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Review

Review and harmonization of the life cycle global warming impact of five United States aquaponics systems

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ABSTRACT

Global human population is estimated to increase by a few billion over the next century. Food security concerns has become more prevalent throughout the world. Conventional agriculture methods have been sufficient but have become increasingly unsustainable with the anticipated increase in global food demand. Alternative food production systems have been developed to mitigate the negative implications of conventional methods. Aquaponics is a food production method that utilizes a closed loop system to artificially propagate fish and plants. An aquaponics system takes the effluent water from the fish tank and cycles it to the plants to help mitigate waste streams from the system. Life cycle assessment is a tool that determines the environmental impacts of a product or process. A comparison using life cycle assessment methodologies was conducted between five United States centric aquaponics systems to determine the similarities between studies. Global warming potential was the main focus of the harmonization study due to the similarities in methods and units. When the life cycle assessments were dissected, it was found that the studies were similar and the differences were easily explained through disparities in assumptions, timescale, and operation sizes. Further work into aquaponics systems in the United States and assessing their environmental feasibility is nessecary to develop a more complete picture of any given system.

1. Introduction

Conventional agriculture utilizes chemicals, genetically modified seeds, and innovative irrigation techniques to further enhance crop yield (Boone et al., 2019; Meier et al., 2015; Pimentel, 1993; Pimentel et al., 2005; Reganold et al., 1987; USDA, 2015). This method of farming has been ideal for the growing overall population but is becoming increasingly unsustainable (Boone et al., 2019; Meier et al., 2015; Pimentel, 1993; Pimentel et al., 2005; Reganold et al., 1987; United Nations, 2019; USDA, 2015). Global populations are projected to increase by about three billion people in 2100, so it is crucial to produce food as efficiently as possible to mitigate environmental impacts over time (United Nations, 2019). Conventional farming practices are detrimental to future global food security due to the negative impacts on the local and global environment. Food security has been defined as a region's ability to provide food to its residents in a reliable manner (U.S. Department of Agriculture, n.d.). The reduction of soil quality over time, the overuse of chemicals, and water quality and quantity constraints are several unsustainable consequences and procedures that can be found in standard food production practices (Boone et al., 2019; Meier et al., 2015; Pimentel, 1993; Pimentel et al., 2005; Reganold et al., 1987; USDA, 2015). Currently, many parts of the world are struggling with the negative effects of excessive fertilizer use, also known as eutrophication (Boone et al., 2019; Meier et al., 2015; Pimentel, 1993; Pimentel et al., 2005; Reganold et al., 1987; USDA, 2015). Eutrophication gives way to the growth of algal blooms in shallow warm bodies of water, creating anoxic zones in the affected areas (Chorus and Bartram, 1999). In order to feed an increasing global population, synergistic food production alternatives must be considered.

Hydroponics (HP) is a soil-less plant food production system that utilizes methods like a nutrient pool and artificial light sources to maintain ideal growing conditions (Pattillo, 2017a). HP is a respectable food source alternative as systems can have somewhat unrestrained growth seasons and overall improved yield and growth (Pattillo, 2017a). Generally, leafy greens and herbs are grown using HP but other commonly grown edible plants have also been successful (Pattillo, 2017a). HP setups like floating rafts and nutrient films are commonly used and can be applied for many smaller plant species (Pattillo, 2017a).

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The main concern with HP as a food production source is the system's water usage and the continued use of synthetic fertilizers and pest prevention chemicals (Pattillo, 2017a). Developing a system that could mitigate chemical use and close the production loop to reduce waste and water use would further improve the food source alternative (Goddek et al., 2019; Junge and Antenen, 2020). Ensuring plant food sustainability is necessary, but it is not the only concern when considering food security.

Another critical global issue in the food industry is major disruptions in fish populations and aquatic food webs due to human interactions (i.e. overfishing and warming water temperatures) (Scheffer et al., 2005; Warfield, 2020). Aquaculture (AQ) was developed to be used as an effective alternative for the aquatic food production industry (Nelson, 2016; Pillay, 2008). AQ is the artificial propagation of aquatic species that can utilize intensive or extensive methods (Pillay, 2008). These alternative production methods have allowed for a reduction in wild population disturbance while also decreasing harvesting time and effort (Henriksson et al., 2012; Pattillo, 2017b; Pillay, 2008). Propagated fish can be used as a food source, restocking wild populations, and providing ornamental species for aquariums. Commonly farmed fish include multiple species of tilapia and catfish and are mostly used as a food source (OECD and FAO, 2020). Conversely, fish feed used in aquaculture is often made from forage fish and the water removed from AQ tanks has an excess of nitrogen, nitrite, and solids (Nelson, 2016). The separate systems (HP and AQ) have been examined and developments were made to combine the systems to further improve efficiency and quality.

