Environmental and Economic Implications of Small-Scale Canadian Aquaponics: A Life Cycle Study

by

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A thesis
presented to the University of Waterloo
in fulfilment of the
thesis requirement for the degree of
Master of Environmental Studies
in
Sustainability Management

Waterloo, Ontario, Canada, 2021

Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Agricultural production will be challenged in the near future to keep up with the rising nutritional demands of a growing global population. Additionally, climate change, through increased frequency of extreme weather events and droughts, will further push food production to its limits. Controlled-environment food production systems (CEFPS) are suggested as viable options to supplement existing agriculture by allowing food production expansion without requiring large amounts of land and by offering protection from changing weather patterns and other undesirable external conditions. Aquaponics is a form of CEFPS that combines recirculating aquaculture with hydroponics to produce both fish and vegetables. However, the environmental and economic performances of these systems in Canada and other cold climates have yet to be explored in depth.

The overarching goal was to evaluate the potential for aquaponics to be a responsible and sustainable solution to maintaining Canadian food security. Specifically, this thesis aimed to identify environmental and economic barriers faced by small-scale Canadian aquaponics systems and provide options for reducing barriers and environmental impacts through the application of life cycle assessment (LCA) and life cycle cost (LCC) analysis.

The major results of this study indicate that aquaponics in its current form is an energy-intensive form of agriculture and is more environmentally impactful than conventional forms of fish and vegetable production with a global warming potential (GWP) of 68 kg CO_{2eq}/kg live fish and 50 kg CO_{2eq}/kg leafy greens. Alternative scenarios, including energy efficiency improvements, renewable energy sources, and insect-based fish feed, were considered in order to address the environmental and economic hotspots identified.

The following specific conclusions can be made: (1) energy consumption for artificial lighting and heating made necessary by cold climates is the biggest contributor to environmental impacts and costs; (2) an alternative scenario with off-site wind energy, LED lighting, and insulation reduces life cycle costs by 5% and GWP by 97%; and (3) alternative scenarios with insect-feed and on-site renewable energy can reduce specific environmental impacts but are more costly. It is recommended to pay particular attention to building design aspects, such as access to natural lighting and energy efficient HVAC systems, and climate-specific choices, such as cold-resistant crops and fish, in order to reduce the inherent energy intensity of operation. Overall, this work will help researchers and businesses improve performance of aquaponics systems, while serving as a foundation for the sustainability assessment of cold-climate aquaponics.

Keywords: aquaponics, indoor agriculture, cold climate agriculture, Canada, life cycle assessment, life cycle cost, energy efficiency

Acknowledgments

The work I’ve done over the past two years would not be possible without the help of some very important people. First and foremost, I would like to extend my sincere gratitude to my two supervisors, Dr. Goretty Dias and Dr. Christine Moresoli. Their encouragement to continually push my boundaries helped me grow and inspired me immensely. I would also like to thank Dr. Jeffrey Wilson for his extensive knowledge and for always being willing to answer my questions. I am also grateful for Dr. Komal Habib for her time and valuable feedback as the external reader for my thesis. An enormous thank you also goes to my partner, Pranit Trivedi, for being there every step of the way, especially the times when this journey seemed particularly difficult. Finally, I would like to thank my parents, Anitha and Muralee Valappil, for opening up a world of opportunities for me and for always being my biggest supporters.

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List of Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CBA	Cost-benefit analysis
CEFPS	Controlled-environment food production systems
CHP	Combined heat and power
DWC	Deep water culture hydroponics
GWP	Global warming potential
HDPE	High density polyethylene
HVAC	Heating, ventilation, and air conditioning
IBF	Insect-based feed
IRR	Internal rate of return
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCC	Life cycle cost
LED	Light emitting diode
LEED	Leadership in Energy and Environmental Design
NFT	Nutrient film technique hydroponics
NPV	Net present value
PVC	Polyvinyl chloride
TEA	Techno-economic analysis

Chapter 1 Introduction

1.1 Background

The current agri-food system is a burden on the earth. With a population expected to hit 10 billion within the next thirty years (Eigenbrod & Gruda, 2015), food systems are being pushed to their production limits and are forced to rely on detrimental methods of increasing yield. These production practices result in land-clearing, unsustainable fertilization practice, and excessive water usage, all of which amount to stresses on Earth's planetary boundaries (Campbell et al., 2017). Reducing these impacts in the face of rising populations and food demand will require huge amounts of agricultural infrastructure, investment, and most importantly, innovation. In an attempt to lessen environmental impacts while still maintaining production yields, controlled-environment food production has been suggested as a solution to food security concerns.

Controlled-environment food production systems (CEFPS) are technologies that separate agriculture from the natural environment, increasing protection from climate fluctuations. In addition, they are typically closed systems that can be monitored and maintained at ideal conditions. Aquaponics is one example of CEFPS that combines the plant cultivation of hydroponics with fish farming of aquaculture. In hydroponics, plants are grown without soil, but require the addition of essential nutrients, while aquaculture produces a large number of fish, but requires the removal of waste and feces. By combining these two systems, waste produced by the fish is converted by microorganisms into a form that can be used as a fertilizer for the plants. The resulting combined system requires fewer inputs than the systems in isolation, making it more desirable than some conventional methods of farming. Furthermore, aquaponics has been popularized because it helps to fill two important production gaps in the food system: vegetables, which are currently underproduced (Bahadur KC et al., 2018), and fish, which is growing in demand despite overfishing concerns (Ghamkhar et al., 2019; Ross et al., 2008). Therefore, these are two key areas of potential food insecurity that aquaponics can help address.

Despite being a relatively new technology, aquaponics research has been growing over the past fifty years. However, research in the past has been heavily focused on productivity and operation parameters, leaving large gaps regarding environmental and economic performance. Especially from an environmental perspective, a number of questions remain surrounding its sustainability. While many studies have been conducted in warm regions, such as the Mediterranean and Hawaii, very few studies have been conducted in regions that experience harsh winters. Controlling growth parameters becomes especially difficult in colder climates due to additional heating and lighting requirements. As a result, differences in climate can greatly affect system operation and subsequent impacts. The few studies that have been conducted in colder climates agreed that energy inputs were large and that renewable energy should be considered (Cohen et al., 2018; Forchino et al., 2018; Ghamkhar et al., 2019; Maucieri et al., 2017). In the era of the local food movement, as more companies across Canada and globally begin to embrace aquaponics and other CEFPS, studies are needed to determine if the benefits of combining productions systems outweigh the environmental impacts and economic strains of this energy-intensive form of indoor farming.

