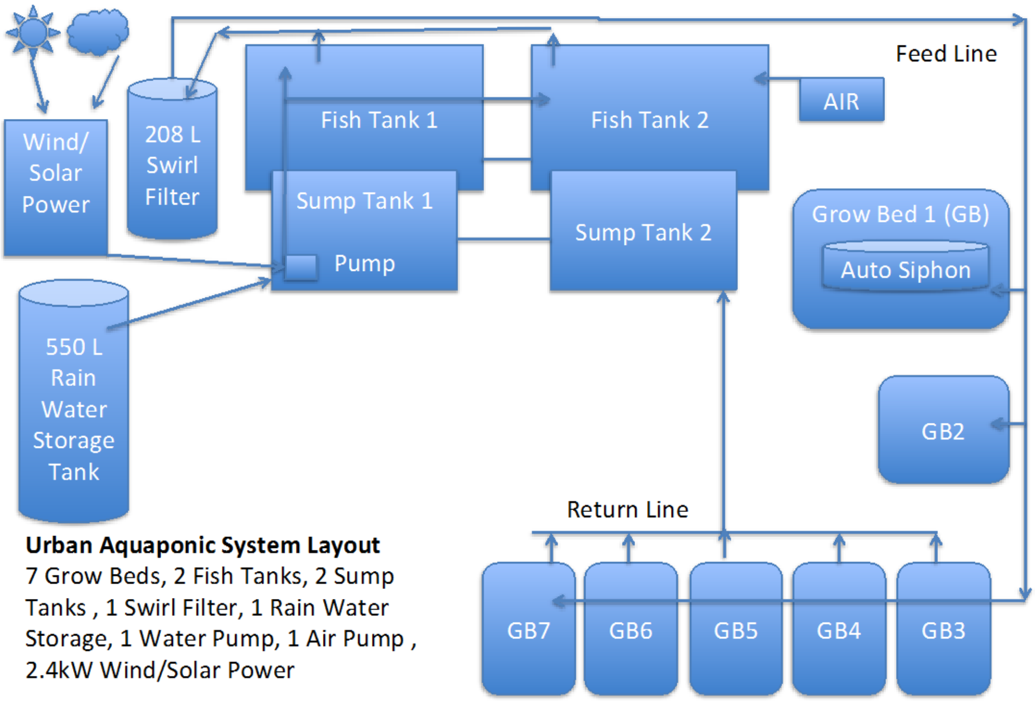

Figure 2. Configuration of Aquaponics system.

Fish tanks 1 & 2 hold 375.5 L each or a total of 751 L of water were connected together with 2" PVC fittings to allow leveling of water. Sump tanks 1 & 2 held 375.5 L each or a total of 751 L of water and were connected together with 3" PVC fittings with a cut-off valve for sump maintenance. This allowed one sump tank to be disconnected from the system while the other sump tank continued to hold water for the pump. A water pump in sump tank 1 pumped water at a rate of 2800 L/h into fish tanks 1 and 2. Water overflowed from fish tanks via a 2" PVC pipe into the 208 L swirl filter to remove heavy solids and uneaten food. When solids generated by the fish are not removed in a timely fashion, the bacteria doing the solids breakdown (mineralization) compete with the fish for oxygen in the system. Removing solids as quickly and efficiently as possible reduces total oxygen competition and allows the fish to more easily use the required amounts [3]. The swirl filter overflowed to a single 2" feed pipe that flowed to 7 connecting growbeds fitted with 1" valves for fine tuning flow rates. Growbeds were filled with hydroton clay stones as the hydroponic substrate. The media-based growbeds acted as the primary location for bio-filtration where bacterial assisted conversion of potentially toxic ammonia (NH_3) is converted to non-toxic nitrate (NO_3). Hydroton is a brand name of LECA (light expanded clay aggregate). Hydroton was chosen for maximum water absorption and ease of maintenance in addition to its tremendous surface area to support nitrification. Each growbed held 539 L; a total of 3773 L for 7 growbeds. Each growbed supported 1.54 m^2 for a total of 10.78 m^2 of surface area for plant growth. Each growbed was configured with an auto siphon device which allowed the bed to fill slowly to a certain level which was dictated by the level of the overflow pipe under the bell housing where it eventually overflowed, triggering the siphon and draining the growbed water via gravity into a single oversized 3" drain pipe which led back to Sump Tank 2. The flood and drain cycle ensured that enough oxygen was pulled into the bed to prevent anaerobic zones and facilitate mineralization. The growbed surface area will always be the area with greatest oxygen and so will perform the bulk of mineralization [3] All growbeds were configured with an auto siphon and connected to the drainpipe. Each growbed fills and drains once every 15 minutes, 4 times per hour. Water throughout the aquaponics system is homogenous. Fish tank aeration is provided by one 70 L/min air pump. One air stone in each fish tank was connected to a manifold on the air pump. Analog air temperature and humidity, digital pH and water temperature gauges were used to data log and document environmental and water parameters. During feeding, water chemistry was data logged using a test kit that tests ammonia, nitrite, nitrate, and pH. All data was logged and documented in a master logbook. Sludge was emptied from the swirl filter once a day and the wet weight of sludge recorded. During system startup, municipal city power was used. Top up water was from municipal city water and stored in a 550 L holding tank to vent off chloramines, as they are harmful to the fish and beneficial bacteria. The system then continued operating from a 2.4 kW hybrid solar and wind based renewable energy system and top up water supplied from a rain catchment funnel for further data collection to compare energy and water consumption for potential future LCA analysis work.