Aquaponics is a closed-loop food production system that combines AQ and HP to create a more effective source of food than other methods (Goddek et al., 2019; United Nations, 2019; Wu et al., 2019). Fig. 1 gives a visualization of a simplified aquaponics system (APS). Setups can deviate from the presented figure to better suit a particular plant species or budget while still saving water and reducing fertilizer use when compared to conventional agriculture (Goddek et al., 2019; Junge et al., 2020). As shown, water from the AQ tank is sent to be filtered, treated, and then pumped to the growing beds in the HP section to hydrate and fertilize the plants (Nelson, 2016). This symbiotic relationship makes aquaponics a promising sustainable food production system as it allows for a reduction in land use and eutrophication potential, due to more compact setups and decreases or complete mitigation of chemical use (Goddek et al., 2019; Nelson, 2016). Aquaponics has become increasingly popular across the United States (US) with system sizes varying from research to commercial scale (Boxman et al., 2017; Chen et al., 2020; Ghamkhar et al., 2019; Hollmann, 2013; Kalvakaalva, 2020). Aquaponics is not currently a prevalent food production system, especially in the US, so it is imperative to analyze the feasibility of any given system to work towards lowering overall environmental impacts.

Life cycle impact assessments (LCIAs) are the calculations of different environmental impact categories relative to a system's functional unit (FU) (Matthews et al., 2014). The FU of a life cycle assessment (LCA) is a quantitative product which can be mass, volume, or economic based that is defined by the function of the evaluated system (Matthews et al., 2014). Using LCIA can help draw comparisons between APSs and other food production methods to determine which method is less environmentally impactful. Utilizing life cycle assessment (LCA) to pinpoint environmental hotspots is essential when considering more sustainable practices, especially for the food industry (Matthews et al., 2014). Examples of impact categories that can be assessed by LCAs are global warming potential (GWP), eutrophication potential (EP), energy use (EU), and others (Bare, 2012). The different categories allow for evaluation of all components in a system that would negatively affect the environment in different ways. Resulting impacts from the evaluated system allows for adjustments, which can reduce overall environmental impacts (Matthews et al., 2014). Assessing the environmental impact of a newer technology is vital when determining if the new methods are better than their predecessors. Ascertaining the environmental impacts on an APS is not new but relating impact assessments to each other is necessary to continue improving the emerging technology.

When initially reviewing the LCA results of different US centric APSs, the environmental impacts seem to be dramatically different. The aim of the study was to investigate any trends in aquaponics' LCAs once the results of the studied systems were harmonized. Once harmonized, the reviewed systems were assessed further to determine if the LCAs were truly different. The harmonization method of US APSs was utilized to ascertain if the assumptions, system boundaries, climate, and system setup of the evaluated LCAs have an effect on the environmental impacts calculated. The study focused on the GWP of each system as all assessment methods use similar ideas when calculating this category. Eutrophication mitigation is a major driver for the investigation of aquaponics but was not a focus in the study as all systems mitigate much of the EP for a food production method (Boxman et al., 2017; Chen et al., 2020; Ghamkhar et al., 2019). Firstly, the examined LCAs were laid out to help with understanding and interpreting the results of the study.

