

# **Environmental Impacts of Closed Loop Food Production: Aquaponics as a Case Study**

By

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**Dedication**

I dedicate this thesis to my mom and dad.

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## **Abstract**

### **Environmental Impacts of Closed Loop Food Production: Aquaponics as a Case Study**

**Marissa Breitenstein**

Under the supervision of Dr. Andrea Hicks, associate professor of civil and environmental engineering at the University of Wisconsin-Madison

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The aquaculture industry is a prosperous means of producing aquatic species and had the goal of bridging the consumer demand gap as the fisheries harvesting wild-caught species have not seen major increases in yields for decades. While aquaculture is a productive way for species of interest to be propagated, the methodology is detrimental to the environment in several ways. The effluent water produced when cycling water out the system, is a nutrient dense substance that is considered a waste stream as well as the emissions produced during raw materials acquisition and operation and the use of fish meal and oil which is produced to using small, wild-caught prey fish are all causes for concern regarding aquaculture. Given the ever-increasing global population, the projected increases in demand for aquatic species, the limited space for propagation, and pitfalls of aquaculture, a more sustainable propagation method is vital in the effort to increase circularity in the Anthropocene.

Aquaponics is largely an untapped propagation method in the United States but has been gaining traction to address the aforementioned considerations. Aquaponics aims to utilize the symbiotic relationship of fish and plants, employing the process of nitrification to enable the plants to efficiently absorb nitrogen and act as a filter for the recirculating water. Since aquaponics is a relatively young industry in the United States, analysis of the food production method is vital in determining its environmental impact of it when compared to its predecessors. The purpose of the investigation is to (1) quantify the environmental impacts of a promising alternative to conventional fishmeal (2) design an educational tool to aid in the exploration of systems thinking and sustainable food production for users, which utilizes aquaponics as a case study, and (3) assess methods for improving business viability from the producer and consumer perspectives. These points were studied through the quantification of several aspects of aquaponics, with a focus on cold-climate systems in this dissertation.

In the first study (Chapter 2), literature review, five aquaponics life cycle assessment studies were reviewed for the purpose of harmonizing global warming potential to determine if and why these studies reported differing impacts. Global warming potential was of particular interest given the units remain the same amongst most life cycle impact assessment methodologies. Other impact categories were not harmonized due to differences in impact calculations and units and currently, no literature exists to reconcile

these issues; however, through the harmonization of the global warming potential category, it is suggested that the other impact categories would also show comparable results to the investigated category. The analysis reported a few differences amongst the harmonized values, which were due to variances in time scales or location and climate of the system, though overall the results were largely similar. For optimal comparisons amongst aquaponics life cycle assessments, it is highly recommended that standards are created regarding a life cycle impact assessment methodology or methods to harmonize other categories, given comparison is a major part of life cycle assessment.

In the second study (Chapter 3), a comparative life cycle assessment was conducted on three types of insect-based meals with the goal of potentially replacing conventional fishmeal given this product is derived from wild, prey fish populations. Insects are of particular interest given their short life cycles, ability to efficiently convert biowaste to biomass, and their high protein content. Black soldier fly larvae, cricket, and darkling beetle larvae (i.e., mealworm) propagated in a theoretical cold climate operation were chosen to be assessed in this investigation. Biotic resource use was an additional impact category included in the assessment due to conventional fishmeal's high reliance on a decreasing biotic population, so a viable alternative must not rely so heavily on an already constrained biotic resource or greatly reduce biotic resource use in general. A few assessments were included in the study for several reasons. First, two functional units (i.e., one tonne of meal and one tonne of protein content) were explored to make the results useful for aquaponics producers and feed producers. Second, a conservative assessment, meaning all environmental burdens were given to the inputs utilized to produce the functional units and an allocated assessment, meaning the environmental burden was allocated to all products produced when producing the inputs used to make the functional units were also conducted for the purpose of determining the worst case scenario for the theoretical operation as well as exploring the benefits of utilizing agricultural by-products in this context. The results were then compared to conventional fishmeal and other promising alternatives to see how viable this meal type is. The results indicate that the meals have similar environmental impacts, with the cricket meal being the most impactful in majority of the categories investigated. The results of the assessments illustrate the promise of insect meal, however, in cold climates, optimizing efficiencies is imperative to reduce overall environmental effects. Relative to conventional fishmeal, insect-based meals have greater environmental impacts when considering common environmental impact categories, though significantly less impact in their use of biotic resources. In its totality, this work aims to address various sustainability considerations of aquaponics with a focus on education, business viability, and fishmeal alternatives.

In the third study (Chapter 4), an aquaponics agent-based model was designed and deployed to aid in educating on the topics of sustainable food production and systems thinking. Education on sustainable food production is a vital part of the success methodologies such as aquaponics to spread awareness of the technology itself, thus

increasing the consumer population and producing future researchers to continue the work in sustainable food production. Systems thinking is an equally important topic to introduce and explore with the population given the prevalence of systems in the Anthropocene as well as in the natural environment. The aquaponics agent-based model offers a top-view of a generalized aquaponics system where the user can adjust fish and plant types, number of fish and plants, climate, and season. The model also explores a simplified impact assessment of global warming potential, where the heating, electricity, and feed are the only parameters considered given they are generally the most impactful inputs in an aquaponics system. By including global warming potential educators can use the model as an introduction to environmental impact and where these impacts come from using a systems perspective. Through testing the aquaponics agent-based model, it was found that the stochasticity of the results is within a reasonable range when compared to the literature, even with differing parameter selections. The results also imitated real operations in terms of the necessity of balancing the fish and plant densities as well as selecting optimal fish and plant types in a given climate when considering global warming potential. The next steps for the model would be to deploy it to classrooms and conduct a comparative study of conventional lesson plans versus lesson plans which include the model and how and what sort of insights were gained during each session for a variety of age groups.

In the fourth study (Chapter 5), a mailed paper survey was designed and deployed to Wisconsin, Michigan, and Minnesota-based aquaculture and aquaponics producers to investigate general operational parameters as well as their interest in value-added and value-recovered products. Value-added and value-recovered products are simpler options for increasing the value of products without high capital investments. The survey was particularly interested in how much producers would be willing to invest in these endeavors and how much more value each product needs to have for them to explore these kinds of products. The results of the survey showed a high diversity in the kinds of fish farmed in respondents' operations, the purpose of their operation, and their product distribution decisions. Less than half of the respondents were interested in value-added and value-recovered products for several different reasons. The results show that, in this region, most producers will likely never invest in value-added and value-recovered products unless incentives or other mitigating circumstances made the endeavor easier.

In the final study (Chapter 6), an online survey was designed and deployed to United States consumers to assess their general food habits and preferences along with their interest in aquaponics products and their willingness to pay for value-added and value-recovered products produced using aquaponics. The survey explored topics related to where the respondents typically purchase their food, what considerations are most important to them when purchasing food, their preferences regarding fruits and vegetables and high-protein sources, and their purchasing of convenience foods (i.e., main type of value-added foods). The end of the survey offers several types of aquaponics value-added

and value-recovered aquaponics products to determine which have the most interest and then explores specific products to assess how much more or less the respondents would be willing to pay for these products produced using aquaponics when compared to conventional products. The results of the deployment show a budding interest in aquaponics and its products and a willingness to pay slightly more for value-added and value-recovered products. A major part of the survey displayed the importance of also assessing the efficacy of the results. While using a pay-per-response platform was convenient regarding collecting responses from all over the country, it also brought on several issues regarding botting, repeat responses, and the use of virtual private networks, making analysis more challenging and many of the responses not useful.

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## Chapter 1

### Research Objectives

The overarching research question explored in this work is as follows, is aquaponics a more sustainable food production methodology than aquaculture and conventional farming, particularly in cold climates? This thesis aims to bridge the knowledge gap in aquaponics by addressing the following objectives:

- Evaluate and harmonize the global warming potential of five United States-based aquaponics systems and determine the mitigating circumstances causing any differences (Chapter 2)
- Quantify the environmental impacts of insect-based meals for the purpose of determining if the protein source is a viable alternative to conventional fishmeal (Chapter 3)
- Design and test a tool used for educational endeavors related to sustainable food production (Chapter 4)
- Develop and deploy a survey geared towards aquaculture and aquaponics producers to better understand general operational parameters and their willingness to invest in value-added and value-recovered products (Chapter 5)
- Design and deploy a survey with the intention of gaining insight into the food habits and preferences of United States consumers and to quantify their willingness to pay for aquaponics value-added and value-recovered products (Chapter 6)

## Chapter 2

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

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#### 2.1 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; Reganold et al., 1987; USDA, 2015a). This method of farming has been ideal for the growing overall population but is becoming increasingly unsustainable (Meier et al., 2015; Pimentel, 1993; Reganold et al., 1987; United Nations, 2019, 2019). 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, 2024). 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 practices (Pimentel, 1993; Reganold et al., 1987; USDA, 2015a). Currently, many parts of the world are struggling with

the negative effects of excess fertilizer use, also known as eutrophication (Pimentel, 1993; Reganold et al., 1987; USDA, 2015a). Eutrophication gives way to the growth of cyanobacteria in shallow warm bodies of water, creating anoxic zones in the affected areas (Mur et al., 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 such as a nutrient pool and artificial lighting to maintain ideal growing conditions (Pattillo, 2017a). HP is a respectable food source alternative as systems can have a 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). 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

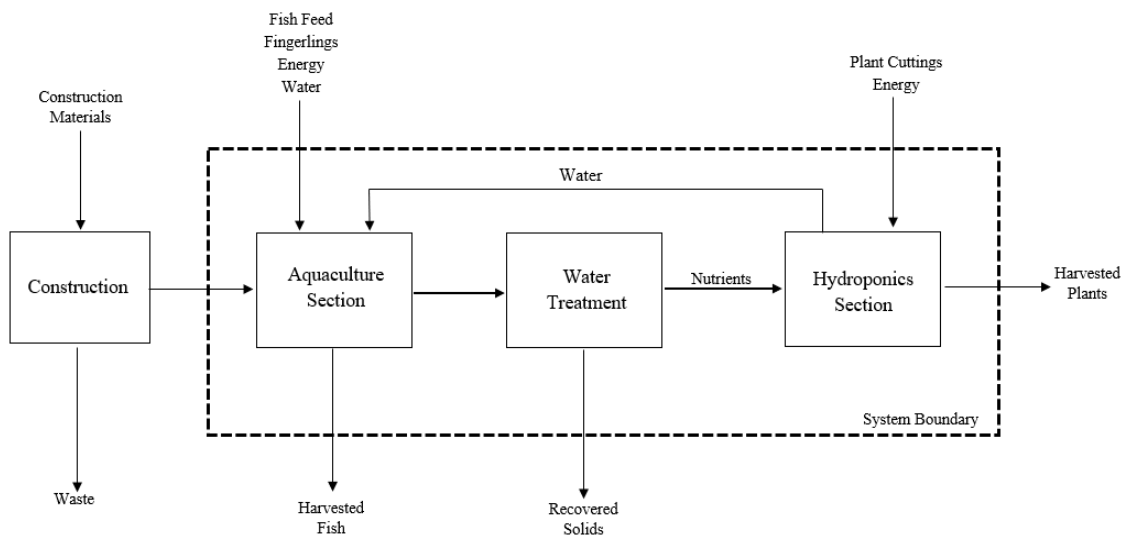
(Nelson, 2016; Pillay, 2008). AQ is the artificial propagation of aquatic species that can utilize intensive or extensive methods (Pillay, 2008). The alternative production methods have allowed for a reduction in wild population disturbance while also decreasing harvesting time and effort (Henriksson 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 (i.e., HP and AQ) have been examined, and developments have been 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). Figure 2.1 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 and Antenen, 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., 2016; Chen et al., 2020; Ghamkhar et al., 2020; Hollmann, 2013; Kalvakaalva, 2020). Aquaponics is not currently a prevalent food production system, so it is imperative to analyze the feasibility of any given system to work towards lowering overall environmental impacts.



**Figure 2.1.** Generalized Aquaponics System

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 to 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 North American (NA) 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 NA 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., 2016; Chen et al., 2020; Ghamkhar et al., 2020) Firstly, the examined LCAs were laid out to help with understanding and interpreting the results of the study.

## **2.2 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.

### 2.2.1 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 that 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. (2016), and Hollmann (2013) all conducted LCAs for their respective APSs with varying parameters like operation size, fish and plant species, system configuration, and FUs (Boxman et al., 2016; Chen et al., 2020; Ghamkhar et al., 2020; Hollmann, 2013; Kalvakaalva, 2020). Two other associated studies were excluded from this review for varying reasons.

Additional NA papers could not be analyzed in the harmonizing study. Cohen et al. (2018) conducted an LCA in Atlanta, Georgia on a research-scale APS. The author compares 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) (Cohen et al., 2018). Endpoint impacts are an important aspect of LCAs, but their results were unable to be included in this midpoint LCA study. Xie and Rosenstrater (2015) also performed an LCA on a research-scale APS in Ames, Iowa. The author had two main goals in the paper, determine the feasibility of the system in terms of the environment and profitability (Xie and Rosenstrater, 2015). Xie et al. (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 can be converted to just one kilogram of LW fish, but the issue arises when calculating GWP relative to the harmonized FU as the author gives emissions for CO<sub>2</sub>, CH<sub>4</sub>, and NO<sub>x</sub>. N<sub>2</sub>O is needed to determine carbon dioxide equivalence and it is unknown on how much N<sub>2</sub>O takes up the NO<sub>x</sub> value, which includes NO, NO<sub>2</sub>, and N<sub>2</sub>O (United States Environmental Protection Agency Office of Air and Radiation, 2016, 2015a, 2015b; Xie and Rosenstrater, 2015). To be able to harmonize the studied LCAs, some assumptions were made to create a clear comparison.

### 2.2.2 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) (Chen et al., 2020; Hollmann, 2013). For Kalvakaalva (2020), dry weight was used in their functional unit, 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 grams of LW fish (Summerfelt, Steven, 1996).

### 2.2.3 Life cycle impact assessment assumptions

Assumptions are imperative to conduct 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 chose to include avoided burdens in their LCIA to provide a more complete analysis of their APS (Boxman et al., 2016). The system produced recovered solids rich with nitrogen and phosphorous, which mitigated the use of synthetic fertilizers and the related environmental impacts were mitigated (Boxman et al., 2016). Plant production of the APS was considered as another avoided burden since the plants were not the main product, reducing water use by averting irrigation (Boxman et al., 2016). Water treatment from the plants instead of artificial treatment is another reduction in impacts from the author's system (Boxman et al., 2016). Boxman et al sums all reductions in their systems and subtracts it from the overall impact of the evaluated system (Boxman et al., 2016).

Hollmann acknowledged the system's use of synthetic fertilizer, but the exact ingredients varied and weren't recorded so the author assumed zero external fertilizer use (Hollmann, 2013). The author's system also includes two different species of fish (HSB and tilapia), but they do not differentiate their individual impact (Hollmann, 2013). Similarly, Hollmann's system grew 60 different species of plants but the author did not calculate individual species impact (Hollmann, 2013). The reviewed studies' parameters are laid out for the harmonization comparison to allow for clear discussions and conclusions.

#### 2.2.4 System parameters

Understanding the differences in the reviewed systems' parameters is essential to better understand important differences in LCA results. Table 2.1 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.

**Table 2.1.** Summary of reviewed systems' parameters

Source	Fish species	Aquafeed	Tank density	Plant species	HP setup type
Kalvakaalva (2020)	Tilapia	Soy-based feed (38% protein)	Not specified	Cucumber	Media beds

Chen et al. (2020)	Nile tilapia	AquaMax Sport Fish 500 (41% protein)	18.3 kg/m <sup>3</sup>	Lettuce and cilantro	Floating rafts
Ghamkhar et al. (2019)	Hybrid walleye	55% protein feed	66, 132, 198 fish/m <sup>3</sup>	Leafy greens	Floating rafts
Boxman et al. (2017)	Nile tilapia	32% protein feed	154 fish/m <sup>3</sup>	Basil	Floating rafts
Hollman (2013)	Nile tilapia & hybrid striped bass	32% protein feed	18 kg/m <sup>3</sup>	Lettuce	NFT, DWC, & media beds

### 2.3 Results

Table 2.2 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 GWP for each paper, showing little 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.

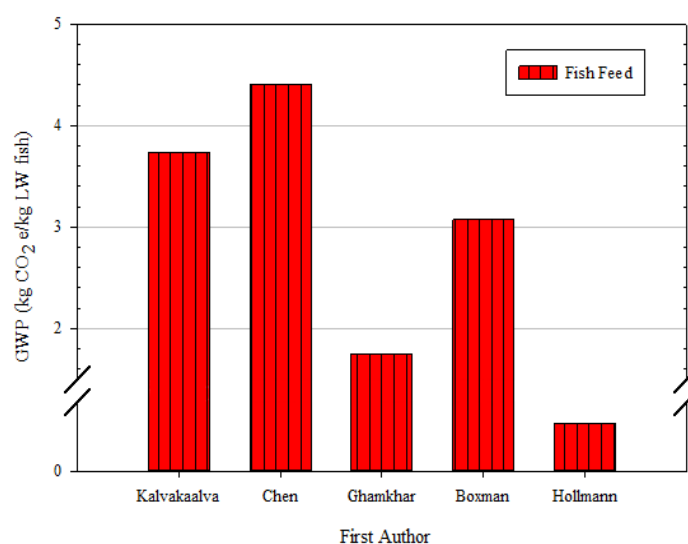
**Table 2.2** United States aquaponic system life cycle assessment summary

Source	System Location	Assessment Method	Operation Size	Climate	Original Functional Unit (OFU)	GWP (kg CO <sub>2</sub> e/OFU)	GWP (kg CO <sub>2</sub> 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. (2016)	Golden Grove, USVI	CML-IA	Commercial scale	Tropical	1-ton live weight	8640.0	8.6
Hollmann (2013)	Denver, CO	ILCD	Commercial scale	Semi-arid	1 kg fish	8.5	8.5

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., 2016; Ghamkhar et al., 2020; 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., 2016; Chen et al., 2020; Ghamkhar et al., 2020; Hollmann, 2013; Kalvakaalva, 2020). Breaking down the individual inputs to compare the papers was important since they varied amongst the studies.

Figure 2.2 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. Figure 2.2 shows how similar the GWPs are when harmonized and divided. The average GWP of the studies for aquafeed is 2.60 kg CO<sub>2</sub> e/kg LW fish, revealing that they all have the same order of magnitude. Hollmann's evaluated system used a low energy aquafeed, minimalizing protein, thus reducing the feed's overall environmental impact relative to other feeds (Hollmann, 2013). Ghamkhar et al. chose a high protein feed as walleye are a carnivorous cold weather fish that require a higher protein diet (Ghamkhar et al., 2020). Kalvakaalva, Chen et al, and Boxman et al provided the feed conversion ratio (FCR) for their respective fishes to ensure

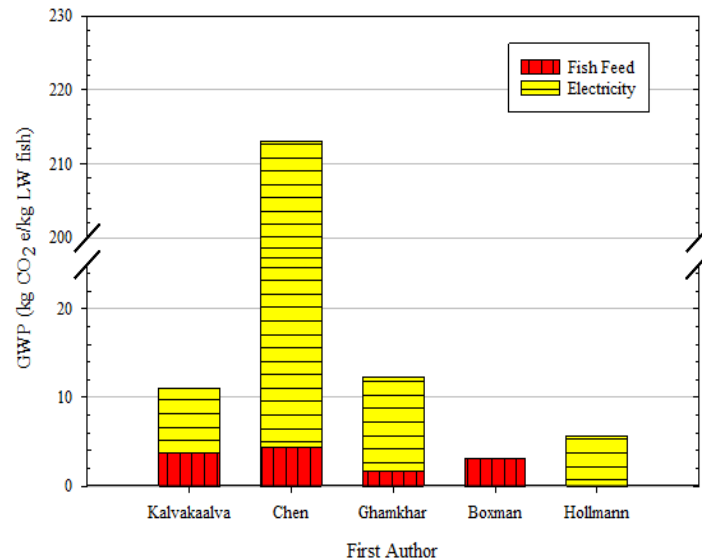
adequate nutrient transfers (Boxman et al., 2016; Chen et al., 2020; Kalvakaalva, 2020). Kalvakaalva gave a ratio of 1.6 for their feed and fish, Chen et al had a ratio of 1.2, requiring a small increase in feed volume, and Boxman et al gave a ranged ratio of 1.3-1.9 (Boxman et al., 2016; Chen et al., 2020; Kalvakaalva, 2020). Figure 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.



**Figure 2.2.** GWP of fish feed for one kilogram of liveweight fish

Figure 2.3 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

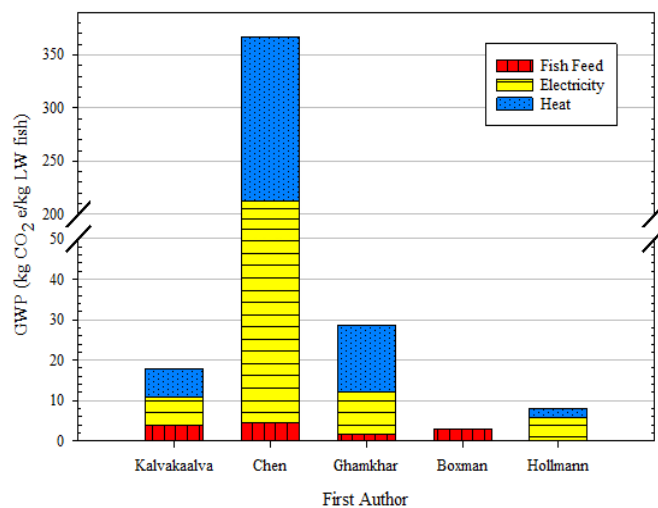
usage since the evaluated system was operated outside in a tropical climate, giving an insignificant GWP impact from the input.



**Figure 2.3.** GWP of fish feed and electricity for one kilogram liveweight fish

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. Figure 2.4 shows how critical climate is as a consideration when comparing LCAs for APSs. The final takeaway from Figures 2.3 and 2.4 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.



**Figure 2.4.** GWP of fish feed, electricity, and heating for one kilogram of liveweight fish

The three preceding figures show similarities amongst North American APSs once the impacts are broken down into the contributing components. Figures 2.3 and 2.4 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.

## **2.4 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 is limited (Boxman et al., 2016; Chen et al., 2020; Hollmann, 2013; Kalvakaalva, 2020). Ghamkhar et al. (2020) 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 system's with leafy plants so differentiation could be made between them and Kalvakaalva (2020) (Boxman et al., 2016; Chen et al., 2020; Ghamkhar et al., 2020; Hollmann, 2013; Kalvakaalva, 2020). Based on the findings, the 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 choose 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 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 (United States Geological Survey, 2021). Water dependence is the use of a water source that is not close to the system using the water (Law Insider, 2021). Defining different water terms is important when understanding what is considered when an author evaluates a system that is so 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 its sustainability in aquaponics. Prior work into the topic has shown that energy use is a major environmental hotspot through LCA (Boxman et al., 2016; Chen et al., 2020; Ghamkhar et al., 2020; Hollmann, 2013; Kalvakaalva, 2020). Boxman et al evaluated three options for energy sources to determine if renewable energy is a more sustainable option (Boxman et al., 2016). The author 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., 2016). 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.

## **2.5 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 (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. 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).

## Chapter 3

# Comparative life cycle assessment of insect farming in North American cold climate for fishmeal alternatives

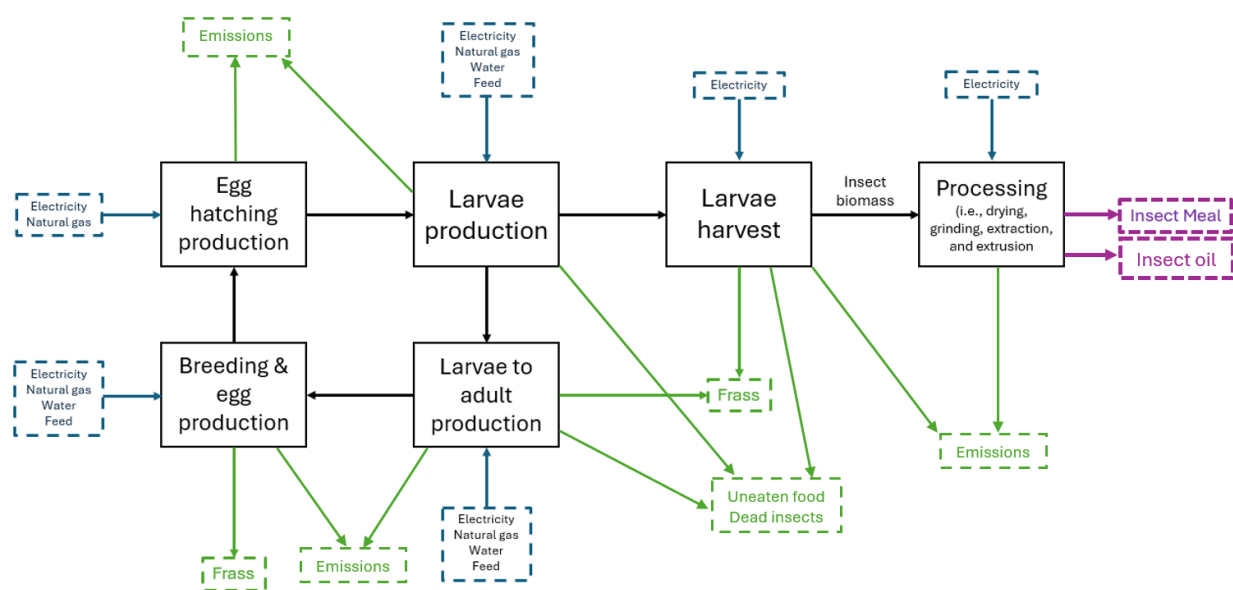
### 3.1 Introduction

Aquaculture is one of the fastest growing industries in the United States (US) today, generating billions of dollars in revenue and is projected to continue to grow for the foreseeable future and is currently the most common method for farming aquatic organisms globally, namely for propagating fish such as tilapia and salmon (FAO, 2024). This farming method is highly beneficial for reliably producing quality sources of protein and fat, while also alleviating some market pressure put on select wild aquatic stocks by industrial fisheries (NOAA Fisheries, 2021; Tacon, 2020; University of Wisconsin, 2024). While aquaculture has several benefits, its negative consequences force further investigation to develop more sustainable system characteristics.

One of the most environmentally impactful attributes of any aquaculture system is the aquafeed (Boxman et al., 2016; Ghamkhar et al., 2020). Conventional aquafeeds, along with many other animal feeds, contain fishmeal (FM) and fish oil (FO) as sources for protein, lipids, and omega-3's (Tacon, 2020). Currently, FM and FO are sourced from wild-caught prey or forage fish such as sardines, menhaden, and mackerel, which is an issue both for the growing aquaculture industry and the wild organisms who depend on that food source, given most wild populations are already at their maximum sustainable yields (Maunder, 2008; Samuel-Fitwi et al., 2013; Tacon, 2020). Because of this constraint,

alternative protein and fat sources are vital in maintaining nutrient compositions in aquafeeds for the growing aquaculture industry.

Several different options for FM and FO alternatives are showing promise in regards to environmental impact, such as vegetable-, insect-, microalgae-, and aquaculture byproduct-based meals and oils. Insects are specifically a favorable potential source of protein and fat for animal farming as they typically have short lifecycles, can be fed waste streams, and require minimal processing for feed (Beyers et al., 2023; Smetana et al., 2019). Figure 3.1 displays the inputs and outputs of a generalized insect farming system, though some species are harvested later in the life cycle of the insect and require other



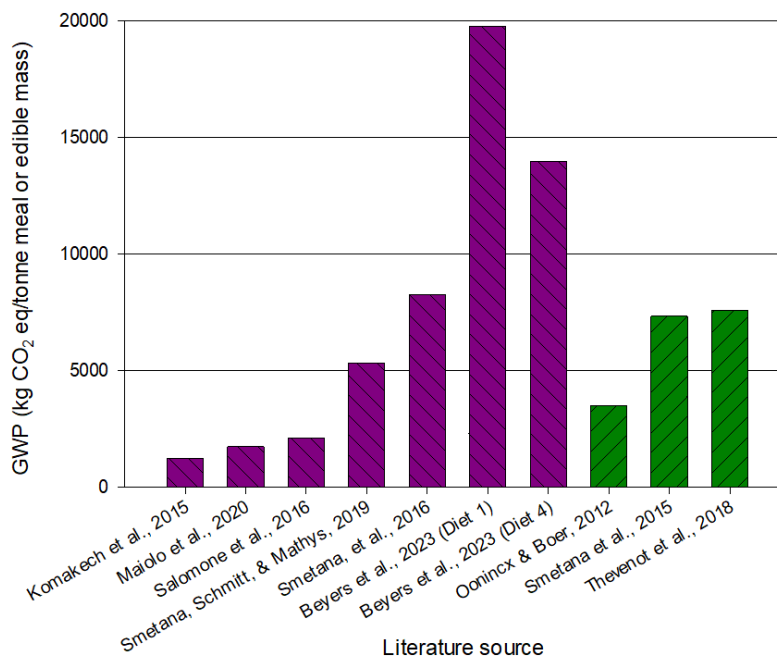
**Figure 3.1.** Generalized insect farming operation to produce meal

inputs such as pumpkin or a cleaning solution for maintaining good hygiene between cycles. In Figure 3.1, the solid boxes refer to the typical farming cycle of insect propagation and processing, the blue dashed boxes refer to the inputs required for each step in the

farming and processing operations, the green box denotes the waste outputs, while the magenta dashed boxes refer to the desired outputs for this type of insect farming operation. Fatty acids can be extracted from insect biomass; however, omega-3 fatty acids (an essential nutrient for aquatic species) are generally limited in insects, requiring either supplements in the insect's feed source or in the final meal and oil products (Oonincx et al., 2020). Though insects seem to be a viable alternative to FM and FO, assessment of their environmental sustainability is critical for ensuring these products are not more environmentally detrimental when compared to their antecedent.

Life cycle assessment (LCA) is a commonly utilized tool for quantifying the environmental impacts of products and processes (ISO, 2006). Environmental investigations of insect farming exist, though mainly from other countries across the world, since more residents consume and utilize insects and they are overall much less taboo in general, making insect farming more viable than the current US market. Since the industry is already beginning to develop in Europe, several LCA studies exist on several kinds of insects such as black soldier fly larvae (BSFL) and mealworms (i.e., darkling beetle larvae) which are fed a diet of either animal feeds, agricultural byproducts, or waste streams. Smetana, Schmitt, and Mathys, (2019) conducted an LCA study of BSFL in the Netherlands with scenarios for the use of standard feed diets and food industry side streams and found the assessed insect-based products to be competitive relative to greenhouse gas (GHG) emissions and land and energy use when compared to other meals. One vital consideration of animal farming in general is the concern of burden shifting within agriculture by using certain feed streams (e.g., wheat middlings and wheat starch slurry).

Many food/feed side and waste streams are already fed to livestock or used as compost/ground cover for crop agriculture, meaning their food source is likely coming from an already saturated source, which is an important consideration given the potential of disruptions in other food and feed industries. Another study by Dreyer et al. (2021) investigated the environmental impacts of the yellow mealworm in Austria. The authors found the electricity input, specifically the electric heater generated the largest environmental impacts for mealworm production. They conclude that insect farming can compete environmentally with conventional animal farming, however, efficiency improvements and large scale operations are necessary to truly be more environmentally sustainable than traditional animal products (Dreyer et al., 2021). A relevant takeaway from the available literature on the environmental impacts of insect farming meals is the differences in reported impacts. Figure 3.2 presents the global warming potential (GWP) of several studies who investigated either BSFL (purple) or darkling beetle larvae (green). GWP calculates the total GHG emissions of a product or process. As shown, there are major



**Figure 3.2.** GWP of published LCAs for either one tonne of larvae or meal using BSFLs

(purple) or mealworms (green)

differences even amongst the same species for this one impact category. The differences in impact arise for a variety of reasons, one being the location of the operation or differences in the annual harvest quantities. Currently, no insect LCAs exist in the US and few commercial-scale farms are operating (about 50 total in North America), though interest is quickly rising (Carpenter, 2020; Larouche et al., 2023).

One major consideration in the investigation of meal alternatives is the biotic resource use (BRU) of these products. BRU considers the quantity of biotic resources or living organisms required to produce the investigated product. Because conventional FM relies almost entirely on wild-caught fish, which is a vital and limited biotic resource, it is critical that these alternatives patently reduce the amount of BRU required and/or that the

biotic resources used are not from the same sources as conventional meals. Many LCAs of FM alternatives do not include the consideration of BRU, which is a more relevant impact category than many of the common ones in this application, making the story expressed by the assessment incomplete with respect to the ecosystem services provided by the oceans in producing FM and FO.

The goal of this work was to assess the environmental impacts of farming three different types of insects (i.e., BSFL, crickets, and beetle larvae) to generate insect meals in a cold climate in the US, specifically Madison, Wisconsin which has a humid continental climate according to the Köppen-Geiger climate classification (Beck et al., 2018). In this work, LCAs were conducted with the inclusion of BRU for the three investigated insects (biomass and protein content) which was then compared to conventional FM, microalgae-based meal, and vegetable-based meal to determine their viability relative to the environment for current and promising meals.

### **3.2 Materials and methods**

In accordance with the International Standards Organization (ISO), LCA involves of four main stages: the goal and scope definition, inventory collection, life cycle impact assessment (LCIA), and interpretation (ISO, 2006). The impact methodology utilized in this assessment was the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), which determined the midpoint impact categories included in the assessment. To perform the LCA, SimaPro 9.5.0.2 software was utilized, which drew from EcoInvent 3, US Life Cycle Inventory (USLCI), and Agri-footprint 6

databases (Durlinger et al., 2014; “EcoInvent, Version 3.10,” 2024; National Renewable Energy Laboratory, 2025).

### 3.2.1 Goal and scope definition

In the agricultural context, the most common environmentally impactful life cycle stages of many products are the raw materials acquisition and the production phases, so a cradle-to-processing gate system boundary was chosen for the LCAs (Asem-Hiablie et al., 2019; Costantini et al., 2021). Cradle-to-processing gate considers the acquisition of the raw materials and processing required to produce the meal, however, waste streams (i.e., frass, uneaten food, and dead insects) were not included in the assessments for consistency and due to limitations within the literature and available databases (Beyers et al., 2023; Halloran et al., 2016; Smetana et al., 2019). These waste streams could be used as an alternative fertilizer but would generally need further processing for optimal usage. The use phase was also specifically excluded as further experimentation would be required for the actual implementation of the insect meals relative to quantity and composition of the feed given the variability of nutrient composition which would depend on the insect’s feed composition, so this phase was not included in the scope of this study. End-of-life was excluded as this phase would severely narrow the applicability of the LCA given the specificity of waste disposal locations, making the transportation required equally explicit. Two functional units (FUs) were selected for the assessment as one provides useful results for current and future insect farmers and the other provides results useful for feed and animal producers and were chosen to be one tonne (i.e., 1000 kg) of insect meal and one tonne of protein.

### 3.2.2 Data sources and inventory

All utilized studies were translated into theoretical operations located in Madison, WI, USA meaning some supplemental heating and lighting are required to maintain environmental conditions during the farming process, depending on the location of the original operations. The US cold climate is specifically noteworthy for investigation due to the increased dependence on energy (for heating and lighting). Five published insect farming inventories were the basis of the three LCAs conducted in this study, though some supplemental inventories and data were needed for completion (Beyers et al., 2023; Halloran et al., 2017; Maiolo et al., 2020; Oonincx and de Boer, 2012; Thévenot et al., 2018). More details on the inventories can be found in Appendix B.

### 3.2.3 Life cycle impact assessment

Following the US Environmental Protection Agency's protocol, TRACI 2.1 (V1.08/US 2008) was utilized to characterize impact categories (Bare, 2012). TRACI 2.1 contains the following impact categories and will be included in the results (though some impact categories are less applicable for this application): Acidification potential (AP, kgSO<sub>2</sub> eq), eutrophication potential (EP kg N eq), fossil fuel depletion (FFD, MJ surplus), global warming potential (kg CO<sub>2</sub> eq), smog formation (SF, kg O<sub>3</sub> eq), respiratory effects (RE, kg PM<sub>2.5</sub> eq), and ecotoxicity (EC, CTUe), ozone depletion (OD, kg CFC-11 eq), human health carcinogenics (HHC, CTUh), and human health non carcinogenics (HHNC, CTUh) (Bare, 2012).

Due to limitations of the current methodology, BRU (kg biotic C) was quantified in this LCA. Since alternative meals aim to mitigate the use of conventional FM, it is vitally important to have an impact category that takes the amount of biotic carbon required to produce the product into consideration. BRU methodology was initially coined by Pauly and Christensen, (1995) and was adapted for this application. The methodology considers the trophic level of the desired product as well as the quantity of carbon-based resources required (Pauly and Christensen, 1995). For FM and plant-based inputs, several published articles were utilized, though some carbon content was provided with the inventories used (Barlow, 2003; Beyers et al., 2023; Firestone, 1999; Ghamkhar and Hicks, 2020; Hasan and Halwart, 2009; Pelletier and Tyedmers, 2007; Šarauskis et al., 2018; Savage et al., 2015; Yiga et al., 2023).

Uncertainty was investigated for all impact categories, with the exception of BRU, as the assumptions and decisions made in the LCA will inevitably lead to a degree of uncertainty. To do this, Monte Carlo simulations were conducted using the SimaPro 9.6 software where 1000 runs of the assessments were completed with 95% confidence. Sensitivity analyses were also conducted to better understand which inputs impact the overall emissions the most by varying each input by 20%. The results of the sensitivity analyses are presented in Appendix B.

#### 3.2.4 Life cycle impact assessment using mass-based allocation

Given there are several inputs of which are co- or by-products of agricultural processes (i.e., wheat bran and endive root) as well as insect meal producing some oil, if

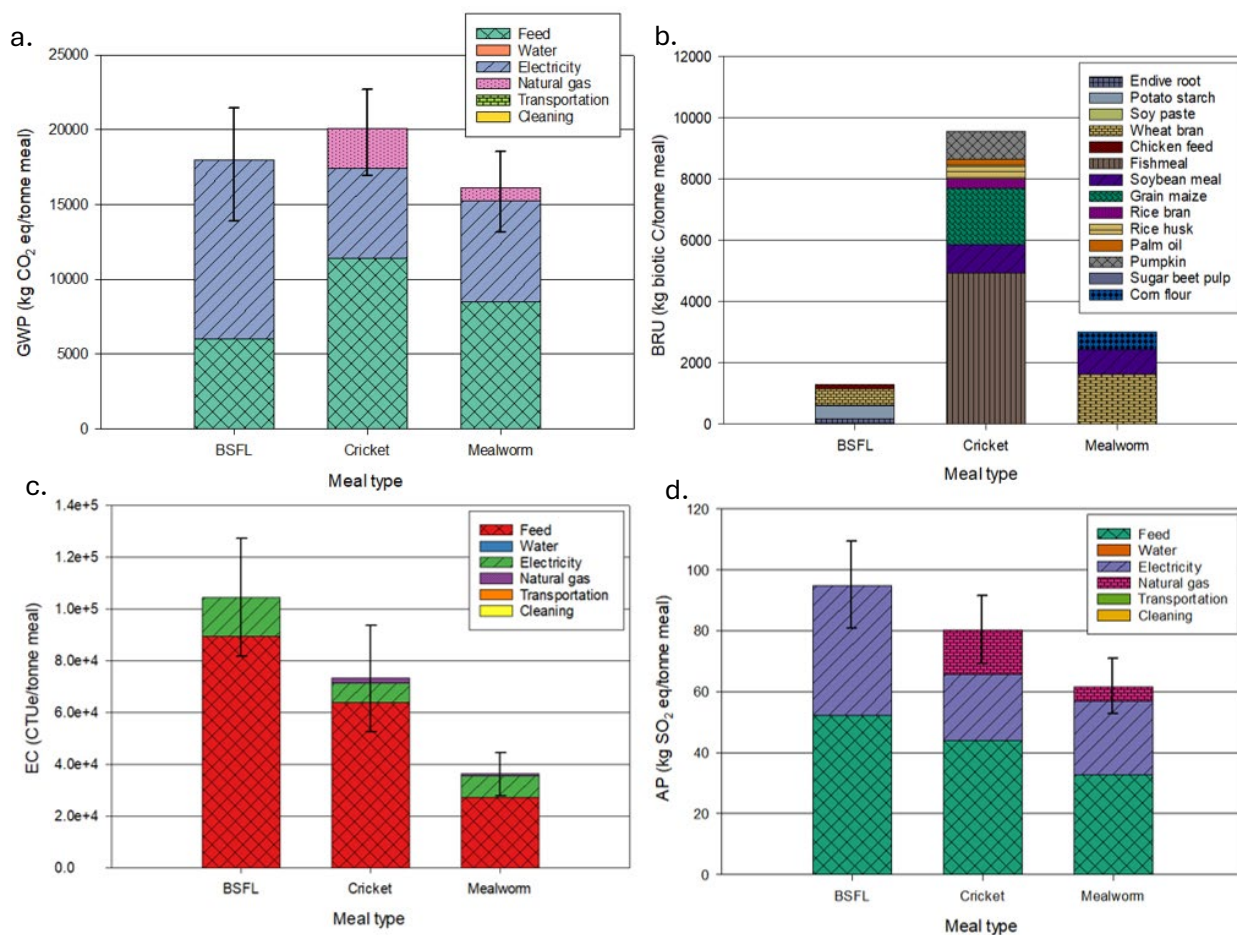
defatted, it is necessary to also investigate impacts with allocation considerations. The original assessment represents a worst-case scenario relative to environmental impacts, while the allocated results are more representative of reality where all products from various processes should bear some percentage of environmental impacts. For example, wheat bran could be considered a “free” product relative to environmental impacts; however, the input is already utilized as a feed input in various livestock feeds, making it already constrained and useful elsewhere. For allocation of wheat bran, the ingredient is considered to be 13% on a mass-basis for a grain of wheat (Hossain et al., 2013). Other similar allocations are discussed in Appendix B.