The inventory list of materials and original weights, and weights amortized for the 15 month life cycle of the experiment are listed below in Table 2. These materials were classified by category and characterized in terms of environmental impact contribution. Electricity consumption, water and feed weights were not included in these calculations as these are real time variables being consumed by the system. PVC was used for all plumbing connections for redirection of water. Bricks were used to elevate the growbeds. HDPE plastic was used for the swirl filter and other miscellaneous fittings and devices. Fiberglass was the construction material for the growbeds. Expanded clay was the equivalent of the Hydroton (LECA) media used inside the growbeds. Cast iron was the material makeup of nails used for the greenhouse. LLDPE was the material used for the greenhouse film. Wood was used for the greenhouse structure and support for growbeds. Tap water used for top up replenishment of system water. Copper was used in the electronic devices such as water/air pumps, meters and cords. Aluminum was the material used for housing for electronic devices and miscellaneous water capture channels. Tilapia feed was the primary feed provided to the aquaculture.

General feed guidelines and stocking densities are based on the UVI Aquaponics model of Dr. James Rakocy and media system design research of Dr. Lennard Wilson noted in his paper "Aquaponics System Design Parameters" [3]. Feeding ratios used are 60-100g fish feed / m^2 plant growing area / day. Total supported grow area is 10.7 m^2. Daily feeding rate is 642g/day (60 g × 10.7) into system at peak operational performance. Stocking densities indicate 5 kg of fish / m^2 of grow space. The calculation used for this ratio is 10.7 m^2 growing area × 5 kg fish = 53.9 kg fish; so, 53.9 kg is the maximum approximate weight of fish in the system the growing area can naturally support without introducing other mechanisms of filtration. The system was operated and maintained to rear fish stock to market size (550-920g) for harvest, and to demonstrate and quantify vegetable harvest.

It is suggested for short experiments such as this, one variety of produce be grown in a predictable cycle for ease of observation and calculation. However, because this research has not been done before in this geographical region, the author considered it perhaps more important to demonstrate what varieties of produce could be grown successfully. To provide the results of production at this scale, net harvest weights of fish and vegetables and kJ of energy per category harvested are listed in Table 3. Derived from the functional unit, mass allocation for the system after analysis indicated 10% fish (65 kg), 50% vegetable (323 kg), and 40% waste sludge (252 kg). These percentages are used to apportion total impacts to each output category. Total nutritional energy content for 15 months of harvests for each category was calculated totaling 694 kJ. It is important to note that the choice of the functional unit is crucial for comparative LCAs between different species as the edible portion and nutritional value of products can differ widely [15].

Due to experimental limitations, the fish grow out cycle was not repeated and so was considered a control volume to provide nutrients for vegetables. Extended duration, equipment and analysis are needed to observe multiple fish rearing cycles. Initial introduction of fish into the system included 140 0.3-g and 60 1-g black male Nile tilapia (*Oreochromis niloticus* sp.) donated for this experiment by Nam Sai Fish Farm of Thailand. At the end of the experiment, there were approximately 90 fish in the system with weights ranging from 550-920 g each. Total production of fish was 65 kg/m^3.