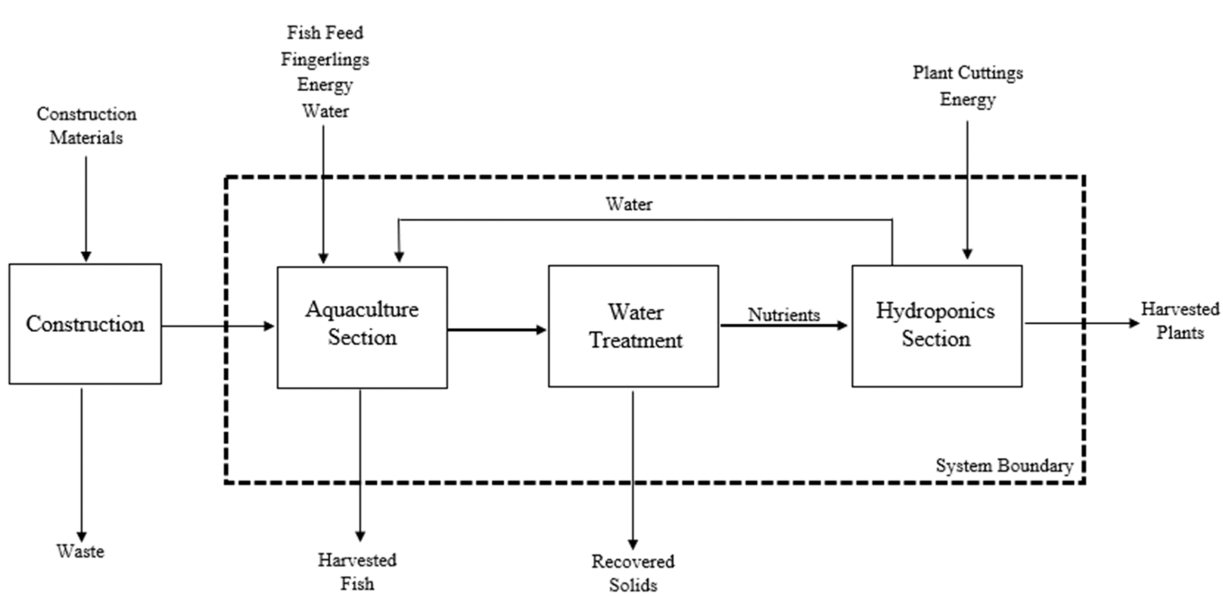

Fig. 1. Generalized aquaponics system.

2. Materials and methods

The evaluation focused on the most important inputs of any given APS and compared each system's global warming impact in order to determine if there were similarities amongst LCAs. Once the results were assessed, further analysis was conducted to better understand the implications of the variables and constraints of the studied systems' environmental impacts. GWP was chosen as the focus of the paper due to consistency in units and methods (Bare, 2012). Seven aquaponics LCA papers were collected and reviewed to determine if they could be reasonably compared.

2.1. Paper selection

The evaluation examined NA aquaponics LCAs to better understand the similarities and differences amongst systems, assumptions, and system boundaries. The main justification for analyzing systems solely from the US was few comparisons have been made in the region, particularly in cold climates, however the LCA papers which exist seem to provide disparate results and conclusions. Five reviewed papers were selected as they contained adequate information to harmonize and compare the assessments. The most important information needed for the harmonization analysis is the system boundary, a well-defined FU, assumptions, and standard midpoint environmental impact categories. Kalvakaalva (2020), Chen et al. (2020), Ghamkhar et al. (2019), Boxman et al. (2017) and Hollmann (2013) all conducted LCAs for their respective APSs with varying parameters like operation size, fish and plant species, system configuration, and FUs. Two other associated studies were excluded from this review for varying reasons.

Additional US papers could not be analyzed in the harmonizing study. The paper by Cohen et al. (2018) analyzed an LCA in Atlanta, Georgia on a research-scale APS. The authors compared the APS to conventional agriculture and aquaculture systems to determine if aquaponics is a more sustainable food production system than other production methods (Cohen et al., 2018). The paper by Cohen et al. (2018) could not be included in this assessment as they only calculated endpoint environmental impacts with units of Disability Adjusted Life-Years (DALYs). Endpoint impacts are an important aspect of LCAs, but their results were unable to be included in this midpoint LCA study. Xie and Rosentrater (2015) also performed an LCA on a research-scale APS in Ames, Iowa. The authors had two main goals in the paper, determine the feasibility of the system in terms of the environment and profitability (Xie and Rosentrater, 2015). Xie and Rosentrater (2015) chose a FU of one kilogram of fish and one kilogram of plants to encompass both outputs of any given APS. Based on tables and graphs in the paper, the FU could be converted to just one kilogram of liveweight (LW) fish, but the issue arises when calculating GWP relative to the harmonized FU as the authors gave emissions for CO_2, CH_4, and NO_x. N_2O was needed to determine carbon dioxide equivalence and it was unknown as to how much of the N_2O took up the NO_x value, which includes NO, NO_2, and N_2O (US EPA, 2016, 2015a,b; Xie and Rosentrater, 2015). To be able to harmonize the studied LCAs, some assumptions were made to create a clear comparison.

2.2. Review assumptions

Assumptions were required when harmonizing the studied LCAs. Some authors excluded information needed to maintain clarity throughout harmonizing the studies. Chen et al. (2020) and Hollmann (2013) do not specify whether the mass evaluated was wet (live) or dry weight, so the assumption made was the mass evaluated was live weight (LW). For Kalvakaalva (2020), dry weight was used in their FU, so the assumption was made by the author that the fish moisture content was about 75%. The final assumption was made for the study by Ghamkhar et al. (2019) that a four-ounce walleye fillet requires 567 g of LW fish (Summerfelt, 1996).