1.2 Research Approach and Goals

Assessing a complex technology such as this one requires a systematic and well-defined method that simplifies analysis where relevant. For agriculture and food systems, life cycle assessment (LCA) is an appropriate and frequently applied research method (Goldstein et al., 2016). LCA is a tool that examines the environmental impacts of a system or product across its life cycle (Finnveden et al., 2009; Notarnicola et al., 2017). Moreover, an additional component of LCA is life cycle cost (LCC) analysis. While not always included in life cycle studies, LCC is a comprehensive tool that examines the economic performance of a product throughout its life. Since both these methods follow standardized guidelines, comparability across other aquaponics LCA studies is ensured.

As shown above, the majority of aquaponics research is concentrated in warm regions and is often through a European lens. North American aquaponics LCAs are rare (Ghamkhar et al., 2019; Savidov et al., 2007), with none conducted in Canada so far. The winter season introduces additional challenges, such as reduced daylight hours, lower average temperatures, and different material and design requirements, which can hinder environmental and economic performance. While summer operations might mirror findings from Europe, the limitations imposed by Canadian winters will undoubtedly affect both environmental performance and profitability of aquaponics systems. These systems must therefore be examined before the widespread adoption of the technology can be justified.

In order to understand the application of aquaponics in a Canadian context, LCA and LCC analyses of a small-scale commercial facility were used as a case study. This now-defunct facility was located in an industrial warehouse in Halifax, Nova Scotia and operated from 2018 to 2019. There is a tendency for urban agriculture systems to operate within converted warehouses like this, which means that building envelopes are often not optimized for controlling agricultural parameters (Laidlaw & Magee, 2014; Love et al., 2015). Therefore, the operation conditions and challenges faced by this facility are expected to mirror current practice. Specifically, this research will address the following questions: (1) what are the environmental and economic barriers faced by small-scale aquaponics systems in Canada; and (2) how can the sustainability of aquaponics systems in cold regions be improved? The overarching goal is to evaluate the potential for aquaponics to be a responsible and sustainable solution to maintaining Canadian food security. Areas for improvement in operation will be highlighted, helping future companies maintain financial stability and environmental sustainability, simultaneously.

1.3 Thesis Contributions

This research is proposed at an opportune time where global development is focused on economic prosperity, but also on sustainability. There is a newly realized urgency for emerging technologies to not compromise sustainability the same way their predecessors did. An LCA will help address the question of whether the implementation of large-scale aquaponics systems will be an additional burden on the environment or a solution to growing food insecurity. These types of concerns are frequent in the field of agricultural technology because they often surpass the resource requirements of traditional farming. In the case of aquaponics in Canada, the objective is to use this and future assessments that build upon these findings to avoid unintended consequences. Furthermore, this study will examine the influence of impact partitioning on the results of aquaponics LCAs by comparing allocation methods as well as the unit process approach where production is split into unit operations. As a result, the study can be used as a basis to evaluate the environmental impacts and benefits of aquaponics systems. Not only will this support researchers and farmers looking to adopt aquaponics systems, but it will also help them to understand impacts and potentially reduce them. Moving forward, this work will serve as a foundation for the sustainability assessment of aquaponics in Canada and similar cold climates.

1.4 Thesis Structure

This thesis will have the following format. First, an in-depth literature review examines concepts important to the field of indoor agriculture and life cycle assessment such as aquaponics design and barriers to operation, environmental implications, socio-economic implications, and gaps in the field. Following the literature review, *Chapter 3* includes a life cycle assessment of a small-scale Canadian aquaponics systems, while *Chapter 4* includes scenario analysis as well as a life cycle cost analysis. The last chapter makes recommendations and closing remarks for future research, aquaponics businesses, and decision-makers.

Chapter 2 Literature Review

Aquaponics is an emerging technology that combines processes and components from aquaculture and hydroponics to simultaneously produce fish and plants for human consumption. Technical components and physical processes are borrowed and adapted from each: the cultivation of plants without soil from hydroponics and the production of fish in a controlled setting from aquaculture. In the past, aquaponics research has mainly focused on warm, subtropical regions where operations are not impacted by cold climates (Tokunaga et al., 2015; Yep & Zheng, 2019). Regions that experience cold climates and reduced sunlight often require extra heating and lighting. These unique requirements influence a number of outcomes, including profitability. Consequently, cold-weather aquaponics can be operationally burdensome in terms of high costs and increased environmental impacts. However, the economic success and environmental implications of operating these systems in cold climates, specifically Canada, is largely unknown. There is a disconnect between literature and practice in terms of tailoring operations to cold climates.

This literature review will examine the environmental benefits and impacts of cold-climate aquaponics operations, as well as their economic performance. Starting with a broad overview of technical considerations, the focus will narrow to operational barriers to sustainability within the context of Canadian aquaponics and the results of previous sustainability assessments in this field.

2.1 System Design: Trends, Advances, and Challenges

2.1.1 Aquaponics Systems

Aquaponics in its simplest form is a combination of hydroponics and aquaculture to simultaneously produce fish and plants. However, these systems are complex by nature because fish and plants have distinct nutritional objectives. The broadest classification of aquaponics systems is based on their configuration: coupled and decoupled (Gibbons, 2020; Monsees et al., 2016). The major difference between these forms is that coupled systems cycle water back and forth between aquaculture and hydroponics, but decoupled systems only allow regulated one-way water flow (Monsees et al., 2017). This is depicted in *Figure 2-1a*, where the coupled system is connected at multiple points allowing for back-and-forth circulation, while the decoupled system, *Figure 2-1b*, is connected by a one-way valve which only allows for controlled water flow when the valve is opened. Research in this area is driven primarily by a few notable researchers, including Monsees and Kloas (Kloas et al., 2015; Monsees et al., 2016, 2017), however researchers in all areas within aquaponics have realized the importance of distinguishing these two systems.