Separating insect meal and oil is an important process as different species of farmed animals require various amounts of protein and lipids for optimized growth and allows feed producers to broaden their markets to virtually all artificial animal propagation operations. For the allocation considerations of the final products, BSFL produces 76.92% meal and 23.08% oil, while crickets produce 76.75% meal and 23.39% oil, and mealworm meal (MM) also produces 11.5% oil all on a mass basis (Maiolo et al., 2020; Rose et al., 2023; Thévenot et al., 2018).

### **3.3 Results**

#### **3.3.1 Life cycle impact assessment and uncertainty analysis**

Figure 3.3 presents four impact categories (GWP, BRU, EC, and AP) with the corresponding uncertainties for one tonne of the three insect-based meals along with their

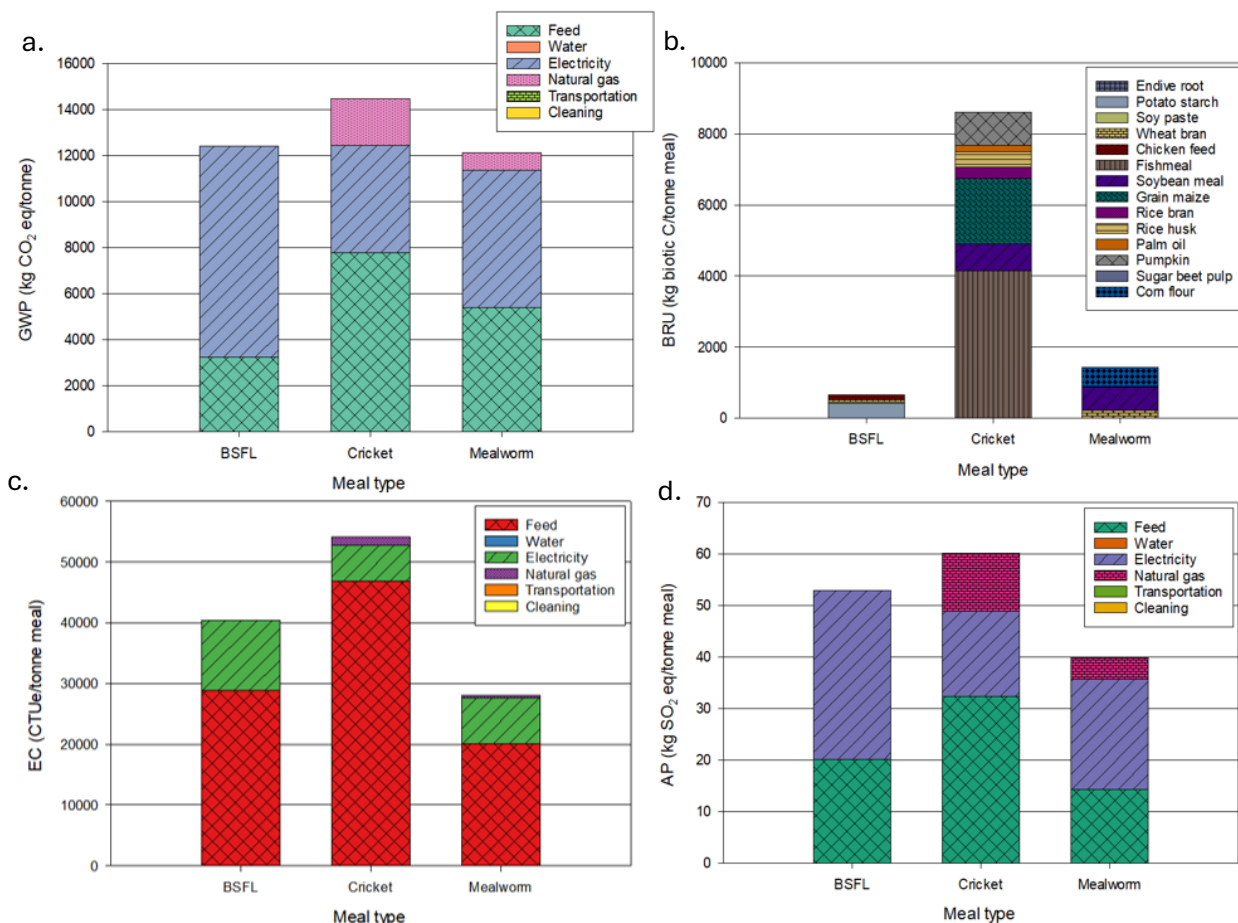


related uncertainties, given GWP is one of the most commonly assessed impact categories in LCAs, BRU is particularly important in this application, EC is vital due to the use of several farmed feed inputs and the emissions of environmentally toxic substances, and AP is included as comparisons are made using this category below. The figures indicate that MM outperforms the other two in EC, AP, and GWP, however, BSFLM is the best option of the three for BRU but is the most impactful in the EC and AP categories. Cricket meal (CM) has by far the largest BRU, mainly due to the operation's dependence on the FM and

soybean meal (SBM) inputs. CM also has the largest impact relative to GWP due to the addition of heating based on calculations of a theoretical operation using average temperatures instead of measurements, given there was no heating in the original inventory. LCA results of the assessed meals using the secondary FU (one tonne protein) and discussion of the uncertainty results can be found in the Appendix B.

### 3.3.2 Mass-based allocation life cycle impact assessment results

With the changes arising from allocation considerations both within the feed inventories and the final products, Figure 3.4 displays the results of the amended assessments. All results from this assessment show some amount of reduction when



**Figure 3.4.** Mass-based allocation impact assessment (a) GWP, (b) BRU, (c) EC, and (d) AP results per tonne meal

compared to the original results. As shown, GWP is reduced a bit for all meal types but the results relative to one another remain the same. BRU overall results also remain the same, though BSFLM and MM have the greatest reduction of impact in this category. EC results do change, with CM now being the most impactful, given endive root impacts were removed from the BSFLM assessment. AP results also changed to have CM as the most impactful, given the large reduction in feed impacts for the BSFLM assessment.

### 3.4 Discussion

The goal of this study was to quantify insect farming in a cold region of the United States for the purpose of producing a FM alternative. Insect farming is highly dependent on energy to maintain proper temperature, humidity, and ventilation, especially since increased temperatures lead to a more productive operation. Insects are relatively simple to artificially propagate and also utilize significantly less biotic resources when compared to conventional FM. Processing insects to produce a meal is also an energy intensive process, given the high dependence on energy which is required for cooking and separating most of the fatty acids from the protein-rich meal. The use of energy disperses amongst several impact categories, namely GWP, FFD, EP, and EC and will be discussed more precisely below.

Based on the results of both assessments, MM seems to be the best choice relative to most environmental impacts amongst the assessed meals. Though MM does not have the lowest emissions for some categories, it also is not the most impactful of the three within said categories (BRU and FFD). Most of the lesser impacts for MM relative to the other two are due to having the fewest total inputs, the use of agricultural byproducts, and lower input requirements of both electricity and NG.

#### 3.4.1 GWP and FFD impacts

GWP is one of the most important impact categories assessed due to rising concerns of anthropogenic GHG emissions and the ever-increasing issue of climate change. GWP investigates the three main GHG emissions commonly produced through industrial processes (carbon dioxide, methane, and nitrous oxide) (Bare, 2011). Within the

BSFLM assessment, electricity was by far the most impactful, followed by potato starch and endive roots. For CM, the most impactful input for GWP is the SBM, followed by electricity and NG, respectively. Within the MM assessment, electricity was the main contributor to GWP, followed by SBM and wheat bran, respectively. Electricity is unsurprisingly a major contributor to GWP for all three assessments given the Midwest's high dependence on coal and NG which produce all three gases of interest in the impact category (Riva et al., 2006; Spath et al., 1999). SBM, potato starch, and wheat bran are also products which utilize or require tilling, harvest, and post-harvest processing that are highly dependent on energy, making them more impactful in the GWP category.

Given the high dependence of energy for insect propagation and processing, investigating FFD is also imperative. Unsurprisingly, electricity and NG inputs were the most impactful for the FFD impact category, given both inputs rely either entirely or primarily on fossil fuels. Relying more on renewable energy sources and improving efficiencies in space requirements, hardware, and feed quantities or switching out some feed ingredients with waste streams or agricultural byproducts (i.e., livestock waste and uneaten feed) would greatly improve the environmental impacts for both impact categories.

#### 3.4.2 BRU impacts

Assessing BRU and abiotic resource use in the Anthropocene in general is vitally important, given the rapid depletion of the Earth's resources (Waring et al., 2023). BRU also aids in accounting for ecosystem services for resources such as forage fish in LCA, which

also allows for a fairer comparison amongst products. In this application, BRU is arguably the most important impact category, given the alternative meals have the intention of replacing FM which is highly dependent on a limited biotic resource (i.e., wild-caught prey fish) (Deutsch et al., 2007). If this impact category were to be omitted, FM seems to be a reasonable protein source for aquaculture in most other environmental impact categories. The main goal of the inclusion of this category for this assessment is to ensure that the insect-based alternatives are not more impactful than their predecessor relative to biotic resources.

For the BSFLM assessment, the most impactful input is the wheat bran given the feed's high reliance on the by-product. The second most impactful input is the potato starch, which is largely comprised of amylose and amylopectin, both of which have a base of several carbon atoms. Within the CM assessment, the most impactful input by far was the FM given the products' reliance on higher trophic level fish. Grain maize and SBM were the next two feed ingredients with the second and third largest impacts, which is reasonable given both are the main ingredients in this assessment's feed. As one goes up the pyramid of trophic levels, it is expected to require more carbon given the transfer efficiency (~10%) of energy between levels (Pauly and Christensen, 1995). The CM operation clearly was operating to maximize efficiency relative to the feed, given the high reliance on meals and the use of palm oil. For the MM assessment, the most impactful input was the wheat bran, followed by SBM and Maize flour, respectively. Both the BSFLM and MM show the benefits of utilizing vegetable-based products and byproducts, though

both could also continue to improve in the BRU category by relying more heavily on agricultural waste streams.

### 3.4.3 EP and AP impacts

Within the agricultural industry, EP is an important impact category to assess due to the high dependence on synthetic fertilizers and production of livestock excrement. EP investigates nutrient runoff caused by anthropogenic activities such as agriculture and the production of wastewater. These activities are important to investigate relative to eutrophication due to excess nutrients to congregate in waterways, causing increased growth of harmful algae and other undesirable plants, both of which negatively impact aquatic ecosystems (Bare, 2011). For all three assessments, electricity was the main contributor to EP. This is mainly due to the release of  $\text{NO}_x$  during the combustion of coal (and natural gas) as well as bottom ash (from coal combustion) being an output of the process which contains phosphorous (Riva et al., 2006; Spath et al., 1999). For the BSFLM assessment, the inputs contributing the second and third most to EP, is endive root and potato starch. For the CM assessment, the next largest contributors in the EP category are palm oil and SBM. For the MM assessment, the second and third most impactful inputs relative to EP are wheat bran and SBM. All these feed inputs contribute to EP due to the utilization of fertilizers, which highly depend on both nitrogen and phosphorus, and some require processing which also often depend highly on energy.

AP is another important category to investigate due to rising concerns of ocean waters' chemical composition and increasing the likelihood of acid rain. Relative to AP in

the BSFLM assessment, the most impactful inputs are electricity, endive root, and potato starch, which is the same as the EP category. Within the CM assessment, the largest contributors to AP are maize grain, electricity, and NG. For the MM assessment, the most impactful inputs are electricity, wheat bran, and maize flour. Electricity and NG contribute to this impact category through the combustion of both coal and NG which produce  $\text{NO}_x$  and  $\text{SO}_2$  (Spath et al., 1999). Coal combustion is one of the main contributors to  $\text{SO}_2$  emission in the anthropogenic scene (National Energy Technology Laboratory, United State Department of Energy, 2024). The feed inputs that also largely contribute to AP are due to the use of fertilizers, which can contain both  $\text{NO}_x$  and  $\text{SO}_2$  to help stimulate growth and there are also no rigorous federal policies and regulations for quantities of fertilizers that can be used, making runoff from these activities a major issue (Hasler et al., 2015).

#### 3.4.4 EC Impacts

EC is an important impact category to assess in LCA as many anthropogenic activities create major detriments for the environment, including leaching of toxic chemicals and metals, as well as these toxins negatively impacting ecosystems and their residents. For BSFLM, the main contributors to EC are endive root, potato starch, and electricity. Based on the allocated results, EC for this assessment would decrease by slightly over 60%, while the other two assessments have a marginal decrease. For the CM assessment, the main contributors for the impact category are maize grain, SBM, and rice bran. Relative to the MM assessment, the inputs with the largest contribution to EC are SBM, maize flour, and electricity. Some impacts for this category are expected but could

still be reduced mainly by using renewable energy for processing of the feed ingredients and as the energy source for electricity.

### 3.4.5 Overall insect meal LCA comparisons

Several studies were chosen for comparison as all are either conventional FM (which is still the most viable in terms of availability and cost) or other potential alternatives. Not all impact categories could be compared due to the differences in methodologies, which lead to differences in units utilized (e.g., EC and EP). Table 3.1 displays this study as well as the referenced literature along with two impact categories (i.e., GWP and AP) that were assessed. As seen in Table 3.1, all insect meals have larger impacts for GWP and AP apart from the second microalgae (*Tisochrysis lutea*) meal.

**Table 3.1.** Meal Comparisons of GWP, AP, and BRU per tonne of meal produced

Meal Type	Source	GWP (kg CO <sub>2</sub> eq)	AP (kg SO <sub>2</sub> eq)	BRU (kg biotic C)
BSFL	This study	18,270	96.48	1,291
Cricket		20,411	81.67	9,113
Mealworm		16,436	63.20	2,997
FM	Pelletier & Tyedmers, 2007	1,050	6.79	19,880
	Silva et al., 2018	1,310	6.37	-

FM from by-products	Pelletier & Tyedmers, 2007	2,690	36.5	79,420
	Silva et al., 2018	5,370	56.7	-
Poultry by-product	Pelletier & Tyedmers, 2007	4,260	35.7	5,960
	Maiolo et al., 2020	2,020	25	-
Soybean	Pelletier & Tyedmers, 2007	333	3.24	429
Corn gluten	Pelletier & Tyedmers, 2007	960	11.1	618
Microalgae ( <i>Tetraselmis succia</i> )	Maiolo et al., 2020	15,371	39	-
Microalgae ( <i>Tisochrysis lutea</i> )		27,089	80	-

Majority of these meal types have existed well before insect meals, allowing their systems to be optimized, which helps to show the glaring lack of optimization of insect operations. Most articles did not explore BRU, however, the paper by Pelletier and Tyedmers, 2007 did for conventional FM, SBM, corn gluten meal, and by-product meals and the results are also

displayed in Table 1. Based on this comparison, all three insect meals are significantly less impactful in the BRU category than conventional FM and FM by-product. The insect meals are unsurprisingly more than the vegetable-based meals, given insects are one trophic level higher than plants, though plant-based meals generally have lower protein contents (El-Shemy, 2011). Given BRU is one of the major points of interest relative to environmental impacts when exploring alternative meals, the investigated meals are all slightly less than or significantly less than 50% of conventional FM in the BRU category.

#### 3.4.6 Recommendations

There are several ways to reduce the environmental impact of insect farming. One way is to utilize waste heat produced during other industrial processes such as papermaking or metal refining, however, this requires another industrial processing plant to be close to the insect operation, which is highly unlikely in most cases. Another, more obvious option is to utilize more renewable energy sources. Currently, the energy mix in the Midwest is highly dependent on coal and natural gas, making both inputs highly impactful for many categories as discussed earlier. One of the main concerns with a meal alternative such as this one is the consistently high temperature and humidity required for proper growth and cycle time. Utilizing renewable energy would greatly reduce environmental impacts, however, costs for said energy source could make this option untenable for some. Improving efficiency within the operation itself is another option for reducing environmental impact, which includes minimizing the total space that needs heating, exploring high densities within the colonies, given there are no stringent standards on this type of farming (the farmer would need to ensure that a non-cannibalistic species is

selected), exploring various kinds of feeds to either significantly decrease cycle time, or investigate feed amounts per cycle (all three operations output large amounts of uneaten food). Relative to the LCA itself, the use of primary data would improve uncertainty surrounding the assessments. Another constraint of the assessments was the lack of US centric data points within the two databases utilized, which again, would improve uncertainty. A final recommendation for assessments such as these in the future is to explore various scenarios to gain further insight into the full scope of the meal's potential, which should include the exploration of all previously discussed recommendations.

#### 3.4.7 Burden shifting

Another consideration with insect farming in the US is the concern of burden shifting when using agricultural byproducts. Most, if not all, byproducts are used in animal farming or cropland supplementation, putting more pressure on an already constrained feed stream. One way to mitigate this issue is to further investigate the potential use of animal waste, given insects' ability to efficiently convert waste into biomass. The main issue currently with this change is that there are restrictions on alternative feed streams in the form of governmental regulations in the US, which would need to be altered to allow for commercial use.

### 3.5 Conclusion

Finding a more sustainable protein source for animal farming, specifically aquaculture, is imperative as global demand for aquatic species increases and wild-caught fish harvests stagnate. Insect meal as an alternative to conventional FM and other

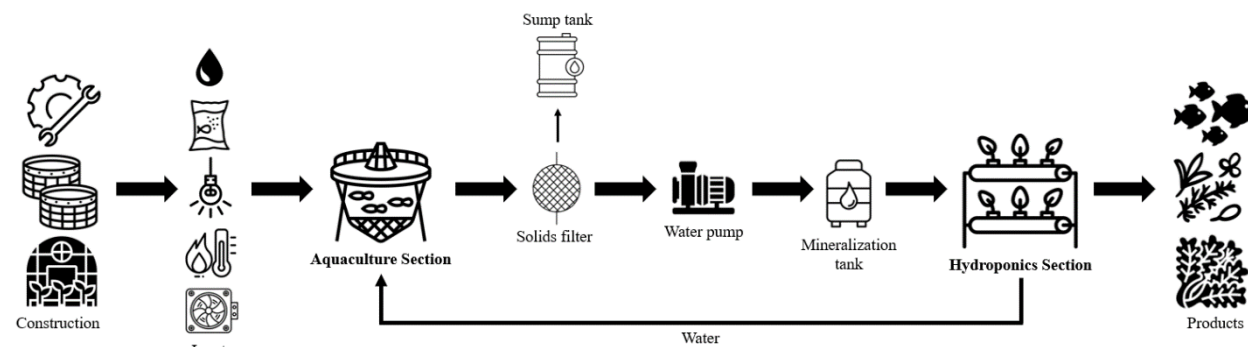
alternatives is currently not viable relative to most of the impact categories, however, does perform better in terms of BRU. Optimization of rearing densities, environmental conditions, overall system design, and energy sources will drastically improve the environmental sustainability of insect meals in the US. As environmental viability improves, the insect farming industry can move towards larger scale operations, thus allowing for economies of scale to take place which will lead to improvements relative to economic sustainability. Once insects are more socially accepted in the US as a useful protein source, new products could become more popular such as protein powders, opening a new market to these farmers.

## Chapter 4

### Exploring aquaponics systems and environmental impacts: An agent-based model case study

#### 4.1 Introduction

Aquaponics (AQP), a symbiotic closed-loop system combining aquaculture and hydroponics technologies, has surfaced as a promising food production methodology with its main goal being the reduction of waste streams while still producing in-demand food products so that aquaculture can eventually be replaced with a more sustainable option (Goddek et al., 2019). For recirculating systems, fish waste and majority of the water from the fish tank are sent through a biofilter and mineralization tank to allow the nitrification process (i.e., ammonia and ammonium produced through fish excretions is broken down to



nitrite and then to nitrate using specific species of ammonia-oxidizing bacteria) to occur before dispersing to the plant tanks to fertilize and hydrate the plants in a generalized AQP system (Eck et al., 2019; Goddek et al., 2019; Junge and Antenen, 2020). Figure 4.1

presents a generalized AQP operation from inception to production. In many cases, small-

rooted, low nutrient dependent plants (e.g., leafy greens and herbs) are grown in AQP systems (Goddek et al., 2019). AQP is more effective than aquaculture and hydroponics

**Figure 4.1.** Generalized AQP operation from formation to fish and plant harvest separately as the ammonia and ammonium produced from fish excrement is largely utilized to produce a second product, which is generally an herb or small-rooted vegetable (Eck et al., 2019; Goddek et al., 2019). AQP operations also output a solid waste stream from the fish which, with some processing, could help to mitigate synthetic fertilizer use in conventional agriculture (Junge and Antenen, 2020). Because AQP is not a widely adopted technology, education on the topic is imperative to increase public exposure, further advancing the general methodology and introducing products to the consumer market thus improving the sustainability of the technology itself.

Approaches for efficiently and effectively educating students on more complex concepts while temporarily minimizing the nuance is a highly investigated issue. Traditional methodologies typically include a presentation or talk given by an educator introducing and discussing the topic, utilizing related videos or case studies to aid in the learning process (Goddek et al., 2019). While these techniques are somewhat effective and resource efficient, developing methodologies which can include more effective, but still accessible, approaches to teaching complex topics is imperative. Another option for education explored by some is the use of on-campus small or micro-systems, which would be one of the most effective methods, however, not all institutions have the funds, resources, and expertise to properly use this option for many students (Goddek et al., 2019; Maucieri et

al., 2017). Prior to the design and development of the AQP agent-based model ABM, education related to AQP was largely inadequate regarding accessibility and effectiveness particularly for low resource regions.

Systems thinking (ST) refers to the method of investigating multifaceted systems without introducing all the complexities of it, which helps in reframing perspectives for many applications. ST is a necessary addition to the educational curriculum as the entire Anthropocene relies on various systems which are also reliant upon ecosystem services (e.g., nutrient cycling and the water cycle). AQP is a useful starting point regarding this concept given its ease in understanding its outputs and the two main system components (i.e., aquaculture and hydroponics). Through a systems thinking approach, AQP can be introduced as a two-system methodology that works symbiotically, and future lessons can delve into the mineralization system, the system as a whole, and broader concepts such as variability of an operation (e.g., type of hydroponics, fish, climate considerations).

ABM is a tool used for simulating real-life phenomena using a systems thinking, 'bottom-up' approach (Wilensky and Rand, 2015). ABM is a valuable tool as it can make the focal point the agent interactions (i.e., individuals contributing to the system) in a system to better understand some phenomena, while also exploring how changing variables in the system (e.g., quantity of agents, a characteristic of the agents, etc.) can change the result (Wilensky and Rand, 2015). ABM is also useful for exploring systems thinking which is key in understanding that our society exists as one overarching system comprised of numerous smaller systems. ABM is often used to simulate natural phenomena such as the predator-prey relationship, the development of waterways, and an ant's use of pheromones to

communicate with others in its colony (Wilensky and Rand, 2015). The use of ABM allows for the laymen, specifically students to grasp the high-level concepts of a complex phenomenon and stimulate discussion amongst users. More specifically with agent-based modeling, the user can gain a bottom-up perspective (i.e., building a model based on the actions and interactions of the individuals in the system) on concepts and systems, which had previously been challenging to model.

The main goal of the study is to design, give justification to, and analyze an AQP ABM which will expand educational opportunities by providing a tool to aid in systems thinking curriculum and future sustainable food production education.

## **4.2 Methods**

NetLogo is a free programmable ABM software for the purpose of simulating biological, physical, chemical, and social phenomena (“NetLogo Home Page,” 2025). Using ABM for educational purposes allows for an interactive learning experience that is simple but stochastic, making the steps by which the predetermined goals of the ABM are investigated in an organic manner. Agent-based modeling is one of the most viable options for simulating an AQP system as the software is free and easily accessible and the mechanisms within a typical system are stochastic in the sense that there are many parameters, constraints, and challenges which could impact the yield and emissions of an AQP operation. NetLogo was utilized to design the AQP ABM and is available through the model library found in the software. The AQP ABM discussed here displays a generalized

commercial scale AQP operation which allows the user to change the fish and plant type, climate, and season (which is assumed to be 84 days per season). The ABM also tracks the greenhouse gas (GHG) emissions produced from the simulated system while in operation. Specifics of the theoretical operation and model are presented, justified, and analyzed throughout the rest of the paper.

If a real operation and the AQP ABM of the same scale were compared, the ABM would show a much lower density of fish and plants given the visual limitations of the interface (2-dimensional model for a 3-dimensional system and computing power of the software. Reduced fish and plants densities were needed so users can gain an understanding of some mechanics of AQP and can relate emissions to what they are seeing.

#### 4.2.1 Model description and specifications

The AQP ABM features a top-down view of a generalized commercial AQP operation. Figure C.A in Appendix C displays the assumed dimensions of the model A-frame greenhouse (i.e., GM32510) made from corrugated polycarbonate, which houses the theoretical AQP operation. Figure C.B in Appendix C displays the model surface area dimensions of the one fish tank and two plant tanks inside the model greenhouse. Figure C.C in Appendix C visualizes the placement of the various components which make up a typical APS but are not shown in the model itself. The operation components include two water pumps, PVC piping, a mineralization tank, a sump tank, grow lights, and a heating element, though they are not shown in the ABM for simplicity's sake. Mineralization tanks

are used to stimulate the nitrification process (i.e., the process of bacteria breaking down ammonia into nitrite and nitrate), so the plants are able to absorb the affluent nutrients effectively. The filters and sump tanks are used to remove and store the solids produced from the fish.

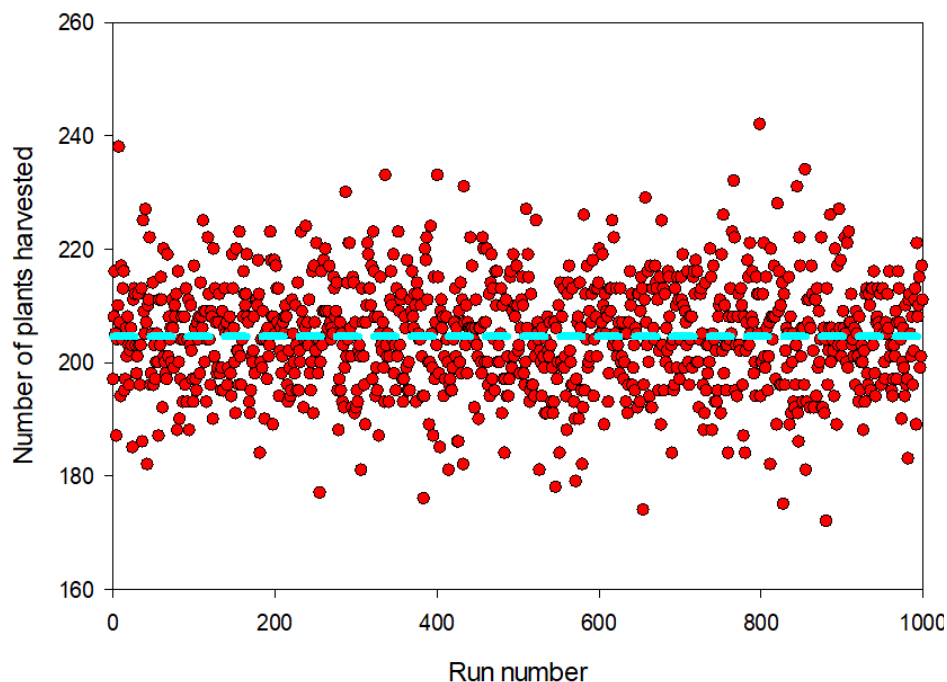
In the AQP ABM, the interface shows the fish and plant tanks being brought together, mitigating the need for piping, the sump and mineralization tanks, and water pumps to be shown. The fish are set to wander in their designated tank, eat, and grow, the feed is set to freely move in the fish tank until eaten and is then turned into a nutrient that can now move into the plant tanks, and lastly, the plants consume the freely moving nutrients and grow. By removing piping and the mineralization processes, this allows the user to focus on the key mechanisms behind an APS. The model also allows the user to select the model's fish and plant types and densities, climate, season, and if the user selects to have the fish restocked, fry replaces a harvested fish. Lastly, once the user selects their desired parameters, the related GHG emissions are displayed on the right side of the interface for each input as well as the total emissions produced over time. GHG emissions are the culmination of air pollutants (i.e., carbon dioxide, nitrous oxides, and methane) which can stay trapped in the atmosphere, causing general warming of the planet (United States Environmental Protection Agency Office of Air and Radiation, 2015). The decision making, parameters, and calculations for the ABM can be found in Appendix C. The number of plants was reduced in the model to plant columns given limitations in the coding of the model.

### **4.3 Results**

Demonstrating case studies of the AQP ABM is vital in ensuring proper outcomes and reasonable variability. Along with the products produced by the model, the AQP ABM also displays if any fish died, total harvested fish and plants, and the related GHG emissions produced by the theoretical system. These metrics are important to include in the model given mortality of fish in a real operation can happen, the fish and the plants are the products of interest, and GHG emissions are a good starting point for users to begin to understand environmental impacts of the Anthropocene. Most fish are harvested with any combination of parameters, however, total number of plants harvested, total model run time (i.e., when all fish have been harvested), and total GHG emissions can vary greatly in the model, even with the same parameters selected.

#### 4.3.1 Results of stochasticity case study demonstration

As with all stochastic models, the ABM was run many times to better understand the range of outcomes for the model (Wilensky and Rand, 2015). To ensure proper functioning of the model and to better understand the possible ranges in results, half of all possible model selections were selected (Appendix B) and tested. Each set of parameter options for the AQP ABM was run 1000 times. Before discussing some data sets produced by this analysis, it is important to understand what is meant by stochasticity in this model. Figure 4.2 displays the total range of plants harvested for a particular set of parameters, which shows the minimum number of

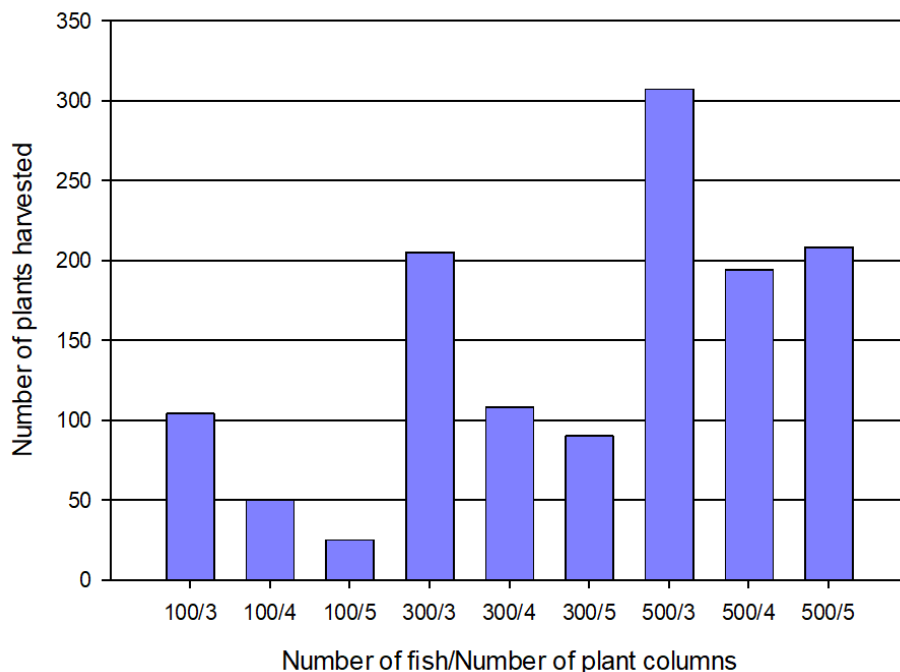


**Figure 4.2.** Total number of plants harvested over 1000 runs for 300 tilapia, 3 columns of basil in the spring in a humid subtropical climate

plants harvested being approximately 172 plants and the maximum being approximately 242 plants. The model does not explicitly show why this range can occur for the same operation for simplicity's sake, however in a real operation, there are several reasons why a real operation may have varied total number of plants harvested per year with the same parameters. First, the system could have an improper water flow rate (e.g., limitations in pumps used or clogging or failure somewhere in the system) causing some plants to receive inadequate nutrients, which would impede growth. Another issue could be around the concentration of nutrients in the water sent to the plant tanks through an imbalance of fish density versus number of plants grown in the system, causing improper growth of the plants in the system. The results of the GHG emissions assessment for any set of

parameters showed similar observations to the testing above. In a real operating system, these differences could show up if there was damage to the greenhouse requiring more heat to maintain the desired temperature or the temperatures for that year were regularly reaching record highs or lows, requiring more or less heating for the greenhouse. Overall, stochasticity testing displayed the efficacy of the AQP ABM and the outcomes having reasonable variability.

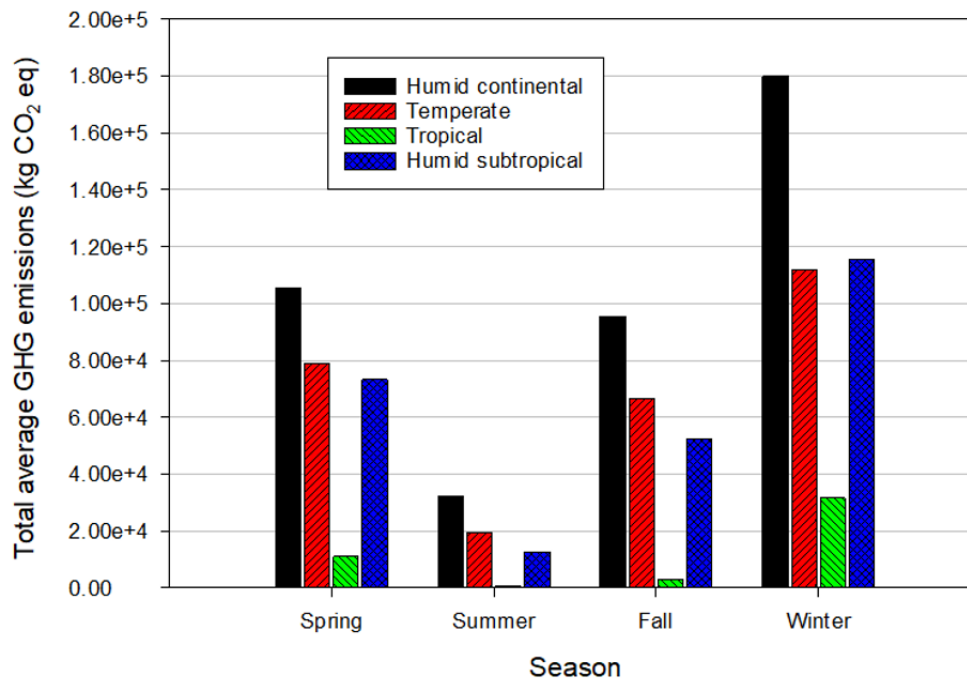
Investigating the broader results related to the number of plants harvested and GHG emissions is vital in displaying the reality of selecting proper parameters in a real operation. Due to the large amounts of data provided by the ABM, a few sets of data were selected from the data to be discussed (see Appendix C for more information). The first set of data selected was the combination of tilapia and basil, which are commonly grown together in real operations (Boxman et al., 2016; Cohen et al., 2018; Love et al., 2014). Figure 4.3 displays the total average number of plants harvested for the different



**Figure 4.3.** The average number of plants harvested for the tilapia and basil parameter selection

combinations of fish and plant densities for any season and climate (it is assumed that conditions remain the same in the greenhouse). Figure 7 illustrates the importance of balancing fish and plant densities and its impact on the number of plants propagated, which translates to real world operations of which are interested in maximizing harvest quantities for both products (Andriani et al., 2017; Manduca et al., 2021).

Figure 4.4 shows the total average GHG emissions produced for the different seasons and climate options for 300 tilapia and 4 basil columns. Each plant column includes 29 individual plants. Unsurprisingly, the tropical climate option resulted in the

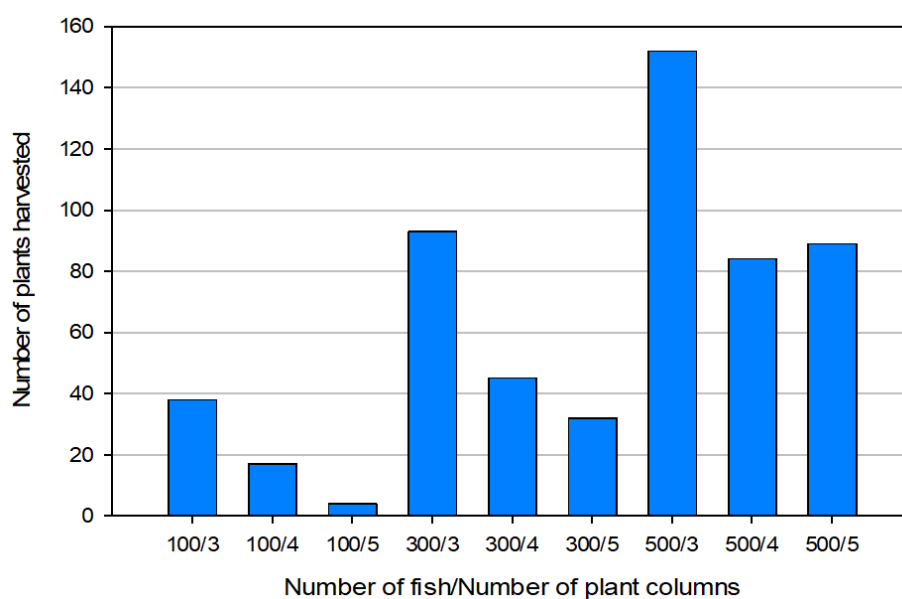


**Figure 4.4.** Total average GHG emissions based on the season for 300 tilapia and 4 basil columns

lowest total emissions, given the somewhat ideal conditions (i.e., seasonal temperatures and sunlight durations) for tilapia and basil growth (Boxman et al., 2016). The other three climate options show relatively similar emissions except for humid continental in the winter, where average temperatures drop much lower on average during the cold months and require more supplemental lighting given the shorter sunlight durations on average per day when compared to the other climates.

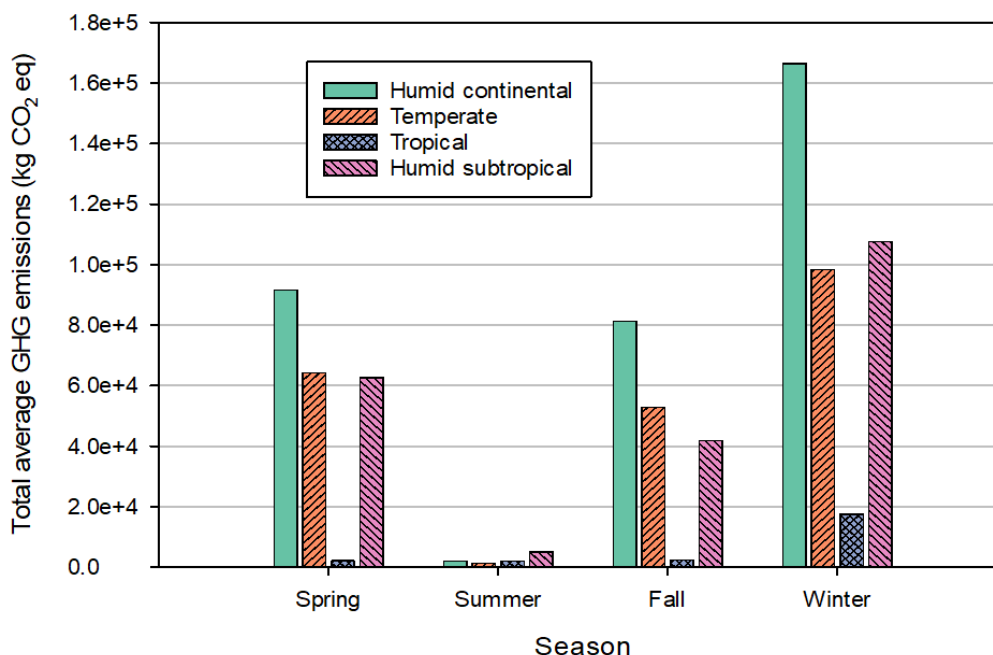
The second set of data selected for investigation is the combination of walleye for the fish type and bell pepper for the plant type. The theoretical operation examined would use media beds (e.g., perlite for the medium in buckets using drip irrigation) for the propagation of the pepper plants, which is different than the standard floating raft method

for the tilapia and basil operation. The model does not show the difference in hydroponics type for simplicity; however, water would not recirculate in this type of operation. Bell pepper plants are also a higher nutrient dependent plant and require more light hours than basil, which will change the number of plants harvested and total GHG emissions. Figure 9 displays the average total number of plants harvested given different combinations of fish and plant densities. Similar trends can be observed relative to the relationship between fish and plant densities, however, the total number of plants harvested is significantly lower than the results in Figure 4.5. Figure 4.6 shows the average total GHG emissions



**Figure 4.5.** Average total number of plants harvested for the walleye and pepper parameter selection

produced for the different seasons and climate options with 300 walleye and 4 bell pepper plant columns. Again, the tropical climate option produced the least number of GHG



**Figure 4.6.** Total average GHG emissions based on season for 300 walleye and 4 pepper columns parameter selection

emissions consistently, though, most climate options had lower emissions overall when compared to the tilapia, basil combination, due to walleye being a cold climate fish, requiring less heating for optimal growth rates.

#### 4.4 Discussion

The goal of this paper was to develop and analyze a tool that could be used to educate students on systems thinking and sustainable food production, using AQP as a case study. By using an ABM for education, the user is not limited to the resources given by their educational institution, which is often restricted by lack of funding. The user can gain insight into the basics of AQP while also learning more about the reality of emissions behind every current product or process.

The first interesting observation from the ABM development and testing is the relationship between the fish and plant densities. Both fish and plant densities can be changed by the user, which allows the user to explore how the fish and plant densities impact the number of products harvested from the theoretical system. The user will find that if the density of the plants is increased at all past three, then the number of total plants harvested decreases. The results of this finding coincide with studies investigating this phenomenon (Andriani et al., 2017). Another interesting component to the ABM is the option to set the climate type. Each reference location had relatively different average seasonal temperatures and hours of sunlight, along with different energy mixes being used for the electricity and heating inputs. For example, the reference location for the humid subtropical climate was chosen to be Tokyo, Japan where electric space heaters are commonplace. The differences in heating modes seem to make little difference in GHG emissions, but the climates themselves tend to dictate the overall emissions produced, which is also what is observed in reality (Boxman et al., 2016; Ghamkhar et al., 2020).