2.3. LCIA assumptions

Assumptions are imperative to running a feasible LCA. Without suitable assumptions, a solid system boundary and well defined inputs and outputs would not be possible. Analysis for each choice in the author's LCAs is important to understand each system's boundary and what parameters were included and excluded in their evaluations. Boxman et al. (2017) included the related avoided burdens in their LCIA to provide a more complete analysis of their APS. The system produced recovered solids rich with nitrogen and phosphorous, which mitigated the use of synthetic fertilizers and the related environmental impacts were also mitigated (Boxman et al., 2017). Plant production in the APS was considered to be another avoided burden since the propagated plants were not considered to be the main product (Boxman et al., 2017). Water filtration from the plants instead of artificial filtration is another reduction in impacts from the author's system (Boxman et al., 2017). Boxman et al. (2017) sums all reductions in their system and subtracts it from the overall impact of the evaluated system. Hollmann (2013) acknowledged the system's use of synthetic fertilizer, but the exact ingredients varied and were not recorded so the author assumed zero external fertilizer use. The author's system also includes two different species of fish, hybrid striped bass (HSB) and tilapia, but they do not differentiate their individual impacts (Hollmann, 2013). Similarly, Hollmann's (2013) system grew 60 different species of plants but the author did not calculate individual species impact. The reviewed studies' parameters were laid out for the harmonization comparison to allow for clear discussions and conclusions.

2.4. System parameters

Understanding the differences in the reviewed systems' parameters is essential to better understand important differences in LCA results. Table 1 presents a summary of the key parameters, including the fish and plant species, aquafeed types, and fish tank density for the studied systems. The main takeaway from the table is the major differences in the aquafeed's protein content and the fish tank densities.

3. Results

Table 2 summarizes the key points of all the systems evaluated in this paper. The table gives baseline information such as system location, operation size, and the original FUs. As shown in the table, the climates and FUs vary greatly amongst most of the evaluated studies, causing differences in electricity and heating inputs. The numerical values are the original and harmonized GWPs for each paper, showing little

Table 1
Summary of reviewed systems' parameters.

Source	Fish Species	Aquafeed	Tank Density	Plant Species	HP Setup Type
Kalvakaalva (2020)	Tilapia	38% protein soy-based feed	Not Specified	Cucumber	Media beds
Chen et al. (2020)	Nile Tilapia	AquaMax Sport Fish 500 (41% protein)	18.3 kg/m^3	Lettuce & cilantro	Floating rafts
Ghamkhar et al. (2019)	Hybrid Walleye	55% protein feed	66, 132, 198 fish/m^3	Leafy greens	Floating rafts
Boxman et al. (2017)	Nile Tilapia	32% protein feed	154 fish/m^3	Basil	Floating rafts
Hollmann (2013)	Nile tilapia & Hybrid Striped Bass	32% protein feed	18 kg/m^3	Lettuce	NFT, DWC, & media beds

Table 2
United States aquaponic system life cycle assessment summary.

Source	System Location	Assessment Method	Operation Size	Climate	Original Functional Unit (OFU)	GWP (kg CO_2 e/OFU)	GWP (kg CO_2 e/kg fish)
Kalvakaalva (2020)	Auburn, AL	ReCiPe 2016	Large Pilot scale	Humid subtropical	1 kg dry weight	77.2	19.3
Chen et al. (2020)	West Lafayette, IN	CML-IA v3.05	Commercial scale	Humid continental	$1 US of products produced by each system	20.8	369.7
Ghamkhar et al. (2019)	Madison, WI	TRACI 2.1	Research scale	Humid continental	1 kg fish fillet	145.7	29.1
Boxman et al. (2017)	Golden Grove, USVI	CML-IA	Commercial scale	Tropical	1-ton live weight	8640.0	8.6
Hollmann (2013)	Denver, CO	ILCD	Commercial scale	Semiarid	1 kg fish	8.5	8.5

correlation. Boxman et al. (2017) shows the largest GWP with their original FU, but when the value is converted the impact falls closer in line with the others. Chen et al. (2020) had a small initial value for the GWP of their system, but the conversion showed that their study had the greatest impact when harmonized and compared to the other systems. Ghamkhar et al. (2019) reported the second highest overall GWP with Kalvakaalva (2020) reporting a slightly decreased potential, making their GWP third highest. After the initial harmonization calculations were complete, the inputs were separated and the GWP of each was assessed.

Once initial conversions were finalized, the harmonized values were separated into aquafeed, electricity, and heat, since they were the main contributors to GWP in APSs, as found by prior studies (Boxman et al., 2017; Ghamkhar et al., 2019; Ghamkhar and Hicks, 2020). Aquafeed and electricity were the first two choices when breaking down the potentials of the inputs since all APSs require a feed source for the fish and electricity for the pumps and aeration systems (Goddek et al., 2019). GWP of heat was chosen third due to ease in measurement and applicability for most systems. Other inputs, such as capital equipment and chemicals, were evaluated in most of the studied papers, but their overall impact relative to feed, electricity, and heat was minor (Boxman et al., 2017; Chen et al., 2020; Ghamkhar et al., 2019; Hollmann, 2013; Kalvakaalva, 2020). Breaking down the individual inputs to compare the papers was important since they varied amongst the studies.