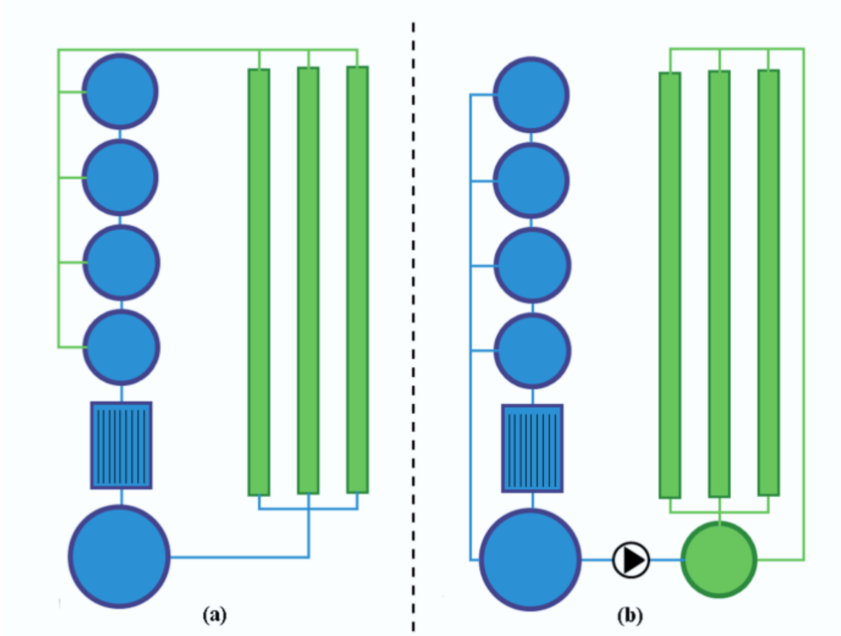

Figure 2-1: System diagrams showing coupled (a) and decoupled (b), where aquaculture (blue) and hydroponics (green) are connected in different configurations (Monsees et al., 2017).

In its original form, aquaponics only existed in the coupled version. For this reason, it is often considered the "classical form" of aquaponics (Monsees et al., 2016). Coupled aquaponics systems consist of one loop, meaning that the hydroponics and aquaculture components cycle the same inlet water back and forth (Goddek & Körner, 2019; Janker et al., 2018; Kloas et al., 2015; Monsees et al., 2016). Researchers agree that one disadvantage of coupled configuration is the fact that a single loop prevents either unit process from being fully optimized, resulting in the needs specific to both the aquaculture and the hydroponics systems not being met (Gibbons, 2020; Goddek et al., 2016; Monsees et al., 2016; Palm et al., 2018). For example, due to the fact that ideal pH levels vary greatly for each species present in the system, directly sharing the water means that one or more of the species will not have access to water at its ideal pH level. On the other hand, coupled systems are often beneficial due to the lower resource requirements, simpler infrastructure, and capacity to have small, low-cost set-ups (Gibbons, 2020; Palm et al., 2018). The consequence of these benefits is the lack of optimal conditions, as mentioned. These include suboptimal pH levels, poor water quality, and the fact that the system design itself prevents making changes to water quality or content without affecting all the species (Gibbons, 2020; Goddek et al., 2016; Monsees et al., 2016; Palm et al., 2018). These discrepancies are primarily what led to the decoupling of aquaponics systems.

Subsequently, decoupled systems were developed as a solution to optimization problems and bottlenecks in operation. The premise of decoupled systems is that water does not cycle back and forth between hydroponics and aquaculture, instead it only flows in one direction when required (Goddek et al., 2016; Monsees et al., 2016). As a result, water that is sent to the hydroponics unit from the aquaculture unit can be adjusted for optimized pH and nutrient levels (Monsees et al., 2016; Palm et al., 2018). Additionally, pest and disease control are much simpler because the water can be processed separately (Goddek et al., 2016). This pH and fertilization management has been proven to make production more effective by Monsees et al. (2017) and Delaide et al. (2016), who found that hydroponics yields were 36% to 39% higher in decoupled systems. Furthermore, Gibbons (2020) found that this ability to manage water and nutrients increases the net present value (NPV) of a decoupled system, representing an economic advantage, due to the increased productivity. As a result, other costs, such as those for infrastructure and management, are more easily offset. Finally, sludge removal and waste recovery are much simpler in decoupled systems, and can potentially result in much better environmental performance (Goddek et al., 2019). On the other hand, decoupled systems can be complex and expensive in terms of infrastructure (Gibbons, 2020) and due to the inherent focus on optimization, more advanced technical knowledge is required for effective management (Love et al., 2015). Therefore, there are trade-offs between coupled and decoupled systems due to the challenges and benefits they each present.

2.1.2 Ecological Relationships

As mentioned previously, a key factor for success in aquaponics systems is symbiosis between distinct species. The symbiotic process starts with the fish that produce waste in the form of ammonia, which is a nitrogen containing substance (Goddek et al., 2015; Konig et al., 2016; Love et al., 2015; Somerville et al., 2014; Tyson et al., 2011; Yep & Zheng, 2019). Ammonia is toxic to fish, and while plants need nitrogen to function, they prefer in the form of nitrites, which is produced via a multi-step process involving ammonia-oxidizing bacteria and nitrite-oxidizing bacteria (Goddek et al., 2015; Tyson et al., 2011; Yep & Zheng, 2019). The plants can then absorb the nutrients and generate clean water to be recirculated back to the fish tanks (Fang et al., 2017; Quagrainie et al., 2017; Tyson et al., 2011). Important here is the integral role that bacteria play in the operation of aquaponics. Without them, neither system would function optimally.

Very few studies have investigated the critical role of bacteria and their symbiosis with the plants in the operation. Junge et al. (2017) draw attention to the fact that the majority of past research on species optimization has focused on the fish and plants. However, the focus in these studies was the individual species, not their symbiosis. More knowledge is needed on the interactions between species because this is what supports the reduced resource load. This includes how to control pests because inputs, such as antibiotics or pesticides, greatly influence all other species and the pH of the water (Goddek et al., 2015; Konig et al., 2016; Yep & Zheng, 2019). Consequently, the necessity of optimization for successful system operation becomes evident. Not only does this include the species themselves, due to their various growth requirements (Tyson et al., 2011), but it also includes the amount of feed required to support various quantities of fish and plants (Cohen et al., 2018; Goddek et al., 2015). These areas must be improved to ensure both economic success and environmental favourability.

2.1.3 Hydroponics Systems

In order to further understand aquaponics systems and their operation, looking at the individual hydroponics and aquaculture components is important. Each of these systems is unique, with different challenges and benefits. Furthermore, hydroponics and aquaculture are far more established than aquaponics, implying that much more research is available related to them. Starting with hydroponics, the following sections describe the configurations available for system design, advances, as well as challenges in the field.