Since the original AQP ABM is meant to be basic to ensure a large range of ages can use the model, many potential iterations could arise from it. The most reasonable iteration of the model would be to simply make it more realistic. Realistic, in this context, means the addition of piping patches to better show the real flow of water and nutrients between the aquaculture and hydroponics sections. Another potential change towards a more realistic system could be changing the heating to be supplemented during cold parts of the days and seasons instead of throughout the day. Another change could include the addition of the mineralization tank to show the more nuanced nutrient cycling occurring in a real APS.

By making these changes, fewer assumptions would be made for the model, however, a much fewer range of people could reasonably use the model.

#### 4.4.1 Model greenhouse gas emissions verification

One key aspect of the AQP ABM is the GHG emissions displayed to the user.

Electricity (i.e., water pumping and lighting), heating, and fish feed are the inputs included in the ABM, which does exclude other inputs and considerations such as construction and supplemental nutrient additives. Though the studies used for comparison may vary in terms of scale, their overall emissions should be comparable to the model, with reasonable justifications for variability. Because the AQP ABM requires the season to be set and the variability in results, the internal tool was again utilized, setting each season to only run to 3650 ticks or three months in model time and then adding emissions from each season for a complete year. Each season for the selected climate was run 1000 times and the average emissions of those runs were used for comparison. Because the model greenhouse conditions and feed rates are made to remain the same throughout the year, it can be assumed then that the emissions would also remain the same, making this comparison reasonable. The number of fish was set to 500 and 5 columns of plants for all data in the verification step as the stocking density of the fish should be much higher (except for carnivorous fish like walleye) than the model will allow so the model was set to imitate this as closely as it can. The total fish tank volume in the theoretical operation is 22.41 m<sup>3</sup> or 5919.30 gallons, so the stocking density at 500 fish is 22.31 fish/m<sup>3</sup>.

Two AQP life cycle assessment (LCA) papers were selected as the parameters assessed in these papers (i.e., plant and fish types and climates) all can be related to a set of parameters chosen in the AQP ABM. LCA is the quantification of a product or process environmental impacts using a functional unit (FU). A FU refers to an assessable value of the product or process of interest, which was selected to be one kilogram of liveweight (LW) fish for the verification process. The main goal of the verification step is to ensure the GHG emissions produced from the theoretical operation is rooted in reality. The two papers will be briefly described and then compared to a similar set of parameters for the theoretical ABM operation relative to considerations such as operation scale, stocking, and yearly production.

The first paper used was Ghamkhar et al., 2020 where a research-scale AQP operation was analyzed in Stevens Point, Wisconsin, USA, which grew hybrid walleye and different kinds of lettuce. The total fish tank volume in the paper's operation was approximately 3.41 m<sup>3</sup> per system with three separate systems (Ghamkhar et al., 2020). The three fish stocking densities were 66, 132, and 198 fish/m<sup>3</sup>. The climate and types of fish and plants were reflected in the ABM; however, the fish stocking density is quite different due to the limitations of the modeling software and for visual purposes (realistic stocking densities would make the model run too slow and the crowding in model interface would be visually unappealing). The paper used for this verification step reported annual GHG emissions of 13,286.48 kg CO<sub>2</sub> eq/year with the harmonized functional unit of 29.1 kg CO<sub>2</sub> eq/kg LW fish (Breitenstein and Hicks, 2022; Ghamkhar et al., 2020). Comparatively, the model reported annual GHG emissions of 69,244.09 kg CO<sub>2</sub> eq/year with GHG

emissions using the desired functional unit of 152.7 kg CO<sub>2</sub> eq/kg LW fish. As discussed earlier, the stocking density of the model is significantly lower than any of the three densities analyzed in the paper. If the total annual emissions from the model were harmonized using a more proper stocking density (132 fish/m<sup>3</sup>), the emissions using the harmonized FU was 25.81 kg CO<sub>2</sub> eq/kg LW fish (Ghamkhar et al., 2020). The amount of fish feed required is much greater in reality, however, since the main contribution to GHG emissions in an AQP operation stems from heating and electricity, this verification step shows that the model is comparable to the published study relative to AQP operations' GHG emissions.

The second paper used was Kalvakaalva's thesis on a pilot-scale AQP operation based in Auburn, Alabama, which grew tilapia and cucumbers (Kalvakaalva, 2020). The investigated operation was decoupled (the aquaculture and hydroponics setups had their own greenhouses) and not recirculating (because the operation used media beds and drip irrigation, the water from the hydroponics section is not sent back to the fish tank) (Kalvakaalva, 2020). The fish tank volume was found to be 150 m<sup>3</sup> and the stocking density of the tank was not given. The authors reported annual GHG emissions of 38,737.42 kg CO<sub>2</sub> eq/year and using the FU being 19.3 kg CO<sub>2</sub> eq/kg LW fish. The model was required to use a different plant type (peppers) though both are larger plants (Breitenstein and Hicks, 2022; Kalvakaalva, 2020). The model's annual GHG emissions were 51,732.73 kg CO<sub>2</sub> eq/year with the GWP using the desired FU being 152.1 kg CO<sub>2</sub> eq/kg LW fish. Again, if the model had a more realistic stocking density (150 fish/m<sup>3</sup>), the harmonized GHG emissions would

be 22.62 kg CO<sub>2</sub> eq/kg LW fish, an even closer value to the paper's findings (Kalvakaalva, 2020; Manduca et al., 2021).

#### **4.5 Conclusion & future work**

Educating the public on emerging technologies is crucial when there is an interest in sustainability. Academics often develop innovative technologies but often fail to reach the public in a clear and concise manner. Many teaching techniques are relatively productive but given the limited resources allocated for both the educators and those being educated, developing efficient and easily accessible educational tools has become ever more important. Producing and testing an AQP ABM as a starting point for sustainable food production education while also exploring systems thinking was the main goal of the project. The model provides a simplified overview of a complex system and is able to show many different considerations of an operation and the outcomes produced from making various decisions. The testing of the model made clear the stochasticity of it and the results of selecting different parameters. The AQP model also enables users to utilize learned tools to make changes to the model to further explore AQP as a system and the various changes and additions that could be made to it.

The next step for this project will be to deploy the AQP ABM to students of varying ages. As discussed earlier, this model can be used for different age groups for different purposes. For example, a group of students in fifth grade may explore the base model and discuss ways of maximizing plant production while minimizing GHG emissions, but a group of university students in a systems thinking class may explore the code of the model to

understand how the model works and make meaningful changes to the code to explore a different aspect of AQP. Lesson plans to effectively deploy the model will also need to be developed and tested for the different age groups to ensure the various goals are achieved.

## Chapter 5

### **A survey-based approach to understanding aquaculture and aquaponics general operational parameters and attitudes towards value-added and value-recovered products**

#### **5.1 Introduction**

Aquaculture arose as a viable alternative to industrial fisheries, given the stagnation of industrial fisheries total harvests (FAO, 2024). Industrial fisheries utilize several different kinds of technologies to efficiently harvest wild-caught aquatic species, while aquaculture utilizes tanks or netting and feed to artificially propagate desired aquatic species (Avadí and Fréon, 2013; Henriksson et al., 2012). The farming of these species is required to answer the ever-increasing global demand for aquatic species, given industrial fisheries would need to travel further out into seas and oceans to find new populations to harvest, which would in turn increase the price of seafood for the consumer. Globally, aquaculture generates hundreds of billions of dollars annually in sales, making this part of the food sector highly lucrative from an economic perspective (FAO, 2024). Aquaculture has proven to be effective in reliably propagating large quantities of aquatic specimens in relatively small volumes of water, however, this food production method also brings many negative considerations and consequences along with it. First, aquaculture currently depends heavily on forage fish (i.e., small, wild-caught prey fish), which is growing more unsustainable as aquaculture production continues to increase while again industrial fishery harvests have largely remained stagnant for some time and the growing concern of

ecosystem disruption for the wild life remaining in the oceans (Ayer and Tyedmers, 2009; FAO, 2020). Second, aquaculture operations output nutrient dense effluent water and is currently considered a waste stream, causing further concern for consequences such as eutrophication (i.e., nutrient runoff which collects in waterways and causes algae blooms and weeds) (Bare, 2011; Henriksson et al., 2012). Because demand for aquatic species continues to increase and the downsides related to aquaculture, other alternatives are essential for more sustainable food production.

Sustainability is the amalgamation of economic, environmental, and social considerations for products and processes, where the goal is to minimize environmental impact while maintaining proper profit margins and consumer demand. As discussed earlier, aquaculture leads to several environmental concerns, leaving significant room for improvements when considering sustainability, making aquaponics a reasonable food production alternative. Aquaponics uses a symbiotic relationship between aquaculture and hydroponics (i.e., generally a water-based method for growing plants) for the purpose of using the outputs produced in aquaculture to hydrate and fertilize the plant production section which then acts as a natural nutrient filtration system for the fish tank (Breitenstein and Hicks, 2022; Goddek et al., 2019; Nelson, 2016). This food production methodology has proven to be effective in reducing waste streams and water use when compared to aquaculture (Bernstein, 2011). Though promising on some fronts, aquaponics can be energy intensive and conventional fish feeds are also commonplace (Goddek et al., 2019). As renewable energy and alternative feeds are being investigated, ensuring a stable industry and market in the meantime, is critical.

While aquaponics is becoming increasingly popular in the United States (US), many venturing into the aquaponics industry seem to be floundering with the general business model under the current economic system, especially in light of the recent pandemic (Quagraine et al., 2018). Love et al. (2014) conducted an international survey of aquaponics practitioners which investigated baseline operational information. For example, plant and fish types, annual harvest quantities, purpose of the operations, facility information, energy sources, and more were collected to better understand the overall landscape of aquaponics globally (Love et al., 2014). The authors found that many of these operations were small-scale hobby projects, showing interest for this type of food production, but they also do not have the necessary tools to scale-up the operation to make it into a formal business (Love et al., 2014).

In another related paper by Quagraine et al. (2018), a comprehensive economic analysis of hydroponics versus aquaponics in the Midwest (a region in the US) was conducted and a separate analysis of three different scales of aquaponics operations was also conducted to better understand the current financial landscape of the industry in that region and the repercussions of choosing a certain scale of operation. The authors investigated four active operations along with conducting a literature review of other operations analyzed in published work (Quagraine et al., 2018). The authors found that the largest farm tended towards more consistent success due to lower production costs (i.e., economies of scale), however, with proper operational choices, such as certified organic plant production, most aquaponics businesses can be successful in the Midwest. The authors identify limitations of this work as having no consideration for distribution and

marketing, two crucial factors for a fruitful business in the US. Though production is a major aspect of an aquaponics operation, sales and distribution are other major considerations relative to overall business success in the industry.

Prior to this study, limited investigation into aquaponics products themselves has been conducted, particularly in the US. Most work investigates consumers' willingness to pay (WTP) for products and characteristics such as organic-certified labeling. For example, Meyer et al., 2025 explores consumers' WTP for different kinds of labeling that aquaponics products could have as well as considerations such as environmental concern and health consciousness. The authors found that the surveyed population is WTP more for eco-friendly products and locally grown produce when compared to field-grown products (Meyer et al., 2025). While it is vital to investigate these parameters from the consumers' perspective, investigation into the producers' perspective is equally important while also exploring a potential method for increasing revenue generation and stability for these businesses.

Since economic success can be difficult to bring to fruition in the aquaponics industry, the use of value-added (VA) and value-recovered products (VRPs) has been proposed to help stimulate revenue generation and increase potential for more stable product distribution. Value-added products (VAPs) are produced using post-harvest processes (e.g., smoking, dehydration, freezing techniques, etc.) to make the final distributed product more valuable. VRPs are produced using operation by-products or waste streams and performing processes (e.g., drying, grinding, digestion, etc.) to make a valuable product. Several studies have investigated options for byproducts produced in

aquaponics. For example, Shahidi and Ambigaipalan (2015) discuss the many different substances and products that could come out of seafood byproduct. They discuss omega-3's, chitin, collagen, protein, vitamins, and more as several options for value-recovered products for the purpose of describing the nuance of each one, how they could be used and discussed where these substances would come from relative to seafood byproducts (Shahidi and Ambigaipalan, 2015). However, the authors do not consider the viability and economics of said products or the processes to make the products and no other study exists investigating VA and VRPs in the aquaculture and aquaponics industry, requiring further investigation.

The goal of this study is to investigate cold climate aquaculture and aquaponics operations' general operating parameters as well as qualitatively and quantitatively understanding producers' willingness to invest in the addition of value-added and value-recovered processes to their current operations.

## **5.2 Methods**

While the survey conducted by Love et al. (2014) was thorough in gaining a periphery understanding of many operations across the world, the survey did not consider certain noteworthy areas, such as distribution decisions and gauging interest in VAPs and VRPs. Literature into current and former aquaculture and aquaponics operations is somewhat limited, but investigation into US cold climate operations is even more so, making the survey a fruitful endeavor.

The main country of focus was the US as investigation into aquaponics sustainability is extremely limited and interest in the methodology is increasing. US cold climate operations were specifically the target population for the survey as these operations have an additional layer of complexity given the higher dependence on energy (from increase heating and lighting demands) for the cold months of the year, which is an additional expense for these producers to consider, particularly Wisconsin, Minnesota, and Michigan, given the interest in local impact and the ease of access to permits and thus mailing information. The survey was approved by the University of Wisconsin – Madison Institutional Review Board (ID: 2023-0285). Informed consent was described at the beginning of the survey and was assumed if the respondent completed and submitted the survey and was only applicable for adult producers. Aquaculture producers were also included in deployment for multiple reasons. First, aquaculture producers with already intensive (i.e., dedicated tanks for propagation) operations could transition to aquaponics, making it an interesting avenue to explore in the survey. Lastly, though the plant side of aquaponics is generally more fiscally productive (some waste from plant production can be produced but is generally sporadic and minimal), one of the main waste streams leaving these systems (aside from the effluent water and solids) are the carcasses produced by the fish, making their opinion and interest in value-recovered products equally valuable. Mailing paper surveys was the main mode of deployment, given the information available from the licenses, however, the survey was also made into an online version to be distributed using social media to ensure minimal operations were missing in the three

states. A financial incentive of five dollars was awarded to respondents who completed and returned the survey.

The initial part of the survey was developed using the support of the survey deployed by Love et al. (2014), given the lack of standardization of surveys in the aquaculture industry. The survey consists of eighty-three total questions with separate sections for aquaculture and aquaponics operations (full survey instrument in Appendix D). The first and third sections of the survey ask questions related to overall operational information for aquaculture (first section) and aquaponics (third section) operations. General operation questions were posed (e.g., types of fish, annual harvest amounts, distribution methods, changes to their operation over time, etc.) to gain some interesting parameters so comparisons can be made amongst all respondents. The general information section also allows for analysis to include the exploration trends relative to financial success as well as allowing for a better understanding of potential external factors which would make the producer more inclined to make changes to their operations or achieve overall success. Other lesser components (e.g., impact of a pandemic) are also contained within this section and will be discussed further in the subsequent sections.

The second section explores interest in aquaculture producers transitioning to aquaponics operations, which aims to understand potential interest in transitioning into aquaponics, any potential challenges related to the transition, and quantifying the rate of return these producers would like to see if they were to make the transition.

The fourth section examines producers' willingness to invest in the addition of value-added and value-recovered processes for the purpose of making their final product more valuable without requiring high capital investments. The section initially investigates how the operation's products are currently sold and asks about VAPs and VRPs that have already been considered by producers and the potential challenges with these post-harvest processes. Questions related to willingness to invest in VAPs and desired product characteristics from a producer's perspective were also posed. WTP is generally utilized for the consumer side of product endeavors, however, understanding producers' willingness to invest is also necessary in this case to understand if VAPs and VRPs are even a venture that is of interest to producers. While using direct surveys for WTP can be flawed, it is needed to better understand if producers have reasonable expectations for these products, so several key pieces of literature were used to design this section of the survey (Breidert, 2007; Breidert et al., 2006; Voelckner, 2006).

The fifth section surveys the producers themselves. This section aims to understand previous education and experience related to agriculture. The purpose of this section is to gain some insight into how previous education and experience can impact an aquaculture or aquaponics operation and its success. The final section collects some general demographic information to understand any trends related to considerations such as age, gender, or region and their potential relations with choices in fish types, distribution method, etc.

### **5.3 Results & Discussion**

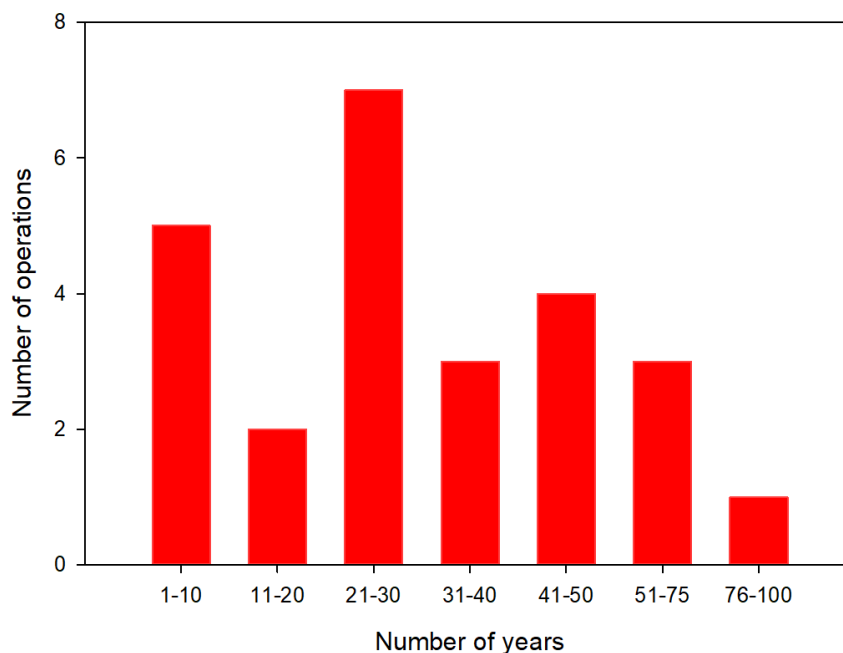
The purpose of this study is to gain insight into aquaculture and aquaponics as a business venture and assess producers' attitudes towards value-added and value-recovered products. Three hundred and eighty paper surveys were deployed 05/05/2023 to aquaculture license holders in Wisconsin (one hundred seventy-nine), Minnesota (one hundred twenty-six), and Michigan (forty), with an online version being published 05/05/2023, and closed 07/25/2023. Based on investigation into the license holders, twenty-five operations in Wisconsin, one operation in Michigan, and nine operations in Minnesota are likely aquaponics operations. After working through address corrections and other errors, eight paper surveys could not be delivered for various reasons. Three paper surveys were returned, and four emails were received from those who did not wish to take the survey, or the survey was not applicable to them.

From the deployment, forty-seven total responses were collected, mostly from the distribution of the paper survey. Due to incomplete responses or inadequate information given, only twenty-five were able to be analyzed and compared. Of the twenty-five responses, twenty-three were from aquaculture producers and two were from aquaponics producers.

### 5.3.1 General operational background information

The goal of this section is to better understand the different factors and constraints under which these producers are working. Exploring years of operation was one of the necessary bases of the survey and this section to better understand the age of the industry

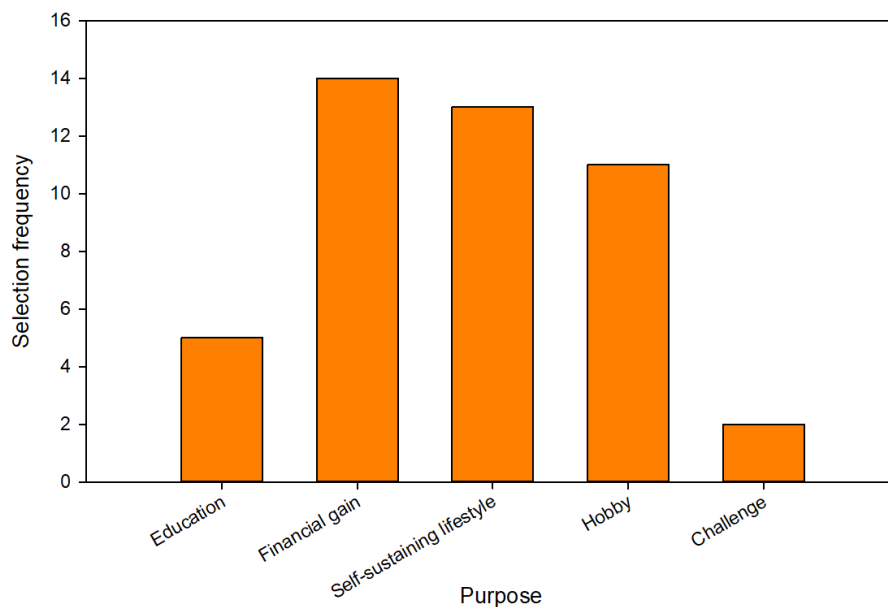
in the region and is established in Figure 5.1. Figure 5.1 shows the surveyed operations have been/were in business for a wide variety of time, with “21-30 years”



**Figure 5.1.** Years of operations for surveyed producers, including closed operations

in operation being the most common and “76-100 years” being least. The figure shows the relative success in terms of time for these operations, though three aquaculture operations are no longer in operation for various reasons. One operation was seemingly forced to close due to a loss of equipment because of a missed loan payment, while another struggled to sell their product in general. The causes for closure of these operations are all within the confines of reason, though the value-added and value-recovered products are aiming to help avoid these failures in the future. Both aquaponics operations were in the “1-10 years” range (one of the operations is also no longer in operation), expressing the relative infancy of aquaponics in these states.

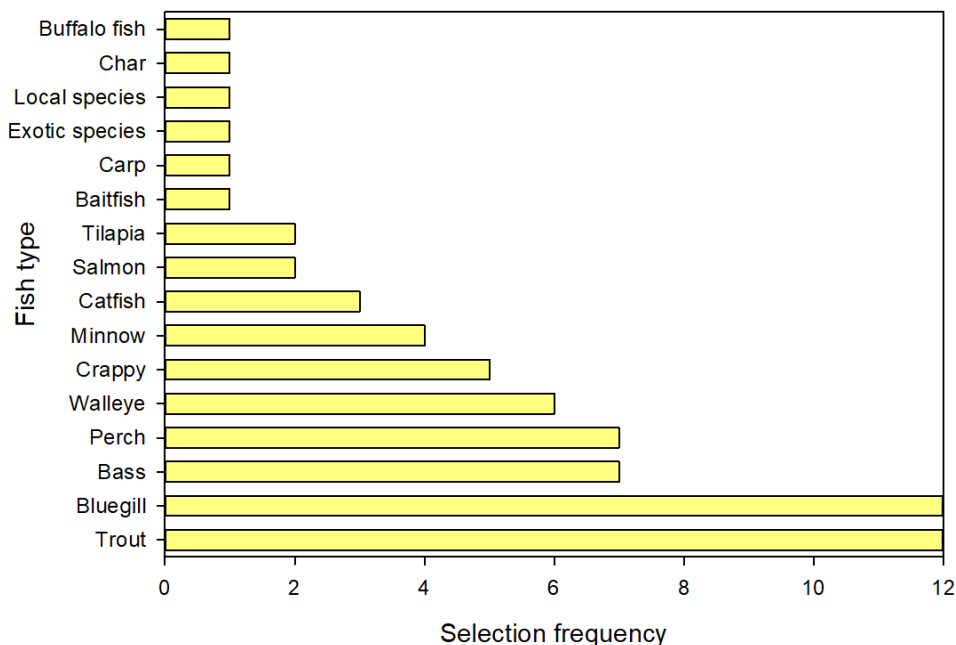
Another point of interest in the survey was to better understand the original purpose and motivation of the operations. Figure 5.2 shows the original purpose of the surveyed



**Figure 5.2.** Original purpose(s) of surveyed operations

operations, with “financial gain” being the most selected option (fourteen) and “self-sustaining lifestyle” being a close second at thirteen times selected. Wanting a challenge and “education” were the two least selected options. Another question asked in the survey was similar to the previous one but was meant to draw more distinction relative to their motivations (Table D.A in Appendix D). The highest motivators were “economic benefit” (six), “grow your own food” (six), and “improve community food security” (five). Interestingly, “economic benefit” was also one of the lowest ranked motivators for five operations. Figure 5.2 and Table D.A illustrate these producers’ desire to turn profit, while also working to benefit both themselves and their communities.

Following operational timeline, purpose, and motivation, delving into the particulars of the operation was the next step. For the aquaculture operations, five were intensive systems, eight were extensive (i.e., utilizing netting and waterways to farm aquatic species), and eight were a mixture of both intensive and extensive systems. In these different systems, many types of fish were propagated in the same operation, with eight operations opting to focus on one (see Appendix D). Surprisingly, over half of the operations had two or more species being propagated, which expresses promise for success using multiple species in the aquaculture industry, given different consumers may prefer one species over the other. For example, some operations were growing fish such as catfish, bluegill, bass and others, which would imitate a particular trophic level in bodies of freshwater while also allowing the business to sell multiple products (e.g., some sold as fresh fillets, some sold for stocking, some could be processed further). Figure 5.3 displays the different kinds of fish grown



**Figure 5.3.** Types of fish propagated in surveyed operations

by the surveyed operations. The two most propagated types were bluegill and trout (twelve each) with perch and bass following those, implying demand serviced by these operations is mainly for local species, though a decent variety of fish are currently being grown in cold climates (shown through the other operations). The choice of local species is noteworthy because concerns with importation permits and contamination with natural bodies of water would be largely mitigated. The choice of local species helps with reducing operating costs as these species are already acclimated to cold climates, unlike tilapia. One of the two aquaponics systems grew bluegill and lettuce, while the other grew tilapia and several kinds of vegetables and leafy greens (e.g., lettuce, cucumbers, herbs, and edible flowers). The choice of combinations by the aquaponics producers is interesting because while both chose commonly propagated fish in aquaculture, one chose a textbook type of plant (lettuce) and the other seemingly explored many different options, which allowed them to sell in a few different markets (i.e., schools, restaurants, grocery stores, and specialty shops). Further discussion will accompany harvest quantity and distribution methods.

Another point of exploration was the estimated annual harvests of the previously investigated fish (see Appendix D). First, estimated annual fish harvests were highly varied amongst surveyed operations. Six operations harvest an estimated “10,000+ pounds” annually, while six produced forty-nine pounds or less. For the two aquaponics operations, their estimated annual fish harvests were both “100-499 lbs,” along with estimated annual plant harvests of “100-499 lbs” and “5000-9999 lbs.” The stark difference in plant harvest quantities is unsurprising given the latter operation produced many plants including

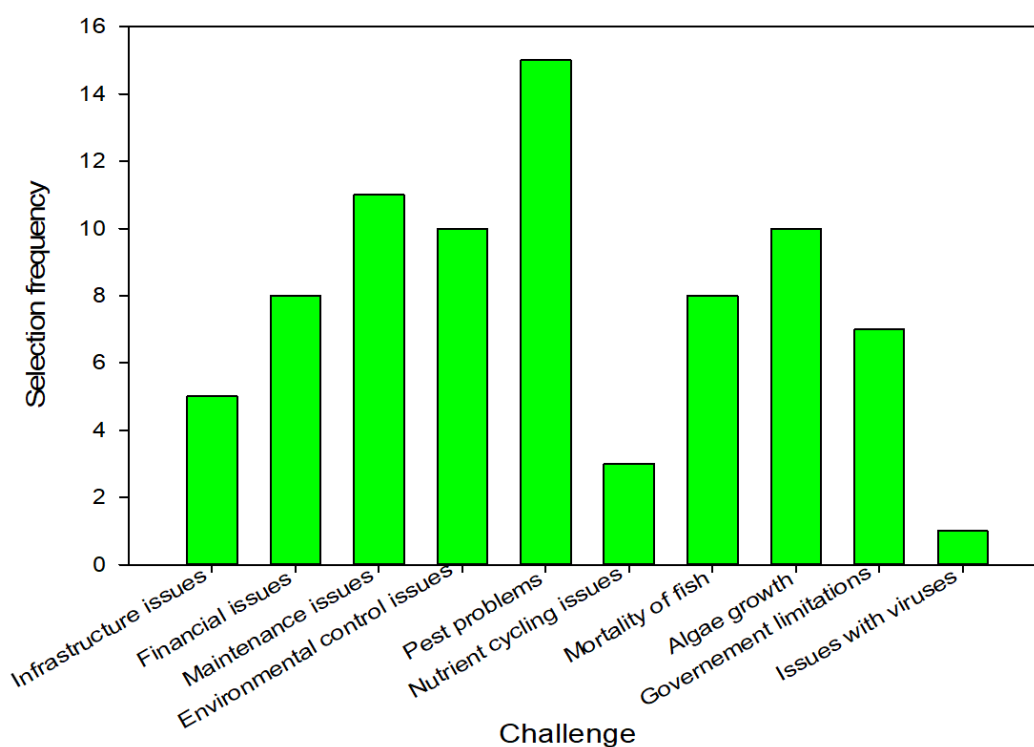
vegetables. Though the plant annual harvests were vastly different, harvest quantities of the fish were similar, causing curiosity relative to nutrient cycling and stocking densities of the fish.

How the products were prepared for sale and the distribution of the producers' products is another point of interest explored by the survey. First, many producers sold their fish live for the purpose of stocking local bodies of water. Other producers were propagating baitfish for stocking and recreational fishermen, while the rest were growing fish for consumption. The producers growing fish for consumption prepared for sale in different ways. Most operations sold their product as fillets directly, while one other sold their fish whole, and two others already sold VAPs. Four operations did not sell their fish either because they had a particular license where sale was excluded, or they only produced enough for their own consumption. Product types and distribution choices by these producers are interesting because choices such as selling directly can be easily disrupted when compared to selling into food services and grocery stores. Two operations already producing VAP also demonstrate some promise in the market by showing consumer interest in relevant products.

Along with current standings, the survey explored any scaling that had occurred while these operations were in business. Thirteen operations reported to have scaled up, three operations scaled down, and seven operations stayed the same. Reported challenges related to scaling include having more to manage, limitations due to regulations, and increased staffing costs. The scaling of these operations is fascinating because it shows an

upward trajectory for many, which allows for reduced production costs (i.e., economies of scale) to take place.

Exploring the many challenges faced by the surveyed producers is useful for informing future ventures in the aquaculture and aquaponics industries. Figure 5.4 displays the many different operational challenges the respondents have had to overcome. The



**Figure 5.4.** Operational challenges faced by surveyed operations

main issues reported were “pest problems” and “maintenance issues.” One aquaponics operation reported dealing with a virus plaguing their plants. The other least selected challenges were “nutrient cycling issues” and “infrastructure issues.” All these challenges are worthy of note because one (“pest problems”) is largely out of the producer’s control once operation begins, especially if the products are certified organic. Producers also

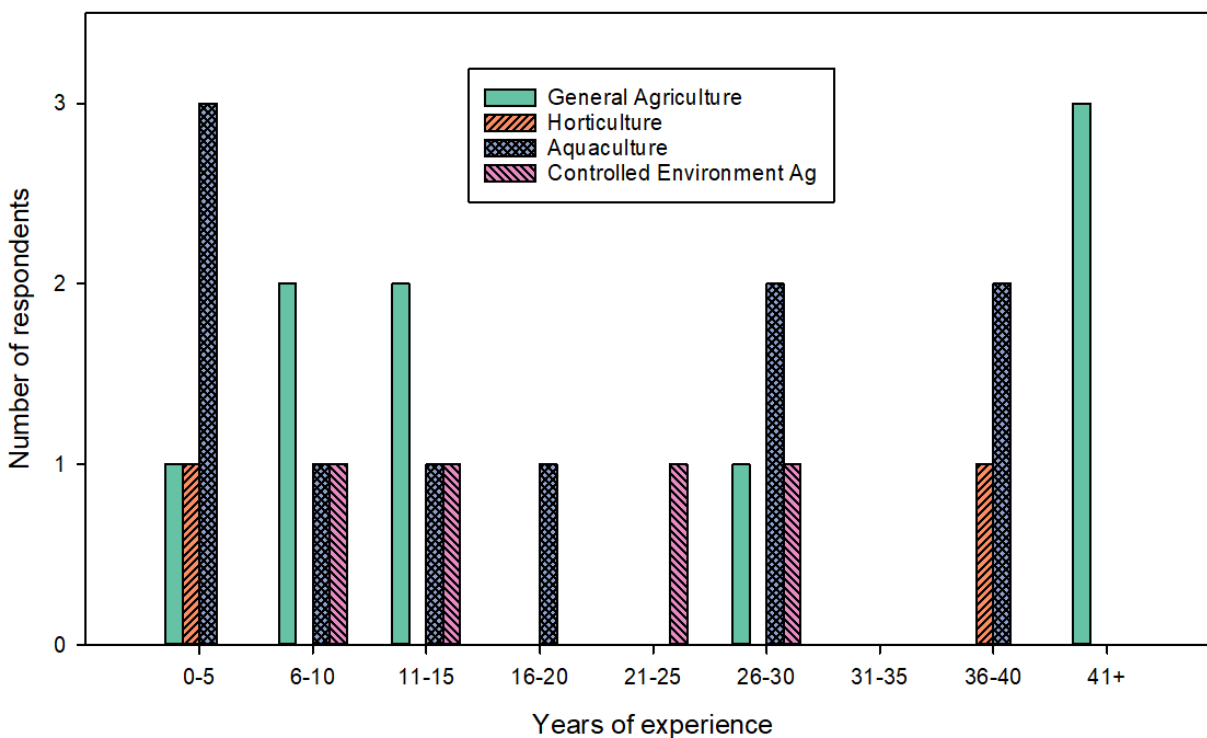
cannot control when their operations have issues, however, regular checks and tests could help to alleviate the negative repercussions of a component failing. The set of challenges faced by the producers demonstrates the nuances of owning and operating aquaculture and aquaponics businesses, though they are not the only potential challenges.

Another set of challenges was realized during the COVID-19 pandemic and was explored by the survey. The pandemic was an extraordinary event which brought to light many pitfalls in many different industries. All but two operations were operating during the pandemic and the main issue reported was, unsurprisingly, the disruption of distribution and sales. The next most common responses were delayed funding/loans, their associated business shutdown, workforce limitations, and the loss of necessary equipment. The responses to this part of the survey were interesting because it showed this industry was also heavily impacted by the pandemic and showed the importance of further investigation into practical ways to prevent future disruptions.

Exploring the idea of transitioning the aquaculture operations to aquaponics was also investigated. Based on other questions, seven operations should be able to physically make the change, though more creative techniques could be used to allow all operations to be transitioned. Eight producers responded that they would be interested in making the transition. With an overall goal of sustainability in mind, aquaculture operations introducing the hydroponics section to their operation would help to mitigate nutrient loss and waste streams, while also opening a new market and revenue source to the operation with minimal effort.

### 5.3.2 Agricultural previous knowledge and experience

The goal of this section was to learn more about the producers themselves and better understand their prior experiences related to agriculture. The first set of questions focused on the prior educational opportunities and experiences on various agricultural topics prior to the start of their operations (see Appendix D). The topics offered were “general agriculture,” “hydroponics,” “horticulture,” “aquaculture,” and “controlled environment agriculture.” There were a wide variety of responses to this set of questions, though most respondents reported a decent amount of schooling relative to general agriculture and aquaculture. The next set of questions focused on the prior “hands-on” experiences of the respondents in various agricultural applications. Figure 5.5 is the culmination of the responses to these questions. Figure 5.5 shows a wide array of prior



**Figure 5.5.** Prior experience gained before starting aquaculture or aquaponics business experiences over a wide expanse of time. Based on the two sets of results from the section, producers seemed to have had at least some experiences around agriculture and aquaculture and some experience in other parts of the agriculture sector or with other aquaculture operations before starting/investing in their own.

Asking the opinions of the producers was essential for better understanding the resources they used and those that would have helped them when beginning their aquaculture/aquaponics operations. First, the surveyed producers reported to have used many different resources to aid in their entrepreneurial endeavors such as the use of manuals, online forums, and mentoring (see Appendix D). The most reported resource was simply various classes either through school or third-party organizations. Next, the producers' most suggested resource was grants offered to this industry, which will be discussed further in the discussion of permits and policy. The other two suggestions were related to an increase in relevant classes offered, which will also be discussed further in a future section. Some useful online resources for aquaponics include tutorials from Iowa State University and online forums run by The Aquaponics Association, which both help to raise the curtain on aquaponics as an operation and a business (Patillo, 2017; The Aquaponics Association, 2024). Schools are also beginning to recognize the utility of aquaculture and aquaponics, so parts of classes are being allotted to these subjects. Based on their responses and recommendations, these producers clearly recognized the importance of education and experience prior to their endeavors, but it is also clearly not the only factor for success in this industry.

### 5.3.3 Interest in aquaculture and aquaponics value-added and value-recovered products

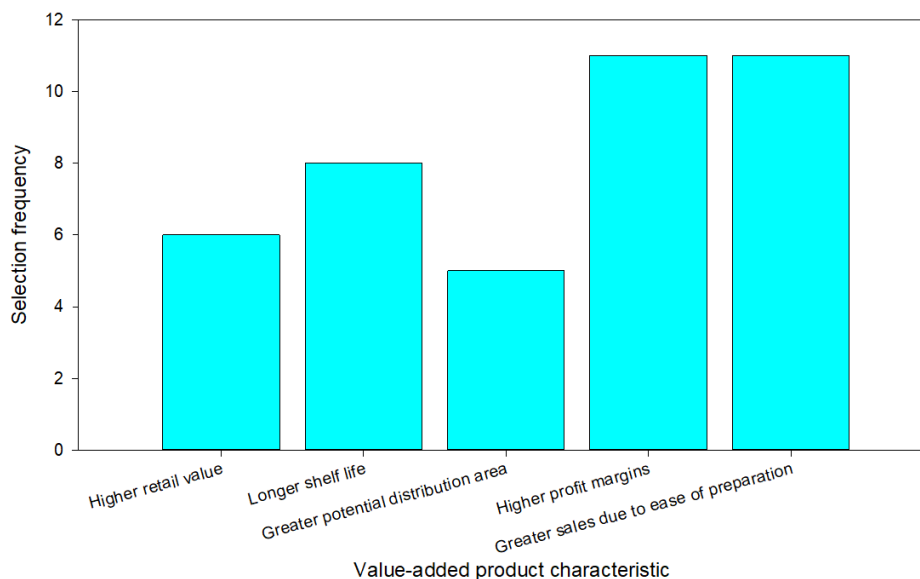
The goal of this section is to gauge interest in value-added and value-recovered products for the purpose of helping to improve the stability of general aquaponics businesses in the current market. The section explores any prior interest in value-added and value-recovered products along potential challenges they could foresee with said products. Eight producers reported to have considered producing value-added and value-recovered products, while one operation did smoke some of their product already. For the challenges, the most common responses were related to government regulations around the processes used to the products, which was also a key reason why many respondents were hesitant to invest. The other challenges reported were the need for additional employees, initial costs, and the increase in time needed. The challenges that concern the producers are reasonable, however, if done correctly, the government should not interfere given the proper permits were attained and the quality of the products is ensured.

To quantify the producers' interest in VAPs, they were asked for the desired return on investment for a VA filet (see Appendix D). The responses (seven) show limited interest of these products in general, though those most that were interested tended to have a reasonable desired extra revenue (between \$2 and \$12 per pound), given the general sale per pound of typical raw fish filet is anywhere from an estimated one to twenty-five dollars per pound or more depending on the species of fish (Perdue and Hamer, 2019). Eighteen respondents either chose not to answer or answered they would not invest with any increase in revenue. The latter would not invest for multiple reasons with the main one being the old age of respondents and unwillingness to further invest in the business. Other

reasons include having limited time and wanting a more stable market, which was assumed to mean having a consistent distribution of their products. Based on earlier answers, the producers recognize the potential of VAPs, however, for many reasons, they are not currently able to invest into a new and challenging endeavor.

To further quantify interest in VAPs, the producers were asked for their desired payback periods for a \$100,000 initial investment into VAPs (see Appendix D). The purpose of this question was to see if producers would be willing to wait a reasonable amount of time for recouperation of invested funds for value-added products. The most selected years were two, three, and five, requiring a sizeable amount of return in a short period of time. However, when looking back at the ages of these operations, some operations have not even been in business for the above amounts of time, making the venture reasonably seem less achievable, given they likely do not have capital to reinvest yet.

Desirable characteristics of VAPs from a producer's perspective were also explored. Figure 5.6 explores various advantageous VAP characteristics of which they were asked to choose the ones most desirable to them. The two most selected options are related to the

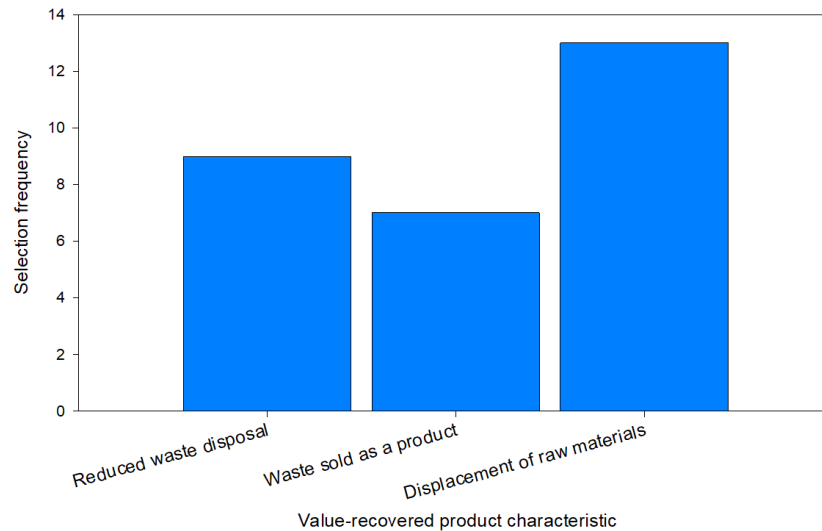


**Figure 5.6.** Desired characteristics of VAPs from a producer's perspective

economic side of the characteristics, suggesting less of an issue with storing or distribution. This is important because economic gains were the original reasoning for investigating interest in VAPs for aquaculture and aquaponics to aid in stability of the individual business. The figure also shows that investigated products should lean more towards a higher value product rather than one that can be sold to more places or stored for longer, though, ideally, all characteristics would be found in an optimized VAP.