Waste Sludge Content

This system generated a total of 252 kg wet weight of bio sludge from the aquaculture operation. Approximately 0.55 kg of sludge was produced per day. Two wet sludge samples were dried, weighed, and tested for elemental nitrogen, carbon, hydrogen and sulfur at a CHNS analysis testing laboratory at the Joint Graduate School of Energy and Environment, (JGSEE) in 2012. Results of the sample test are shown in Table 4. To distinguish how much total nitrogen is available in the functional unit of 252 kg of discharged sludge to be applied as a nitrogen credit to the system, the weight of water needed to be quantified and removed from the calculation.

Table 2. Original system inventory material weights (direct measure).

Inventory Item Description	**Weight (kg)**
PVC Pipe	128
Brick	1369
HDPE	10.5
Fiberglass	114
Expanded Clay	533
Cast Iron	3.4
LLDPE Film	10
Wood Board	140
Tap Water	27352
Copper Wire	0.3
Aluminum Alloy	5.2
HDPE	0.6
Tilapia Feed	190
	Energy (kWh)
Electricity used over 15 months (Thai EGAT + MTEC)	1058

Table 3. Description of Fish, Vegetable Harvest, weight and kJ energy from each category over 15 months.

Harvest Description	**Total Weight (kg)**	**Kilo Joules Energy (kJ)**
Tilapia Fish (Oreochromis Niloticus)	65	386
Morning Glory	88	70
Chinese Kale	35	72
Gourde	32	23
Sweet Tomatoes	82	62
Holy Basil	15	14
Cabbage	37	39
Mustard Lettuce	6	7
Chinese Celery	27	18
Chili Peppers	1.5	3

Table 4. CHNS Analysis Testing – JGSEE, KMUTT – Oct – Nov 2012.

Sample Name	**Element (% dry weight)**			
	Nitrogen	**Carbon**	**Hydrogen**	**Sulfur**
Sludge Waste Oct 12, 2012	3.07	29.62	3.87	0.29
Sludge Waste Nov 26, 2012	2.85	31.04	4.38	0.34

The total dry weight of the sludge (16.38 kg) was multiplied by the percent nitrogen content (2.96) to determine that the total weight of nitrogen removed by the sludge was 0.484 kg. This output is considered a credit to the Life Cycle Impact Assessment as it may be reused in traditional soil based agriculture in place of inorganic chemical based fertilizers. According to SimaPro analysis, the nitrogen content, which was calculated above as 0.484 kg, had an equivalent impact of 2.97 kg CO_2-eq based on the a possible substitution of chemical fertilizers. This translates to 0.34 % of the global warming impact of the aquaponics system. The acidification impact was 0.02 kg SO_2-eq (0.4% acidification of the system). The fresh water eutrophication impact was 0 kg P-eq. The marine eutrophication impact was 6.1×10^{-4} kg N-eq (0.02% fresh water eutrophication of system).

Electrical Energy Used

A total of 1058.40 kWh, or 3808.8 MJ was consumed as electrical power to produce the functional unit of 65 kg Fish, 323 kg Vegetables, and 252 kg of waste sludge. The operation of an air pump (58 W), a water pump (40 W) and water pH meter (6 W) consumed 2.35 kWh per day, or 70.56 kWh per month. This translates to 1058.40 kWh per 15 month. A large proportion of the impacts of the production system is related to its energy demand which is thus considered a hotspot. Electricity consumption for the functional unit contributed 65% of the global warming impact and 23% of acidification impacts. This was likely due to the Thailand energy mix of which as of 2014, 79.9% of electrical generation is from fossil fuels, 10.4% from renewable energy, 7.6% by imported hydro power, and 2.1% by large hydro power. [16]. The use of renewable energy alternatives has great potential to change the outcome of the impact assessment.

Fish Feed

The production of fish feed was the largest contributor to eutrophication and acidification in this assessment. This was likely due to nitrogen based fertilizers used in the agri-production of the main ingredients (Table 5) such as rape seed, wheat and soy meal and the use of fishmeal from the fisheries industry. Formulated feed varies greatly by manufacturer and region and can include rice bran, wheat bran, mustard oil cake, duckweed, dried blood, poultry viscera, corn and starch and shrimp-head meal. Feeds are also supplemented with essential vitamins and amino acids. The manufacturer of the feed used in this assessment was contacted and explained the details of their formula is proprietary and thus a generic trout feed formulation was used. The starting information in this table is cited from the EcoInvent-99 and ETH-ESU-96 databases using SimaPro 7.1 software for standard trout feed of 42% protein content. The ingredients of the trout feed were adjusted to create a common tilapia feed for 32% protein. The feed used in the system caused over 90% of the fresh and marine water eutrophication, over 60% acidification and over 25% for global warming impacts.