Hydroponics systems are often complex in design due to the number of physical and mechanical requirements for supporting adequate plant growth in the absence of soil. In general, the following types are the most commonly used: media-based grow beds (MBG), deep water culture (DWC), and nutrient film technique (NFT). First of all, media-based grow bed hydroponics (*Figure 2-2a*) consist of plastic troughs as well as some sort of media, such as gravel, clay, or other inert substances, which both serve to support plant growth and root development while delivering nutrient-rich water to the plants (Somerville et al., 2014; Tyson et al., 2011; Yep & Zheng, 2019). Furthermore, the media provides multiple surfaces that support healthy microbial populations (Somerville et al., 2014; Yep & Zheng, 2019), which are necessary for the symbiosis that supports plant growth. These systems are advantageous because the media acts as a natural biofilter and solids filter while still providing a high degree of root-to-water contact, ensuring that nutrient uptake is efficient (Somerville et al., 2014; Tyson et al., 2011; Yep & Zheng, 2019). However, these systems are not always ideal because the media used is often heavy and difficult to clean (Palm et al., 2018; Yep & Zheng, 2019). Next, DWC systems (*Figure 2-2b*) consist of polystyrene rafts, within which the plants sit, that float directly atop nutrient-rich water ensuring the roots are in full contact with water (Forchino et al., 2017; Goddek et al., 2015; Yep & Zheng, 2019). These systems are beneficial because there is significant root contact with water, and compared to MBG, the infrastructure is much simpler (Pattillo, 2017b; Yep & Zheng, 2019). However, due to proximity of the roots to the water, large biofiltration systems are needed because filtration does not occur naturally (Goddek et al., 2015; Yep & Zheng, 2019). Finally, NFT systems (*Figure 2-2c*) have plants sitting atop plastic channels in which a thin layer of water flows, ensuring constant and direct contact with water without complete submersion (Goddek et al., 2015; Palm et al., 2018; Yep & Zheng, 2019). These systems are advantageous because their designs are simple and effective, making them light enough in weight for vertical systems in existing buildings (Yep & Zheng, 2019). Nevertheless, while the design may be simple, the cost of infrastructure is often high (Sanyé-Mengual, Orsini, et al., 2015). Some less commonly used systems include drip irrigation, ebb and flow, and vertical towers and wells (Goddek et al., 2015; Pattillo, 2017b; Yep & Zheng, 2019), however these tend to have more specific applications while the formerly mentioned three can be widely used.

(a)

(b)

(c)

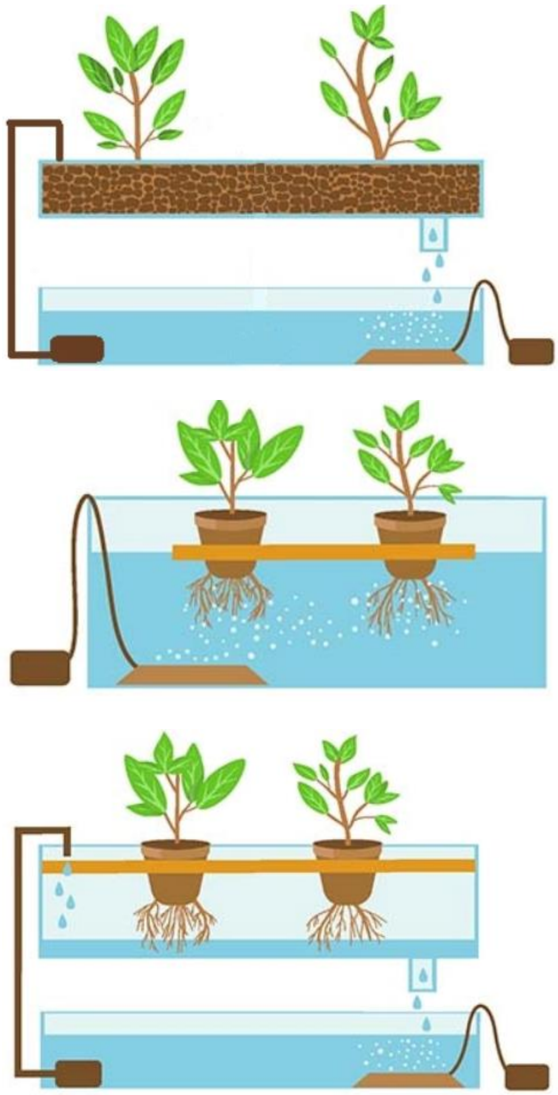

Figure 2-2: Illustrations of Media-Based Grow Bed (a), Deep Water Culture (b), and Nutrient Film Technique (c) Hydroponics (*Main Methods of Hydroponics*, 2019)

Within hydroponics, many technological advances have made it so that these systems are comparable to conventional farming. For example, water use is often less than in conventional farming in these systems because their irrigation systems are much more controlled (Goddek et al., 2015, 2016; Kloas et al., 2015). Furthermore, development of lightweight systems, such as NFTs, mean hydroponics can potentially be implemented in existing buildings, particularly in urban areas. However, the most significant hurdle for hydroponics operation is the technical expertise required for system operation, which is often the limiting factor (Goddek et al., 2019; Love et al., 2015). Specifically, due to the wide variety of hydroponics system design and plants that can be grown, as well as various growth parameters such as temperature and water levels, optimization is often difficult to achieve (Goddek et al., 2015; Yep & Zheng, 2019). This is an area that researchers are focused on, with future research concentrating on energy demand (Lages Barbosa et al., 2015), impacts of cold, winter seasons (Moreno et al., 2007), and optimal balances of plant type and system type (Yep & Zheng, 2019).

2.1.4 Aquaculture Systems

Like aquaponics systems, aquaculture systems are complex and must be understood individually in great depth. In general, aquaculture can be defined as the cultivation of fish and other aquatic organisms, such as molluscs and aquatic plants, in a controlled manner (Yep & Zheng, 2019). Like hydroponics, aquaculture can take many forms, ranging from nets in the ocean, to outdoor ponds and lakes, to indoors in tanks. Systems can be set up in open water using floating nets or floating concrete tanks, both of which are preferred in marine environments (Ayer & Tyedmers, 2009). They can also be set up in lakes and ponds using raceways or nets (Ayer & Tyedmers, 2009; Somerville et al., 2014). Finally, land-based, indoor recirculating systems exist where tanks are placed indoors, providing better wastewater management and less risk of predation (Ayer & Tyedmers, 2009; Somerville et al., 2014). The systems themselves can be simple or complex in terms of infrastructure and operation, meaning a wide variety of economic limitations can be accommodated. In contrast, unlike hydroponics, only one of these aquaculture configurations can be used in aquaponics systems: recirculating aquaculture systems (RAS). This is because this is the only form that allows for capture of nutrient-rich wastewater that can then be used as an input to the hydroponics system. Moving forward, researchers have highlighted a need for a deeper understanding of feeding behaviour, stresses on the fish, feed formulations, and other naturally occurring cycles in order to produce fish in a more effective manner (Hannon et al., 2013; Yildiz et al., 2017). Despite these concerns, aquaculture technologies have advanced significantly over the years, which means the challenges they face are well understood, unlike those faced by emerging technologies like aquaponics.