WTP and payback period were not explored for VRPs as the finances of these products are less straightforward. Quantifying interest in VRPs was not included in the survey as technologies necessary to make these products such as micro-scale anaerobic digestors are still in their infancy, making estimating the cost and value of the products fruitless. Exploring desirable characteristics is, however, useful so products (with these attributes) could be explored in the future. Disposing of aquaculture byproduct can be a

costly endeavor, so VRPs could also help in alleviating disposal costs (Yan and Chen, 2015). Figure 5.7 lastly explores desirable VRP characteristics, and the survey again asked respondents to choose those most interesting to them. The most selected option was the



**Figure 5.7.** Desired characteristics of VRPs from a producer's perspective

“displacement of raw materials,” suggesting unified interest in reducing waste streams produced in the operations, while also selling new products.

#### 5.3.4 Limitations of the study

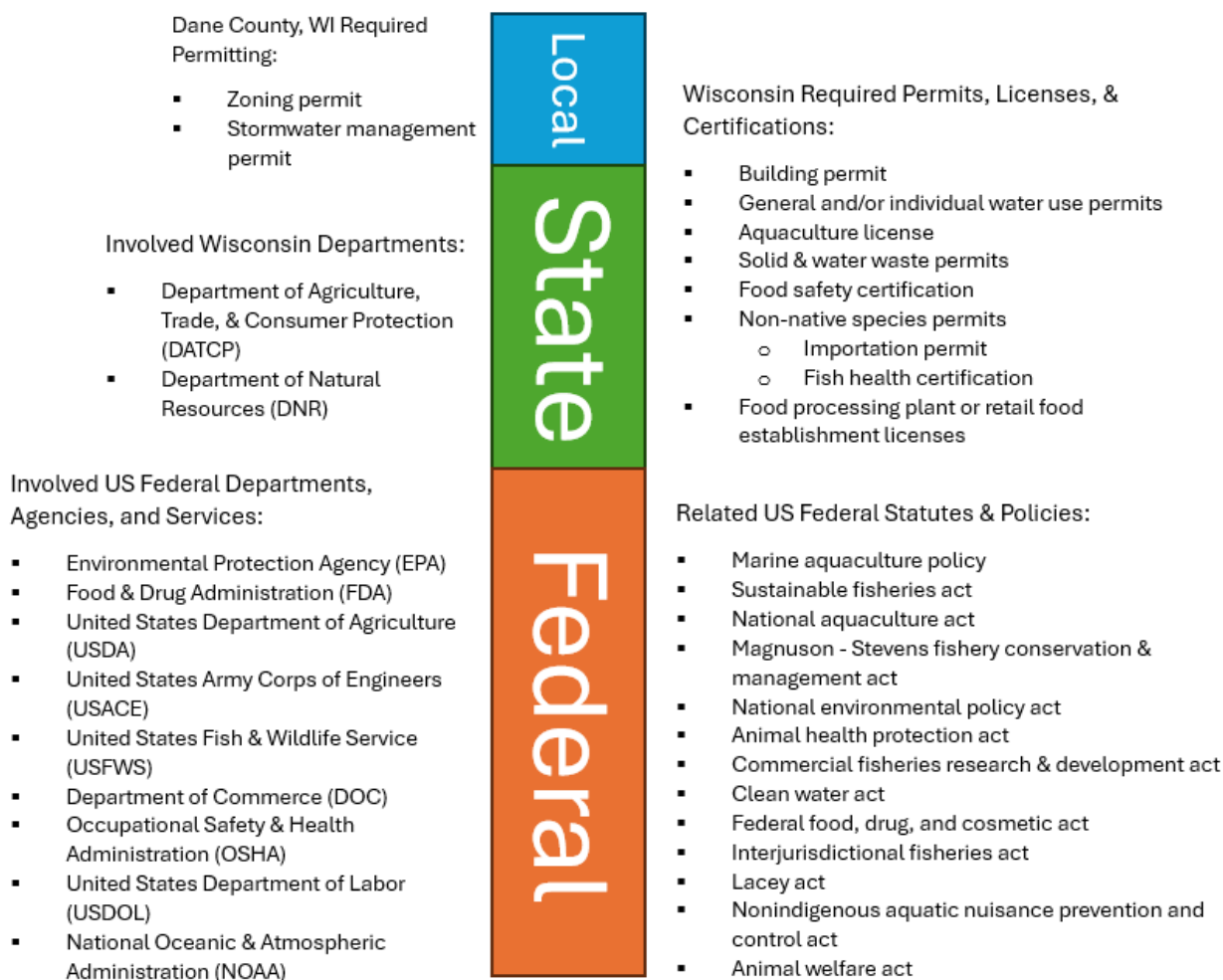
Several limitations arose from the decisions made in the design and deployment of the survey. One major limitation is the sample size and the decision to assess only three states in the US. The choice to only investigate three states was made for two reasons: (1) cold climate operations are particularly interesting due to the consideration of seasonality and increases in energy demands and (2) these states’ aquaculture licenses are easily accessible. The relatively small sample size is also a limitation, however, when parsing

through the licenses, many of them were needed for unrelated activities such as adding a water fountain to a pond or restocking a body of water owned by the license holder with fish. A constraint relating to the survey itself is the limited number of questions posed regarding WTP, which was due to the number of questions already asked before. Several questions were related to general operational parameters, operational challenges, and business failure modes, making the survey already extensive. Lastly, the survey did not explore WTP or invest in particular kinds of certifications or labelling, which would be interesting given the existence of studies conducted on consumers' WTP for these types of labels.

#### 5.3.5 United States aquaculture and aquaponics legislation and permitting discussion

One essential and arguably the most perplexing part of almost any agricultural operation in the US is acquiring permits, licenses, certificates along with abiding by all statutes and regulations set forth by federal, state, and local governments, which can cause delays and disruptions in operations that can lead to failure for some. Based on investigation, there is not one single resource to understand all the different rules and regulations around aquacultural and aquaponic activities, leaving tremendous room for error. Figure 5.8 explores some applicable statutes and policies, while also displaying the parts of governments involved and the many permits, licenses, and certifications required before even beginning operation. Dane county, Wisconsin was used as the example location because the rules and permitting could be different depending on the state and county. The main governmental stakeholders involved are the USDA, EPA, and FDA as they are concerned with considerations such as the health of the fish, what the operation

considers waste streams, how much water is being used, the quality of the food produced, etc. The list of federal legislation is not a complete list; however, these policies and acts are most relevant to aquaculture, which is also the part of aquaponics with the most restrictions in the US.



**Figure 5.8.** Example of Federal (USA), State (Wisconsin), and local (Dane county, WI)

involved government sectors, statutes, policies, permits, etc.

As discussed previously, surveyed producers recommended increased access to grants, which would aid in the success of aquaculture and aquaponics. Today, many

financial aid options exist from both federal and state governments in the form of loans and grants. First, loans and grants from the USDA and NOAA are currently available (NOAA Fisheries, 2024; United States Department of Agriculture, 2024). Lastly, as a part of the 2000 Farm Bill, a value-added grant program was introduced, recognizing the potential in the additions (Rupasingha et al., 2018). The grant program aims to ensure businesses' success in their value-added investment, alleviating some financial pressure with initial investments. In 2023, the grant programs made \$31 million available for this endeavor (USDA, 2015b).

#### **5.4 Future Work & Recommendations**

Since aquaponics is in its infancy in the US, there are many routes for future research to go. First, conducting in-person interviews would allow for a more comprehensive understanding of an operation over time and enable more nuance around operational and business challenges and explore avenues such as life cycle assessments of the operation. Second, investigating the “complete” economics (i.e., initial investment, operating costs, profitability, etc.) around operations (with more responses) would allow for a better understanding of the landscape in the US. Lastly, because so little investigation into current markets and trends exists, gaining more high-level information (e.g., relative operation locations, fish types, distribution methods, etc.) from the US relative to the industry is necessary to better understand where successes and potential improvements are.

#### **5.5 Conclusion**

Working to address food security in a sustainable manner is imperative with an ever-growing global population. In the name of sustainability, ensuring economic viability of sustainable food production is equally important. This study focuses on gaining insight into value-added and value-recovered aquaculture and aquaponics products, which is needed to ensure these revenue generating options are even of interest from producers' perspectives. A survey sent to Midwest aquaculture and aquaponics producers was utilized to fulfill the purpose of the study while also exploring various operational parameters and future directions. The results of the survey found operations of all scales, economic movement, and design. Though many variables were different, challenges such as pests and algae growth were common amongst them. At minimum, most producers recognized the utility in value-added and value-recovered products, while a few seemed genuinely interested in making the investment. Interest in these products by these producers is a dim light, but all new things come with reluctance.

## Chapter 6

### Investigation of consumer interest in aquaponics value-added and value-recovered products

#### 6.1 Introduction

Aquaponics (AQP), as a promising sustainable alternative to high yield food production, is being studied for commercial propagation of aquatic species and plants, which is a closed-loop system aiming to replace aquaculture as the more sustainable method for producing fish, crustaceans, and mollusks, while also producing plants (Goddek et al., 2019). Mitigating the use of aquaculture altogether is not a viable option as global demand for aquatic species continues to increase and harvests of wild-caught species remains relatively stagnant (FAO, 2024). Aquaculture also needs to be improved for several environmental reasons, such as the issue with the effluent water produced containing high quantities of nutrients, which is detrimental to waterways due to eutrophication (i.e., nutrient runoff which causes growth of algae blooms and aquatic weeds) (Bare, 2011). On the other hand, aquaculture is a reasonable base to utilize when exploring alternatives given the consistency in production and quality of products, the high productivity of systems, and minimal land use relative to other livestock operations (Ayer and Tyedmers, 2009; Wu et al., 2019).

Sustainability is the underlying theme when exploring alternatives for already on the market systems and products. Put simply, sustainability explores the economic, environmental, and social branches of the product or process of interest (Ruggerio, 2021).

While the economic and environmental impacts of AQP in the United States (US) have been studied, the social aspect of the methodology remains largely unexplored (Adler et al., 2000; Boxman et al., 2016; Cohen et al., 2018; Ghamkhar et al., 2020; Quagraine et al., 2018; Xie and Rosentrater, 2015). Many regions, particularly the US, view artificially propagated aquatic species as a lower quality product when compared to wild-caught, though the tide is slowly turning, making investigations into consumers opinions and purchasing choices and preferences imperative (Nguyen et al., 2023; Shamshak et al., 2019; Shaughnessy et al., 2023). While selling raw products produced from AQP systems is a reasonable choice for operators, considering other options is necessary for the success of the business.

One way to increase profit for AQP operations and make a more realistic business model is to invest in value-added products (VAPs) and value-recovered products (VRPs). VAPs are produced by implementing post-harvest processes (which are often simple and inexpensive) to make the final product more valuable (e.g., seasoned and smoked filets or premade salads) (Clark et al., 2021; Martínez Michel et al., 2011). VRPs utilize waste streams and processing to create a new valuable product (e.g., fertilizer and pet food) (Kumari et al., 2024; Pal and Suresh, 2016; Yukesh Kannah et al., 2020). Due to AQP being relatively underutilized, particularly in the US, assessing not only the economic and environmental viability of the methodology but also the social considerations of it are necessary for ensuring the sustainability and success of the generalized business model.

Many studies exist, mainly outside the US, on consumers' willingness to pay (WTP) for aquaponics products and their promising attributes (Davis et al., 2025; Meyer et al.,

2025; Suárez-Cáceres et al., 2021). A study conducted by Meyer et al., 2025 explored consumers' WTP for labelling on aquaponics products such as organic-certified as well as WTP for aspects such as being eco-friendly when compared to field-grown produce. The authors found that the surveyed population is WTP more for aquaponics-based organic produce as well as more eco-friendly products when compared to their predecessors (Meyer et al., 2025). While understanding what kind of labelling and attributes to emphasize for aquaponics products is needed, exploring alternatives for increasing revenue generation is imperative for the stability of these businesses in the US. Currently, no known studies exist that investigate US consumers' willingness to pay (WTP) for AQP VAPs and VRPs. Exploring this is necessary for the success of future AQP endeavors in terms of generic business models and flexibility of product distribution. The investigation is also needed to ensure that there is even a market for these potential products before producers fully invest. The goal of this study is to assess consumer food preferences and convenience food preferences, assess knowledge and interest in AQP in general and the resulting value-added and VRPs, while also explore the effectiveness of online survey deployment.

## **6.2 Methods**

Investigating consumer interest in a product or process allows few options, including in-person interviews and surveys, mailing paper surveys, and online surveys either deployed using emails or through a platform. In-person investigations ensure a single person is linked to a single set of answers; however, bias is a concern given deployment is set in only one region, generally only in one city (Belson, 1977; Spaeth, 1992). Mailing paper

surveys is also a viable option for gauging consumer interest and attitude; however, a mailing list is required and again would likely lead to some bias depending on the origin of said mailing list. Online surveys allow for a broader range of responses in terms of location, while also reducing logistical difficulties during deployment. Bias also appears given the use of an email list or platform since only a select number of respondents are part of the list or utilize said platform, though is likely the least amount of bias while also providing responses from broader regions of interest (Alessi and Martin, 2010; Johnson et al., 2024; Schonlau et al., 2002).

In this study, an online survey was designed and was deployed using a platform called MTurk (an Amazon web service) from 06/24/2024 to 07/1/2024 and was approved by the University of Wisconsin-Madison Institutional Review Board prior to deployment (2024-0550). The survey was designed using the census of agriculture and aquaculture and the Love et al., 2014 study and literature related to survey design and deployment (Ball, 2019; Epstein and Klinkenberg, 2002; FAO, 2024; Vilsack and Hamer, 2024). A financial incentive of five dollars was offered through MTurk for respondents of the survey who completed and submitted their response. Consent to the survey was described at the beginning of the survey and was ascertained by the individual by submitting their responses. Anonymity was ensured by excluding questions relating to their name, email, or other personal identifiable information and the metadata provided by the survey platform was not included in the results and discussion. The full survey instrument can be found in Appendix E.

The survey instrument is comprised of six sections with the first section gaining insight into who the respondent is answering for and how many people are included if they

are answering for their household. The second section investigates general food preferences related to fruits, vegetables, and meats with a couple questions related to seafood preferences. This section was included to better understand the potential underlying interest or disinterest in AQP products due to general food preferences and can also help to inform producers of the kinds of aquatic species and plants that would best suit their consumer base. The third section explores respondents' choices in consuming convenience foods and what types to assess the populations' general interest, specifically in value-added products. Sections two and three essentially aim to find reasons why a respondent may be disinterested in AQP VAPs. The fourth section assesses respondents' prior knowledge of AQP and their prior procuring habits of or interest in purchasing products from these operations. These sections were included as it aids in showing a potential knowledge and availability gap for respondents. The fifth section delves into consumers' WTP for aquaponics VA and VRPs and the final section gains insight into the demographics of the respondents. Assessing consumers' WTP for these products is needed to better understand what kinds of prices will be seen as acceptable by consumers for these kinds of products, given a likeliness of increased prices when compared to conventional wild-caught, aquaculture-based or commercial crop farming products.

In the WTP section, respondents were offered a WTP value range of how much more or less they are willing to pay when compared to the same products produced using conventional methods. Some respondents may perceive these products as being less valuable than their predecessors, so it was vital to include a positive and negative range. Each WTP question also offered an "other" option if the respondent thought they were

willing to pay more or less than the range. To aid in the design of the survey, several studies and methodologies were referenced to maximize the utility of this section, though most related studies were conducted outside the US and not on VAP and VRPs (Alsubhi et al., 2023; Breidert, 2007; Breidert et al., 2006; Martínez Michel et al., 2011; Nielsen, 2011).

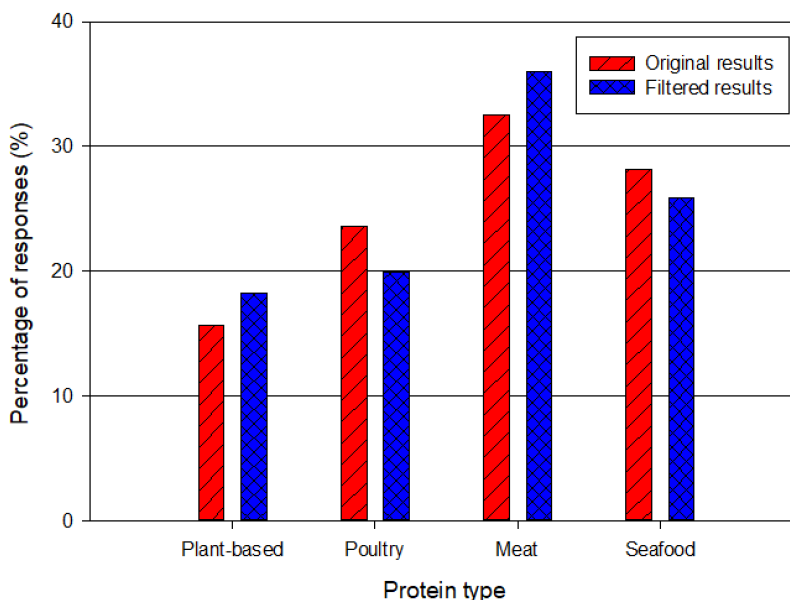
### **6.3 Results**

The survey was assessed in two ways with the first analyzing all responses as though they are all from unique individuals residing in the US. Using the meta data provided by Qualtrics, a second analysis was conducted which removed all repeat responses and responses from outside the US. Each subsection below will include the results from related questions for both assessments. A total of 1,808 responses were collected from the survey deployment; however, several were removed due to incomplete or duplicate responses, making the total number of responses 1,805. After filtering the results, the total number of responses was brought down to 97 responses. Further discussion of this in the context of online surveys will occur later in this paper.

Based on the introductory questions for the survey, 71.8% of respondents were answering the survey for themselves only (58.8% for the filtered assessment), while 28.3% of respondents were answering for their entire household (41.2% for filtered assessment). For those answering for the whole household, the original results report majority of respondents have a household size of “8+” members (37.6%) with four members coming in second (30.8%). The filtered results report four member households (42.5%) being most common amongst respondents, with three members (20%) being second most common.

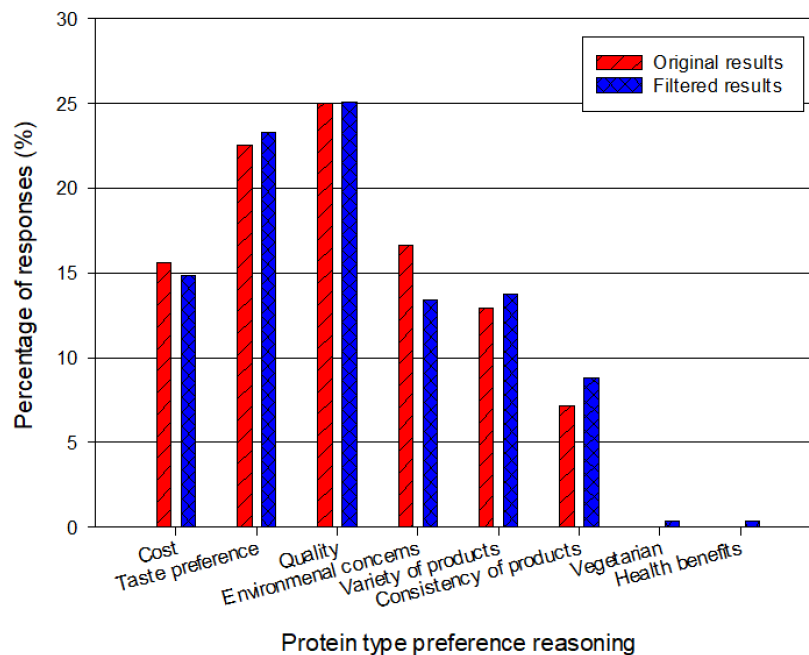
### 6.3.1 Consumer food preferences

Before assessing respondents' WTP for AQP VAPs and VRPs, it was important to determine their general food preferences and considerations to gauge the applicability of the proceeding questions and what kinds of fish and plants may be of higher interest to grow in an APS. Protein preference was investigated in this section to determine if respondents even had a partiality towards aquatic protein; the results for both assessments are displayed in Figure 6.1. Figure 6.1 clearly shows respondents' preference



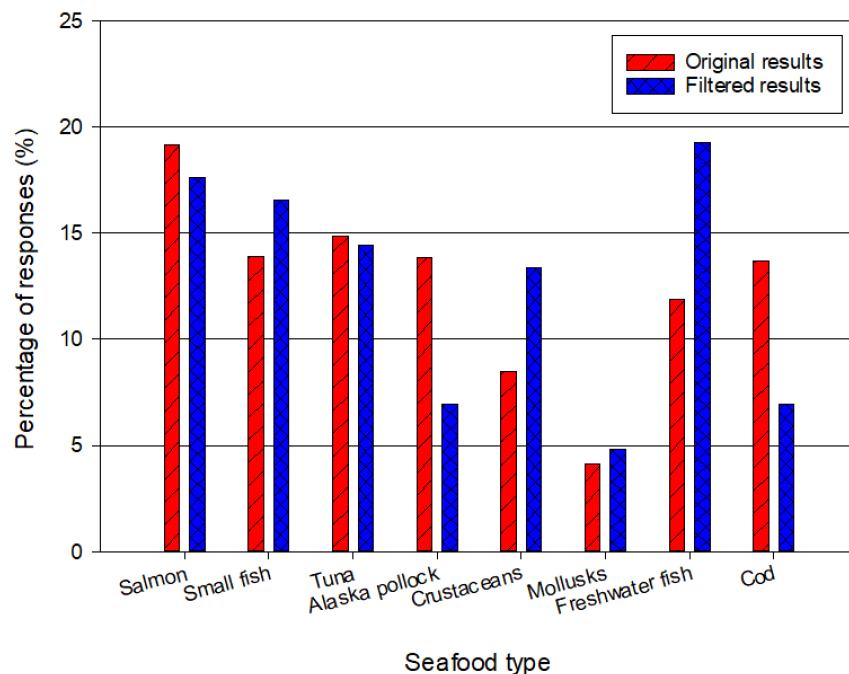
**Figure 6.1.** Respondents' protein inclinations – Question: “When purchasing protein, what do you typically prefer? (Select all that apply)”

for meat (e.g., cattle and swine), however, seafood is a close second. Also, the difference between the original results and the filtered results is small for this dataset. Along with this line of questioning, the survey also examined their reasoning for their protein preferences. Figure 6.2 presents respondents' reasoning for their protein preferences, which shows



**Figure 6.2.** Respondents' reasoning for their protein preferences – Question: “What is your reasoning behind your answer(s) to question 6? (Select all that apply)”

quality and taste as being the most important preference type considerations for responses. Figure 6.3 shows particular types of seafood that are preferred by the respondents who had selected seafood as a favored protein source, which shows relatively even distribution amongst the types offered with mollusks being the least selected for both



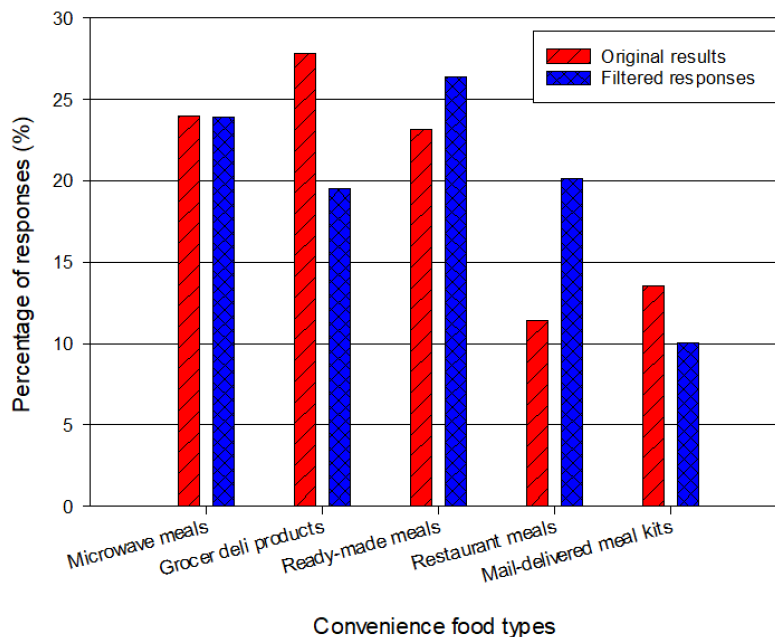
**Figure 6.3.** Percent of responses regarding seafood type preferences – Question: “Which types of seafood do you currently or typically eat? (Select all that apply)”

results. This section of the survey also investigated fruit and vegetable preferences, given AQP includes the production of plants, and this part of the section can help to inform producers of plants to grow in their systems. The results of this inquiry as well as respondents’ cooking frequency can be found in Appendix E.

### 6.3.2 Consumption of general value-added foods

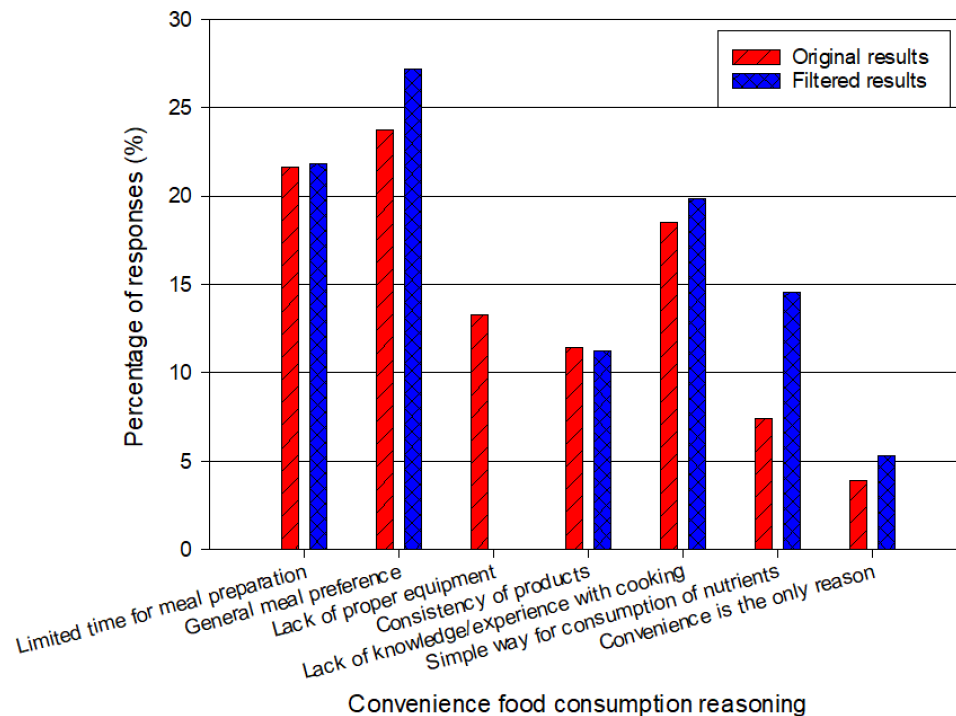
The subsequent step for the survey was to assess the respondents’ habits related to the obtainment and consumption of general convenience foods. According to the original set of responses, 82.8% of respondents do purchase convenience foods, while 71.9% respondents reported regularly purchasing convenience foods according to the filtered

responses. Figure 6.4 presents the results of what kinds of convenience foods are purchased by respondents, which reports varying results amongst the two assessments.



**Figure 6.4.** Types of convenience foods purchased by respondents – Question: “What kinds of convenience products do you or the people in your household typically buy and eat? (Select all that apply)”

For the original results, the most commonly selected convenience food type is deli products and microwave meals and for the filtered results, ready-made meals are the most preferred convenience food type with microwave meals placing second. The last point of interest in this section was respondents’ reasoning for purchasing VAPs, which is shown in Figure 6.5. Based on Figure 6.5, respondents’ main reasoning for purchasing convenience



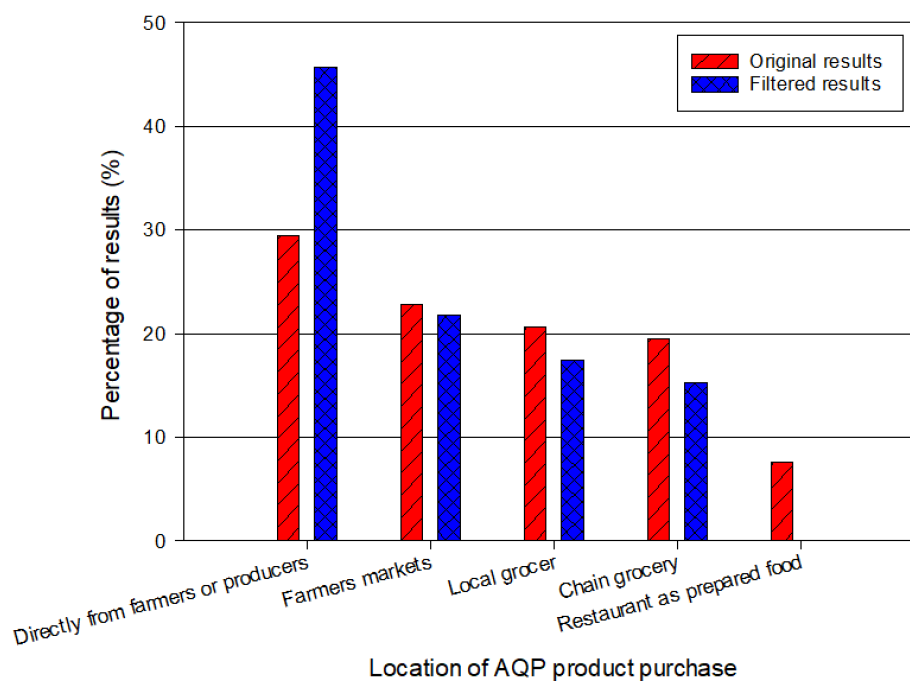
**Figure 6.5.** Respondents’ reasoning for purchasing convenience foods – Question: “Other than convenience, why do you or the people in your household typically buy convenience food items? (Select all that apply)”

foods is that they are their general meal preference and have limited time for meal preparation. On the other hand, convenience being the only reasoning was the least selected option.

### 6.3.3 Consumer aquaponics knowledge and interest in aquaponics products

This section of the survey was designed to investigate respondents’ prior knowledge and consumption of aquaponics and its products. 82.5% of respondents are aware of AQP, though 71.8% of respondents have consumed products produced from AQP, and 67.8% of respondents actively seek out AQP products (13.9% seek out AQP products, but they are

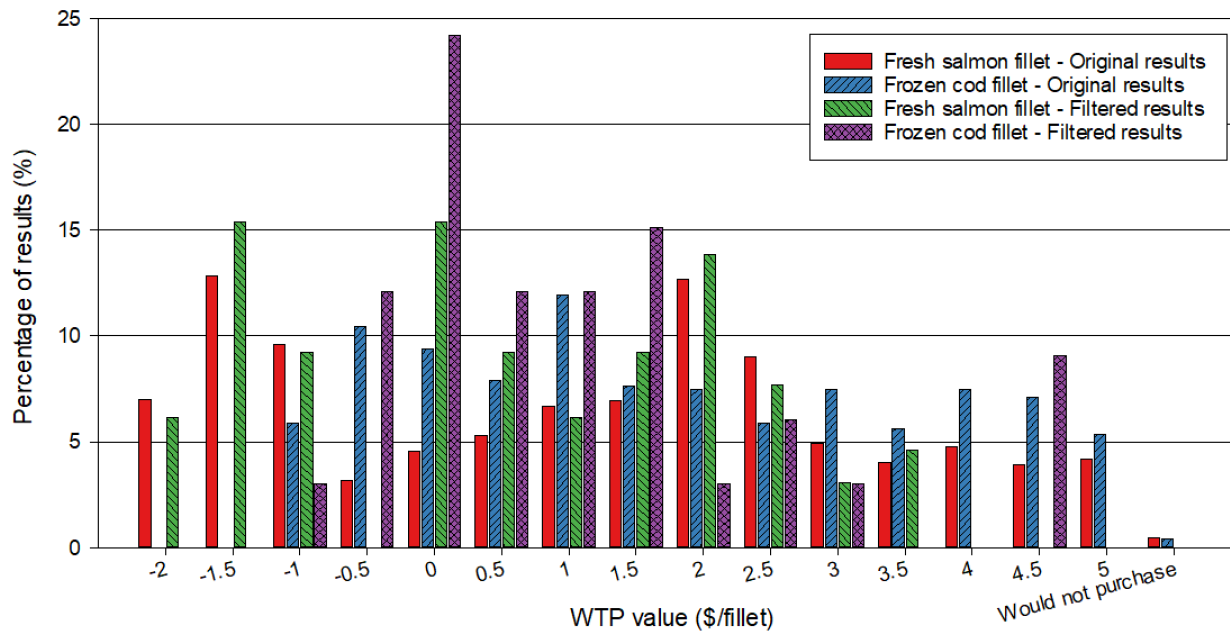
not available in their region). For the filtered results, 71.9% of respondents have prior knowledge of AQP, 57.3% have consumed AQP products, and 46.4% actively seek out and purchase these products (27.8% look for related products, but they are not available in their local area). Results for purchasing factors related to AQP products can be found in Appendix E. Figure 6.6 displays the locations where respondents generally purchase AQP products, which shows a clear trend of respondents going directly to producers to obtain AQP products.



**Figure 6.6.** Location of respondents' AQP product obtainment – Question: “Where do you generally purchase food grown by produced from aquaponics?”

6.3.4 Consumer's willingness-to-pay for aquaponics value-added and value-recovered products

After investigating the general behavior of the respondents regarding food, the survey then investigated these consumers' WTP for AQP VA and VRPs. From the original set of responses, 84% of respondents reported to be interested in VAPs, while the filtered results reported 81.3%. Percent of respondents interested in various kinds of AQP VAPs will be reported with their corresponding particular product WTP values. Each of these VAP types were then investigated relative to respondents' WTP for more specific products based on similar prices to the conventional products (e.g., wild-caught, frozen whitefish fish sticks). The values displayed in the figures refer to how much more or less the respondent is willing to pay for the same product produced using AQP. The set of prices offered to respondents were both positive and negative values for those who may consider the AQP versions of these products to be of less value. An "other" option was also made available to respondents for each question, if they believed they would pay more than the options provided. Based on the original results, 27.64% of responses to the question of AQP VAP types were interested in fresh, seasoned or battered, fish fillets (28.5% of the responses reported in the question for the filtered results) and 18.82% were interested in frozen, seasoned or battered fish fillet (14.5% for the filtered results). Figure 6.7 displays respondents' WTP for fresh or frozen, seasoned filets. The fresh seasoned fillet refers to a salmon fillet which was assumed to have an original price of \$2.00/fillet, while the frozen seasoned or battered fillet referred to a cod fillet and was also assumed to have the same original price. The results show highly varied WTP values for the two products displayed, though a good portion of interested respondents are WTP the same or more for both

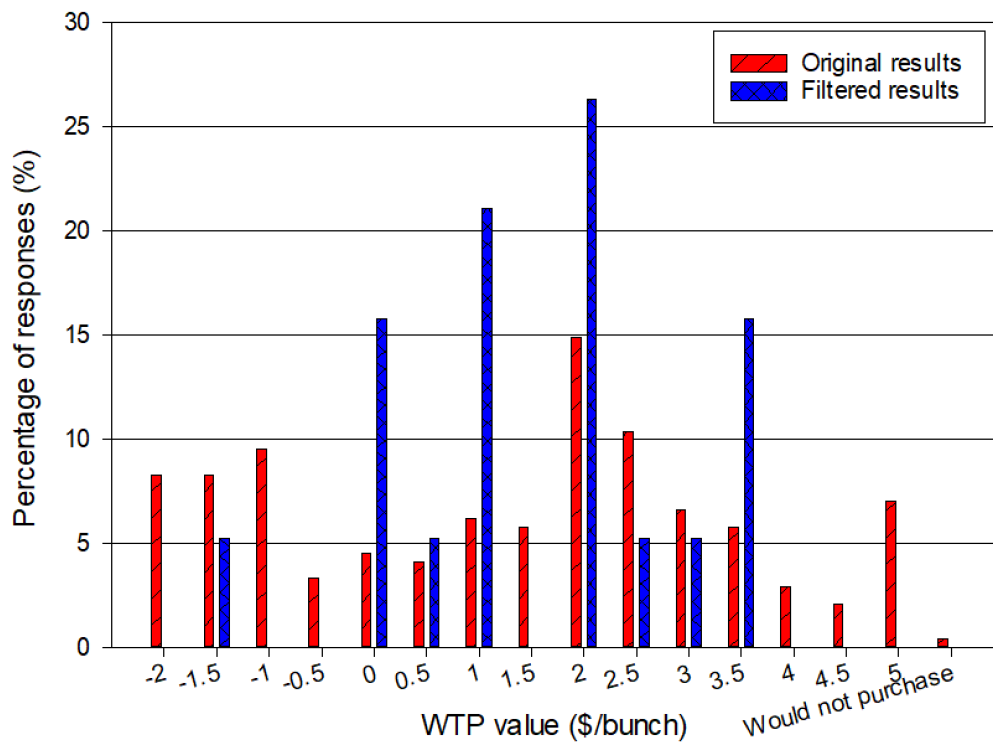


**Figure 6.7.** Respondents' WTP for a fresh, seasoned or battered salmon fillet (Original price: \$2.00/fillet) and a frozen, seasoned or battered cod fillet (Original price: \$1.00/fillet) – Questions: “If the typical fresh, seasoned salmon fillet cost \$2/fillet, about how much more or less would you be willing to pay if the same fillet were to be produced by aquaponics?” and “If the typical frozen (seasoned or battered) cod fillet cost \$1/fillet, how much more or less would you be willing to pay if the same fillet were produced using aquaponics?”

products. Figure 6.8 displays the results of respondents' WTP for washed and pre-cut herbs produced from AQP when compared to conventional products and prices (\$2/bunch).

Based on Figure 6.8, most respondents are WTP more for an AQP-based bunch of herbs.

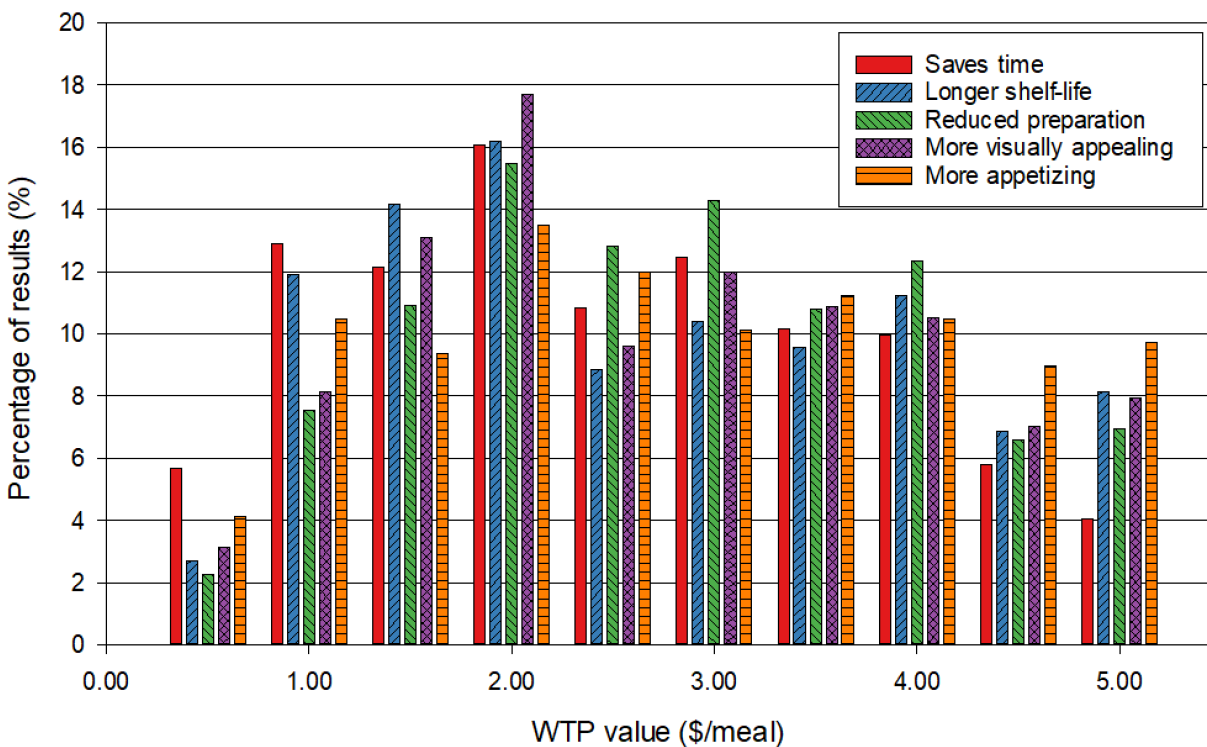
Results for other product options can be found in Appendix E.