Table 5. Percent main ingredients formula (32%) protein Tilapia feed.

Tilapia Feed 32% Protein	
Rapeseed	32
Fish meal	23
Wheat	24
Soymeal	21
Total	100

3 Results and Discussion

The primary aim of this research was to contribute to the topic of Aquaponics using the Life Cycle Assessment methodology of validating the statement of its sustainability. Establishing meaningful metrics and data capturing practices resulted in robust data collection, which allowed conclusions to be made. The results of this study showed environmental impacts associated with the operation of a small aquaponics system to be 883.93 kg CO_2-eq, 4.69 kg SO_2-eq, 0.01 kg P-eq, and 4.18 kg N-eq. A breakdown of co-product mass allocation of impacts apportioned to the functional unit is shown in Table 6. The production weights: 65 kg of fish, 323 kg of vegetables, and 252 kg of sludge, were reported to be 10%, 50%, and 40%, respectively, of the net impact categories. However it should be noted, if sludge is to be credited back to the system, it must be removed from the allocation equation. In this case, the revised formula would be 65 kg fish + 323 kg vegetables providing a total weight of 338 kg. The revised equation indicates 17 % of impacts attributed to fish (65 kg / 388 kg), and 83% to vegetables (323 kg / 388 kg). The provisions of the electricity mix in Thailand and the fish feed contributed to 65%, and 25%, respectively, for a total of 90% of the global warming impact significance, while infrastructure material impacts only contributed 10%. The feed and electricity mix categories also contributed to over 80% impact significance in regards to acidification, and over 90% to fresh water eutrophication. There is potential for further analysis as the sludge impact credit reduced the net impacts for global warming by 0.33%, acidification by 0.4% and marine eutrophication by 0.02%. Final system net impacts with these credits considered resulted in: 880.96 kg CO_2-eq, 4.67 kg SO_2-eq, 0.01 kg P-eq, and 4.18 kg N-eq (Table 7).

Regarding energy carriers, there is potential for further integration of renewable energy technology to reduce impacts. As for alternative materials use, for example, replacing fiberglass growbeds with lined wood or other structures could further reduce impacts. Advantages of aquaponics for minimizing water usage and nutrient discharge to the environment have been observed. However, there is opportunity for improvement in

Table 6: Impact Category equivalents – with co-product allocation by mass.

Impact	**Unit**	**Amount**	**65 kg Fish (10%)**	**323 kg Veg (50%)**	**252 kg Sludge (40%)**
Climate Change	kg CO_2 eq	883.93	88.39	441.96	353.58
Acidification	kg SO_2 eq	4.69	0.47	2.35	1.88
Fresh Water Eutrophication	kg P eq	0.01	0.001	0.005	0.004
Marine Eutrophication	kg N eq	4.18	0.42	2.09	1.67

Table 7. Net impact category equivalent including sludge credit to system.

Impact	**Unit**	**Amount**	**Sludge Credit**	**Net Impact Total**
Climate Change	kg CO_2 eq	883.93	2.97	**880.96**
Acidification	kg SO_2 eq	4.69	0.018	**4.67**
Fresh Water Eutrophication	kg P eq	0.01	0	**0.01**
Marine Eutrophication	kg N eq	4.18	6.14×10^{-4}	**4.18**

further decreasing acidification impacts of the feed aspect by using natural and renewable feed alternatives such as worms, and fly larva that may facilitate in closing the loop of recycling in the system even further while benefiting from efficient waste management. Reduced water use due to the recycling nature of aquaponics may also be considered to strengthen the environmental performance assessment in comparison with traditional agriculture, which is generally known to use 70% of global fresh water for irrigation [8]. Additional observations regarding stocking density suggested the calculated 53.9 kg of aquaculture loading capacity was exceeded by 11.1 kg with little consequence to system performance. The concluding stocking density was 65 kg of fish

To further compare the difference allocation models that could be applied to this study, energy content and economic pricing data for fish and vegetables are discussed briefly.

Energy Content

Analysis showed a total of 694 kJ produced from the aquaponics system as seen in Table 3. 386 kJ of fish and 308 kJ of vegetables. This allocation method indicates 55% of net impacts are attributed to fish (386 kJ / 694 kJ), and 44% to vegetables (308 kJ / 694 kJ).