Fig. 2 shows each studies' GWP for fish feed, an input required for all APSs. The GWP of aquafeed compared to heat and electricity in an APS is relatively low but as stated previously, is an important input to continue to study. Fig. 3 shows how similar the GWPs are when harmonized and divided. The average GWP of the studies for aquafeed is 2.60 kg CO_2 e/kg LW fish, revealing that they all have the same order of magnitude. Hollmann's (2013) evaluated system used a low energy aquafeed,

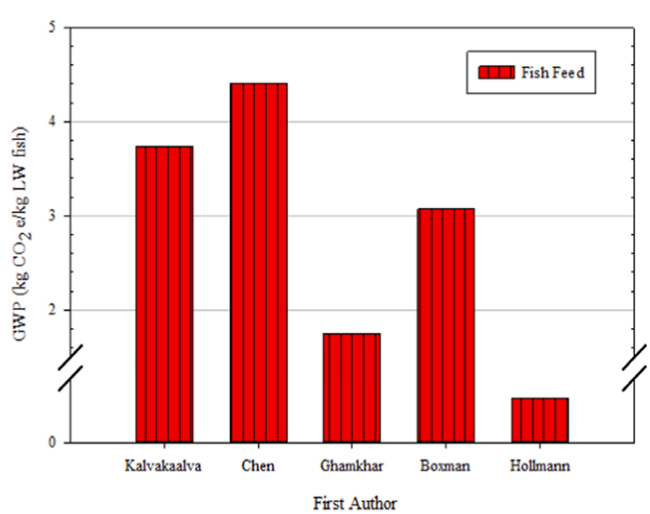

Fig. 2. GWP of fish feed for one kilogram of liveweight fish.

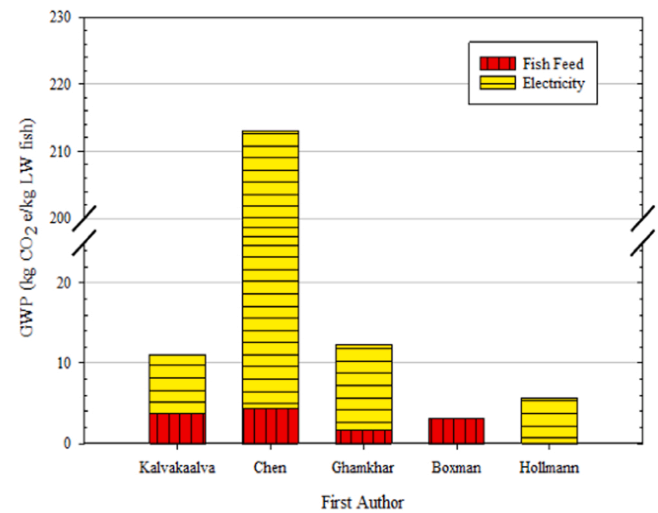

Fig. 3. GWP of fish feed and electricity for one kilogram liveweight fish.

minimalizing protein, thus reducing the feed's overall environmental impact relative to other feeds. Ghamkhar et al. (2019) chose a high protein feed as walleye are a carnivorous cold weather fish that require a higher protein diet. Kalvakaalva (2020), Chen et al. (2020) and Boxman et al. (2017) provided the feed conversion ratio (FCR) for their respective fishes to ensure adequate nutrient transfers. Kalvakaalva (2020) gave a ratio of 1.6 for their feed and fish, Chen et al. (2020) had a ratio of 1.2, requiring a small increase in feed volume, and Boxman et al. (2017) gave a ranged ratio of 1.3–1.9. Fig. 2 shows a similar relationship to the related FCRs. The following graph adds the second most important input to the system's GWP calculations to further compare the systems.

Fig. 3 combines electricity and fish feed into the bounds of the results for GWP. The figure shows a large increase in GWP for Chen et al. (2020) when electricity is added. Unlike the other studies, Chen et al. (2020) chose to evaluate their system over a one-month time period (Feb. 25 – March 25), requiring increased electricity usage, specifically lighting. The system studied by Chen et al. (2020) was in a humid subtropical climate meaning the winter months require significantly more artificial lighting to ensure proper conditions for the plants (Beck et al., 2018). Boxman et al. (2017) reported minor electricity usage since the evaluated system was operated outside in a tropical climate, giving an insignificant GWP impact from the input.