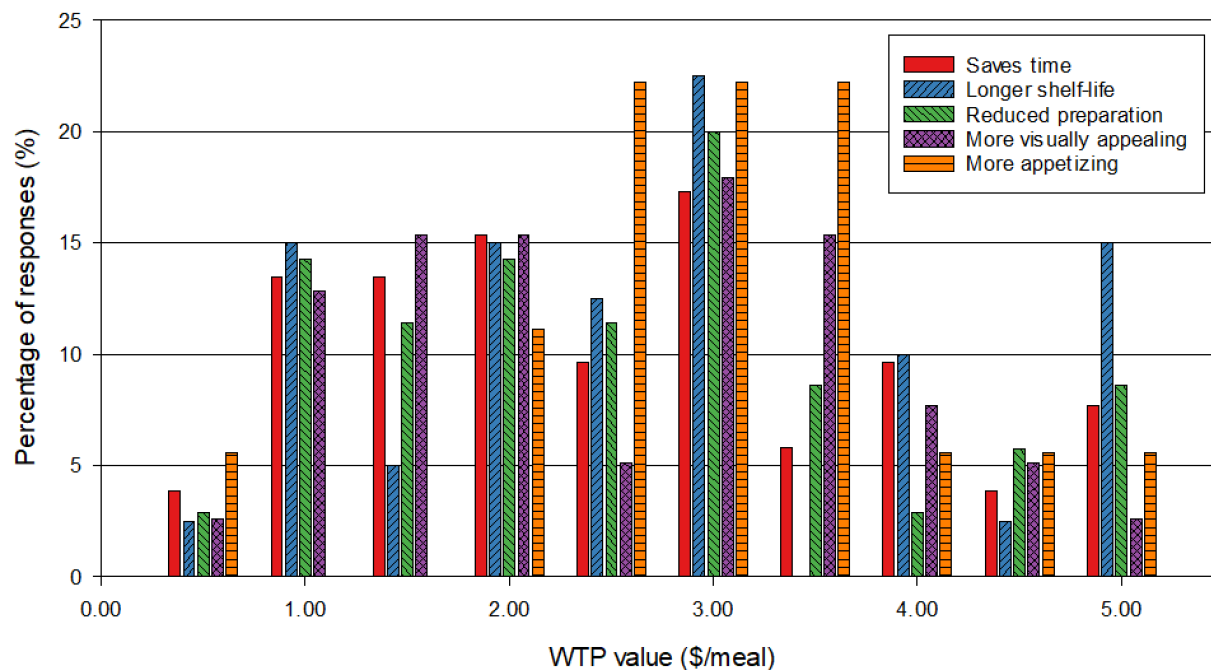
**Figure 6.8.** Respondents’ WTP for washed and pre-cut herbs produced from AQP – Question: “If the typical bunch or prewashed and cut, fresh herbs cost \$2 per bunch, how much more or less would you be willing to pay if the same herbs were made using aquaponics?”

The survey also explored respondents’ WTP for specific types of attributes that are generally a part of VAPs. Based on the original results, 26.9% of responses prefer a VAP that saves time, 24.9% want a product that has a longer shelf-life, 24.5% want a product that minimizes effort, 15.9% prefer a product that is more visually attractive, and 7.9% want a product that is more palatable than raw ingredients. Figures 6.9 and 6.10 present the respondents’ WTP values for the various characteristics typical of VAPs for each assessment. The original results show a bit of a distribution in responses, though

\$2.00/meal is most commonly selected for all characteristics. For the filtered results, responses skew a little higher to around \$3.00/meal.

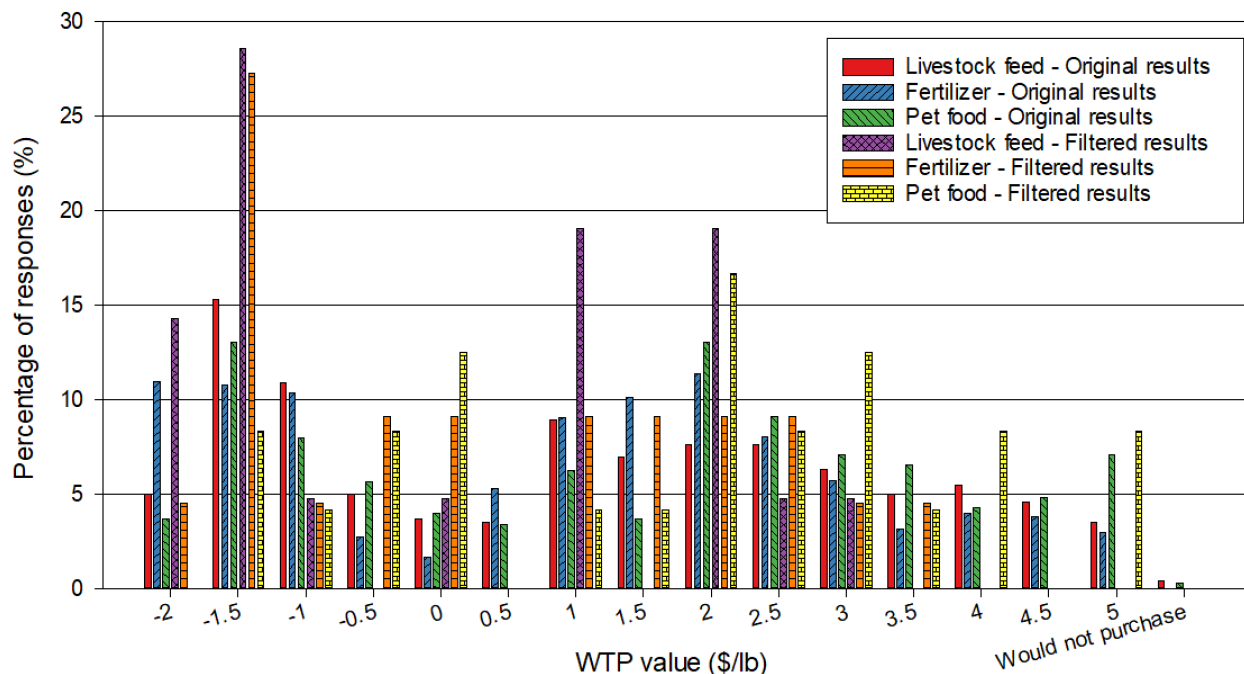


**Figure 6.9.** Respondents' WTP for VAP characteristics (\$/meal) – Original results – Sample question: “How much more do you think you would spend per meal to save time (30 minutes) through buying a value-added product?”



**Figure 6.10.** Respondents' WTP for VAP characteristics (\$/meal) – Filtered results

The last part of this section investigated AQP VRPs of interest. From the original set of responses, 82.6% of respondents indicate an interest in AQP VRPs, while the filtered set reported 81.3% of respondents. Fertilizer (32.4%) and livestock feed (31.3%) were the two products that respondents were most interested in based on the original results, while pet food (30.9%) was the main product of interest based on the filtered results, though fertilizer (27.2%) and livestock feed (28.4%) followed closely behind. Figures 6.11 and 6.12 display respondents' WTP for livestock feed, fertilizer, and pet food which were produced using AQP byproducts (each product was assumed to have an original price of \$2/lb). Again, these results show a wide variety of WTP values for the investigated products, however, some respondents are clearly WTP more for the three products.



**Figure 6.11.** Respondents' WTP for livestock feed, fertilizer, and pet food produced using AQP by-products – Original results – Sample question: “If the cost of conventional, synthetic fertilizer is \$2 per pound, how much more or less would you be willing to pay for natural fertilizer produced from aquaponics?”

## 6.4 Discussion

AQP is swiftly gaining traction as a means for producing high yields of aquatic species and plants; however, investigation into consumer interest in aquaponics products is key for the success and overall sustainability of aquaponics in the consumer market. The survey design and deployment aimed to fill this knowledge gap specifically in the US. VA and VRPs are a simple way to gain more value from producers' products without the need for high capital investment. The results from the deployed survey aid in showing several key

points related to consumers food habits, consumers WTP for AQP VA and VRPs, and the efficacy of online survey deployment using a pay-per-response platform.

The results of the initial section of the survey showed a promising sample size, however, many of the responses stemmed from respondents who took the survey more than once, which is a common issue amongst online surveys (Alessi and Martin, 2010; Johnson et al., 2024). To account for the repetitions, the first response was pulled for the filtered set of responses, which was decided based on open-response results that showed more genuine responses occurring in the first response. Other responses were also excluded from the filtered set as they lacked the proper metadata. Because of these exclusions, the sample size dramatically decreased, making the utility of the results much less useful, though some understanding can still be gained. There are several ways for future surveys to prevent these issues, which include requiring a password provided by MTurk prior to taking the survey, including a metadata check at the start of the survey to ensure the VPN and location are not the exact same as previous responses, and a check at the start of the survey to determine if a robot is trying to take the survey (Alessi and Martin, 2010; Johnson et al., 2024). Deploying the survey using an email list or a known population (e.g., social media groups or university campuses), or conducting the survey in-person at grocery stores or events would also alleviate several of the issues seen in this study (Belson, 1977; Spaeth, 1992). The original purpose of this study's deployment decisions was to minimize geospatial bias and maximize visibility of the survey to US residents, however; the results clearly show the faults in these choices.

The first two sections of the survey facilitated gaining insight into typical food purchasing and consuming habits of the respondents, which will help AQP producers and food producers in general better understand what their consumer bases favor relative to food and convenience foods. One of the initial points of interest in these sections was the food purchasing ranking, which showed freshness and price as being the most important and taste and environmental sustainability as being least important. These results indicate the importance of getting the price of AQP products as low as possible, while still maintaining high quality, however; a major selling point of AQP is the environmental sustainability but consumers do not seem to consider this regarding food. Protein preferences were also an important topic to explore to determine the applicability of AQP products for this survey population. The results showed that meat made from cattle and swine were preferred by the most respondents, but seafood/aquatic species was second, making the rest of the survey useful for a good portion of respondents. The main reasons for these preferences were quality, taste preference, and cost, meaning some respondents could transition to consuming more seafood if products were high quality at a minimum cost. In the context of seafood, most respondents preferred fresh seafood, with frozen being second most, which helps AQP producers make informed decisions on which types of VAPs to explore and invest in. Lastly, most respondents report regularly purchasing and consuming convenience foods and prefer deli products, microwave meals, and ready-made meals, according to the original, while the filtered responses reported ready-made, microwave, and restaurant meals as being the most preferred types of convenience foods. Respondents' reasoning behind these selections were largely being their general meal

preference, having limited time, and having limited knowledge/experience relating to cooking. These results signal that the surveyed population would be more likely to be interested in AQP VAPs relative to generalized convenience food consumption.

The third and fourth sections explored respondents' prior knowledge of and interest in AQP and their WTP for VA and VRPs produced using AQP. Most respondents are aware of AQP and slightly less are interested in its products. These results show promise regarding the potential population size of those interested in making AQP products a regular part of their diet. Many respondents reported an inability to obtain these products, which is unsurprising given the infancy of the industry in the US. For those uninterested in AQP products, many respondents reported to not be interested in these products due to price concerns and quality concerns, meaning some could be persuaded with the proper products and prices. Finally, exploring quantitative values of potential AQP VA and VRPs was needed to better understand the viability of the products from the producers' perspective. Relative to VAPs, the fresh, seasoned or battered, fish fillet was the most popular choice amongst respondents, however; a large portion of respondents would pay less or the same amount for an AQP-based salmon fillet, though the third most common choice was \$2/fillet showing some viability for this particular product without the requirement of economies of scale. The VAPs with positive results related to WTP were the vegetable and seafood salads and the pre-cut and washed herbs. The product with the least viability offered by the survey was the oven-ready meal kit. For the part investigating respondents' WTP for various VAP characteristics, all of them had the most responses for \$2 or \$3/meal, showing moderate financial interest in the benefits of VAPs. In terms of

VRPs in the filtered results, pet food, fertilizer and perfume WTP questions reported a more positive WTP, while the livestock feed reported mainly negative responses. The WTP results indicate that there is a smaller population of the respondents who would spend more on AQP products, however, lower prices would obviously increase the number of interested consumers.

The final section of the survey was designed to investigate general demographic information of the respondents. The overall age range was decently diverse, but it is unsurprising that majority of the respondents were on the younger side given the platform utilized for the deployment. In terms of gender, some bias seems to arise from the platform given the respondents were mostly male. The annual household income makes sense as the average is within the range found in the survey's results. This section's results indicate some level of bias, which is expected given the inevitability of bias with surveys.

#### 6.4.1 Comparison to published data

Currently, there are no studies investigating WTP for specific aquaponics products relative to conventionally made, raw products, however, several studies on consumers' WTP for raw aquaponics products do. The first study by Davis et al. (2025) explores consumers' perceptions and WTP for aquaponics products in United Kingdom. Regarding WTP, the authors found that majority of their survey respondents were WTP the same amount for vegetables (56.6% of respondents) and fish (53.4%) produced using aquaponics. 41.8% of respondents were WTP more for aquaponics vegetables and 44.6% were willing to pay more for fish produced using AQP (Davis et al., 2025). A one-to-one

comparison cannot be made with this study, however, the studies are similar enough to gain some insight. When comparing the results of the salmon VAP in this study, it was found that 62.4% of respondents were WTP more for the AQP-based salmon, which is slightly higher than the study conducted by Davis et al. (2025). The second study by Suárez-Cáceres et al. (2021) investigated consumers' WTP for aquaponics products in Spain and Latin America. This study had 636 respondents and found that majority of respondents were WTP five to ten percent more for AQP-based products, regardless of their gender, age, educational level, place of residence, household income, and knowledge of AQP (Suárez-Cáceres et al., 2021). Again, a one-to-one comparison cannot be made between this reviewed study and the results of this study, however, some discernments can be gained. When looking at the salmon and cod VAPs investigated in this study, it was found that over half of the total respondents (62.4% and 73.9%, respectively) were WTP an increase of ten percent or more for these VAPs, which makes sense given the value of these assessed products is higher than the raw products (which was assessed in the reviewed study).

#### 6.4.2 Limitations of the study

Several limitations exist due to the decisions and deployment strategies made for the survey. First, the sample size of the survey is relatively small when compared to the number of adult US residents, which was due to the necessity of filtering out repeat responses and the limited number of MTurk users. Another limitation was the decision to only assess US residents, which was made due to the limited number of studies on the topic in the US, growing interest in seafood in the region, and the applicability of products such as convenience foods. There was also little to no consideration of WTP for

certifications and raw products, since the survey was already relatively extensive, exploring topics such as food preferences and habits and knowledge of aquaponics. Lastly, the survey was only offered through MTurk, which caused some bias and limitations given only users of the platform had the opportunity to take the survey.

Overall, based on the results of the survey, if aquaponics producers were to invest in the endeavor of VAPs and VRPs, they should produce fresh or frozen fish filets and prewashed and cut herbs. The waste produced by processing the fish should then be used to make pet food, thereby maximizing product value and consumer interest while minimizing waste produced. These results can also be applied to aquaculture operations by excluding the plant farming considerations. By making these changes to their businesses, aquaponics and aquaculture producers could see more stability and likely more profit. Further work will be required for product distribution optimization and marketing strategies.

## **6.5 Conclusion**

AQP has promptly risen as a more sustainable method of farming aquatic species, however, for a truly more sustainable food production method to replace aquaculture, it is necessary to investigate all three branches (i.e., environmental, economic, and social) and optimize where possible. While much work has been done investigating environmental impacts and economic viability, the social consideration and consumers' views towards AQP has largely been left untouched. The goal of this study was to gain insight into general consumer interest in value-added and value-recovered aquaponics products as well as the

quantitative values consumers were WTP for a product produced using more sustainable means, which was conducted using an online survey. Through the deployment, it was found that people across the US have diverse preferences towards protein sources and vegetables and fruits, making it challenging to recommend a specific kind of fruit or vegetable for producers to grow in their AQP operations. The deployed survey also revealed that respondents that were interested in AQP VA and VRPs were largely willing to pay more for some of the products explored in the survey when compared to conventional products, making this undertaking promising for producers. Regarding the utility in the survey deployment, many issues did arise from this deployment, however, several insights were gained from the unforeseen dilemmas. Future studies with similar dynamics and reasonable resources should consider employing a multi-faceted survey. If the deployment includes an online survey, the practitioner should consider utilizing security methods to prevent the issues found in this study. Relative to AQP VA and VRPs, the next steps should include an economic analysis of these products of interest, which should include estimated costs for the producers as well as estimated prices for consumers. Future work should also include consumer testing in the form of in-person interviews to better understand consumer's actual opinions on the products in terms of taste, quality, theoretical prices, and environmental impacts.

## Chapter 7

### Conclusion and future work

The overall research question investigated in this work is as follows, is aquaponics a more sustainable food production methodology than aquaculture and conventional farming, particularly in cold climates? This thesis aims to bridge the knowledge gap in aquaponics by addressing the following objectives:

- Evaluate and harmonize the global warming potential of five United States-based aquaponics system and determine the mitigating circumstances causing any differences (Chapter 2)
- Quantify the environmental impacts of insect-based meals for the purpose of determining if the protein source is a viable alternative to conventional fishmeal (Chapter 3)
- Design and test a tool used for educational efforts related to sustainable food production (Chapter 4)
- Develop and deploy a survey geared towards aquaculture and aquaponics producers to better understand general operational parameters and their willingness to invest in value-added and value-recovered products (Chapter 5)
- Design and deploy a survey with the intention of gaining insight into the food habits and preferences of United States consumers and to quantify their willingness to pay for aquaponics value-added and value-recovered products (Chapter 6)

#### 7.1 Summary of contributions

In summary, there are three main aspects where this work advances the state of aquaponics and sustainable food production. First, harmonization of US-based aquaponics life cycle assessments was done to better understand the similarities and differences amongst the studies and why these similarities and differences might arise amongst similar methodologies (Chapter 2). Next, a life cycle assessment was conducted on different types of insect meals with the inclusion of biotic resource use to determine if insect meal is a practical alternative to fishmeal regarding environmental impact, which was the first of its kind in the United States (Chapter 3). Third, an aquaponics agent-based model was designed to improve the social branch of sustainability of aquaponics through education (Chapter 4). Lastly, surveys were designed and deployed to help improve the economic branch of sustainability of aquaponics by quantifying if value-added and value-recovered products are a feasible option as a means of increasing revenue generation (Chapter 5 and 6).

The main motivation behind this work is to evaluate several aspects of the sustainability of cold climate aquaponics. The insect meal LCA (Chapter 3) demonstrated the viability relative to the environmental impact of insect meals as an alternative to conventional fishmeal, especially as farming methods are optimized. This project contributes to the body of knowledge related to the environmental sustainability of aquaponics by exploring a potential replacement option for a highly environmentally detrimental input required in aquaponics which included the assessment of biotic resource use to more fully understand insect meal impacts versus conventional fishmeal given prior investigations into similar topics lacked this consideration. This work progresses

investigation into fishmeal alternatives by specifically exploring insect meal, which is a highly necessary line of work given wild fish populations are declining. The new impact category (i.e., biotic resource use) also bridges the knowledge gap related to the true environmental impacts of conventional fishmeal and its potential alternatives by addressing biotic resources required to produce these meals. This is critically important, as when only conventional LCA impact categories are used, the ecosystem services provided by the ocean in the creation of the fish meal are neglected.

The aquaponics agent-based model will contribute to society by acting as a tool for the education of systems thinking and sustainable food production, while also introducing the field of LCA using simplified methods (Chapter 4). The model helps to address the accessibility gap in systems thinking and sustainable food production education, by using aquaponics as a case study. By designing the model, more people can be introduced to different types of food production and begin to understand that business-as-usual is not necessarily the best path forward for a growing global population. With an educated public on these topics, progression of aquaponics and sustainable food production will increase, thus growing the market for aquaponics, leading towards a more sustainable society.

The producer survey (Chapter 5) contributed to the overall research question of this work by exploring a potential option for improving the generalized business model and stimulating revenue generation without high capital investments. This project aimed to better understand if producers were interested in (both qualitatively and quantitatively) a promising revenue generating mechanism. The consumer survey (Chapter 6) investigated the other side of the coin compared to the producer survey to better understand the

viability of value-added and value-recovered from the consumers perspective, which will help producers gain insight into whether value-added and value-recovered products are a viable option for increasing revenue, the kinds of products consumers are interested in, and the prices they should aim for when looking into the investment.

## 7.2 Future work

As optimization of aquaponics systems continues to improve, there are several other research routes that are needed to maximize the sustainability of the technology.

Future work will aim to answer the following questions:

- How do the environmental impacts of insect farming in the United States change with the use of renewable energy, space optimization, and the exclusive use of agricultural by-products when compared to current operations?
- What is the composition of an aquatic diet for a commonly farmed species such as tilapia which includes insect meal that ensures no impact on fish growth?
- What are the environmental impacts of microalgae-based meal produced in the United States with the inclusion of biotic resource use?
- What does market optimization look like for aquaponics value-added and value-recovered products?
- Is multi-trophic aquaponics less environmentally impactful than replacing conventional fishmeal and oil for a typical aquaculture or aquaponics operation?

These research questions work to advance the overall sustainability of high yield food production specifically for aquatic species and plants. The first two research questions

have the goal of progressing investigation into US-based insect farming as a sustainable conventional fishmeal alternative, given its promise regarding biotic resource use. The third question aims to explore microalgae as another potential fishmeal alternative since no work has been done on quantifying the environmental impacts of microalgae farming in the US with the inclusion of biotic resource use to ensure a more complete story is told by the assessment. The fourth question will advance the work done in Chapters 5 and 6 by investigating the feasibility of value-added and value-recovered aquaponics on the market, specifically what kind of prices would be required based on the scale of operation, what the particular consumer demographics are for these products, what product distribution should look like to ensure the target consumer is reached, where advertising should be to optimize product awareness, etc. The final research question explores a different type of aquaponics which aims to more closely emulate the nutrient cycling process in bodies of water (i.e., microalgae is grown using ultraviolet light and the nutrients produced by the two levels which would feed the level that grows small, prey fish that then feeds the level for a typical type of fish to be grown such as tilapia). Investigation into this type of system could mitigate the need for fishmeal and oil alternatives for future operations and develop a system that is closer to closing the system loop, however, very little work has been done on the topic in general and no work has been conducted in the US. The environmental impacts in particular are interesting due to conventional fishmeal and oil's high dependence on a constrained biotic resource and can help to better optimize operations, thus improving the sustainability of aquaponics.

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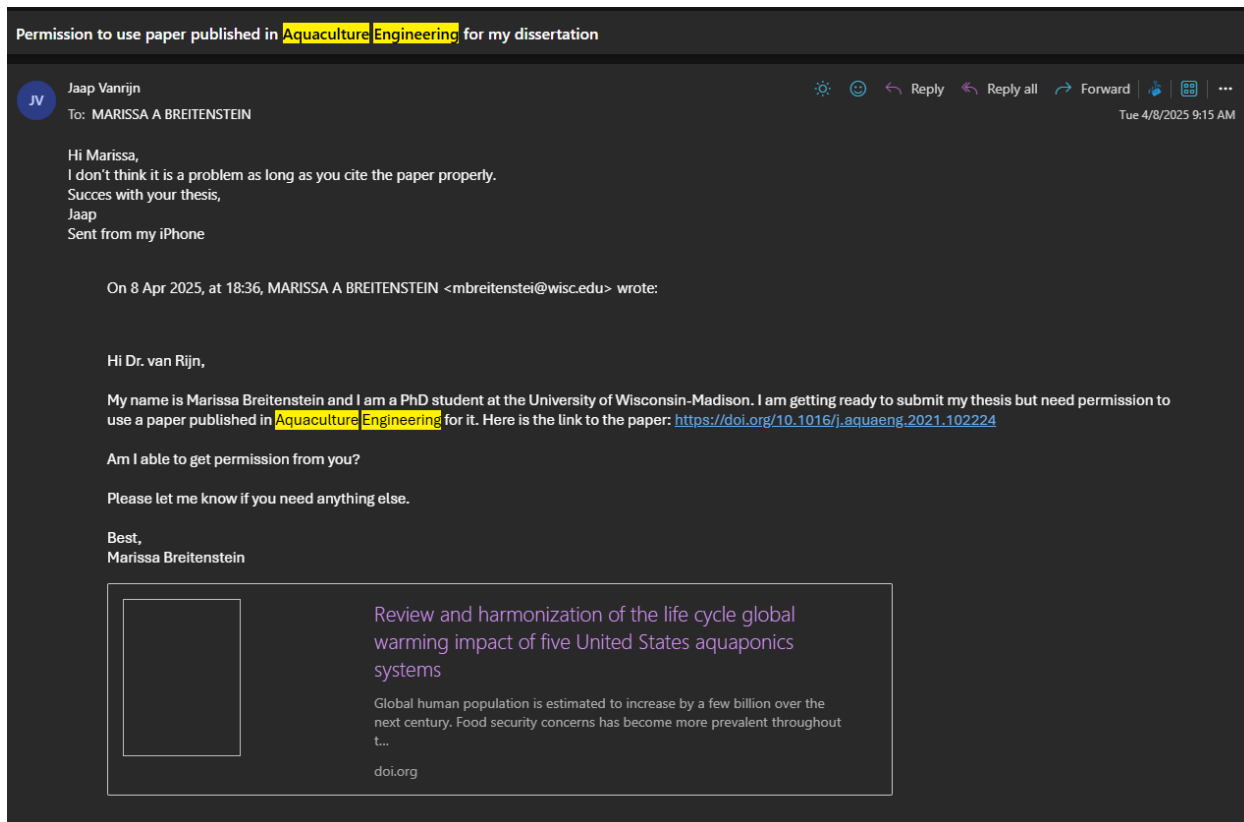
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## Appendix A - Review and harmonization of the life cycle global warming impact of five United States aquaponics systems



### A.A. System Boundary & Assessment Methods

FUs are used in LCA to quantify environmental impacts of a system, but there is no standardized FU for an aquaponics LCA. Common examples of aquaponics FUs include mass and economic based units of either the fish or plants produced (i.e. one kilogram fish) (Boxman et al., 2016; Chen et al., 2020; Ghamkhar et al., 2020; Hollmann, 2013; Kalvakaalva, 2020). Boxman et al and Hollmann evaluated a liveweight fish mass as their functional unit, whereas Ghamkhar et al. chose three units (one kg fish fillet produced, one kg of harvested vegetable, and one kg of combined fish and vegetable produced using

mass ratios) to encompass different goals and outcomes for their assessment (Boxman et al., 2016; Ghamkhar et al., 2020; Hollmann, 2013). Kalvakaalva also used a fish mass as the assessment's FU but opted to use dry weight as the fluctuations in moisture content among fish can vary greatly (Kalvakaalva, 2020). Chen et al desired an economic based comparison, so they picked a FU of \$1 US of product produced (Chen et al., 2020). The FUs varied amongst studies, so conversions were required to harmonize the systems' impacts (found in Appendix A). Understanding the system boundaries and what is included and excluded from each study is also needed when comparing the LCAs.

The system boundary evaluated for all systems, but Hollmann (2013) was cradle-to-gate which includes the beginning stages of the fish and plant production, up to the products leaving the farm (Boxman et al., 2017; Chen et al., 2020; Ghamkhar et al., 2019; Kalvakaalva, 2020). Hollmann (2013) chose a cradle-to-grave system boundary to better understand the impacts of the whole life of the fish produced by the system. Hollmann (2013) also chose to break the boundary into three components (pre-, on-, and post-farm) so the separate parts could be evaluated as well as the whole life of the FU (Hollmann, 2013). Kalvakaalva (2020) excluded the fish hatchery step from their LCA, as the author found the impacts to be minimal relative to the rest of the system (Ayer and Tyedmers, 2009). Finally, the impact assessment methods were laid out to determine if the method encompassed the same GHGs amongst the different methods.

Ensuring the utilization of the most applicable impact assessment method was important to confirm the appropriate parameters were included. Chen et al. (2020) and Boxman et al. (2017) chose to use the Institute of Environmental Sciences (CML) baseline

midpoint method as their assessment method, as it is among the most common method used for food production systems. Hollmann (2013) chose International Life Cycle Data (ILCD) over Tools for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) as the latter does not account for water usage, which is a vital parameter in aquaponics (Bare, 2012; Hollmann, 2013). Ghamkhar et al. (2019) used the TRACI method since it was the most applicable for the impact categories needed for the analysis and is a US centric method (Bare, 2012; Ghamkhar et al., 2019). Kalvakaalva (2020) chose ReCiPe as their assessment method to include water depletion as an impact category. Though the methods were different, greenhouse gases (GHGs) and the procedures for determining overall GWP impact were the common denominator amongst the studies allowing for harmonization. Separating the AQ and HP sections and understanding each of their parameters for the studies was important when comparing the systems.

### **A.B. Fish Choices, Aquaculture Configuration, & Aquafeed**

Selecting an appropriate species of fish for an APS can be a relatively complex choice. Physical and environmental considerations such as local climate, water source conditions, heating requirements, fish feed conversions, harvest size, and local species demand are critical factors to take into account when deciding. Aquaculture has been studied for decades, so the ideal choices are known. Kalvakaalva (2020), Chen et al. (2020), Boxman et al. (2017), and Hollmann (2013) analyzed systems with tilapia, which is a fish that is commonly produced in AQ. Tilapia has a high resilience to disease and changes in environment and their growth rates relative to other fish grown in aquacultural systems is high (Nelson, 2016). Hollmann's (2013) system introduced HSB during data collection to

their tilapia system but does not differentiate the two species. The justification for the addition of HSB was local demand shift, but tilapia also remained an ideal choice (Hollmann, 2013). Ghamkhar et al. (2019) chose hybrid walleye due to their resistance to low temperatures and local preference. Fish tanks and stocking densities are also important factors when evaluating an APS.

The AQ section of the reviewed systems varied in fish tank size and quantity, and fish densities. Operation size also plays a role in the size and quantity of tanks for a given APS. Kalvakaalva (2020) studied a large pilot scale system with a 150,000 L fish tank. Kalvakaalva's (2020) system was decoupled meaning it was separated into two greenhouses (one for the HP section and the other for the AQ section). The author did not specify the tank's fish density, but it is known that about 23 kg of tilapia were produced weekly from the system (Kalvakaalva, 2020). Chen et al. (2020) evaluated a research scale system that consisted of a 350 L fish tank stocked at a biomass density of  $18.3 \text{ kg/m}^3$  (Chen et al., 2020). Ghamkhar et al. (2019) studied a research scale system that included six separate systems, each consisting of two fish tanks stocked at different densities for each system. The first two tanks were stocked at  $66 \text{ fish/m}^3$ , the second at  $132 \text{ fish/m}^3$ , and the third at  $198 \text{ fish/m}^3$  (Ghamkhar et al., 2019). Boxman et al. (2017) evaluated a commercial scale system with four 3-meter diameter fish tanks stocking each at densities of 77 and 154  $\text{fish/m}^3$ , depending on the species of tilapia. Hollmann (2013) also studied a commercial scale operation which used three different fish tanks depending on the age of the fish. The tanks were stocked at a biomass density of  $18 \text{ kg/m}^3$  (Hollmann, 2013). Tank size & fish

density are two important considerations in the AQ section of an APS but are not the only factors.

Aquafeed has been found to be an environmental hotspot in previous LCAs (Boxman et al., 2017; Ghamkhar et al., 2019; Ghamkhar and Hicks, 2020). Many aquafeed producers use forage fish as their fish meal and oil inputs which has high environmental impacts and negative implications for wild fish stocks (Ghamkhar and Hicks, 2020; Tacon and Metian, 2008). The protein content in fish feeds is one of the most important inputs in any given aquafeed. Feed conversion ratios vary for different marine species, so appropriate feed compositions also vary (Ghamkhar and Hicks, 2020; Tacon and Metian, 2008). Kalvakaalva (2020), Hollmann (2013), Boxman et al. (2017), and Chen et al. (2020) evaluated systems with 30-40% protein aquafeed. Ghamkhar et al. (2019) evaluated a system that fed their fish a 55% protein feed, making it the highest protein content feed. The author goes on to discuss alternative options for aquafeed as the impact for the feed was especially high (Ghamkhar et al., 2019; Ghamkhar and Hicks, 2020). Hollmann (2013) chose a low energy feed for the fish, reducing the protein in the recipe making their feed contain the least amount of protein. Next, the HP sections of the APSs were reviewed, breaking down the growing methods and plant species.

### **A.C. Plant Selection & Growth System**

Options for plant species is relatively limitless in aquaponics if the growing conditions are ideal. Growing circumstances can be manipulated in a greenhouse, but APSs can be successful outdoors, too. Leafy greens and herbs such as basil were often

chosen to be grown in APSs. All authors but Kalvakaalva (2020) evaluated systems that grew leafy greens or herbs; Chen et al. (2020) studied a system that grew Swiss chard, kale, mustard greens, cilantro, lettuce, and arugula (Boxman et al., 2017; Ghamkhar et al., 2019; Hollmann, 2013). Ghamkhar et al. (2019) grew butterhead lettuce, romaine, kale, and pak choi in their hydroponics section. Kalvakaalva (2020) evaluated a system that grew cucumbers, requiring Dutch buckets and a drip irrigation setup. Kalvakaalva (2020) studied a decoupled system, so the system setup had the ability to vary more greatly. The system evaluated by Boxman et al. (2017) grew basil in a tropical climate allowing for an outdoor setup, which can significantly reduce GHG emissions and electricity usage. One downside the setup by Boxman et al. (2017) was the need for insecticides, adding an input not needed for the other systems. The reduction of synthetic fertilizers is another positive aspect to APS; however, Chen et al. (2020), Boxman et al. (2017), and Hollmann's (2013) systems used small quantities to make up for any missing nutrients from the filtered fish tank water. Hollmann (2013) discussed the facilities usage of a "homebrewed" fertilizer but excluded it in their evaluation as the exact ingredients were being experimented with at the time. The growth systems for the plants are another aspect that varies amongst authors in the HP section of their systems.

The HP growing mechanisms were similar for most of the evaluated authors. Floating rafts are often used in HP systems due to their financial feasibility and ease of maintenance (Pattillo, 2017a). Kalvakaalva's (2020) HP system utilized a media-based approach in Dutch buckets (with drip irrigation) since cucumbers were being grown by the system and the plants would not remain stable in any other configuration. Hollmann (2013)

studied a system that used three different growing techniques as an educational opportunity for visitors (Hollmann, 2013). The three growing methods included deep-water culture (DWC), nutrient-film technique, and media beds. The methods were not evaluated separately, so their individual impacts are unknown. DWC, also known as floating rafts, is the most common setup amongst APSs (Hollmann, 2013). The method uses low density material like polystyrene to hold the plants slightly above the water in a net pot. Leafy greens and herbs are often grown in this design (Pattillo, 2017a). Nutrient film technique (NFT) uses shallow channels of nutrient-rich water to grow crops along it. The surface area of the setup is much smaller relative to the others, so it has the potential for more crops to be grown in the same size greenhouse. A media bed HP setup utilizes a material like a perlite mixture to stabilize the roots and act as a biofilter (Pattillo, 2017a). Media beds are generally used for smaller scale operations due to high expenses and clogging concerns. Because both sections of an APS depend heavily on water, recording and evaluating water use is needed for a complete assessment.

#### **A.D. GWP Harmonization Calculations**

**Equation A.A. Kalvakaalva (2020)** (original FU: 1 kg dry weight fish)

$$W_f = W_i \times \frac{100 - MC_i}{100 - MC_f} = (1 \text{ kilogram dry weight}) \times \frac{100 - 0}{100 - 75} = 4 \text{ kilograms liveweight}$$

$$\frac{77.19 \text{ kg } CO_2 \text{ eq}}{\text{kg DW fish}} \times \frac{1 \text{ kg DW fish}}{4 \text{ kg LW fish}} = \frac{19.3 \text{ kg } CO_2 \text{ eq}}{\text{kg LW fish}}$$

**Equation A.B. Chen et al. (2020)** (original FU: \$1 of products produced)

Outputs: 5734 g/month (\$28.60) – 0.2 kg/\$

Fish output: 1606 g/month (\$12.39) – 0.13 kg/\$

$$\frac{20.77 \text{ kg } CO_2 \text{ eq}}{\$ \text{ product produced}} \times \frac{\$ \text{ products produced}}{0.2 \text{ kg products}} \times \frac{5.734 \text{ kg products}}{1.606 \text{ kg LW fish}} = \frac{369.7 \text{ kg } CO_2 \text{ eq}}{\text{kg LW fish}}$$

**Equation A.C. Ghamkhar et al. (2019)** (original FU: 1 kg fish fillet)

$$\frac{145.7 \text{ kg } CO_2 \text{ eq}}{1 \text{ kg fish fillet}} \times \frac{0.1134 \text{ kg fish fillet}}{0.567 \text{ kg LW fish}} = \frac{29.14 \text{ kg } CO_2 \text{ eq}}{\text{kg LW fish}}$$

**Equation A.D. Boxman et al. (2017)** (original FU: 1 ton LW fish)

$$1 \text{ tonne LW fish} \times \frac{1000 \text{ kg}}{1 \text{ tonne}} = 1000 \text{ kg LW fish}$$

$$\frac{8640 \text{ kg } CO_2 \text{ eq}}{\text{tonne LW fish}} \times \frac{1 \text{ tonne}}{1000 \text{ kg}} = \frac{8.64 \text{ kg } CO_2 \text{ eq}}{\text{kg LW fish}}$$

## **Appendix B - Comparative life cycle assessment of insect farming in North American cold climate for fishmeal alternatives**

### **B.A. Insect Farming in the United States**

Insect farming in the US is a much smaller industry currently when compared to aquaculture for several reasons. One constraint is the negative association many people in the US have with insects, prompting potentially negative emotional responses to the products, thus not purchasing any kind insect-based products (Halloran et al., 2018). At least initially, insects for animal feeds could be the access point for a growing industry in

the US until the consumer culture changes. Another limitation with insect farming in the US is the policy and regulation surrounding food production in general. Since there is no specific governmental oversight yet, insect production is required to abide by standard food and feed production rules set by federal, state and local institutions, which require various waste disposal permits, food safety certificates, and licenses, depending on the parameters of the operation to even begin operation, which could cause potential delays or penalties if not properly informed. Though insects seem to be a promising alternative meal source for aquafeeds, further investigation into the environmental impacts of such operations is vital to ensure these alternatives are truly less environmentally impactful than their predecessors.

### **B.B. Theoretical heating calculations, inventory data sourcing, & life cycle assessment inventories**

Three types of insects (i.e., black soldier fly larvae, crickets, and mealworms) were chosen to be assessed in this study for multiple reasons. All three were chosen as they are currently some of the most in-demand types of insects, these insects are 100% edible, and they have also been assessed (environmentally and economically) in other countries, allowing for data collection and comparison. The three types of insects were also selected for their differences. Black soldier fly larvae (BSFL) was the first to be selected as they are one of the most commonly investigated species globally, they are able to efficiently convert biowaste streams, and their harvest is relatively simple as they leave their food source when they pupate (Beyers et al., 2023; Bosch et al., 2019; Smetana et al., 2019). Crickets were chosen as their life cycle stages are a bit different from the other two, they are

harvested at the adult stage, and the meal produced contains some of the highest protein content for insects (Halloran et al., 2017; Ignacio, 2018). Beetle larvae (specifically mealworms) was the last selected insect type as it is a species that is already commonly farmed in the US in exotic animal feeds and have a relatively short rearing cycle (Dreyer et al., 2021; Thévenot et al., 2018).

The black soldier fly larvae meal (BSFLM) life cycle assessment (LCA) relied mainly on inventory data from Maiolo et al. (2020) who investigated four types of meal alternatives in Italy and France, which included microalgae, BSFL, and poultry byproduct. The annual harvest of this species was 109 tonnes a year, making it the most productive operation of the three. BSFL is assumed to contain 50% protein on a dry matter basis (Maiolo et al., 2020). Feed composition was not provided in the paper, so feed ingredients and quantities are sourced from Beyers et al. (2023), specifically using 'diet 1' from the article.

Supplemental heating was added in this LCA as some seasons' average temperatures in France are higher than in Madison, WI. For all supplemental heating calculations, a theoretical operation was created to determine the size of the room that needs to be heated, given these dimensions were not provided (see Figure A in the SI). Some utilized studies also did not use the operation space efficiently, so a more compacted version was developed so heating can be reduced. The difference between the average monthly temperatures were then translated into each season's average temperature and the difference between the two locations was determined (e.g., Hauts-de-France, France average seasonal temperature – Madison, WI, USA average seasonal temperature) so that the seasonal average supplemental heating could then be translated into the yearly

amount so that it could be divided by the annual harvest quantity, thus producing the amount of heat required for one tonne of meal (see SI for details). The BSFL operation is the only one to use an electric heater while the two others are assumed to use natural gas. Transportation was also added for chicken feed and endive root as the available data only considers the production of these inputs. Transportation from fishmeal (FM) in EcoInvent was used for consistency for all transportation additions, given there is no concrete information on these input origins. Transportation of the harvested insects from an insect farm to a feed processing plant was also sourced from Maiolo et al., (2020) and was applied to all three LCAs as most farms and feed processing companies are two different entities with separate locations.

Halloran et al. (2017) assessed a medium-scale operation in Northeastern Thailand that reared two kinds of crickets (house and field), a relatively common protein source for human consumption in the region. The annual harvest for this operation was 36,741 kilograms per year (Halloran et al., 2017). House crickets are assumed to be 63% protein on a dry matter basis while field crickets are 56% (Halloran et al., 2017). Supplemental lighting and heating were also needed for the cricket LCA in particular given the original operation is in Thailand, which has higher average temperatures and sunlight durations compared to Madison, WI. No heating was included with their inventory given the operation was located in a warm climate, so the input was calculated based off the theoretical setup and the assumption of maintaining a room temperature of 80 °F. Since the two regions are in different parts of the Earth, the months with the most sunlight are opposite of one another. Average daily sunlight durations were ranked by month for each location from

highest to lowest and the difference was taken. If a non-negative number was the result, supplemental lighting was used to cover the difference. A UV reference light was used, and two lights were assumed to be utilized for the additional lighting in the theoretical operation for this assessment. The total light required was determined and translated into input energy required per functional unit (FU). Transportation was added for rice bran and rice husk as these inputs only include the production of these inputs which was determined using the transportation required for FM. During the end stage of rearing these crickets, pumpkins are mixed into their feed for the purpose of making them have an orange coloration and enhance flavor (Halloran et al., 2017). Due to limitations of data availability, melons were selected to replace pumpkins in the LCA as both are fruits and are grown on vines. Processing in their assessment only included drying/cooking the crickets, so processing data from Thevenot et al. (2018) was utilized to determine the impacts of the crickets as meal instead of only being cooked and dried (the fat separating process is energy intensive).