Aquaculture is an extremely important component of many economies worldwide. In fact, 50% of fish eaten globally comes from aquaculture and that number is expected to rise in coming years as overfishing concerns rise (Somerville et al., 2014). Furthermore, hundreds of species have been successfully grown this way (Ayer & Tyedmers, 2009), implying that aquaculture could help to meet the demands of a growing population. Especially with the developments of aquaculture technologies for aquatic plants and non-fish species, there is a possibility that these systems could become significantly less impactful and the food system in general could become more sustainable. However, further work is needed, particularly in the areas of feed management to improve the feed conversion efficiency in order to reduce nutrient leaching and eutrophication from wastewater (Mungkung et al., 2013). In addition, the production of fish feed is an environmental concern due to the life cycle impacts of obtaining fishmeal, fish oil, and other animal-based products used in commercial feeds (Cohen et al., 2018; Goddek et al., 2019; Junge et al., 2017; Rizal et al., 2018; Somerville et al., 2014). Smetana et al. (2016) suggest that government regulations on aquaculture production and pollution are needed at both the local and regional level to ensure that food systems can be sustainable.

2.1.5 Aquaponics System Optimization: Potential and Barriers

Due to the complexity of aquaponics systems, system optimization is highly sought after. Literature has highlighted three main areas where optimization is needed to improve environmental performance, system efficiency, and economic profitability. These areas are feed, energy consumption, and industrial symbiosis. Each of these is explored in further detail below.

First of all, given the design of aquaponics systems, feed is one of the most significant inputs. Consequently, it is also one of the most environmentally impactful (Cohen et al., 2018; Goddek et al., 2019; Junge et al., 2017; Rizal et al., 2018; Somerville et al., 2014). Optimization of feed ingredients and loading rates are sought after due to the environmental impacts of using fishmeal or fish oil in feeds, as well as the costs of animal-based feeds. In literature, one of the most frequently suggested methods of reducing fish feed-related impacts is switching towards insect-based or plant-based feeds (Goddek et al., 2019; Yep & Zheng, 2019). In fact, it is currently theorized that insect-based feeds will be less impactful than plant-based ones (Cohen et al., 2018; Goddek et al., 2019; Afton Halloran et al., 2016; Smetana et al., 2016; Somerville et al., 2014); however, little quantitative evidence is presented for aquaculture and hydroponics because the field of insect-rearing itself is just emerging. Furthermore, as concerns about overfishing and availability of arable land increase, insect-farming has been looked to as a potentially low-impact, low-land requirement form of production (Junge et al., 2017). Finally, one other option is to switch to species of fish that are omnivorous, rather than carnivorous, so that their protein demands can be met more easily with substitute feed ingredients (Knaus & Palm, 2017). In general, feed is a complex system input that is affected by various factors and in turn, results in a number of environmental and economic impacts that must be addressed in aquaponics systems.

Another similar input that has complex relationships with system design is energy consumption, specifically for lighting and heating. The environmental impacts incurred from energy use in aquaponics systems are most frequently named as the biggest concern these systems pose (Goddek et al., 2015; Hindelang et al., 2014; Somerville et al., 2014; Yep & Zheng, 2019), especially in cold climates (Forchino et al., 2018; Ghamkhar et al., 2019; Xie & Rosentrater, 2015). In many cases, researchers have demonstrated that switching to renewable forms of energy, including wind, hydroelectric, and nuclear, result in fewer impacts than relying on fossil-based energy (Atlason et al., 2017; Forchino et al., 2018). However, in some cases, economic limitations and dependence on regional grids prevent the use of renewable energy so some other ways of optimizing energy use are suggested. Junge et al. (2017) suggest that improving the overall climate management of indoor systems can drastically reduce energy use. In this case, heating and lighting needs would be lowered through the use of energy efficient lighting, better insulation, and building automation systems to effectively monitor energy use and efficiency (Goldstein et al., 2016; Junge et al., 2017; Love et al., 2015). Furthermore, research into LED design and optimal spectrums have shown that certain ranges of wavelengths of light are more beneficial to plant growth and that the number of hours of artificial lighting provided can be optimized to each plant species (Avgoustaki, 2019; Kang et al., 2013; Pennisi et al., 2019; Rehman et al., 2017; Sabzalian et al., 2014). This strategy is frequently suggested for optimization because it would serve the purpose of reducing energy use and making infrastructure more sustainable while simultaneously improving production and yields.

Finally, industrial symbiosis is another area where aquaponics systems could potentially be optimized. Industrial symbiosis is the process of connecting various industrial material and energy flows, such that "waste" outputs from one process are used as inputs to another, thereby reducing impacts and waste in the process (Chance et al., 2018; Fraccascia et al., 2020). Therefore, because aquaponics systems share resources and wastes to reduce input requirements, it is a form of industrial symbiosis in itself, but there is room for improvement. In general, the potential of industrial symbiosis in agricultural systems is growing in popularity through the development of agro-industrial networks (Chance et al., 2018; Concha et al., 2016; Fernandez-Mena et al., 2016; Fraccascia et al., 2020). In aquaponics specifically, many possibilities exist due to the sheer number of energy and material flows present. These networks can take various forms. For example, heat recovery is a promising concept where industrial waste heat can be used to heat other facilities or processes (Andrews & Pearce, 2011; Law et al., 2012; Legorburu & Smith, 2018). Since heating demands are such a major concern in cold climates, heat recovery could help to reduce environmental impacts as well as energy costs (Andrews & Pearce, 2011). Similarly, anaerobic digestion is another form of industrial symbiosis, where waste is converted into biogas by microorganisms, which can then be used for energy production (Andrić et al., 2017; Bong et al., 2018). The waste used for biogas production can be from a variety of sources, including on-site sludge and green waste produced by the aquaponics system (Goddek & Körner, 2019), specifically for large-scale systems that produce substantial quantities of sludge (Gigliona, 2015). This introduces circularity to the material and energy flows in the system, thereby lowering environmental concerns. In conclusion, industrial symbiosis is a complex solution to many problems faced by aquaponics systems, including energy use and waste production. However, the methods by which it is applied require careful consideration to reach an optimal balance.