The proceeding figure adds in the heating for the APSs. Similar to Fig. 3, the fourth figure shows a large difference in heating impact between Chen et al. (2020) and the other papers due to the author's limited study duration. Boxman et al. (2017) had no impact from heating since the system was conducted outdoors in a tropical climate. Ghamkhar et al. (2019) studied a setup in a humid continental climate, requiring more heating and lighting in the winter months. Kalvakaalva (2020) and Hollmann (2013) reported relatively small heating impacts since their systems were run in semiarid and humid subtropical climates, respectively. Fig. 4 shows how critical climate is as a consideration when comparing LCAs for APSs. The final takeaway from Figs. 3 and 4 was the importance of understanding the implications of choosing suitable timescales for an LCA since the time of year for most climates will affect the impacts of an APS. Most aquaponics' operations are run during the entire year so it is critical to evaluate the time scale of a year for the given systems.

The three preceding figures show similarities amongst North American APSs once the impacts are broken down into the contributing components. Figs. 3 and 4 show a significant difference in the results from Chen et al. (2020) relative to the others, but their timescale was set to be a one month period that took place late winter/early spring, increasing the need for heat and electricity. Ghamkhar et al. (2019) and Kalvakaalva were the next highest in terms of electricity and heat usage. Ghamkhar et al. (2019) evaluated a system in a humid continental climate, so the need for increased energy usage is expected (Ghamkhar et al., 2020). Kalvakaalva also found that propane usage was higher in the winter, combined with lower fish and plant yields during the season (Kalvakaalva, 2020). Both considerations caused the author's GWP to increase relative to the others (Kalvakaalva, 2020). Another variable to consider is the operation size of the systems and how the results compare. Kalvakaalva (2020), Boxman et al. (2017) and Hollmann (2013) studied large scale operations, resulting in lower overall impacts per kilogram of LW fish. Ghamkhar et al. (2019) evaluated a research scale operation, so the efficiency relative to one kg of fish is inherently lower. This phenomenon is known as economies of scale. Economies of scale is the idea that a product becomes less costly as the scale of operation increases. The results of the harmonization study were compared and analyzed based on their inputs, constraints, parameters, and scale of operation.

4. Discussion

Once the studies are harmonized (FU of one kg LW fish), the inputs were then dissected into the GWP category and evaluated. The study showed similarities in GWP impacts and the differences can be explained through considerations like timescale. The GWPs were then related to plant and fish species, operation size, system location, and more. As discussed previously, there are quite a few differences in the studied systems. The first consideration is the aquatic and plant species chosen to be grown in their APS.

Most of the considered systems grew Nile tilapia so differentiation with respect to that was limited (Boxman et al., 2017; Chen et al., 2020; Hollmann, 2013; Kalvakaalva, 2020). Ghamkhar et al. (2019) chose a local species, likely giving reduced environmental impacts in their climate when compared to a warmer water fish like the tilapia. Utilizing what the study found, choosing an aquatic species that suits the local climate is ideal for reducing environmental impacts. Plant products are the other output of any given APS and can vary greatly. Kalvakaalva (2020) evaluated a system that grew cucumbers, a very different species than the others therefore requiring a different HP setup. As discussed previously, the rest of the authors assessed systems with leafy plants so little differentiation could be made between them and Kalvakaalva (2020) (Boxman et al., 2017; Chen et al., 2020; Ghamkhar et al., 2019; Hollmann, 2013). Based on the findings, plant species does not have a major influence on reducing GWP for any given system. The second parameter to be considered is the operation size and how it changes the impacts relative to the FU.

Boxman et al. (2017) and Hollmann (2013) studied commercial APSs and all three preceding figures show that both authors reported minimal impacts relative to the other authors. Kalvakaalva (2020) evaluated a large pilot scale system, implying a middle ground environmental impact relative to the other systems. Chen et al. (2020) and Ghamkhar et al. (2019) studied research scale systems, giving the worst efficiency in terms of operation size, which correlates with this study's findings. System location and local climate are other important considerations for APSs and their environmental impacts.

Climate is another major consideration when evaluating LCAs for APSs. Boxman et al. (2017) studied a system in a tropical climate, mitigating any heating and lighting that system would need elsewhere, thus reducing overall impacts. Chen et al. (2020) is the other extreme in terms of impacts, but that was due to the limited timescale, time of year, and geographic location when the data was collected. Though the study reviews only five aquaponics LCAs, much can be learned from the evaluation and comparison. Boxman et al. (2017) and Kalvakaalva (2020) gave results that suggest an APS in a warmer climate for warm water fish will require less energy, thus reducing overall environmental impacts. Kalvakaalva (2020), Boxman et al. (2017) and Hollmann's (2013) studies showed that a larger operation size will reduce impacts per kilogram of fish produced (Boxman et al., 2017; Hollmann, 2013; Kalvakaalva, 2020).