Economic

Analysis discovered a total of 58,939.57 baht (1964.65 USD) worth of fish and vegetables were produced based on current market price. Net tilapia product was worth 7800.00 baht (260.00 USD) and net vegetables product was worth 51,139.57 baht (1971.31 USD). This allocation method indicates 13% of net impacts are attributed to fish (7800 baht / 58,939.57 baht) and 86% to vegetables (51,139.57 baht / 58,939.57 baht).

It is clear to see how controversial allocation modeling can be when comparing the results in (Table 8). Fish resulted in 17% mass allocation vs. 55% energy content allocation vs. 13% economic allocation. Vegetables resulted in 83% mass allocation vs 44% energy content allocation vs. 86% economic allocation.

Table 8. Comparison of allocation methods (these models assume, sludge allocation removed for credit).

	Mass Allocation	**Energy Content Allocation**	**Economic Allocation**
Tilapia Fish	17 %	55 %	13 %
Vegetables	83 %	44%	86 %

A comparison of other aquaculture systems performance (Table 9) is important in order to make further observations and suggestions for improvements for future designs, system integration and intelligent utilization of resources. The values of the aquaponic production in this study were scaled up to values equivalent to the production of 1 ton of fish to maintain proper units for comparison. Note that systems being compared used the mass allocation method for their LCA case studies. In addition, these studies used Phosphate (PO_4) equivalent as their unit for eutrophication. As a result, to do a fair comparison, the P-equivalent values of this LCA were converted to PO_4-eq. This was achieved by considering the ratio of the atomic weight of P and molecular weight of PO_4 while scaling up the results of this LCA study to compare with 1 ton of fish.

As can be seen from Table 9, the impact values in the three rows titled "Tilapia % of Mass / Energy Content / Economic Allocation" are significantly lower than the comparable systems demonstrating that the system is significantly more sustainable from the perspective of the three allocation methods as mentioned in Table 8. The global warming potential seems to be the only exception with this study. The impacts results are higher due to electrical consumption emissions. The other methods used for aquaculture comparisons such as netpen and flow through do not depend on the requirements of a recirculating system. Many factors may make this to be the case such as country energy mix, and, since this study was carried out in the tropics, there may have been additional energy use emissions associated with the RAS systems in other countries to keep water temperature consistent.

The aquaponics system, while using significantly less energy, produces comparable or less global warming burdens than other systems for the mass and economic allocation models, but more for the energy content allocation model. Energy use and eutrophication impacts are significantly lower than other systems compared, again, with the exception of eutrophication according to the energy content allocation model. As for acidification impacts, with the exception of the energy content allocation model result, the system contributes less than the average (22.9 SO_2-eq) environmental burdens compared to other systems for producing 1 metric ton of fish. Also it is worth noting the comparison is done with an assumption of linear expansion of the allocation model. The amortization of the potentials of equipment is assumed to be linear. Another consideration worth noting is that energy demands and associated impacts can change drastically based on the region of consumption primarily due to the method of the energy production mix. For example, France uses nuclear power which produces very little CO_2, and provides for cleaner generation despite its disastrously impactful radioactive waste. Canada's primary method of energy production is natural gas and fuel, and Norway produces much of their energy using hydropower plants. In this case, the region of energy production and use will affect the impact analysis. An aquaponics system is generally more sustainable in the tropics because it has a modest infrastructure burden and there are no requirements for heating. The percent of the impacts allocated to the tilapia only shows a significantly more sustainable system compared to the other systems in Table 9.

Table 9. Perspectives of 3 Allocation Models Comparison of aquaponics vs. recirculating (RAS) / flow through (FT) system performance comparisons (values shown are per ton of fish).

	GWP (kg CO_2eq)	EU (MJ)	EP (kg PO_4eq)	AP (kg SO_2eq)	Reference
Tilapia (Mass Allocation)	**13553 × 17% = 2,304**	**58597 × 17% = 9,961**	**0.45 × 17% = 0.08**	**71.8 × 17% = 12.2**	**This Study**
Tilapia (Energy Allocation)	**13553 × 55% = 7,454**	**58597 × 55% = 32,228**	**0.45 × 55% = 0.25**	**71.8 × 17% = 39.5**	**This Study**
Tilapia (Economic Allocation)	**13553 × 13% = 1,761**	**58597 × 13% = 7,618**	**0.45 × 13% = 0.06**	**71.84 × 13% = 9.34**	**This Study**
Rainbow Trout - FT	2,015	34,869	28.5	13.4	D'Orbcastel, et al 2009 [17]
Rainbow Trout -RAS	2,043	63,202	21.1	13.3	D'Orbcastel, et al 2009 [17]
Rainbow Trout - FT	2,753	78,229	65.9	19.2	Aubin et al, 2009 [18]
Seabass – Net Pen	3,601	54,656	108.9	25.3	Aubin et al, 2009 [18]
Turbot – RAS	6,017	290,986	77	48.3	Aubin et al, 2006 [18]
Atlantic Salmon –Net Pen	2,073	26,900	35.3	18	Ayer and Tyedmers, 2009 [19]