Oonincx and de Boer (2012) studied two kinds of commonly reared beetles in the Netherlands, however, the assessment is to the farm gate, so processing data was again sourced from Thevenot et al. (2018). The annual harvest of mealworms was 83,200 kilograms per year, which is significantly less productive than the other two (Oonincx and de Boer, 2012). According to the same article, mealworms are assumed to have a protein content of 53% on a dry matter basis. Supplemental heating was also required for this LCA given the differences in average temperatures and was calculated using the same

approach as described above. Transportation was again added for sugar beet pulp as the available data only considers materials acquisition and production.

Endive roots in the BSFL inventory were replaced with chicory roots in the assessment due to limitations in the available databases, however the Beyers et al. (2023) article considers endive root a “free” product given the main desired product is the leafy part of the plant, while the root system is a waste product or is used for ground cover and a nutrient source on cropland for future farming endeavors. Endive root and chicory root systems are slightly different (the chicory root has a main root with a larger diameter, while the endive root system is comprised of a smaller main root with many roots growing from it). The inclusion of the root was an important addition to the assessment given endive can continue to grow after harvest and transportation of said roots is an important consideration as transportation can be a highly impactful input (Liu et al., 2023). Rice bran is also a byproduct of white rice production but is already allocated within the Agri-Footprint database and there are no alternative options in EcoInvent, Agri-Footprint or USLCI. SBM production also produces an oil product and represents 18.14% of the products (i.e., SBM and oil) produced on a mass basis (Silva et al., 2018). FM is another ingredient in the cricket meal (CM) assessment which also produces fish oil which accounts for 16% of the total products produced on a mass basis (Avadí and Fréon, 2013). Rapeseed meal was utilized in the chicken feed within the BSFLM assessment, and the production of the meal also produces an oil product which represents 37.7% of the total products on a mass basis (Lehuger et al., 2009). Palm oil was used in the CM assessment and while palm fruit also produces palm kernels which can also make an oil if processed,

however, no allocation was given to the kernels as this oil source would need to be processed separately.

**Table B.A.** BSFLM inventory and sourcing

Inputs	Quantity	Unit	Database source	Literature source
Chicken feed	296.5	kg	Agri-footprint 6	Beyers et al., (2023)
Potato starch	960		Ecoinvent 3	
Sodium chloride	6.538		Agri-footprint 6	
Endive root	2964		Ecoinvent 3	Beyers et al., (2023); Maiolo et al., (2020)
Wheat bran	1236			
Water	6300			
Sodium hypochlorite	6.538			
Lorry transport	2.231		tkm	Thévenot et al., (2018)
Electricity	2.01E+04	kWh	Maiolo et al. (2020); Calculations	

**Table B.B.** CM inventory and sourcing

Inputs	Quantity	Unit	Database source	Literature source
Tap water	2576	kg	Ecoinvent 3	Halloran et al., (2017)
Sodium chloride	77.73			
Soybean meal	2176			
Maize grain	3964		Agri-footprint 6	
Rice bran	699.6			
Palm oil	233.2		Ecoinvent 3	
Calcium carbonate	233.2			
Pumpkin	2135			
Fishmeal	388.7		Agri-footprint 6	
Rice husk	1570			
Lorry transport (insect biomass to processing plant)	2.231	tkm	Ecoinvent 3	Thévenot et al., (2018)
Electricity	10180	kWh		Halloran et al., (2017); Thévenot et al., (2018)
Natural gas	6541	m <sup>3</sup>		Halloran et al., (2017); Calculations

**Table B.C.** Mealworm meal (MM) inventory and sourcing

Inputs	Quantity	Unit	Database source	Literature source
Tap water	9732	kg	Ecoinvent 3	Thévenot et al., (2018)
Sugar beet pulp	762.7		Agri-footprint 6	
Wheat bran	3813		Ecoinvent 3	
Soybean meal	1869			
Maize flour	1182			
Lorry transport	2.231	tkm	Ecoinvent 3	Thévenot et al., (2018);Calculations
Electricity	11340	kWh		
Natural gas	2158	m <sup>3</sup>		

**Table B.D.** BRU calculations and sources for BSFLM

Carbon-based ingredients	Quantity (kg C/kg ingredient)	Quantity (tonne C/tonne meal)	Source
Endive root	0.0607	1.799E+02	Beyers et al., 2023
Potato starch	0.4322	4.149E+02	
Soy paste	0.04286	3.600E+01	
Wheat bran	0.4272	5.280E+02	
Chicken feed	0.4453	1.320E+02	Ghamkhar and Hicks, 2020; Pelletier & Tyedmers, 2007
	Total	1290.89	-

**Table B.E.** Chicken feed BRU calculations

Ingredient	Amount (g/kg feed)	Ingredient carbon content (kg C/kg ingredient)	Carbon content (kg C/kg feed)
Soybean meal	250	0.528	0.132
Rapeseed meal	50	0.404	0.0202
Maize	630	0.465	0.29295
Calcium carbonate	10	0.012	0.00012
		Total	0.44515

**Table B.F.** BRU calculations and sources for CM

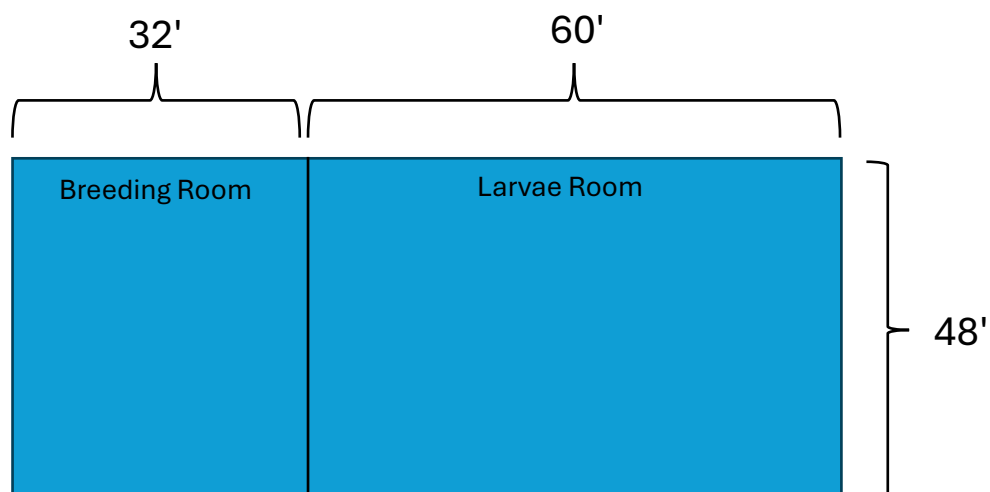
Carbon-based ingredients	Quantity (kg C/kg ingredient)	Quantity (tonne C/tonne meal)	Source
Fish meal	12.68	4.9281E+03	Barlow, 2003; Hasan & Halwart, 2009
Soybean meal	0.429	9.3369E+02	Pelletier & Tyedmers, 2007
Grain maize	0.465	1.8434E+03	Ghamkhar and Hicks, 2020
Rice bran	0.444	3.1061E+02	
Palm oil	0.7692	1.7937E+02	Firestone, 1999
Pumpkin	0.43	9.182E+02	Savage et al., 2014
Rice husk	0.288	4.523E+02	Yiga et al., 2023
	Total	9565.55	-

**Table B.G.** BRU calculations and sources for MM

Carbon-based ingredients	Quantity (kg C/kg ingredient)	Quantity (tonne C/tonne meal)	Source
Sugar beet pulp	0.022	1.678E+01	Sarauskis et al, 2018
Wheat bran	0.4272	1.629E+03	Beyers et al., 2023
Corn cereal flour	0.465	5.497E+02	Ghamkhar and Hicks, 2020
Soybean meal	0.429	8.016E+02	Pelletier & Tyedmers, 2007
	Total	2997.11	-

**Table B.H.** BRU calculations and source for palm oil

Input	Amount (kg/kg palm oil)	Carbon content (kg C/kg input)	Carbon content kg C/kg palm oil)
Palmitic acid	0.44	0.7494	0.3297
Oleic acid	0.366	0.7653	0.2801
Myristic acid	0.01	0.7363	0.007363
Stearic acid'	0.043	0.75997	0.03268
Linoleic acid	0.091	0.7709	0.07015
Carotenes	0.055	0.8948	0.04921
		Total	0.7692



**Figure B.A.** Theoretical insect operation dimensions

**Equation B.A.** Theoretical operation heating:  $Q = U \times A \times \Delta T$

Q is the average heat requirement (BTU/hr), U is the overall heat transfer coefficient, A is the total surface area of the rooms (ft<sup>2</sup>), and  $\Delta T$  is the change in temperature from inside the operation to outside (°F).

### B.C. Supplemental LCA Results

**Table B.I.** Completed LCA results for one tonne meal

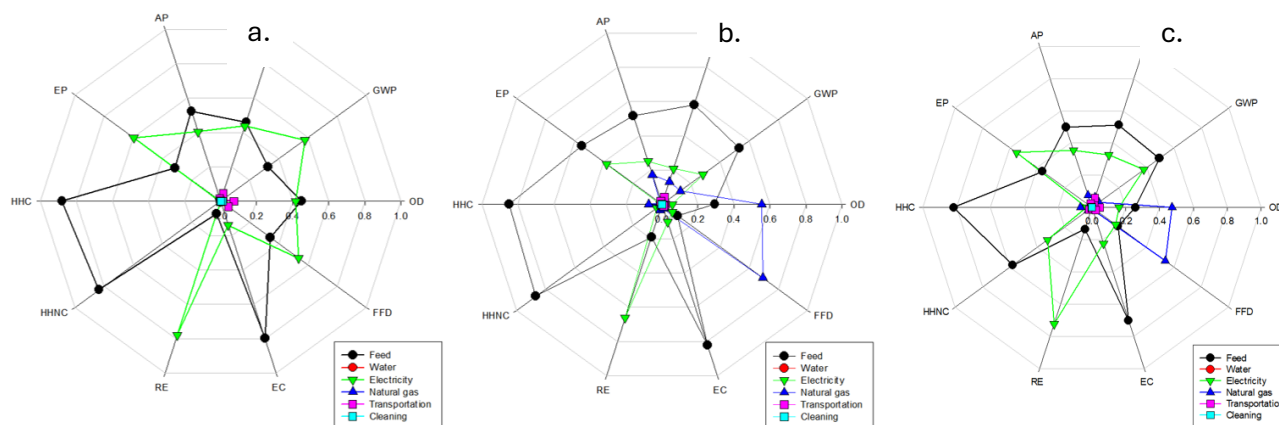
Impact category	Unit	BSFL	Standard deviation	Cricket	SD	Mealworm	SD
Ozone depletion	kg CFC-11 eq	9.734E-04	2.617E-04	3.838E-03	1.689E-03	1.502E-03	7.082E-04
Global warming	kg CO2 eq	1.827E+04	3.792E+03	2.041E+04	2.875E+03	1.644E+04	2.691E+03
Smog	kg O3 eq	818.6	123.4	917.1	97.25	641.0	83.9
Acidification	kg SO2 eq	96.48	14.33	81.67	11.17	63.20	9.038
Eutrophication	kg N eq	188.1	82.92	157.0	53.17	116.4	69.80
Carcinogenics	CTUh	5.347E-05	9.083E-06	2.050E-05	3.041E-06	7.492E-06	8.720E-07
Non carcinogenics	CTUh	1.935E-02	4.074E-03	3.430E-04	6.315E-05	4.017E-05	1.272E-05
Respiratory effects	kg PM2.5 eq	57.12	14.68	35.03	7.290	35.21	8.441
Ecotoxicity	CTUe	1.048E+05	2.289E+04	7.342E+04	2.064E+04	3.645E+04	8.362E+03
Fossil fuel depletion	MJ surplus	1.209E+04	2.409E+03	5.152E+04	1.101E+04	2.281E+04	4.133E+03
BRU	kg C	1290	-	9113	-	2997	-

**Table B.J.** LCA results for one tonne of insect meal protein

Impact category	Unit	BSFL	Cricket	Mealworm
OD	kg CFC-11 eq	1.803E-03	6.331E-03	2.200E-03
GWP	kg CO2 eq	3.593E+04	3.380E+04	2.481E+04
SF	kg O3 eq	1.562E+03	1.479E+03	9.283E+02
AP	kg SO2 eq	1.900E+02	1.348E+02	9.489E+01
EP	kg N eq	3.755E+02	2.634E+02	1.786E+02
HHC	CTUh	1.069E-04	3.439E-05	1.146E-05
HHNC	CTUh	3.869E-02	5.753E-04	6.052E-05
RE	kg PM2.5 eq	1.138E+02	5.854E+01	5.383E+01
EC	CTUe	2.091E+05	1.230E+05	5.569E+04
FFD	MJ surplus	2.287E+04	8.551E+04	3.408E+04
BRU	kg biotic C	2580	15318.953	4744.251

### B.D. Sensitivity Analysis Results

Sensitivity analysis is an important step in LCA to better understand which inputs impact environmental and human health emissions the most. For all meal types, each input was varied by 20% and each impact category was assessed to determine the most sensitive inputs using the non-allocated LCA results. Figure B displays the results of the analysis and will be discussed further below.

**Figure B.B.** Sensitivity analysis of inputs for one tonne a. BSFL b. CM c. MM

### B.E. Discussion of Uncertainty and Sensitivity Analyses

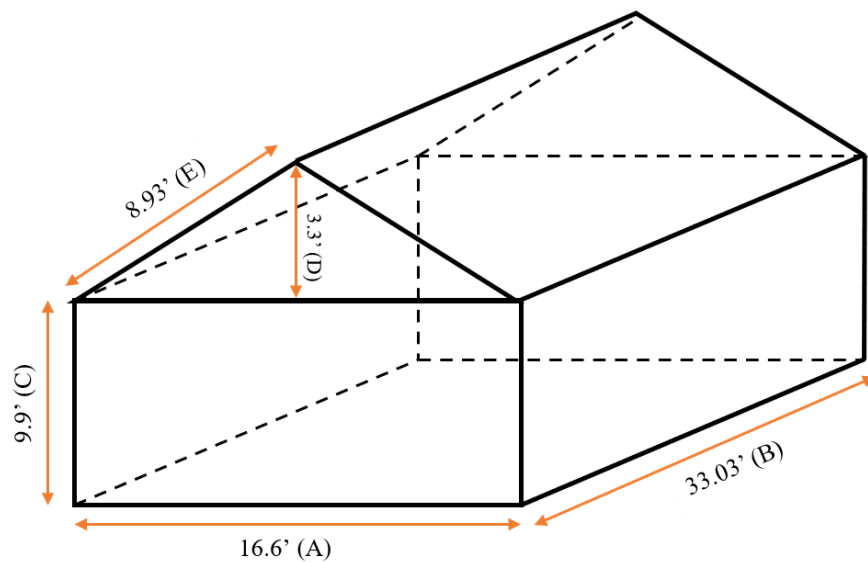
Uncertainty within the context of an LCA is vitally important as uncertainty arises for a multitude of reasons but mainly from data availability limitations. Within the modeling, the most conservative choices were made so the full potential range of impacts could be assessed, given the lack of primary data and lack of any standards in the insect propagation industry. Uncertainty also arises from selections made within the databases used for the assessments themselves. Often, there are no data points that are US centric, requiring the selection of data points which are either global or are categorized as the rest of the world.

Sensitivity analysis is another assessment utilized to develop a more comprehensive investigation of the environmental impacts of products and processes. For BSFL meal, electricity was the most sensitive for global warming potential (GWP), eutrophication potential (EP), fossil fuel depletion (FFD), and respiratory effects (RE), while the feed was the most sensitive for acidification potential (AP), smog formation (SF), ozone depletion (OD), human health carcinogens (HHC), human health non-carcinogens (HHNC), and ecotoxicity (EC), mainly due to the endive root input. For CM, electricity was the most sensitive input for RE, feed for GWP, SF, AP, EP, HHC, HHNC, and EC, and natural gas for OD and FFD. For MM, the feed was the most sensitive input for GWP, SF, AP, EP, HHC, HHNC, and EC. Electricity was the most sensitive for EP and RE, while NG was the most sensitive input for OD and FFD. The findings of this analysis are useful in showing the potential utility in tweaking the input quantities to make them more efficient relative to environmental impact or finding input alternatives, especially for heating and electricity, while the other side of the coin shows the potential concerns with slight increases in input

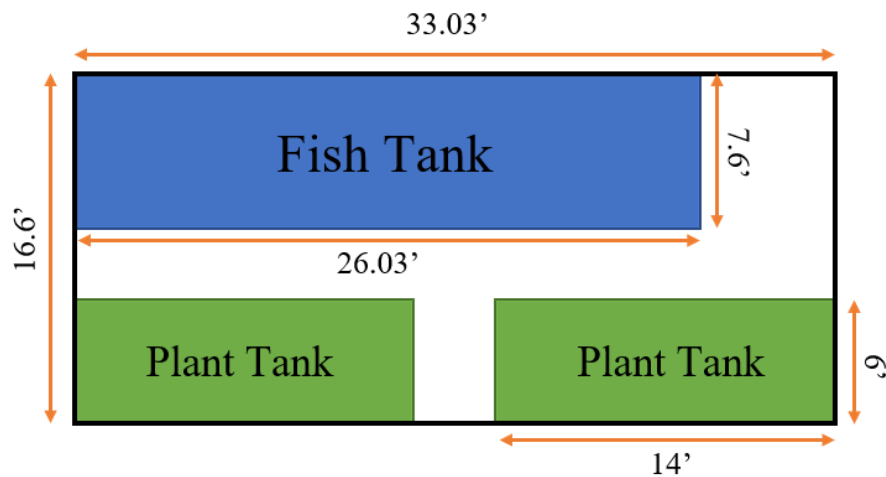
quantities.

## Appendix C - Exploring aquaponics systems and environmental impacts: an agent-based model case study

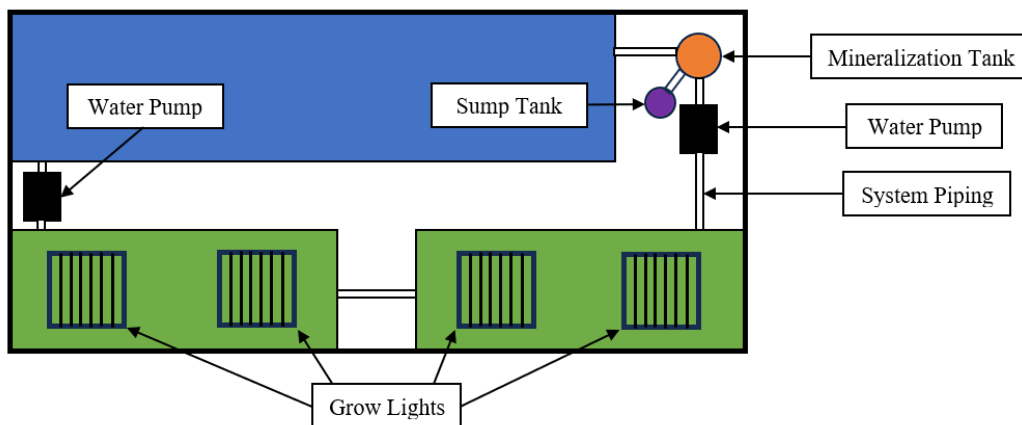
### C.A. Theoretical Model Parameters



**Figure C.A.** Model Greenhouse Dimensions



**Figure C.B.** Top View of Model Greenhouse with Tank Dimensions



**Figure C.C.** Top View of Model Greenhouse General Aquaponics Setup

### **C.B. Model Climates and Seasons**

The climates were deliberately selected to show the variety of climates that could be expected for AQP. The generic climate types for the model are designed to offer the concept of climate to the user without exploring the intricacies behind climate. The seasonal temperatures in a particular climate were determined by averaging the averages of the minimum and maximum monthly temperatures within each season at each reference location. Ensuring the climate and time of year is important as the temperatures and sunlight durations can vary greatly, carrying along a highly varied number of emissions. Adding the different climates in the model allows the user to explore the idea that some climates are better suited for an operation in terms of temperature and sunlight duration throughout the year. Including the consideration of climate also allows for potential discussion to arise related to other possible climate considerations, potential for taking an operation fully outdoors and what that would require, and discussion related to understanding the importance of considering climate when making sustainability decisions. The ABM requires that a particular season is selected to keep the base of the

model as simple as possible. Table A presents the various reference locations' climate information that was used when designing the model.

**Table C.A.** Model climate reference information

Climate & reference	Reference locations	Köppen-Geiger climate classification	Spring		Summer		Fall		Winter	
			Temperature (°F)	Sunlight duration (hrs/day)	Temperature (°F)	Sunlight duration (hrs/day)	Temperature (°F)	Sunlight duration (hrs/day)	Temperature (°F)	Sunlight duration (hrs/day)
Humid continental (National Oceanic and Atmospheric Administration 2022a)	Madison, WI, USA	Dfb	34.5	7.1	71	8.3	49.5	9.2	25	3.6
Temperate (Atlas 2025)	Madrid, Spain	Csa	54.8	13.3	74	15.8	59	11.2	44.6	9.7
Tropical (National Oceanic and Atmospheric Administration 2022b)	Miami, FL, USA	AW	75	13	82.3	13.5	78	11.5	68.2	11
Humid subtropical (Anon 2022)	Tokyo, Japan	Cfa	56.8	13	76.3	14	64	11.5	43.3	10

### C.C. Model Fish Densities, Types, and Feed

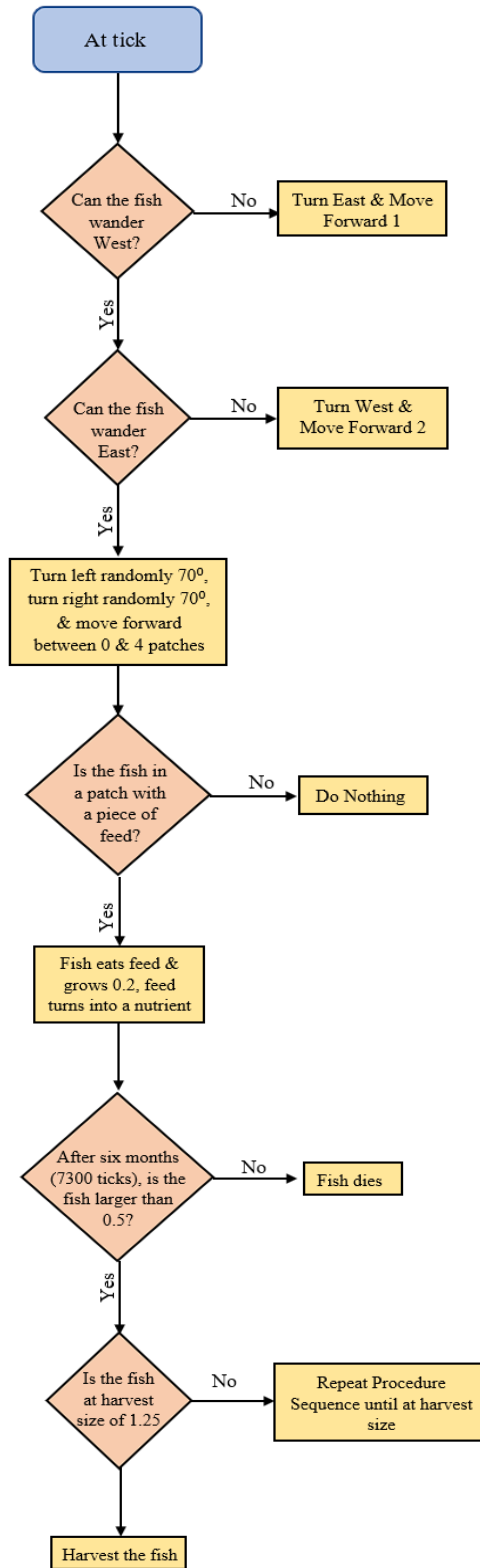
Four species of fish were chosen to grow in the ABM, each one was selected for various reasons such as temperature requirements and life cycle durations. In a typical operation, fish would be separated based on age, sex, and for mating, however, the model assumes all fish are in one tank for simplicity. Table B displays useful information related to the fish modeled by the

**Table C.B.** Model fish types' details

Fish type	Scientific name	Ideal temperature range (°F)	Model temperature (°F)	Feed protein content (%)
Nile tilapia (Bahnasawy et al., 2003; Manduca et al., 2021; Philippart and Ruwet, 1982)	<i>Oreochromis niloticus</i>	80-86	80	32
Hybrid walleye (Summerfelt, 1996)	Sander vitreus x Sander Canadensis	72-79	75	55
Atlantic salmon (Lall, 2009)	<i>Salmo salar</i>	51-61	60	42.3
Channel catfish (Boyd et al., 2024.; Wurts, 2001; Wyatt et al., 2006)	<i>Ictalurus punctatus</i>	65-75	85	32

ABM. Three options of fish densities are available in the model, “100”, “300”, and “500” fish, which were selected to show the effect of varied stocking densities on individual growth, plant growth, and emissions. Given the theoretical operation size of the model, the stocking densities would vary greatly for each fish and should be significantly higher than the model, depending on the type of fish. For example, Boxman et al., (2017) analyzed an outdoor AQPs operation in the Virgin Islands, which had fish tanks that were over double the size of the model’s fish tank, but the stocking density for the operation is over ten times that of the model (Boxman et al., 2016). Stocking densities were chosen to be lower than real operations as the interface shows only a two-dimensional view of the tank, which would be overwhelming visually to the user, and the model would run significantly slower. Feed quantities and composition were determined using published data for each species of fish. All information related to the growth and feed rates of each modelled fish, along with the conversion factors for the corresponding emissions of the feed can be found in

Tables F and G. Figure D shows the action sequence the fish go through in the model to imitate eating, swimming, growing, and excreting.



**Figure C.D.** AQP ABM Fish Procedure

### C.D. Model Plant Types and Densities

The plants propagated in an APS are arguably the primary product produced as revenue generation from these products is generally significantly higher when compared to the fish (the plants' harvest cycles are shorter than the fish). The different plant types were chosen to show the variety of species that could be grown but also maintaining a realistic perspective relative to the limitations with the methodology. The plants chosen to be in the ABM were sweet basil, romaine lettuce, tomatoes, and bell peppers. Supplemental lighting is the main input dependent on the plants, so lighting requirements for each plant are shown in Table C. Sweet basil was the first plant type selected as it is one of the most commonly

**Table C.C.** Model plant types' specifications

Plant type	Scientific name	Required sunlight duration range (hrs/day)
Sweet basil(Boeckmann, 2024)	Ocimum basilicum	6-8
Romaine lettuce(Cohen et al., 2018; Matysiak et al., 2023)	Lactuca sativa L. var. longifolia	6-14
Tomato(Cornell College of Agriculture and Life Sciences, 2024)	Solanum lycopersicum	8-12
Bell pepper(Albaho et al., 2008)	Capsicum annum	12-18

propagated plants in AQP currently. Romaine lettuce was selected as the second plant type in the AQP model for similar reasons as basil. Lettuce is commonly grown in hydroponics and AQP as this type of plant grows small root systems, has low nutrient dependence, and can withstand heat better than many other lettuce types. Tomatoes were selected as another product to be included in the model as this type would require a different hydroponics setup (media beds), prompting opportunities for discussion related to system options and logistics. Tomatoes are also a good selection, to show the wide range of options for propagated plants in AQP. For more advanced classes, discussion into supplemental nutrient additives could be discussed with this plant type too. Bell peppers were selected last as this type of plant also requires a different hydroponics setup, but this plant type also requires more sunlight than any of the other plant types.

#### **C.D. AQP ABM GHG Emissions**

Typically, a life cycle assessment (LCA, the quantification of the environmental impact of a product or process) would include multiple environmental impact categories such as eutrophication, acidification (i.e., a chemical's inclination to form acidic compounds), and ecotoxicity (i.e., how harmful a substance is to the environment and its inhabitants) but in order to avoid overcomplication of the main topic at hand (AQP), only global warming potential (GWP) was included in the model (Bare, 2012). GWP is an impact category defined by the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) as a way of quantifying GHG emissions for a given system (Bare, 2012). In this context, GHG emissions include carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O), but all is boiled down to carbon dioxide equivalence based on

each gases' conversion factors (Bare, 2012). The main inputs producing emissions in a general APS are electricity, heating, and fish feed (Boxman et al., 2016; Ghamkhar et al., 2020; Kalvakaalva, 2020). Depending on the products produced, some operations require other inputs such as aeration systems and nutrient additions, however these are not necessarily vital when educating students on AQP and can also heavily depend on operation location and fish and plant type. Infrastructure and construction of the operation was also excluded in the GWP calculation as the data required for the materials was not available. Other assumptions made for the model can be found in Table D.

Supplemental lighting and water pumping are the two components which comprise the emissions produced for the electricity input in the AQP ABM. As determined in LCAs of APSs, electricity is observed to be one of the most environmentally impactful relative to the other inputs to the system (Boxman et al., 2016; Breitenstein and Hicks, 2022; Ghamkhar et al., 2020). Because of the related GHG emissions, electricity was a necessary input to include in the AQP ABM. Lighting in the model is dependent on the plant type, climate, and season. The GHG emissions produced by supplemental lighting are distributed throughout the day (i.e., a plant needs eight extra hours of light for a given day, then the emissions produced for those eight hours are spread to the entire 24 hours). The power required for each grow light was determined as well as the supplemental lighting required for each plant type in each climate and season. Four grow lights are used when the user selects three or four columns of plants in the model, but six lights are used when the user selects five columns of plants to ensure sufficient lighting for all plants in the model. With the data provided on the lights themselves and equation 3, the power required for the different

variables was calculated. SimaPro 9.2 software was employed with the EcoInvent 3 database to convert energy input quantities into the related GHG emissions.

Water pumping is the second input for the AQP model that produces emissions for electricity. The water in the system is assumed to circulate twice per hour, with no dependence on any selection by the user. The flow rate is solely dependent on the volumes of the fish and plant tanks (959.312 ft<sup>3</sup> or 27.164 m<sup>3</sup>). From the flow rate, Equation 4 was used to determine the total power required to run the pumps. The rate of power needed throughout the day for the pumps was then converted into the corresponding emissions based on each reference location (each location has a different heating and electricity energy mix). SimaPro 9.2 was again employed to convert energy input quantities into GHG emissions produced. Aeration systems were excluded as an input for electricity in the model as they are not always needed, and the flow rate of the water (produced by the water pumps) and aeration stones satisfy the dissolved oxygen requirements for the theoretical system (Khater et al., 2021).

Heating is another important aspect of APSs, especially depending on where the operation is located. For example, outdoor systems are more viable in tropical climates, mitigating supplemental heating entirely, though other consequences arise. On the other hand, cities such as Tokyo would need an indoor system with supplemental heating. Various methods of heating are used for the respective reference locations (e.g., cities such as Tokyo use electric powered heating systems). Heating was determined using Equation 2 and was then converted into the related GHG emissions using SimaPro 9.2 software. Heating emissions are broken down to emit throughout the day to remain as

simple as possible relative to the GHG emissions. Emission rates used in the model for electricity and heating can be found in Table E.

Because different types of fish require different types of fish feed, the daily intake, and thus the related emissions are also varied. The average weight of each fish was determined using the weight of the average fish at the time they are born until harvest.

### **C.E. Model Options Example and Agents' Coded Procedures**

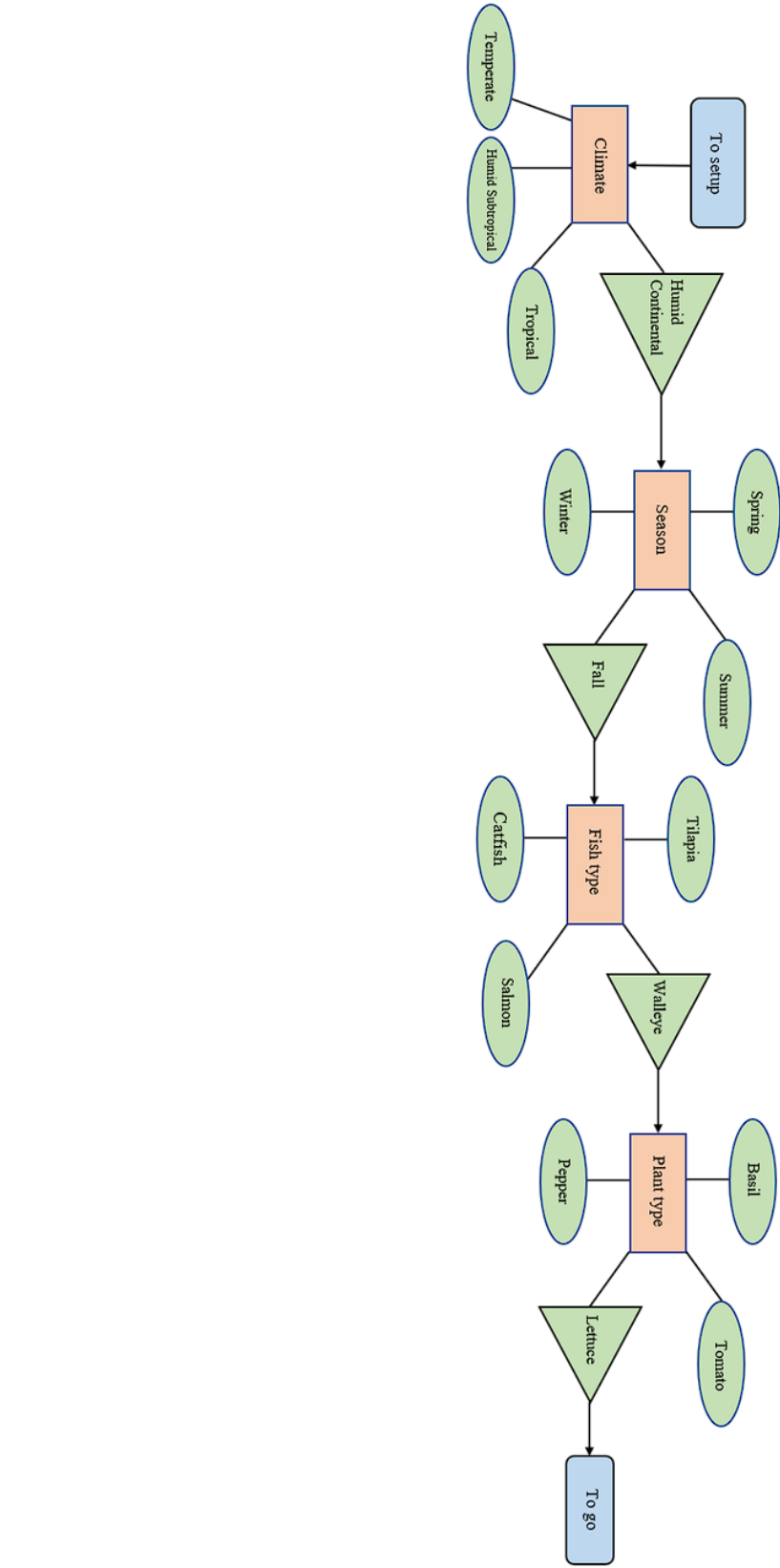
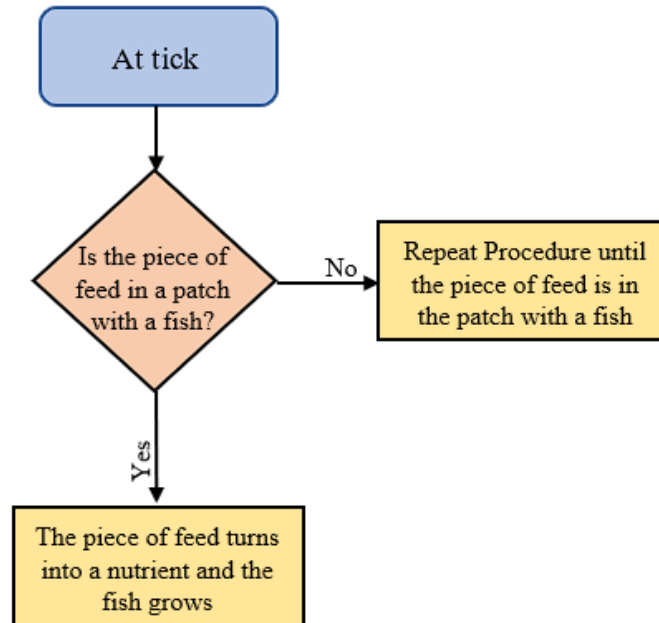
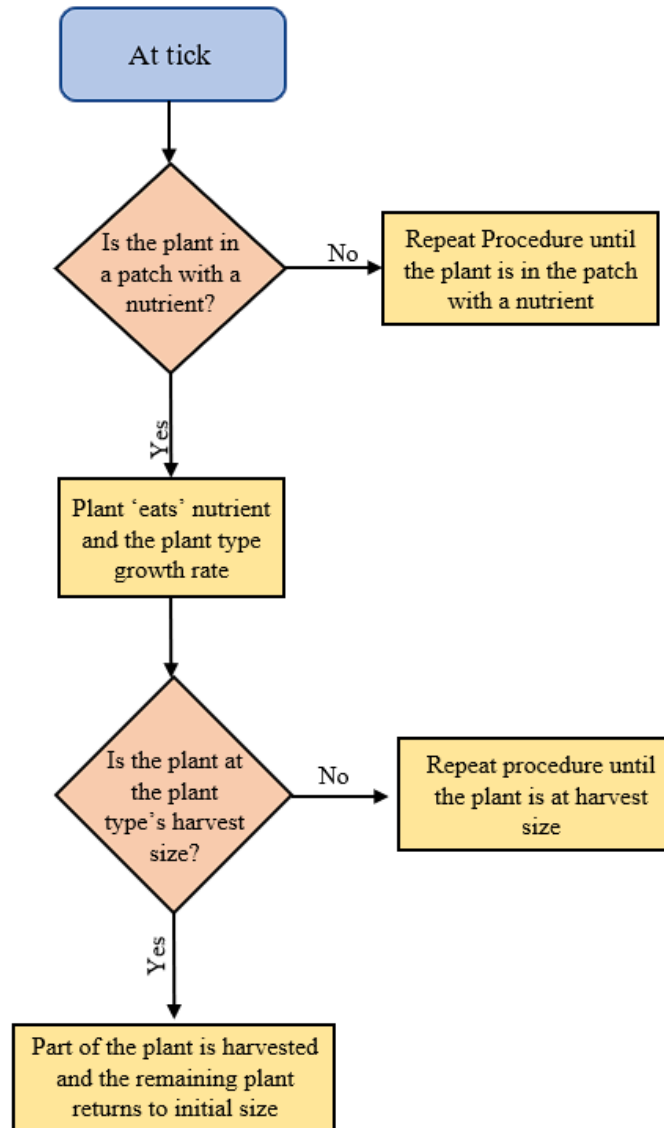


Figure C.E. Aquaponics ABM parameter selection example



**Figure C.F.** Aquaponics ABM Feed Procedure



**Figure C.G.** Aquaponics ABM Plant Procedure

### C.F. Model Greenhouse Gas Emissions Calculations

**Equation C.E. Model greenhouse surface area (please refer to figure A):**  $2 \times (A \times C) + 2 \times (B \times C) + 2 \times (E \times B) + (A \times D) = SA_{A-frame} = 2 \times (33.03' \times 9.9') + 2 \times (16.6' \times 9.9') + 2 \times (8.93' \times 33.03') + (16.6' \times 3.3') = 1627.37 \text{ ft}^2$

**Equation C.F. Model Greenhouse Heating:**  $Q = U \times A \times \Delta T$

Q is the average heat requirement (BTU/hr), U is the overall heat transfer coefficient, A is the total surface area of the greenhouse (ft<sup>2</sup>), and ΔT is the change in temperature from inside the greenhouse to outside (°F)

**Equation C.G. Greenhouse Lighting Calculation:**  $P = V \times I$

P is the input power (W), V is the input voltage (V), I is the input current (Amps)

$$120.04 V \times 6.682 \text{ Amps} = 799.3 W \text{ (Per light)}$$

Assumed grow lights used: Growers Choice ROI-E720 Full-Spectrum 700 W LED Grow Lights

**Equation C.H. Water Pumping Power Calculation:**  $P = \frac{Q \times H \times \rho}{367 \times \eta}$

P is the pump input power (kW), Q is the flow rate of the liquid being pumped (m<sup>3</sup>/hr), H is the total developed head (m), ρ is the density of the liquid being pumped (kg/m<sup>3</sup>), and η is the efficiency of the pump (between 0 and 1)

Assumed pumps used in model: Advance 4000 Pump (mdminc.com)

Pump efficiency = 75%, total developed head = 2.33 ft = 0.7102 m, density of water = 1000 kg/m<sup>3</sup>

Fish tank volume (refer to Figure C.B):  $7.6' \times 26.03' \times 4' = 791.312 \text{ ft}^3$

Plant tanks volume (refer to Figure C.B):  $6' \times 14' \times 1' \times 2(\text{tanks}) = 168 \text{ ft}^3$

Total water volume: 959.312 ft<sup>3</sup>

Water flowrate (water cycled twice per hour): 11393.32 gal/hr = 43.128 m<sup>3</sup>/hr

**Equation C.I.** Water pump power input (kW):  $\frac{43.128 \times 2.33 \times 1000}{367 \times 0.75} = 111.277 \text{ kW}$

**Table C.D.** Aquaponics ABM Assumptions

Model Assumption	Notes
The greenhouse is facing South with nothing obstructing the sunlight	These assumptions are ensuring ideal conditions related to the physical state of the operation
The operation scale is assumed to be commercial	In reality, commercial scale operations would likely produce significantly more fish and plants
Assumed relative humidity of 70%	In reality, humidity would be a parameter occasionally measured to ensure it is within a range for the propagated plants
Three pieces of feed are designated as a single meal for a single fish	
Aeration stones are assumed to be in the fish tank	

**Table C.E.** Aquaponics ABM Greenhouse Gas Emissions Conversion Factors

Model Climate	Reference Location	Electricity GHG Conversion Factors (kg CO <sub>2</sub> eq)		Heating GHG Conversion Factors (kg CO <sub>2</sub> eq)	
Humid Continental	Madison, WI, US	1 MJ =	$3.84 \times 10^{-2}$	1 BTU =	$3.17 \times 10^{-4}$
Temperate	Madrid, Spain		$5.73 \times 10^{-2}$		$1.64 \times 10^{-4}$
Tropical	Miami, FL, US		$3.94 \times 10^{-2}$		$2.05 \times 10^{-4}$
Humid Subtropical	Tokyo, Japan		$1.94 \times 10^{-1}$		$2.05 \times 10^{-4}$

**Table C.F.** Aquaponics ABM Fish Type Specifications

Fish Type	Model Greenhouse	Initial Model	Average Weight (lbs)	Model Harvest Weight (lbs)	Feeding Frequency (daily)	Feed Protein
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	Temperature (°F)	weight (lbs)				Content (%)
Tilapia (Bahnasawy et al., 2003; Philippart and Ruwet, 1982)	80	0.01	0.8	1.5	2	32
Walleye(Summerfelt, 1996)	75	0.01	1.0	2.0	2	55
Salmon (Lall, 2009)	60	0.05	3.3	6.6	4	42
Catfish (Boyd et al., 2024; “Channel catfish - Ictalurus punctatus,” 2024; Wurts, 2001; Wyatt et al., 2006)	70	0.05	1.5	3.0	2	32

**Table C.G.** Aquaponics ABM Fish Feeding Greenhouse Gas Emissions Calculations

Fish Type	Feed Rate (lb feed/fish/day)	GWP Conversion (kg CO2 eq/lb feed)	GWP Rate (kg CO2 eq/fish/day)
Tilapia (Ng and Romano, 2013)	0.00331	0.753	0.00249
Walleye (Summerfelt, 1996)	0.0201	0.392	0.00788
Salmon (Lall, 2009)	0.0833	1.994	0.166
Catfish (Wurts, 2001)	0.0458	0.999	0.0457

**Appendix D - Understanding aquaculture and aquaponics general operational parameters and attitudes towards value-added and value-recovered products - Surveying current and former United States Midwest cold climate producers**

**D.A. Producer Survey Instrument**

1. Does your operation include aquaculture systems, aquaponics systems, both, or neither?



12. What motivated you to begin your aquaculture operation? (Please rank the motivations below from most important motivation – 9 to the least important motivation – 1 or no consideration at all for this motivation – 0)

Initial Motivation	Motivation Rank
Grow your own food	
Improve health & wellbeing	
Improve community food security	
Educational outreach	
Economic benefits	
Faith-based work	
International aid & development	
Environmental sustainability	
Adapting to climate change	
Other (describe)	

13. Has your motivation for your aquaculture operation changed over time?
- Yes (please explain)

b. No

14. Please estimate your operation's average annual fish production.

- None
- 1 – 49 pounds
- 50 – 99 pounds
- 100 – 499 pounds
- 500 – 999 pounds

- f. 1,000 – 4,999 pounds
  - g. 5,000 – 9,999 pounds
  - h. 10,000 pounds or more
15. Does/did your aquaculture operation employ anyone other than yourself?
- a. Yes
  - b. No
16. (If yes to Q15) How many employees (including yourself)? \_\_\_\_\_ employees
17. What was the original purpose of your aquaculture? Circle all that apply.
- a. Financial gain
  - b. Education
  - c. Hobby
  - d. Self-sustaining lifestyle
  - e. Other \_\_\_\_\_
18. What type of aquaculture setup does your operation use?
- a. Intensive (i.e., dedicated tanks for the fish)
  - b. Extensive (i.e., operation conducted in a natural body of water)
  - c. Other (please describe)
19. What types of fish are/were reared in your operation?
- a. Tilapia
  - b. Catfish
  - c. Bluegill
  - d. Perch
  - e. Ornamental fish (e.g., Koi, goldfish, tropical fish)
  - f. Bass
  - g. Trout
  - h. Shrimp
  - i. Other \_\_\_\_\_
20. What is/was the approximate total tank volume of your aquaculture system?  
\_\_\_\_\_ ft<sup>3</sup> or \_\_\_\_\_ m<sup>3</sup>
21. Has the size of your operation changed since its initial opening?
- a. Yes
  - b. No
22. (If yes to Q21) Did your operation scale up or down?
- a. Scaled up
  - b. Scaled down
23. (If yes to Q21) Did you face any new challenges when you scaled up/down?
- a. Yes (please explain)

- b. No
24. What are/were the major challenges your operation has/had experienced? Circle all that apply.
- Environmental control issues
  - Nutrient cycling issues
  - Mortality of fish
  - Algae growth
  - Pest problems
  - Infrastructure/construction issues
  - Financial issues
  - Operation maintenance issues
  - Other (please explain)

### Potential Aquaponics Transition Section

**Note:** Aquaponics is the combination of aquaculture and hydroponics. The water and nutrients from the fish tank are filtered and sent to the plant tanks to hydrate and fertilize the plants. The water from the plant tank is then sent back to the fish tank.