Harmonizing the reviewed studies was an important initial step when comparing LCAs. If the FUs and system boundaries were different then no reasonable conclusion could have been made due to vastly different results. Moving forward, several key takeaways from the harmonizing the studies can be considered. If the operator of an APS can choose the location and fish species, a tropical climate and a warm weather fish are ideal parameters to help reduce overall environmental impacts of any given system (Boxman et al., 2017; Ghamkhar et al., 2019). Another important takeaway is the operation size of an APS and its implications on environmental impact. Economies of scale ideas can be applied to APSs, meaning that the larger the scale of operation, the lower the overall unit cost will be of a single product produced by the system. The second key learning experience from harmonizing the LCAs is understanding the importance of a sufficient timescale for data collection since seasons and climate can greatly affect an LCA with a small timescale. To continue improving the environmental feasibility of aquaponics, more investigation into water use, aquafeed alternatives, and energy sources are necessary.

Further investigation into aquaponics is necessary to continue to improve the sustainability of the food production alternative. Evaluating water usage relative to all impact categories is a key step in getting a more complete idea of the overall impacts since water is an important input in aquaponics. LCIA methods such as TRACI, do not currently consider water use or dependence in assessed systems, requiring authors to use their own methods if they chose to analyze the resource at all. Water efficiency relative to conventional methods is one of the main reasons for using aquaponics as an agricultural technology (Goddek et al., 2019). Studies have suggested that aquaponics uses about 10% of

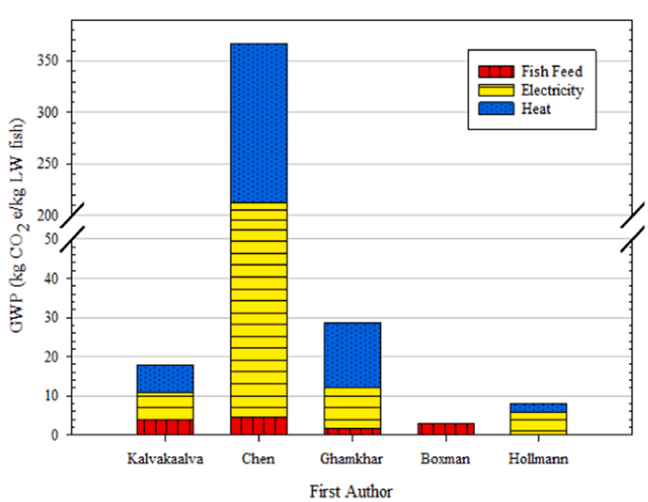

Fig. 4. GWP of fish feed, electricity, and heating for one kilogram of live-weight fish.

the water compared to conventional farming methods (Bernstein, 2011). Water is a key component to APSs, it creates the aquatic environment and carries nutrients to and hydrates the plants (Goddek et al., 2019). Observing and evaluating water use and dependence in any given system is important to fully understand the overall environmental impact of it. Water use is defined as the usage of the resource for a particular purpose (US Geological Survey, n.d.). Water dependence is the use of a water source that is not close to the system using the water (Law Insider, n.d.). Defining different water terms is important when understanding what is considered when an author evaluates a system that is this heavily dependent on the resource. With the two terms defined, additional understanding of the crucial resource in an APS can be observed and compared.

Three authors chose to evaluate different water impacts (i.e. water usage, dependence, and depletion) in their LCAs, making it difficult to reasonably compare (Boxman et al., 2017; Hollmann, 2013; Kalvakaalva, 2020). Kalvakaalva (2020), Boxman et al. (2017) and Hollmann (2013) study water in their APSs, but they are defined differently, emphasizing the significance of creating a well-defined water impact category. Boxman et al. (2017) compares their system's water usages to other livestock products. The author utilized water usage relative to each product's nutritional value (L/kCal) and found that overall average fish production uses much less water when compared to other products (Boxman et al., 2017). Hollmann (2013) determined the GWP of their system's water use and found that the impact relative to the other inputs was minimal (2% of the overall GWP). Kalvakaalva (2020) defined water depletion in their system but does not define overall water use so no comparisons could be made. As stated previously, reporting water use for APSs when conducting LCAs would allow for a more complete idea of the environmental impacts. Defining water use amongst systems would also allow operators to learn and adjust their systems to further reduce use of the resource. Results can be understood on an even broader level to make further conclusions about key outcomes of the harmonizing study. Aquafeed is an input in aquaponics that has a relatively high GWP and overall negative environmental implication so investigation into alternatives is needed for further improvement.