2.2 Environmental Implications

Despite the appeal of reduced resources, environmental sustainability remains one of the main reasons for the adoption of aquaponics. Symbiosis allows aquaponics to mimic natural ecosystems, which is proposed to increase system efficiency and reduce resource use. In fact, multiple studies concur that fewer resources are required in aquaponics than in traditional agriculture (Goddek et al., 2015; Kloas et al., 2015; Rizal et al., 2018; Tyson et al., 2011). In addition to the reduced requirements for water and fertilizer, aquaponics does not require soil, which is beneficial because agricultural production is the largest driver in surpassing earth's land-system change planetary boundary (Campbell et al., 2017). Junge et al. (2017) emphasize that this also makes aquaponics suitable for non-traditional agriculture locations, such as cities. This adds further appeal by increasing the resilience and food security of those areas.

In addition to the benefits gained from symbiosis, Cohen et al. (2018) suggest that aquaponics allows for a circular, closed system where inputs are shared and waste is reduced, as opposed to the linear, open system that traditional agriculture follows. This developing idea of using controlled-environments and shared resources is especially significant today because this disconnect from the natural world protects the crops against extreme weather and provides greater opportunities to control effluents and impacts (Cohen et al., 2018). For example, numerous studies have found that the small daily water losses in aquaponics systems, ranging between 0.5 and 4%, are far lower than the literature maximum of 10% (Forchino et al., 2017; Kloas et al., 2015; Love et al., 2015; Maucieri et al., 2017). These studies effectively demonstrate that aquaponics crops could be protected from water shortages and droughts that will continue to be a pressing concern in the future. The consensus in the literature is that a number of potential environmental benefits exist, especially when compared to traditional agriculture, which is why the systematic environmental analysis of aquaponics remains an important research objective.

However, due to the complexity and a lack of sufficient understanding surrounding aquaponics systems, there are also drawbacks. Currently, the most critical impacts of aquaponics operation originate from the three main inputs to the system: fish feed, energy, and water. This implies that future means for improvement can be focused in these areas. Within these studies, fish feed, which often consists of fishmeal and plant-based protein meals, is quantitatively determined to be the most impactful component of aquaponics (Cohen et al., 2018; Forchino et al., 2017; Rizal et al., 2018). In general, the use of fishmeal and fish oil in commercial fish feeds adds pressure to already scarce agricultural resources because the varieties of pelagic fish used in these feeds are frequently overfished (Malcorps et al., 2019; Olsen & Hasan, 2012). Furthermore, plant-based feeds, which are composed mainly of soybean meal, impose land-use change concerns due to the already large portion of arable land used for animal feed globally (Malcorps et al., 2019). Cohen et al. (2018) maintain that there are several options for impact reduction, including using insect-based proteins; however, these feeds still require full impact assessment before wide-scale adoption.

In terms of energy requirements, of the few studies that examined aquaponics systems in cold climates, the consensus is that the occurrence of reduced daylight hours and lower temperatures translate to higher heating and lighting costs and impacts (Forchino et al., 2018; Ghamkhar et al., 2019; Love et al., 2015). This means that aquaponics in Canada will face similar challenges, including higher greenhouse gas emissions and global warming potential, than warm-climate aquaponics. In spite of that, renewable energy use has great potential to reduce impacts and operation costs (Forchino et al., 2018; Forchino et al., 2017; Ghamkhar et al., 2019; Junge et al., 2017; Tokunaga et al., 2015). Finally, while aquaponics uses less water than traditional agriculture, multiple studies have suggested ways to reduce water use further, including the use of covers and vent traps to limit daily water losses (Pattillo, 2017a; Kloas et al., 2015) and rainwater collection (Pattillo, 2017a; Junge et al., 2017; Love et al., 2015; Rizal et al., 2018; Somerville et al., 2014). Overall, system inputs are a potential area for improvement and while a number of methods to reduce their impacts have been proposed, their success, especially in cold climate environments like Canada, has yet to be determined and will rely on adoption of effective methods of sustainability assessment.

2.3 Life Cycle Assessment (LCA) of Food Systems

Life cycle assessment (LCA) is a method of examining the environmental implications of a product or system through its life, from raw material extraction to end-of-life disposal. Due to this extensive coverage across life cycle stages, LCA is often called a "cradle-to-grave" assessment. It is a systematic way of quantifying environmental impacts per a unit quantity, or functional unit, of a product by considering all input and output flows within specified system boundaries. In general, an LCA study requires a detailed goal and scope, a life cycle inventory including all process-related material and energy flows, impact assessment, and interpretation of results. Details regarding this methodology are provided in *Chapter 3*, but the following section provides a summary of the methodological challenges posed by life cycle assessment of agriculture and food systems reported in literature. In brief, these include functional unit definition, allocation of impacts, boundary selection, and data availability and quality.

2.3.1 Method and Methodological Issues

Firstly, functional unit definition is one of the most commonly faced problems in food systems. When conducting LCA, a functional unit based on a quantity of the final output is selected in order to evaluate the portion of impacts incurred per unit output. The reason the functional unit causes concern is that most food systems have multiple functions and multiple outputs (Halloran et al., 2017), but LCA guidelines only allow for selection of one main functional unit (*CAN/CSA-ISO 14044*, 2006). In general, functional units for food systems are defined in terms of mass, economic value, calories, or other nutritional values (Halloran et al., 2016; Notarnicola et al., 2017). Some researchers suggest that the true function of food is to provide energy, therefore calorie-based functional units should be the standard (Hayashi et al., 2005; Notarnicola et al., 2017). In fact, by using energy or calories as the functional unit, studies are able to capture the share of energy that the plant or animal devoted to production, making it a more accurate representation of impacts (Pelletier et al., 2009). In contrast, for food products consumed for their protein content, researchers suggest that protein content should be used as a functional unit (Bohnes & Laurent, 2019; González-García et al., 2014; Halloran et al., 2016). However, the majority of aquaponics LCAs select simpler functional units based on mass or economic factors (Jaeger et al., 2018; Mungkung et al., 2013). In these cases, mass-based functional units are preferable to economic ones because economic values tend to shift depending on market conditions, rather than by system operation. Furthermore, the relationships between mass-based functional units and energy or protein are constant, thereby making it easier convert between units as necessary. Moving forward, some LCA practitioners concur that nutrition-related functional units, whether that be caloric, protein, or a complex nutrient-based index (Bianchi et al., 2020; Hallström et al., 2018), should be the new direction for life cycle assessment in food (Hayashi et al., 2005; Notarnicola et al., 2017).