25. Do you have any interest in potentially converting to an aquaponics system?
- Yes
  - No
26. Based on your current setup, would it be physically possible to transition to an aquaponics system?
- Yes
  - No
27. (If yes to Q26) At what point would you be financially incentivized to make the transition to aquaponics (e.g., 1:1.5 or for every dollar you put into the operation, you will see a \$1.50 return)? Please provide a ratio of investment to return.
- 
28. If you are physically able to make the transition, what are the potential challenges in making this transition?

**\*\*skip to question 57 if you do not have an additional aquaponics operation beyond aquaculture\*\***

### Aquaponics Operation Section

29. Is your aquaponics system a part of a larger business (e.g., bait shop, restaurant, etc.)?
- Yes
  - No
30. (If yes to Q29) What type of business is/was it?
31. (If yes to Q29) What types of products are/were produced?
32. Is your aquaponics system currently in operation?
- Yes
  - No
33. (If yes to Q32) Approximately how long has your system been in operation? \_\_\_\_\_ months \_\_\_\_\_ years
34. (If no to Q32) Approximately how long was the system in operation? \_\_\_\_\_ months \_\_\_\_\_ years
35. (If no to Q32) What years was your business in operation?
36. What is/was the name of your operation?
37. Was your system operating during the COVID-19 pandemic?
- Yes
  - No
38. (If yes to Q37) What were the challenges you and/or your operation faced relative to operating during a pandemic? Please explain.

39. What motivated you to begin your aquaponics operation? (Please rank the motivations below from most important motivation – 9 to the least important motivation – 1 or no consideration at all for this motivation – 0)

Initial Motivation	Motivation Rank
Grow your own food	
Improve health & wellbeing	
Improve community food security	
Educational outreach	
Economic benefits	
Faith-based work	
International aid & development	
Environmental sustainability	
Adapting to climate change	

40. Has your motivation for the operation changed over time?

a. Yes (please explain)

b. No

41. Please estimate your operation's average annual fish production.

a. None

b. 1 – 49 pounds

c. 50 – 99 pounds

d. 100 – 499 pounds

e. 500 – 999 pounds

f. 1,000 – 4,999 pounds

g. 5,000 – 9,999 pounds

h. 10,000 pounds or more

42. Does/Did your aquaponics operation employ anyone other than yourself?

a. Yes

b. No

43. (If yes to Q42) How many employees (including yourself)? \_\_\_\_\_ employees

44. What was the original purpose of your aquaponics system? Circle all that apply.

- a. Financial gain
- b. Education
- c. Hobby
- d. Self-sustaining lifestyle
- e. Other \_\_\_\_\_

45. What type of aquaculture setup does your operation use?

- a. Intensive (i.e., dedicated tanks for the fish)
- b. Other (please describe)

46. What types of fish are/were reared in your operation?

- a. Tilapia
- b. Catfish
- c. Bluegill
- d. Perch
- e. Ornamental fish (e.g., Koi, goldfish, tropical fish)
- f. Bass
- g. Trout
- h. Shrimp
- i. Other \_\_\_\_\_

47. What is/was the approximate total tank volume of your aquaculture system?

\_\_\_\_\_ ft<sup>3</sup> or \_\_\_\_\_ m<sup>3</sup>

48. What type(s) of hydroponics setup(s) are/were used in your operation?

- a. Floating rafts
- b. Deep water culture
- c. Media beds
- d. Other (please explain)

49. What types of plants are/were grown in your system (please be specific)?

50. Please estimate your operation's average annual plant production.

- a. 1 – 49 pounds
  - b. 50 – 99 pounds
  - c. 100 – 499 pounds
  - d. 500 – 999 pounds
  - e. 1,000 – 4,999 pounds
  - f. 5,000 – 9,999 pounds
  - g. 10,000 pounds or more
51. Of your previously listed crops, what percentage by weight does each comprise of your annual harvest?
52. What is/was the approximate total tank volume of your hydroponics setup (please write NA if media beds are used in your operation)? \_\_\_\_\_ ft<sup>3</sup> or \_\_\_\_\_ m<sup>3</sup>
- a. If your setup includes/included media beds, please estimate the size of the hydroponics setup area. \_\_\_\_\_ ft<sup>3</sup> or \_\_\_\_\_ m<sup>2</sup>
53. Has the size of your operation changed since its initial opening?
- a. Yes
  - b. No
54. (If yes to Q53) Did your operation scale up or down?
- a. Scaled up
  - b. Scaled down
55. (If yes to Q53) Did you face any new challenges when you scaled up/down?
- a. Yes (please explain)
  - b. No
56. What are/were the major challenges your operation has/had experienced? Circle all that apply.
- a. Environmental control issues
  - b. Nutrient cycling issues
  - c. Mortality of fish
  - d. Mortality of plants
  - e. Algae growth
  - f. Pest problems
  - g. Infrastructure/construction issues
  - h. Financial issues
  - i. Operation maintenance issues

j. Other (please explain)

**Value-added & value-recovered section**

**Note:** If your operation is no longer running, please respond to these questions as if your aquaculture/aquaponics setup were still operating currently.

**Value-added products** - products that receive additional processing to add economic value, such as making frozen fish dinners. **Value-recovered products** – Waste products which receive additional processing to valuable feedstocks for other industries.

57. How are the products from your operation processed and sold (Please be specific)? For example, are the fish sold whole or as filets? Are they sold at a farmer's market directly to buyers or to a restaurant?

58. Have you previously considered producing value-added and/or value-recovered products from your operation?

- a. Yes
- b. No

59. (If yes to Q58) What opportunities would be interesting to you? What do you see as the potential benefits?

60. (If yes to Q58) What do you see as potential challenges if you were to produce value-added and/or value-recovered products?

61. (If no to Q58) What instances would make it more attractive to you to consider producing value-added and/or recovered products.
62. If it cost \$1 more per pound (of fish filet) to produce a value-added fish product than your current costs, how much more would the sale revenue need to be than current revenue for you to consider the addition of a new value-added process as a viable option?
- a. \$1.00
  - b. \$1.50
  - c. \$2.00
  - d. \$2.50
  - e. \$3.00
  - f. \$3.50
  - g. Other \$\_\_\_\_\_
  - h. Not interested at any revenue value
63. If producing value added and recovered products required a capital investment of \$100,000, what would be the largest acceptable amount of time for your operation to recoup or payback the initial investment?
- a. Less than 1 year
  - b. 1 year
  - c. 2 years
  - d. 3 years
  - e. 4 years
  - f. 5 years
  - g. 6 years
  - h. Other (please specify)
64. Value-added products often have the following characteristics, select all of the characteristics which would appeal to you as a producer:
- a. Higher retail value
  - b. Longer shelf life
  - c. Greater potential distribution area
  - d. Higher profit margins
  - e. Greater sales due to ease of preparation for consumption

65. Value-recovered products often have the following characteristics, select all of the characteristics which would appeal to you as a producer:

- a. Reduced waste disposal
- b. Waste sold as a revenue generating product
- c. Displacement of raw materials in other processes or products

### **Agricultural Knowledge and Experience Section**

66. For this question, you are asked about your gained knowledge and experience **before** you began your aquaculture or aquaponics operation. If you respond yes to any of the prompts below, please also provide your best estimate of how many years of knowledge/experience you had prior to beginning your operation.

Types of Food Production	Yes/No	Years of knowledge
General agriculture		
Hydroponics		
Horticulture		
Aquaculture		
Controlled environment agriculture		

Types of Food Production	Yes/No	Years of experience
General agriculture		
Hydroponics		
Horticulture		
Aquaculture		
Controlled environment agriculture		

67. What resources have you used to help with learning the particulars of operating an aquaculture/aquaponics system, either from an agricultural or business standpoint (Select all that apply)?

- a. Online/in-person classes
- b. Formal training (university or industry)
- c. Manuals
- d. Online forums
- e. Other (please explain)

### **Open-ended Questions**

68. What are/were some of the challenges your operation has/had experienced?

69. What has been the most challenging aspect of maintaining your aquaculture/aquaponics operation?

70. What resources do you think could have aided in the success of your operation (e.g., online classes, forums, formal training, grants, etc.)?

71. In your opinion, how accessible was learning the specifics of operating an aquaculture/aquaponics system? Please explain.

72. What excites you most about aquaculture/aquaponics as a food production system?

73. What recommendations would you give to someone just starting a new aquaculture/aquaponics operation?

74. **OPTIONAL.** Please describe or draw your aquaculture/aquaponics operation (e.g., how you built your operation, what materials were used for the tanks, what the configuration of your operation looks like, etc.).

### Demographics Information

**Note:** In this section we would like to know a bit more about your aquaculture or aquaponics system and yourself. As a reminder, your information will be held in confidence and only aggregate information will be shared with others.

75. Where is/was your aquaculture or aquaponics operation located?

- a. City: \_\_\_\_\_
- b. State: \_\_\_\_\_
- c. Zip or Postal code: \_\_\_\_\_

76. What is/was your role in the organization?

- a. Owner or operator
- b. CEO
- c. Executive Director
- d. School Official
- e. Farm Manager
- f. Educator
- g. Employee
- h. Consultant
- i. Volunteer
- j. Other \_\_\_\_\_

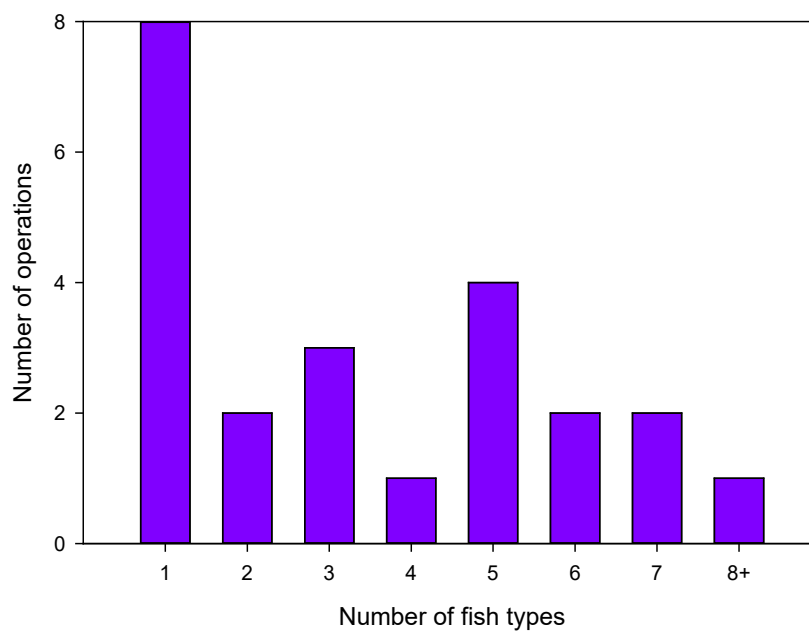
77. What is your age? \_\_\_\_\_
78. What is your gender?
- Male (both cis and transgender)
  - Female (both cis and transgender)
  - Other \_\_\_\_\_
  - Prefer not to say
79. What is your highest level of education?
- Less than high school
  - High school or GED
  - Some college
  - Undergraduate college degree
  - Graduate master's degree
  - Graduate Doctorate degree
80. Would you be interested in joining an online aquaponics collaborative that would encourage operators to connect and share information and ask questions?
- Yes
  - No
81. Would you like to be contacted when the survey findings are released?
- Yes
  - No
82. May we contact you by email for future studies? Please note, this information will be kept confidential and will not be released with your study responses.
- Yes
    - Email: \_\_\_\_\_
  - No
83. **Receiving incentive contact information.** If you want the incentive for the survey, please provide your contact information, so we can send a check. Please note, this information will be kept confidential and will not be released with your study responses.
- First name: \_\_\_\_\_
  - Last name: \_\_\_\_\_
  - Home address: \_\_\_\_\_

## D.B. Supplemental survey results

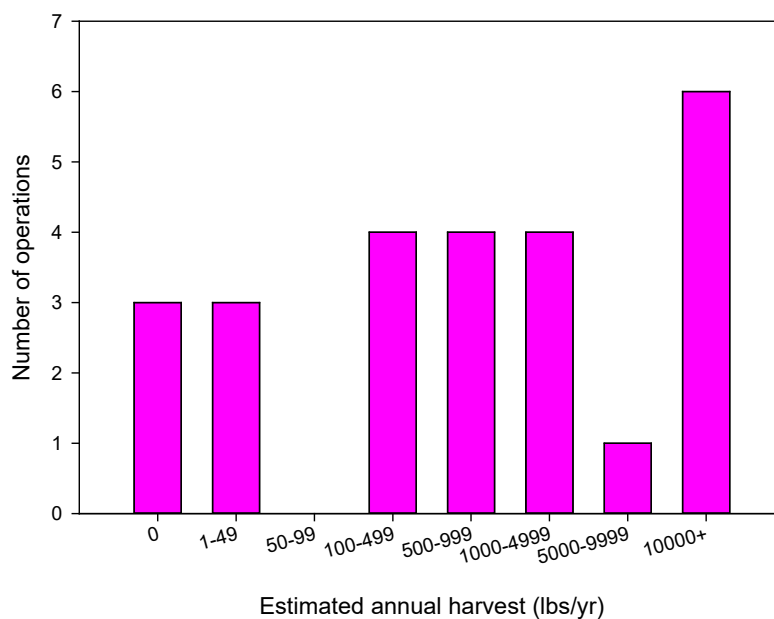
**Table D.A.** Surveyed operation's initial business motivations

Motivation type	Highest motivation	Lowest motivation	No motivation
	Number of operations		

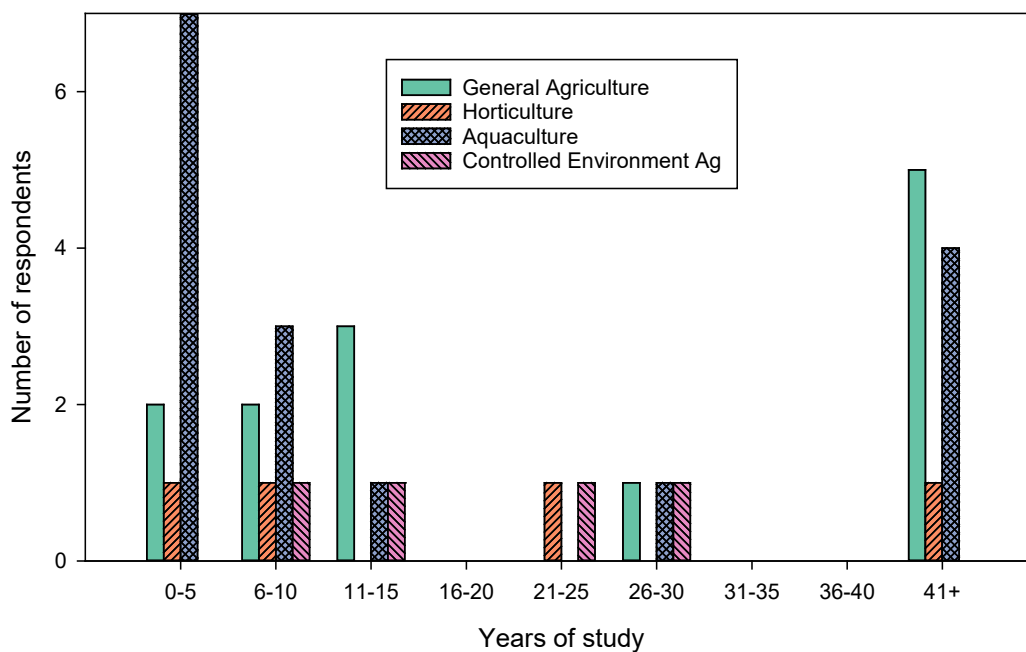
Grow your own food	6	2	9
Improve health and wellbeing	2	1	11
Improve community food security	5	0	11
Educational outreach	2	4	9
Economic benefits	6	5	6
Faith-based work	1	4	14
International aid & development	1	1	18
Environmental sustainability	4	6	7
Adapting to climate change	0	2	14



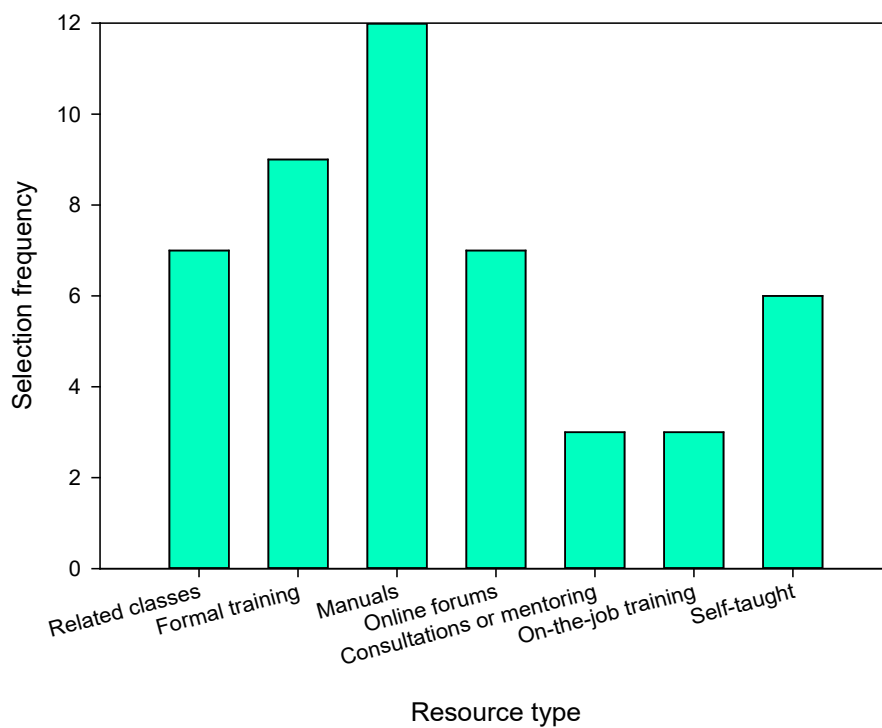
**Figure D.A.** Number of different types of species being propagated by surveyed operations



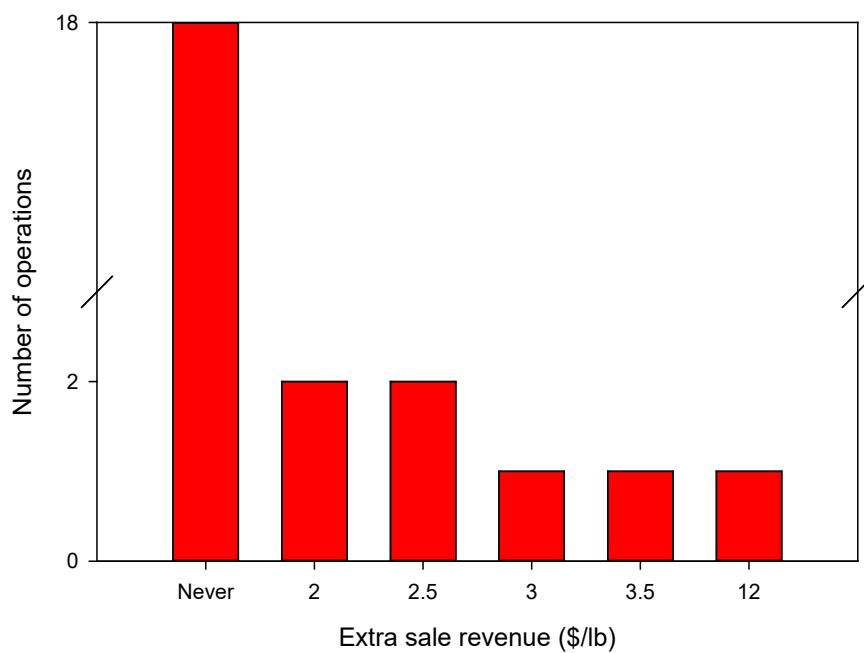
**Figure D.B.** Estimated annual fish harvest weight



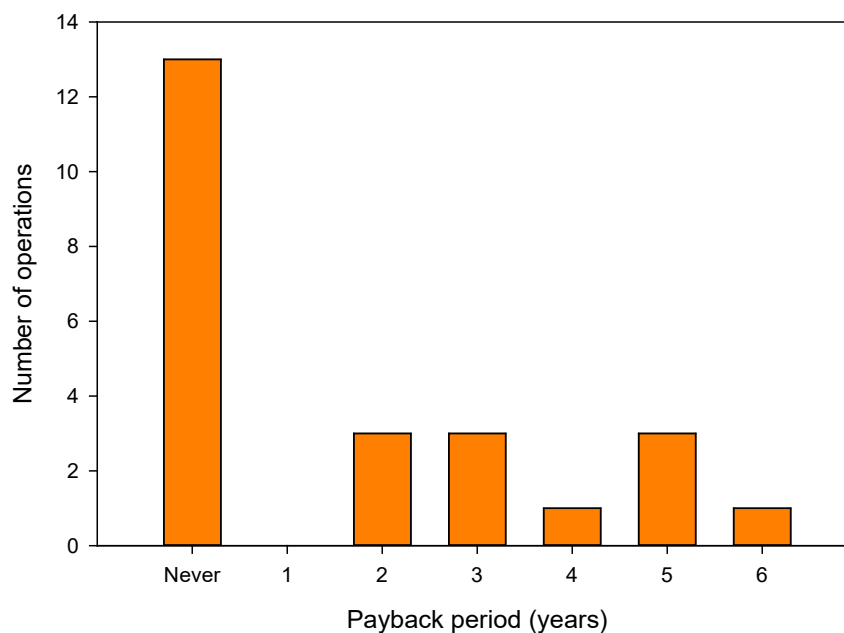
**Figure D.C.** Producers' prior knowledge gained before beginning aquaculture or aquaponics operation



**Figure D.D.** Types of resources used by surveyed producers to aid them in their operations



**Figure D.E.** Desired extra sale revenue from the value-added process per pound of filet



**Figure D.F.** Desired payback period for an initial \$100,000 investment into VAP/VRP

**Table D.B.** Survey respondents' demographic information

Operation's general location	Number of respondents
Wisconsin	13
Michigan	2
Minnesota	10
Gender	Number of respondents
Male	24
Female	1
Age	Number of respondents
40-49	2
50-59	7
60-69	7
70-79	6
80-89	2

Highest level of education	Number of respondents
High school or GED	4
Some college	10
Undergraduate college degree	6
Graduate masters degree	4
Graduate doctorate degree	1

## Appendix E – Investigation of consumer interest in aquaponics value-added and value-recovered products to explore online survey deployment efficacy

### E.A. Consumer survey instrument

1. Will you be responding to this survey for yourself or for your whole household?
  - a. Myself
  - b. Whole household
2. (If B is selected for Q1) How many people are in your household (including yourself)? \_\_\_\_\_
3. (If B is selected for Q1) How many people are 17 years and younger in your household? \_\_\_\_\_

### Consumer Preference Section

4. Where do you most frequently purchase/obtain food for you and your household?
  - a. Supermarkets or Superstores
  - b. Small or mid-sized grocery stores
  - c. Corner stores, gas stations, or dollar stores
  - d. Farmers markets
  - e. Foodbank/charity
  - f. Directly from farmers or producers
  - g. I grow/harvest/forage my own food
  - h. Other \_\_\_\_\_
5. When purchasing food, what are the most important factors you consider? Rank how important each factor is from 0-7, with 7 being the most important and 0 being not important.

Purchasing Factors	Importance Rank (0-7)
Freshness	
Price	
Organic certification	

Location of food source	
Nutritional value and health benefits	
Environmental sustainability	
Taste	
Other _____	

6. When purchasing protein, what do you typically prefer? (Select all that apply)
- Poultry (e.g., chicken, turkey)
  - Meat (e.g., beef, pork)
  - Seafood/Aquatic protein (e.g., fish, shellfish, crustaceans)
  - Plant-based protein (e.g., beans, lentils, tofu, plant-based meat)
  - Other \_\_\_\_\_
7. What is your reasoning behind your answer(s) to question 6? (Select all that apply)
- Cost
  - Quality
  - Taste preference
  - Environmental concerns
  - Variety of products
  - Consistency of products
  - Other \_\_\_\_\_
8. (If C to Q6) Which types of seafood do you currently or typically eat? (Select all that apply)
- Salmon
  - Alaska Pollock
  - Cod
  - Tuna
  - Small fish (e.g., mackerel and sardines)
  - Crustaceans (e.g., shrimp, crab, and lobsters)
  - Freshwater fish (e.g., catfish, bass, and walleye)
  - Mollusks (e.g., mussels, clams, scallops, and oysters)
  - Other \_\_\_\_\_
  - I do not prefer to or cannot consume seafood/aquatic food products
9. (If C to Q6) How is your seafood typically prepared when you purchase/obtain it (Select all that apply)?

- a. Fresh
  - b. Frozen
  - c. Canned
  - d. Smoked or dehydrated
  - e. Other \_\_\_\_\_
10. What kinds of vegetables and fruit do you buy and eat regularly (at least a couple of times a week)? (Select all that apply)
- a. Leafy greens (e.g., lettuce, kale, spinach, etc.)
  - b. Tomatoes
  - c. Cucumbers
  - d. Peppers
  - e. Root vegetables (e.g., carrots, potatoes, beets, radishes, etc.)
  - f. Squash
  - g. Berries
  - h. Melons
  - i. Apples and/or pears
  - j. Citrus
  - k. Bananas
  - l. Peas
  - m. Broccoli and/or cauliflower
  - n. Brussel sprouts
  - o. Other \_\_\_\_\_
11. How often on average do you cook food at home?
- a. Several times per day
  - b. Once a day
  - c. Twice a day
  - d. 2-3 times a week
  - e. 2-3 times a month
  - f. Rarely
12. Do you or does anyone in your household eat convenience food (i.e., ready-made dinners, microwave dinners, pre-made products from your store's deli, etc.)?
- a. Yes
  - b. No
13. (If yes to Q12) What kinds of convenience products do you or the people in your household typically buy and eat? (Select all that apply)
- a. Ready-made dinners
  - b. Microwave dinners
  - c. Grocer deli products
  - d. Mail-delivered meal kits
  - e. Restaurant meals
  - f. Other \_\_\_\_\_
14. (If yes to Q12) Other than convenience, why do you or the people in your household typically buy convenience food items?

### General Aquaponics Knowledge Section

15. Have you heard of anything related to **aquaponics** (i.e., farming fish and plants in the same system) as a more sustainable food production methodology?
- Yes
  - No
16. (If yes to Q15) How did you first learn about aquaponics?
- Social media
  - News or media outlet
  - School
  - Word of mouth
  - Unsure
  - Other \_\_\_\_\_
17. (If yes to Q15) In your opinion, what do you think is the most interesting part of aquaponics?

### Interest in Aquaponics Products Section

**Note: Aquaculture** is the controlled cultivation of fish, shellfish, and aquatic plants in controlled environments such as ponds, tanks, or ocean enclosures. **Hydroponics** is a water-based food production method which generally produces herbs, vegetables, or fruits. **Aquaponics** is the combination of aquaculture and hydroponics. The water and nutrients from the fish tank(s) are filtered and sent to the plant tanks to hydrate and fertilize the plants. The water from the plant tank is then sent back to the fish tank.

18. Have you ever eaten food produced from aquaponics?
- Yes
  - No
  - Maybe/Not sure
19. Do you seek out food produced from aquaponics on purpose?
- Yes
  - Yes, but they are not available in my local area
  - No
20. (If yes to Q19) What foods do you generally purchase from aquaponics?
21. (If yes to Q19) When purchasing food grown by aquaponics, which of the following factors are most important to you? Rank how important each factor is from 0-7, with 7 being the most important and 0 being not important.

Purchasing Factors	Importance Rank (0-7)

Freshness	
Price	
Organic or pesticide-free certification	
Local or regional sourcing	
Environmental sustainability	
Taste	
Other _____	

22. (If yes to Q19) Where do you generally purchase food grown by produced from aquaponics?
- Aquaponics farm
  - Local grocer
  - Chain grocery store
  - Farmer's markets
  - Restaurant as prepared food
  - Other \_\_\_\_\_
23. (If yes to Q19) How important is it for you to have a variety of fish and produce options available when purchasing from aquaponics?
- Very important
  - Moderately important
  - Somewhat important
  - Not important at all
24. (If yes to Q19) How often do you purchase food grown by aquaponics?
- Daily
  - Weekly
  - Monthly
  - Rarely (once or twice a year)
  - Almost never (once or twice ever)
25. (If yes to Q19) Have you ever faced any challenges or concerns when purchasing products grown by aquaponics (e.g., quality issues, price, availability, etc.)?
- Yes (Please describe)
  - No
26. (If yes to Q19) How likely are you to continue purchasing food grown by aquaponics in the future?
- Very likely
  - Likely
  - Neutral

- d. Unlikely
  - e. Very unlikely
27. (If yes to Q19) Are there any specific fish and/or produce types or items you would like to see more of in aquaponics? Please describe.
28. (If no for Q19) What would make you want to purchase aquaponics products?  
(Select all that apply)
- a. Cheaper prices
  - b. More consistently available
  - c. Aquaponics 'ready-to-eat' products more consistently available
  - d. More variety in products
  - e. Other \_\_\_\_\_
  - f. I would never purchase aquaponics products

**Willingness-to-pay for aquaponics value-added & value-recovered products section**

**Value-added products** go through processing to add more dollar value to the final product, such as making frozen fish dinners. **Value-recovered products** are made from waste streams that go through simple processes to make the final product more valuable.

29. Would you be interested in purchasing aquaponics value-added products (e.g., animal feed, preprepared meals, premade salads, etc.) if they were available to you?
- a. Yes
  - b. No
30. (If yes to Q29) If more aquaponics value-added products were made available to you, what kinds of products would you hope to see? (Select all that apply)
- a. Fresh (seasoned or breaded) fillets
  - b. Frozen (seasoned or breaded) fillets
  - c. Frozen, battered, ready to cook fish sticks
  - d. Oven-ready dinner kits
  - e. Premade vegetable salads
  - f. Premade seafood salads
  - g. Pre-cut and washed herbs
  - h. Other \_\_\_\_\_
31. (If A to Q29) If the typical fresh, seasoned salmon fillet cost \$2/fillet, about how much more or less would you be willing to pay if the same fillet were to be produced by aquaponics?
- a. -\$2.00/fillet
  - b. -\$1.50/fillet
  - c. -\$1.00/fillet
  - d. -\$0.50/fillet
  - e. \$0.00/fillet (I would pay the same amount only)
  - f. \$0.50/fillet
  - g. \$1.00/fillet

- h. \$1.50/fillet
  - i. \$2.00/fillet
  - j. \$2.50/fillet
  - k. \$3.00/fillet
  - l. \$3.50/fillet
  - m. \$4.00/fillet
  - n. \$4.50/ fillet
  - o. \$5.00/fillet
  - p. Other \$\_\_\_\_\_ /fillet
  - q. Would not purchase
32. (If B to Q29) If the typical frozen (seasoned or battered) cod fillet cost \$1/fillet, how much more or less would you be willing to pay if the same fillet were produced using aquaponics?
- a. -\$1.00/fillet
  - b. -\$0.50/fillet
  - c. \$0.00/fillet (I would pay the same amount only)
  - d. \$0.50/fillet
  - e. \$1.00/fillet
  - f. \$1.50/fillet
  - g. \$2.00/fillet
  - h. \$2.50/fillet
  - i. \$3.00/fillet
  - j. \$3.50/fillet
  - k. \$4.00/fillet
  - l. \$4.50/fillet
  - m. \$5.00/fillet
  - n. Other \$\_\_\_\_\_ /fillet
  - o. Would not purchase
33. (If C to Q29) If the typical bag of frozen, battered, ready to cook fish sticks cost \$3 per pound, how much more or less would you be willing to pay if the same product were made using aquaponics?
- a. -\$3.00/lb
  - b. -\$2.50/lb
  - c. -\$2.00/lb
  - d. -\$1.50/lb
  - e. -\$1.00/lb
  - f. -\$0.50/lb
  - g. \$0.00/lb (I would pay the same amount only)
  - h. \$0.50/lb
  - i. \$1.00/lb
  - j. \$1.50/lb
  - k. \$2.00/lb
  - l. \$2.50/lb
  - m. \$3.00/lb

- n. \$3.50/lb
  - o. \$4.00/lb
  - p. \$4.50/lb
  - q. \$5.00/lb
  - r. Other \$ \_\_\_\_\_/lb
  - s. Would not purchase
34. (If D to Q29) If the typical oven-ready dinner kit costs \$15, how much more or less would you be willing to pay if the same kit was made using aquaponics?
- a. -\$15.00/dinner kit
  - b. -\$14.00/dinner kit
  - c. -\$13.00/dinner kit
  - d. -\$12.00/dinner kit
  - e. -\$11.00/dinner kit
  - f. -\$10.00/dinner kit
  - g. -\$9.00/dinner kit
  - h. -\$8.00/dinner kit
  - i. -\$7.00/dinner kit
  - j. -\$6.00/dinner kit
  - k. -\$5.00/dinner kit
  - l. -\$4.00/dinner kit
  - m. -\$3.00/dinner kit
  - n. -\$2.00/dinner kit
  - o. -\$1.00/dinner kit
  - p. \$0.00/dinner kit (I would pay the same amount only)
  - q. \$1.00/dinner kit
  - r. \$2.00/dinner kit
  - s. \$3.00/dinner kit
  - t. \$4.00/dinner kit
  - u. \$5.00/dinner kit
  - v. \$6.00/dinner kit
  - w. \$7.00/dinner kit
  - x. \$8.00/dinner kit
  - y. \$9.00/dinner kit
  - z. \$10.00/dinner kit
  - aa. \$11.00/dinner kit
  - bb. \$12.00/dinner kit
  - cc. \$13.00/dinner kit
  - dd. \$14.00/dinner kit
  - ee. \$15.00/dinner kit
  - ff. Other \$ \_\_\_\_\_/dinner kit
  - gg. Would not purchase
35. (If E to Q29) If the typical premade vegetable salad cost \$4 per salad, how much more or less would you be willing to pay if the same salad were made using aquaponics?

- a. -\$4.00/salad
  - b. -\$3.50/salad
  - c. -\$3.00/salad
  - d. -\$2.50/salad
  - e. -\$2.00/salad
  - f. -\$1.50/salad
  - g. -\$1.00/salad
  - h. -\$0.50/salad
  - i. \$0.00/salad (I would pay the same amount only)
  - j. \$0.50/salad
  - k. \$1.00/salad
  - l. \$1.50/salad
  - m. \$2.00/salad
  - n. \$2.50/salad
  - o. \$3.00/salad
  - p. \$3.50/salad
  - q. \$4.00/salad
  - r. \$4.50/salad
  - s. \$5.00/salad
  - t. Other \$\_\_\_\_\_ /salad
  - u. Would not purchase
36. (If F to Q29) If the typical premade seafood salad costs \$10 per salad, how much more or less would you be willing to pay if the same salad were made using aquaponics?
- a. -\$5.00/salad
  - b. -\$4.50/salad
  - c. -\$4.00/salad
  - d. -\$3.50/salad
  - e. -\$3.00/salad
  - f. -\$2.50/salad
  - g. -\$2.00/salad
  - h. -\$1.50/salad
  - i. -\$1.00/salad
  - j. -\$0.50/salad
  - k. \$0.00/salad (I would pay the same amount only)
  - l. \$0.50/salad
  - m. \$1.00/salad
  - n. \$1.50/ salad
  - o. \$2.00salad
  - p. \$2.50/salad
  - q. \$3.00/salad
  - r. \$3.50/salad
  - s. \$4.00/salad
  - t. \$4.50/salad

- u. \$5.00/salad
  - v. Other \$\_\_\_\_\_/salad
  - w. Would not purchase
37. (If G to Q29) If the typical bunch or prewashed and cut, fresh herbs cost \$2 per bunch, how much more or less would you be willing to pay if the same herbs were made using aquaponics?
- a. -\$2.00/bunch
  - b. -\$1.50/bunch
  - c. -\$1.00/bunch
  - d. -\$0.50/bunch
  - e. \$0.00/bunch (I would pay the same amount only)
  - f. \$0.50/bunch
  - g. \$1.00/bunch
  - h. \$1.50/bunch
  - i. \$2.00/bunch
  - j. \$2.50/bunch
  - k. \$3.00/bunch
  - l. \$3.50/bunch
  - m. \$4.00/bunch
  - n. \$4.50/bunch
  - o. \$5.00/bunch
  - p. Other \$\_\_\_\_\_/bunch
  - q. Would not purchase
38. (If yes to Q29) Generally, value-added products are chosen for particular characteristics and/or considerations. Which characteristics/considerations would compel you to buy aquaponics value-added products over raw seafood and vegetable products? (Select all that apply)
- a. Saves time
  - b. Longer shelf life
  - c. Minimal effort
  - d. More visually attractive
  - e. More palatable
  - f. Other \_\_\_\_\_
39. (If A to Q38) How much more do you think you would spend per meal to save time (30 minutes) through buying a value-added product?
- a. \$0.50/meal
  - b. \$1.00/meal
  - c. \$1.50/meal
  - d. \$2.00/meal
  - e. \$2.50/meal
  - f. \$3.00/meal
  - g. \$3.50/meal
  - h. \$4.00/meal
  - i. \$4.50/meal

- j. \$5.00/meal
  - k. Other \$\_\_\_\_\_/meal
40. (If B to Q38) How much more do you think you would spend per meal for the meal to have a longer shelf life (from one week to one month)?
- a. \$0.50/meal
  - b. \$1.00/meal
  - c. \$1.50/meal
  - d. \$2.00/meal
  - e. \$2.50/meal
  - f. \$3.00/meal
  - g. \$3.50/meal
  - h. \$4.00/meal
  - i. \$4.50/meal
  - j. \$5.00/meal
  - k. Other \$\_\_\_\_\_/meal
41. (If C to Q38) How much more do you think you would spend per meal to reduce the preparation effort (i.e., meal planning and actual meal preparation) required by you to prepare the meal?
- a. \$0.50/meal
  - b. \$1.00/meal
  - c. \$1.50/meal
  - d. \$2.00/meal
  - e. \$2.50/meal
  - f. \$3.00/meal
  - g. \$3.50/meal
  - h. \$4.00/meal
  - i. \$4.50/meal
  - j. \$5.00/meal
  - k. Other \$\_\_\_\_\_/meal
42. (If D to Q38) How much more do you think you would spend per meal to have it be more visually appealing?
- a. \$0.50/meal
  - b. \$1.00/meal
  - c. \$1.50/meal
  - d. \$2.00/meal
  - e. \$2.50/meal
  - f. \$3.00/meal
  - g. \$3.50/meal
  - h. \$4.00/meal
  - i. \$4.50/meal
  - j. \$5.00/meal
  - k. Other \$\_\_\_\_\_/meal
43. (If E to Q38) How much more do you think you would spend per meal to make it more appetizing?