The system trial was done as a batch culture media system that removed solids. Thus feeding rates were low during stocking and ramp up and increased consistently until end of trial. The system completed the nitrification maturation cycle and nutrient levels increased as expected. It was noted as feeding rates increased to match fish growth, the loading of 642g/day feed into the system proved to add too much organic particulate into the water column which increased bio-fouling due to high temperatures in Thailand, thus feeding rates were reduced to 400g/day to control bio-fouling to a manageable level. This reduced feeding rate did not seem to impact growth of the vegetables as they were staggered and harvested at different times. Due to high temperatures, system maintenance increased as stocking density increased. Un-eaten food and fish waste not caught by the swirl filter were introduced into the growbeds and compounded the maintenance requirement. It was found that too much solid waste was still entering the growbeds, channelizing water flow, and increasing stagnation. Additionally, the system was not operated inside of a traditionally enclosed greenhouse which allowed birds into the garden, which eventually introduced worms into the growbeds. Overtime, the worms exponentially compounded the clogging of growbeds due to population reproduction and worm castings produced from consuming un-filtered waste products. When this occurred, growbed vegetable production became reduced until non-productive. In addition, due to anaerobic conditions of waste products in the growbeds, water quality parameters quickly exceeded accepted ranges of proper requirements. This caused water pH to rise as undesired denitrification occurred. Thus, growbeds needed to be cleaned regularly and organic wastes discharged as sludge.

Water loss from the system occurred from crop uptake and evaporation due to high temperatures. Logging indicated that the average water consumption was 73.15 L per day. The system may rely on rain water collection for top up purposes to increase the sustainability factor.

A well-designed recirculating aquaponics system offers a number of advantages: conservation of both land and water resources, location in areas not conducive to open pond culture or where arable land is unavailable. Operators have a great degree of control of the fish culture environment and can grow fish year-round under optimal conditions. The crops grow quickly due to optimized nutrient uptake and can be harvested at any time. However, environmental factors, system design and required maintenance should be carefully considered to optimize system performance. Design improvements such as increased sediment filtration efficiency, gravity assisted water flow and oversizing of plumbing should be considered for ease of maintenance, and maximum fish and crop productivity.

Additionally, this study established the boundary of the aquaponics system in an urban environment. It did not take into account any transportation based emissions for the output products. When comparing a consumer's purchase of grocery store fish and vegetables, there would be substantial packaging, handling, refrigeration, and transportation based emissions. An urban aquaponics model, growing local and consuming local eliminates these emissions, thus making urban aquaponics-produced products even more attractive from a sustainability perspective.

4. Conclusion

The use of the Life Cycle Assessment technique has allowed for the identification of hot-spots in the production of the Aquaponics system that may have been obscure in other methods of assessing. With this perspective, improvements to design and selection of material inputs and operation are the next step in increasing sustainability statements of this methodology. The comparison of this study with other life cycle assessments of aquaculture systems indicates less impact potentials for an aquaponics system. Depending on the method of allocation applied, the results change significantly. The additional benefit allowing aquaponics to outshine other fish production systems is that a secondary vegetable crop is produced. In consideration with the production of 1 ton of fish, the system would also produce about 5000 kg of vegetables. Traditional aquaculture systems do not have this extra production benefit as they are using mechanical filtration, and/or are releasing unused nutrient back into the environment. In contrast, aquaponics recycles nutrient and uses the vegetables as the "harvestable" filtration mechanism. This makes aquaponics food production more deserving of attention and research as it has a plethora of environmental and social implications worth considering. With improved allocation data, methods, integration of social implications and economic feasibility, the Life Cycle Assessment methodology is becoming a very valuable tool for planning, marketing, and process control for such systems, which will only enhance and promote sustainable development of food production.

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