Decreasing the environmental impacts of the aquafeed in an APS is another crucial step for the industry. Currently, most fish feeds contain fish oil and meal, both stemming from forage fish (Tacon and Metian, 2008). Working to reduce the need for forage fish is imperative to lessen overfishing impacts. Ghamkhar and Hicks (2020) conducted another LCA on different aquafeed options including standard feeds with varying protein percentages, fish meal free, fish oil free, and fish meal and oil free feeds. The authors found that the replacement of fish meal with options such as soybean meal and blood meal could help reduce emission and resource-based impact categories (Ghamkhar and Hicks, 2020). Fish oil alternatives alone were not ideal choices in terms of reducing environmental impacts due to energy use staying relatively the same when compared to traditional feeds. Ghamkhar and Hicks (2020) recommended further work to reduce energy use or find other feed alternatives to more effectively reduce impacts . Conducting an LCA on insects for fish feed is a possible next step to determine the feasibility for a potentially better alternative. Investigation into insects for fish feed is a promising replacement to traditional aquafeeds. Several insects seem to be a good potential substitute as the impacts environmentally and economically are low relative to the other options (Cadinu et al., 2020; Halloran et al., 2016; Niyonsaba et al., 2021; van Huis, 2013). Insects such as *Hermetia illucens* (black soldier flies) have been investigated as a promising source of food for humans and many animals (Bosch et al., 2019; Park, 2016). The flies take about three weeks to reach adulthood, they can be fed a variety of foods, and they are high in protein and fat, making them a viable alternative food source for fish (Bosch et al., 2019; Park, 2016). Utilizing traditional aquafeeds has been a major concern in the aquaculture industry, but electricity is another major input for an APS, so further inquiry is necessary.

Renewable energy sources for aquaponics is another recommendation that needs further investigation to determine the sustainability in aquaponics. Prior work into the topic has shown that energy use is a major environmental hotspot through LCA (Boxman et al., 2017; Chen et al., 2020; Ghamkhar et al., 2019; Hollmann, 2013; Kalvakaalva, 2020). Boxman et al. (2017) evaluated three options for energy sources to determine if renewable energy is a more sustainable option. The authors found that a renewable energy grid would significantly reduce energy use by about half compared to the normal U.S. Virgin Island electricity mix. For the other impact categories, the reductions were minor (Boxman et al., 2017). Renewable energy efficiency and economic viability have continued to increase in the last decade (Balali et al., 2017). Building systems with solar panels or connection to a renewable energy grid could greatly reduce the impact of high energy dependent systems. The main concern with technologies like solar panels and windmills is their end of life (Chowdhury et al., 2020). At this point, there are no sustainable technologies that will recycle or upcycle the parts of renewable technologies (Chowdhury et al., 2020). More work into accessibility and the reduction of end of life impacts for renewable energy is the next step to reducing environmental impacts from APS.

5. Conclusion

Aquaculture has been a part of the global food industry for centuries (Nelson, 2016). Technology has advanced from nets in rivers and lakes to creating systems that are combined with rice paddies to develop a symbiotic relationship (Frohlich et al., 2013; Henriksson et al., 2012; Pattillo, 2017b). The negative impacts of other food production systems was reason enough to create aquaponics to help mitigate the HP and AQ effects, but continued inquiry is required to further reduce environmental impacts (Pattillo, 2017a,b). Before conducting the harmonization study, the LCA results of the reviewed papers seemed to disagree. Once harmonized, the results were compared and showed that the results were quite similar and impacts varied due to climate and timescale differences. The data gives explicit evidence that an LCA for a given APS can be related to others to better understand the efficiency and efficacy of all the systems. Further, the conclusion can be made that APSs are not quite so different environmentally, though methods and other considerations make LCA results seem to contrast on the surface. APSs have many different considerations such as operation size, fish and plant species, and climate that dictate how environmentally friendly any system can be. Continuing to investigate better aquaponics' practices such as choosing alternative aquafeeds and optimizing maturation and fertility cycles of the fish will go on to improve the systems (Cai et al., 2019; Ghamkhar and Hicks, 2020; Pankhurst and King, 2010; Taranger et al., 2010).

CRediT authorship contribution statement

MB and AH are both authors of this work. MB initiated the research and wrote the manuscript. AH originated the idea and revised the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

Both authors contributed to the paper. AH and MB collected potential papers to be used, MB conducted the literature review and wrote the paper, and AH reviewed the paper and gave feedback.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.aquaeng.2021.102224.

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