Related to the challenge described above, multifunctionality in food systems, where co-products are produced in addition to a main product, also introduces complications. It creates a methodological challenge because a decision needs to be made regarding how impacts are associated with each co-product (Ayer & Tyedmers, 2009; Finnveden, 2000; Luo et al., 2009). Allocation is the most common method used in a variety of food systems, including aquaculture (Hindelang et al., 2014; Mungkung et al., 2013), broiler chicken production (González-García et al., 2014; Kalhor et al., 2016), and dairy farming (Yan & Holden, 2018; Zhang et al., 2013). In this way, multifunctionality is managed by partitioning impacts between co-products based on some factor selected by the researcher (Finnveden, 2000; Pelletier et al., 2015). Similar to functional units, allocation can be based on physical factors, such as mass, or on economic value of products (Finnveden, 2000; Lopez-Andres et al., 2017; Reap et al., 2008b). However, allocation can create discrepancies in the model because selection of allocation based on mass can create imbalances when energy is split between co-products and vice versa (Pelletier et al., 2015; Weidema & Schmidt, 2010).

Therefore, ISO guidelines recommend against allocation where possible, instead suggesting to either divide the process into individual unit processes which only have single outputs or to apply system expansion (*CAN/CSA-ISO 14044*, 2006). In general, splitting multifunctional processes into unit processes is considered the ideal approach (Pelletier et al., 2015). In the case of aquaponics, splitting into subprocesses of aquaculture and hydroponics is a possibility, but has yet to be applied from a life cycle perspective. Alternatively where division into unit processes is not an option, system expansion should be conducted, where different means of producing the co-product are considered so that impacts quantified from the alternative process can be subtracted from the process at hand (*CAN/CSA-ISO 14044*, 2006). As a result, system expansion is based on the underlying assumption that the market will change, or reduce production, to accommodate additional production from the system being studied (Pelletier et al., 2015). Because of this, Pelletier et al. (2015) argue that this method of handling multifunctionality is more fitting with consequential forms of LCA, which are change-oriented and aim to understand how the global share of life cycle impacts burdens change with production. Attributional LCA on the other hand, which is the main form of LCA discussed in this work, is meant to calculate absolute impacts of a specific process at a given point in time (Finnveden et al., 2009; Pelletier et al., 2015; Schrijvers et al., 2016). Therefore, the use of system expansion does not logically apply in attributional studies as it would in consequential studies where changes are inherent to the study at hand. Accordingly, attributional LCAs conducted on food systems in the future should first attempt to divide multifunctional processes into subprocesses before considering system expansion or allocation.

Another methodological challenge faced is related to the boundaries of the study itself. In LCA, the broadest possible boundaries include all impacts from cradle, or raw material extraction, to grave, or end of life and disposal (Finnveden et al., 2009; Reap et al., 2008a). The reason boundary selection poses a challenge is because they need to strike a compromise between being feasible and being broad enough to capture the actual reality of the situation (Reap et al., 2008a). Poor boundary selection, like poor functional unit or allocation choices, reduces the accuracy of a study, lessening the efficacy of decision making from their findings (Reap et al., 2008a; Wender et al., 2014). Within food and protein production systems, boundaries are often selected and justified based on data availability and commonly selected boundaries by other studies in the field (Ayer & Tyedmers, 2009; Ghamkhar et al., 2019). However, in doing so, it is unlikely that novel conclusions can be made. Therefore, it is important that boundary selection be closely tied to the desired outcomes and applications of a study, rather than limitations of data or comparable literature.

Finally, the last common challenge in food LCA studies is related to data availability and quality. In most cases, life cycle inventories for food and agricultural systems are either unavailable or unmeasurable (Notarnicola et al., 2017). Available databases are either too region specific or too general (Finnveden, 2000; Finnveden et al., 2009), making the accuracy of the assessment less than ideal. Furthermore, Reap et al. (2008) postulate that when data is not readily available, there can be discrepancies in the model between the results and the actual situation being studied. In depth studies which collect data for all life cycle stages are more likely to be accurate, but they come at the cost of expensive and time-consuming research. Overall, finding a balance between available and collectable data is necessary for both the integrity of studies and their timely completion. This, like the many other challenges presented above, represents an area where LCA studies can potentially lose credibility.

2.3.2 Life Cycle Assessment of Hydroponics Systems

Since there are few full life cycle assessments of aquaponics systems in literature, it is also helpful to examine how researchers have conducted studies on hydroponics and aquaculture systems individually. For the purpose of this review, hydroponics systems examined include soilless, indoor production with any of the configurations described in *Section 2.1.3*. Then, by this definition, a number of studies have been conducted in Europe and North America, all ranging back fewer than ten years. The results of these studies, along with methodological choices made and challenges faced, will be discussed next.

In general, LCAs conducted on hydroponics have highlighted the importance of resource efficiency in agricultural technologies. A number of these studies have been based on European climates and operations. For example, studies conducted by Sanyé-Mengual et al. (2018) in Italy and Dorr et al. (2017) in France found that rooftop hydroponic systems were more environmentally impactful when compared to conventional rooftop farming due to high energy consumption and low resource-use efficiency. In both of these cases, the mild European climate results in fewer concerns about energy use for heating and lighting supplementation. Beyond rooftop farming, a study conducted by Romeo et al. (2018) comparing conventional farming to hydroponics systems in Lyon, France also reported that energy consumption was a problem for hydroponics systems, even considering the mild climate. Vertical hydroponics systems, such as the one investigated by Martin & Molin (2019) in Sweden, are also growing in popularity in Europe. Their study confirmed the environmental impacts of energy consumption for heating and lighting found in previous studies, but it also emphasized the importance of considering infrastructure in hydroponics systems because it represents an important area for potential improvement (Martin & Molin, 2019). This is an important limitation because often, aquaponics studies neglect infrastructure entirely. Moreover, all studies in Europe conclude that room for improvement exists and must be researched to reduce the environmental burdens of hydroponics farming.