- a. \$0.50/meal
  - b. \$1.00/meal
  - c. \$1.50/meal
  - d. \$2.00/meal
  - e. \$2.50/meal
  - f. \$3.00/meal
  - g. \$3.50/meal
  - h. \$4.00/meal
  - i. \$4.50/meal
  - j. \$5.00/meal
  - k. Other \$\_\_\_\_\_ /meal
44. Would you be interested in value-recovered products (e.g., fertilizer, livestock feed, pet food, etc.) produced from aquaponics?
- a. Yes
  - b. No
45. (If yes to Q44) What kinds of aquaponics value-recovered products would interest you?
- a. Fertilizer
  - b. Livestock feed
  - c. Pet food
  - d. Personal care products (e.g., perfume)
  - e. Other \_\_\_\_\_
46. (If A to Q45) If the cost of conventional, synthetic fertilizer is \$2 per pound, how much more or less would you be willing to pay for natural fertilizer produced from aquaponics?
- a. -\$2.00/lb
  - b. -\$1.50/lb
  - c. -\$1.00/lb
  - d. -\$0.50/lb
  - e. \$0.00/lb (I would pay the same amount only)
  - f. \$0.50/lb
  - g. \$1.00/lb
  - h. \$1.50/lb
  - i. \$2.00/lb
  - j. \$2.50/lb
  - k. \$3.00/lb
  - l. \$3.50/lb
  - m. \$4.00/lb
  - n. \$4.50/lb
  - o. \$5.00/lb
  - p. Other \$\_\_\_\_\_ /lb
  - q. Would not purchase
47. (If B to Q45) If the cost of livestock feed is \$2 per pound, how much more or less would you be willing to pay for livestock feed produced from aquaponics?

- a. -\$2.00/lb
  - b. -\$1.50/lb
  - c. -\$1.00/lb
  - d. -\$0.50/lb
  - e. \$0.00/lb (I would pay the same amount only)
  - f. \$0.50/lb
  - g. \$1.00/lb
  - h. \$1.50/lb
  - i. \$2.00/lb
  - j. \$2.50/lb
  - k. \$3.00/lb
  - l. \$3.50/lb
  - m. \$4.00/lb
  - n. \$4.50/lb
  - o. \$5.00/lb
  - p. Other \$\_\_\_\_\_ /lb
  - q. Would not purchase
48. (If C to Q45) If the cost of conventional pet food is \$2 per pound, how much more or less would you be willing to pay for pet food produced from aquaponics?
- a. -\$2.00/lb
  - b. -\$1.50/lb
  - c. -\$1.00/lb
  - d. -\$0.50/lb
  - e. \$0.00/lb (I would pay the same amount only)
  - f. \$0.50/lb
  - g. \$1.00/lb
  - h. \$1.50/lb
  - i. \$2.00/lb
  - j. \$2.50/lb
  - k. \$3.00/lb
  - l. \$3.50/lb
  - m. \$4.00/lb
  - n. \$4.50/lb
  - o. \$5.00/lb
  - p. Other \$\_\_\_\_\_ /lb
  - q. Would not purchase
49. (If D to Q45) If the cost of a perfume is \$5 per ounce, how much more or less would you be willing to pay for a perfume produced from aquaponics?
- a. -\$2.00/lb
  - b. -\$1.50/lb
  - c. -\$1.00/lb
  - d. -\$0.50/lb
  - e. \$0.00/lb (I would pay the same amount only)
  - f. \$0.50/lb

- g. \$1.00/lb
- h. \$1.50/lb
- i. \$2.00/lb
- j. \$2.50/lb
- k. \$3.00/lb
- l. \$3.50/lb
- m. \$4.00/lb
- n. \$4.50/lb
- o. \$5.00/lb
- p. Other \$ \_\_\_\_\_/lb
- q. Would not purchase

**Demographic Information**

Note: Your information will be held in confidence and only aggregate information will be shared.

50. Where is your home located?

- a. Zip or Postal code: \_\_\_\_\_

51. What is your age?

- a. 18-19 years
- b. 20-24 years
- c. 25-29 years
- d. 30-34 years
- e. 35-39 years
- f. 40-44 years
- g. 45-49 years
- h. 50-54 years
- i. 55-59 years
- j. 60-64 years
- k. 65-69 years
- l. 70-74 years
- m. 75-79 years
- n. 80-84 years
- o. 85 years and over

52. What is your gender?

- a. Male (both cis and transgender)
- b. Female (both cis and transgender)
- c. Other \_\_\_\_\_
- d. Prefer not to say

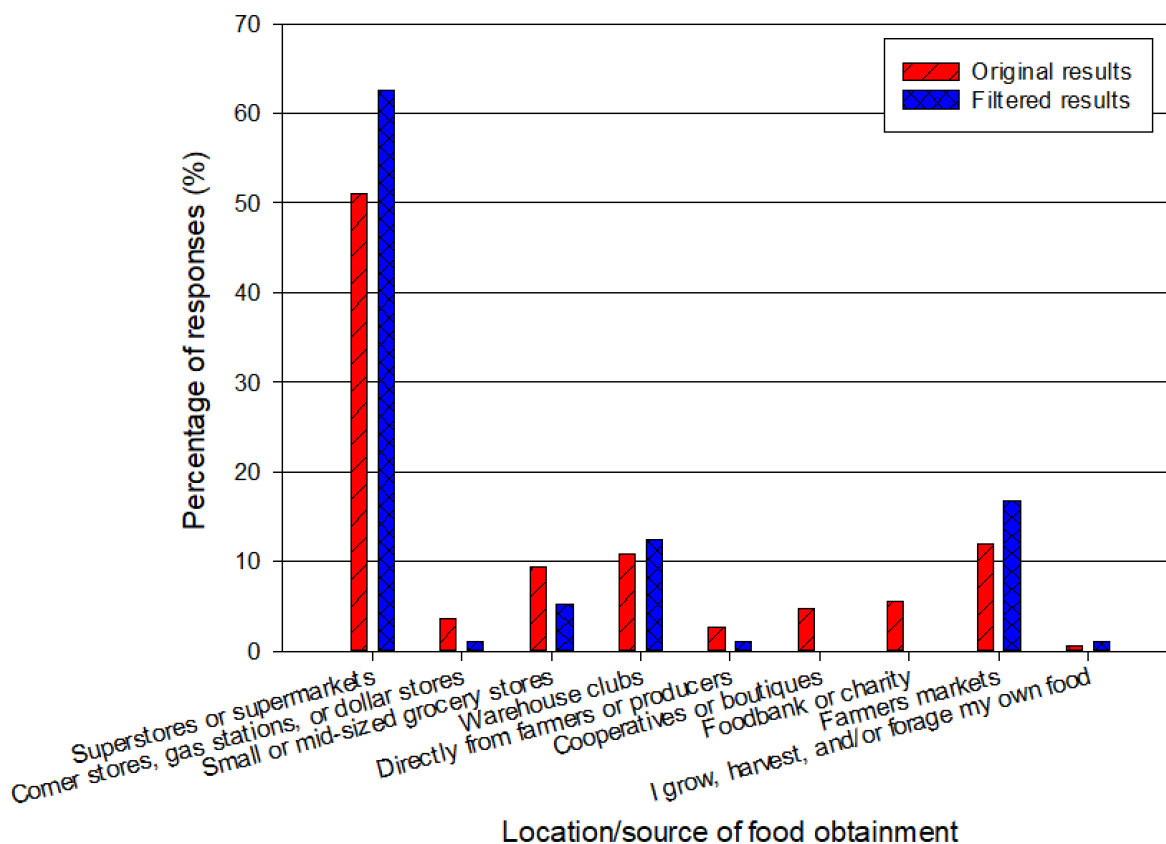
53. What is your highest level of education?

- a. Less than high school
- b. High school or GED
- c. Some college
- d. Undergraduate college degree
- e. Graduate master's degree
- f. Graduate Doctorate degree

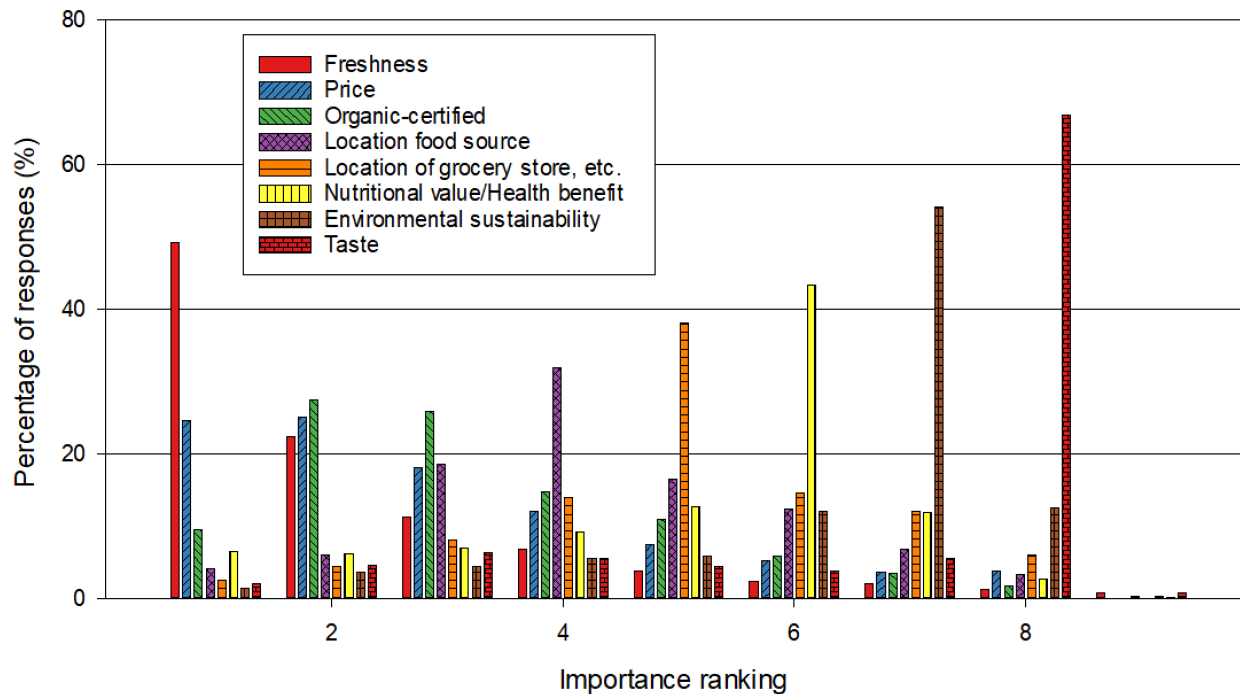
54. What is your approximate annual household income?

- a. Under \$10,000
- b. \$10,000-\$14,999
- c. \$15,000-\$24,999
- d. \$25,000-\$34,999
- e. \$35,000-\$49,999
- f. \$50,000-\$74,999
- g. \$75,000-\$99,999
- h. \$100,000-\$149,999
- i. \$150,000-\$199,999
- j. \$200,000 or more
- k. Prefer not to say

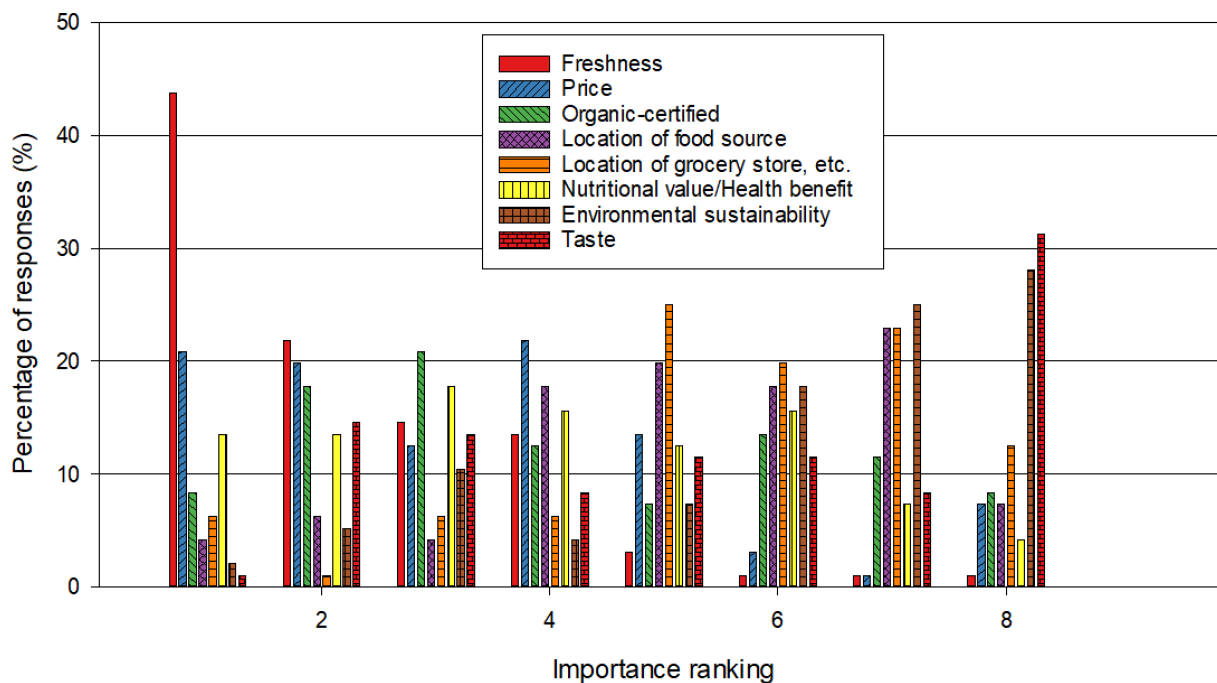
**E.B. Supplemental survey results**



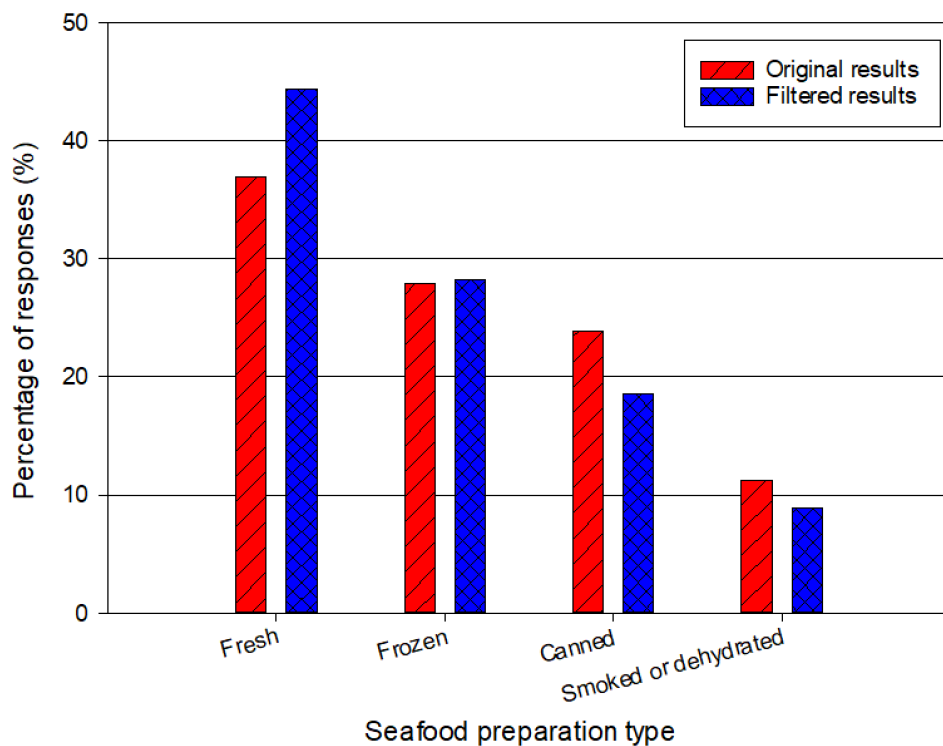
**Figure E.A.** Location of respondents' food purchases/obtainment



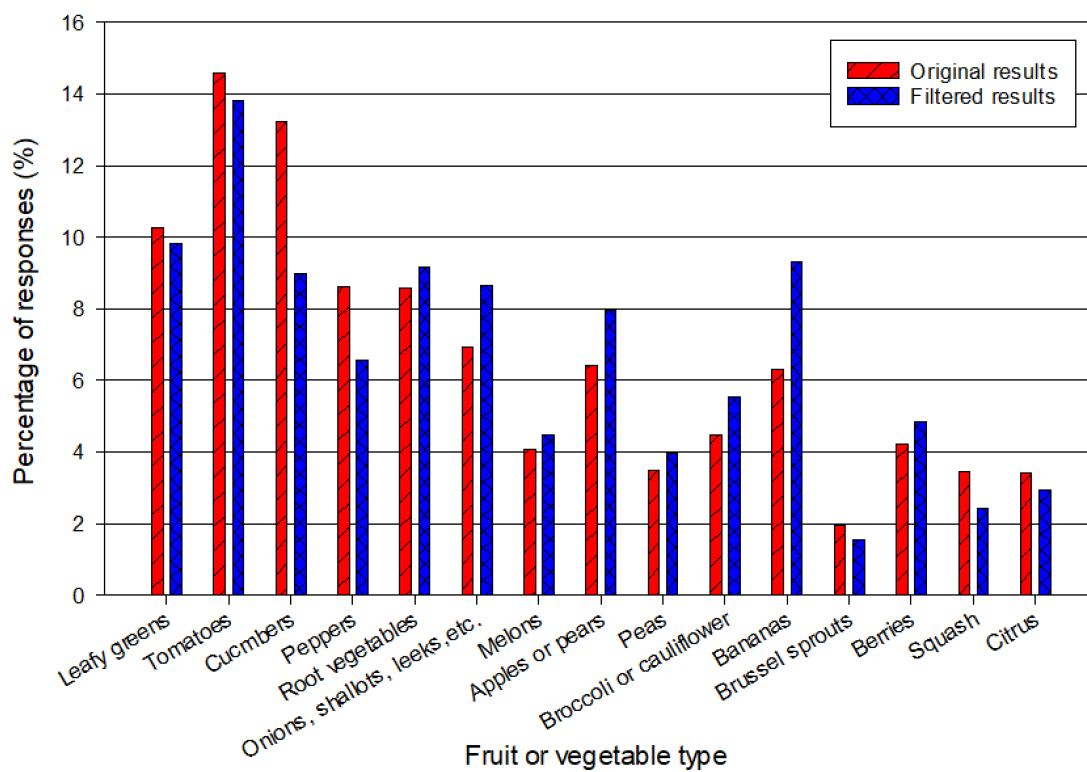
**Figure E.B.** Ranking food purchasing factors (one being most important, nine being least important) - Original results



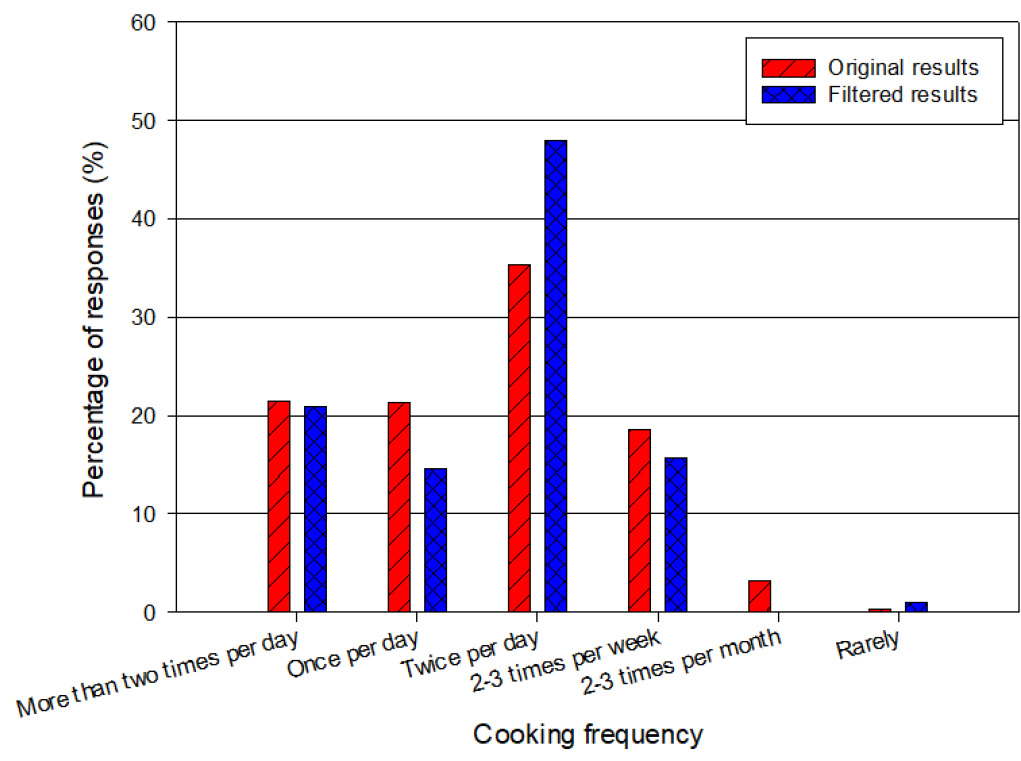
**Figure E.C.** Ranking food purchasing factors (one being most important, nine being least important) - Filtered results



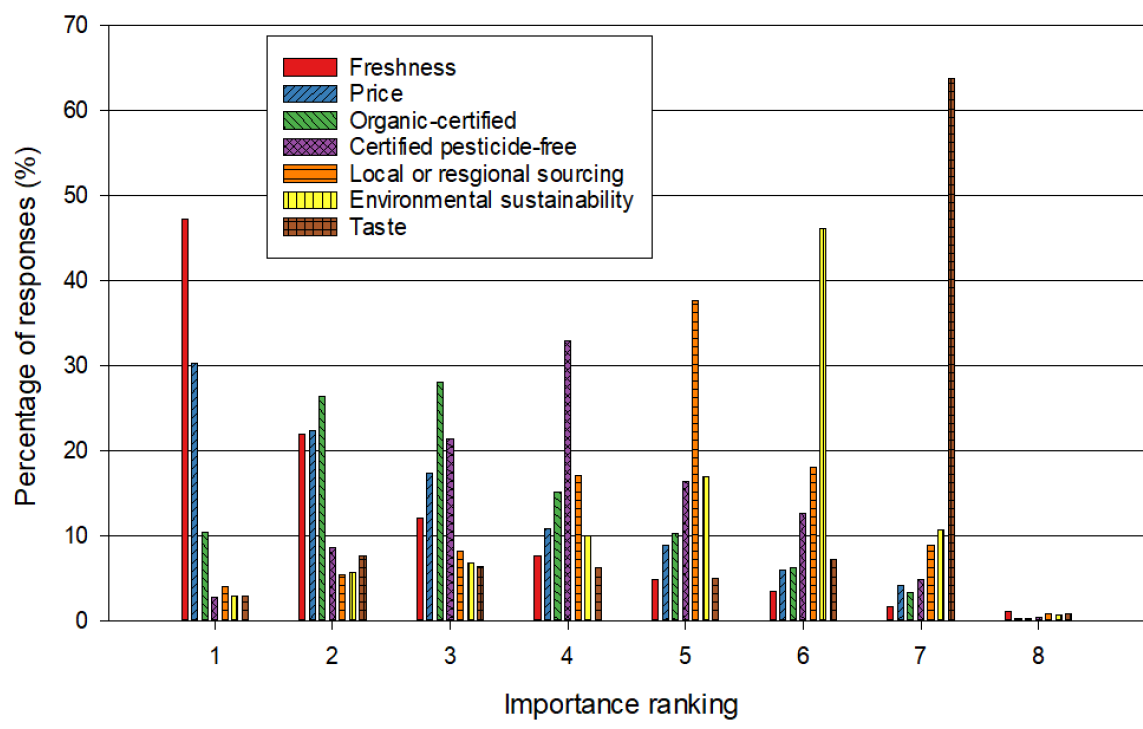
**Figure E.D.** Respondents' preference towards preparation type for aquatic proteins



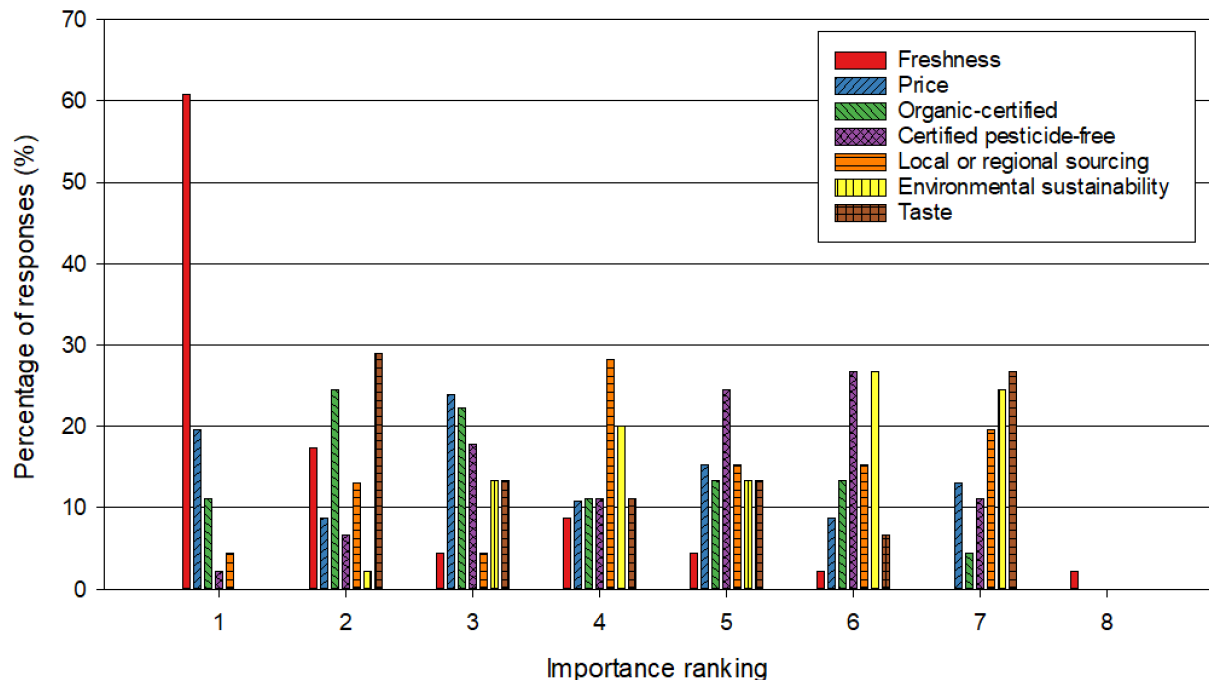
**Figure E.E.** Respondents' fruit and vegetable preferences



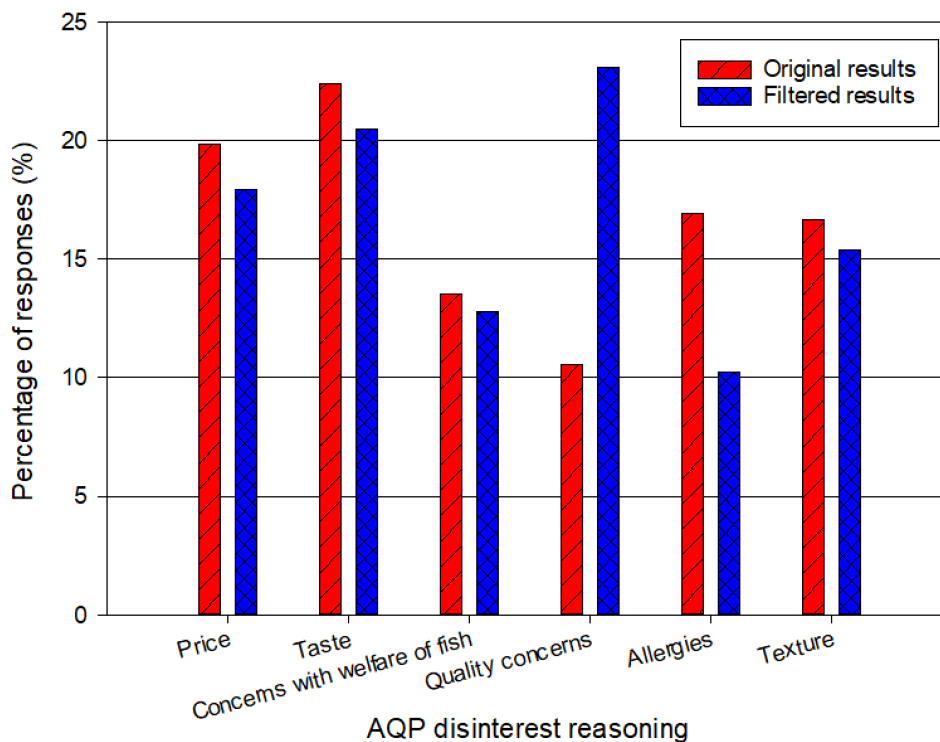
**Figure E.F.** Respondents' cooking frequency



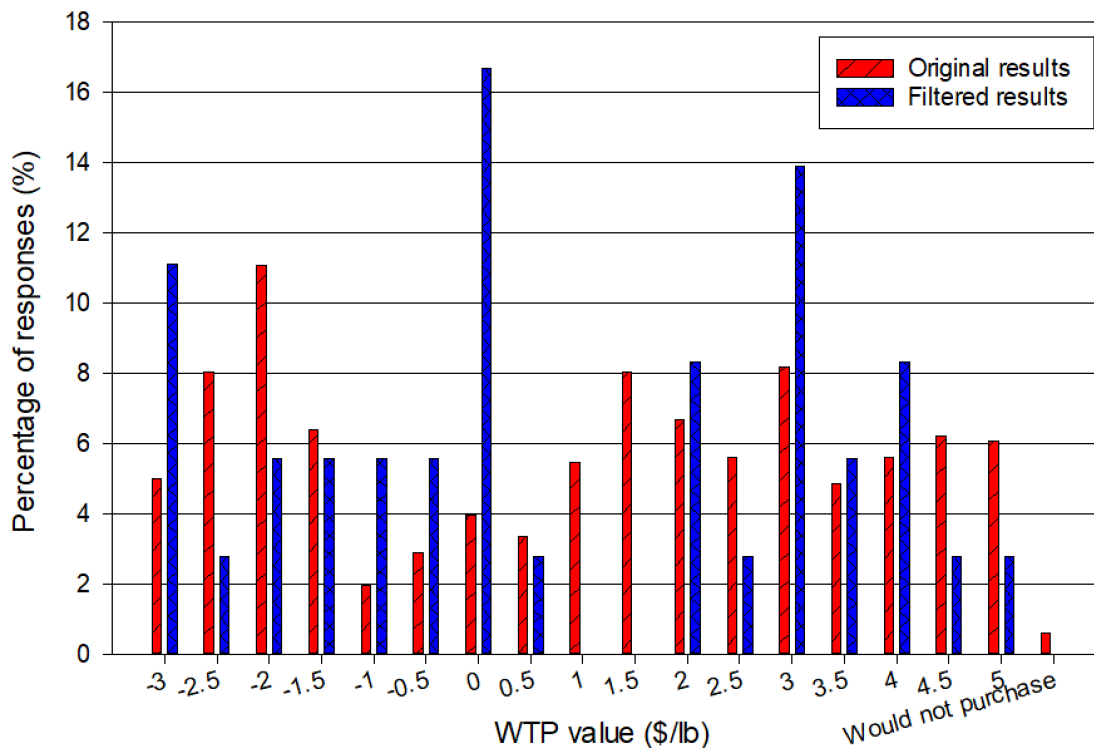
**Figure E.G.** AQP product purchasing factors for respondents (one being most important and eight being least important) – Original results



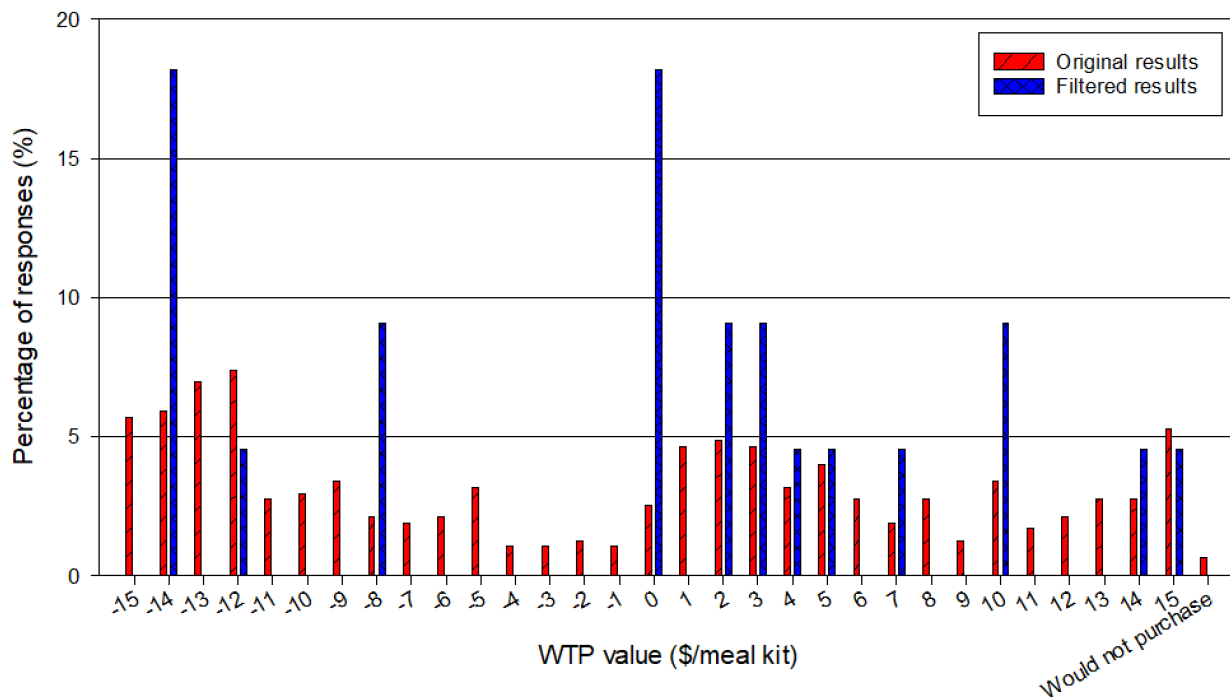
**Figure E.H.** AQP product purchasing factors for respondents (one being most important and eight being least important) – Filtered results



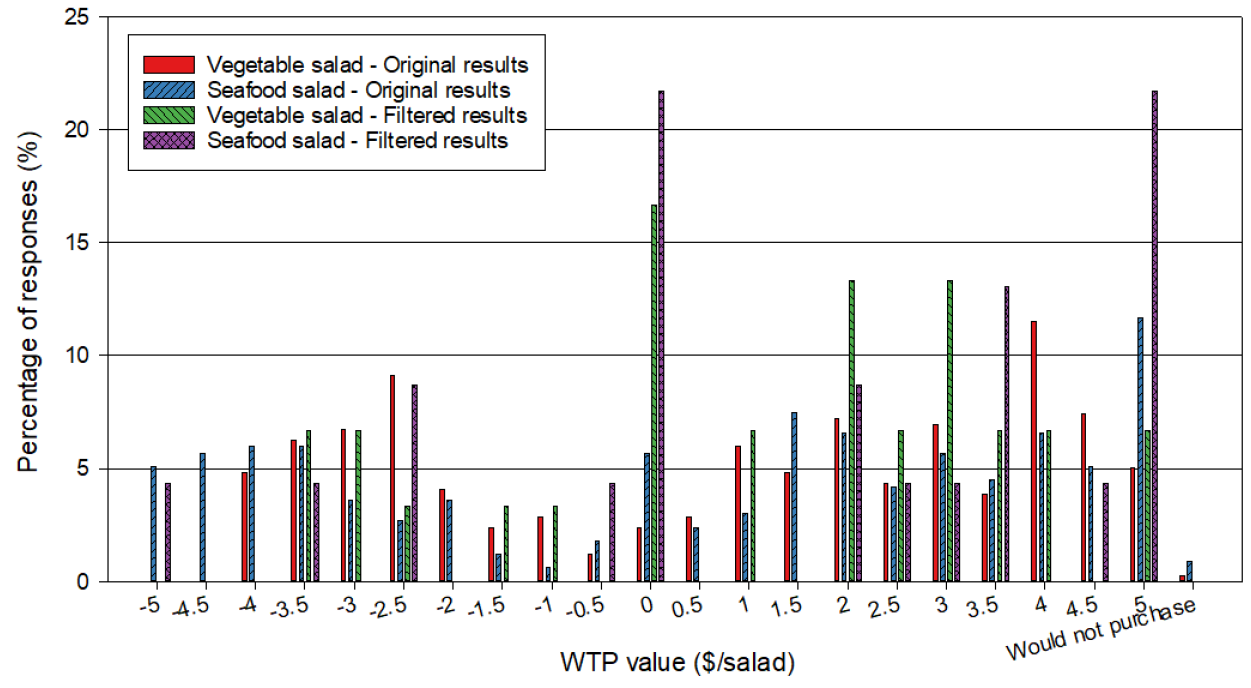
**Figure E.I.** Respondents’ reasons for not purchasing AQP products



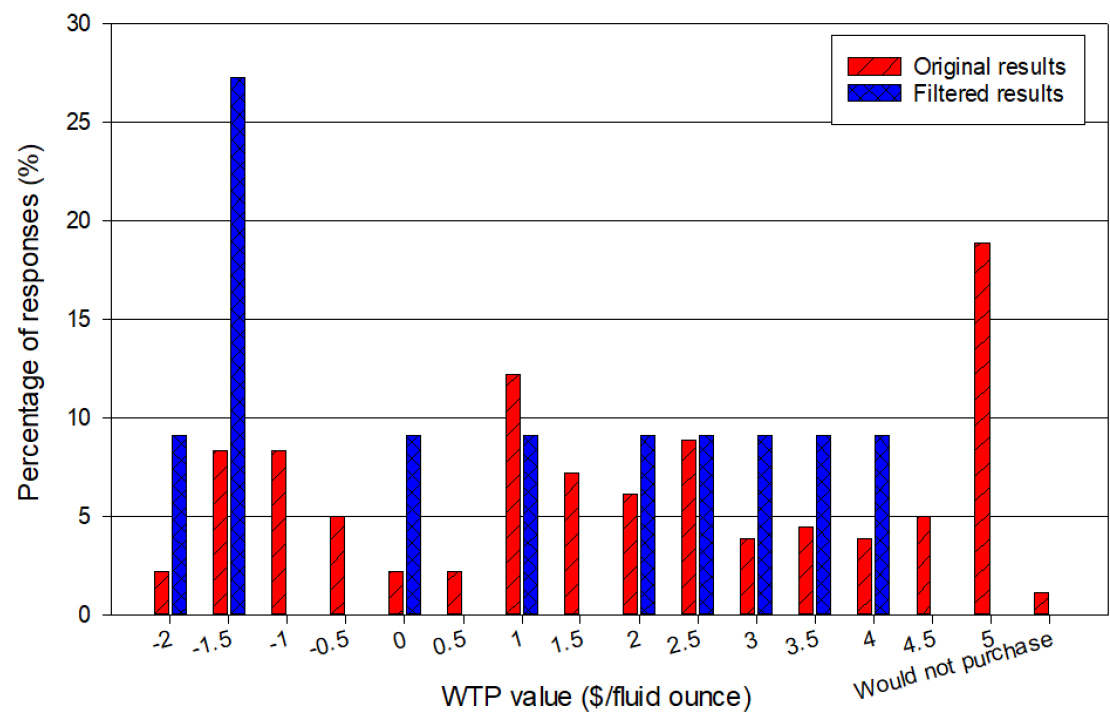
**Figure E.J.** Respondents' WTP for frozen fish sticks produced using AQP (Original price: \$3/lb)



**Figure E.K.** Respondents' WTP for an AQP-based oven-ready meal kit (Original price: \$15/meal kit)



**Figure E.L.** Respondents' WTP for AQP-based vegetable (Original price: \$4/salad) and seafood salads (Original price: \$5/salad)



**Figure E.M.** Respondents' WTP for perfume produced using enzymes extracted from AQP by-products (Original price: \$2/fl. oz)

E.B.A. Demographics

The final section of the survey went through standard demographic data collection. From the original assessment, the main age range was 20-39 with most respondents being in the range of 30-34. Majority of the respondents were male and have either an undergraduate or master's degree with an average income of approximately \$50,000-75,000. From the filtered response assessment, the age range remained the same, male respondents were more common but was much closer to a 50-50 ratio of men to women (58-38), education remained the same, and the main range of income was between \$35,000 and \$75,000.

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