On the other hand, far fewer studies exist from a North American perspective. In terms of the United States, the study conducted in the Midwest by Chen et al. (2020) found that energy intensity was also a significant challenge, especially due to additional heating and lighting requirements in the winter, but that impacts could be reduced if wind power was used rather than coal. Furthermore, their study also compared hydroponics production to aquaponics production, ultimately making the conclusion that aquaponics systems were 45% less impactful than hydroponics due to shared resources and increased production capacity (Chen et al., 2020). Additionally, a hydroponics LCA was conducted from a Canadian perspective by Dias et al. (2017). In addition to energy intensity, this study addressed the water intensity of greenhouse hydroponics systems located in Ontario, Canada (Dias et al., 2017). It was concluded that Ontario greenhouses were more efficient in terms of global warming potential than greenhouses located in milder European climates. This illustrates the importance of efficiency studies to ensure that cold-climate food systems balance production with environmental impacts. Overall, the key finding from the reviewed hydroponics LCAs is that energy use is a significant factor for environmental impacts regardless of climate conditions, but impacts are exacerbated by cold climates.

In terms of methodology applied, most studies described above had a number of similarities. The majority of them selected a mass-based functional unit of 1 kg (Dias et al., 2017; Romeo et al., 2018; Sanyé-Mengual et al., 2018). System boundaries were cradle to system gate to exclude consumption and disposal, as well as other aspects such as fertilizer production and pest management (Chen et al., 2020; Dorr et al., 2017; Romeo et al., 2018; Sanyé-Mengual, Oliver-Solà, et al., 2015). Furthermore, unlike aquaponics systems, most hydroponics systems only have one main product, so allocation was not a concern for these studies. However, the studies did face a variety of other challenges. For instance, the sole use of mass-based functional units, as discussed in *Section 2.3.1*, is a limitation because it fails to capture the true function of food systems (Notarnicola et al., 2017). Furthermore, the systems themselves were all located in mild climates, limiting the applicability of the results to more extreme hot or cold climates. Moving forward, the field of hydroponics LCA would benefit greatly from variety in location and methodology.

2.3.3 Life Cycle Assessment of Aquaculture Systems

Unlike the studies described above, aquaculture life cycle assessments are more widely studied and cover a range of geographical regions. The results from these studies are particularly important to consider for aquaponics systems. This is due to the fact that the aquaculture component in aquaponics controls numerous inputs introduced to the system and its outputs are often considered the main product. Results, as well as methodological decisions and challenges, from aquaculture life cycle assessments are described below.

Overall, the hotspots uncovered by life cycle studies on aquaculture were largely consistent. The majority of studies found that fish feed was the biggest concern, especially those that contained animal products (Mungkung et al., 2013; Pelletier et al., 2009; Rizal et al., 2018; Smetana et al., 2016; Yep & Zheng, 2019). Specifically, the impact categories mainly affected by fish feed were eutrophication and toxicity (Mungkung et al., 2013; Smetana et al., 2016). However, even fish feeds that were mainly composed of plant-products were impactful due to transportation and land-use change impacts (Hochman et al., 2018; Rizal et al., 2018). The general consensus in the field is that other, more environmentally sustainable forms of feed, such as insect-based feeds, should be considered and compared using life cycle studies (Cohen et al., 2018; Goddek et al., 2019; Somerville et al., 2014). Furthermore, transportation was also a major concern for other components in aquaculture, specifically in studies conducted in Asia, including Bangladesh, Vietnam, Indonesia, and India (Henriksson et al., 2018; Robb et al., 2017). Additionally, both indoor and outdoor aquaculture facilities faced concerns related to the impacts of water quality (Ayer & Tyedmers, 2009; Bohnes & Laurent, 2019; Henriksson et al., 2018; Mungkung et al., 2013). The study conducted by Mungkung et al. (2013) found that deteriorating water quality reduced the feed conversion ratio such that additional feed inputs were required to ensure adequate fish nutrition, thereby exacerbating the impacts associated with feed production and consumption. Finally, it was found that systems located indoors had high energy use that resulted in environmental concerns (Ayer & Tyedmers, 2009). It was concluded that indoor recirculating aquaculture systems, which are the kind needed for aquaponics, were the most impactful form of aquaculture due to their energy consumption (Ayer & Tyedmers, 2009). Moving forward, more research is needed on these systems for cold climate regions where additional energy inputs are required to fully understand the implications of indoor aquaculture.

In order to gain a more valuable understanding of aquaculture systems, methodological challenges must be addressed. Similar to hydroponics, aquaculture life cycle assessments had a number of common methodological choices. Most studies selected a functional unit of a single unit of mass of either whole fish or processed fish filets (Ayer & Tyedmers, 2009; Bohnes & Laurent, 2019; Mungkung et al., 2013; Pelletier et al., 2009). Similarly, cradle to farm gate were the boundaries selected in order to include all relevant impacts before distribution and consumption (Ayer & Tyedmers, 2009; Mungkung et al., 2013; Robb et al., 2017). On the other hand, unlike hydroponics, allocation was necessary within aquaculture and was most frequently applied within feed production and for solid waste production (Ayer & Tyedmers, 2009; Bohnes & Laurent, 2019). Furthermore, while hydroponics studies were often based on case studies and single-site assessments, aquaculture studies often relied on surveys to capture regional or national behaviour (Henriksson et al., 2018; Mungkung et al., 2013; Robb et al., 2017), making these studies more applicable in a broader context. Therefore, in general, aquaculture LCAs are more diverse in terms of methodology than hydroponics LCAs.

Nonetheless, aquaculture life cycle assessments still face a number of methodological challenges despite the numerous and broad range of studies conducted. As mentioned above, allocation is a concern in aquaculture because, like most protein production systems, co-products are present at multiple life cycle stages. The papers by Ayer & Tyedmers (2009) and Pelletier et al. (2009) handled the allocation in a well-thought out manner by using nutritional energy content for feed production. Ayer & Tyedmers (2009) went further by applying system expansion at the farm gate to effectively capture the true purpose of each co-product. However, in many other studies, mass-based allocation was applied for its simplicity (Bohnes & Laurent, 2019), bringing into question the reliability of their results. Furthermore, a literature review conducted by Bohnes & Laurent (2019) of 65 aquaculture life cycle assessments concluded that the major methodological issues in the field included: functional units not being representative of the true system function, allocation being poorly handled, and boundaries being too narrow due to data or time restrictions. Furthermore, Bohnes & Laurent (2019) also state that the majority of studies exhibiting these issues rarely addressed methodological challenges or limitations of their results. Therefore, LCA application in aquaculture could be improved by addressing these common challenges and by adjusting methodology accordingly.

2.3.4 Life Cycle Assessment of Aquaponics Systems

For aquaponics systems, like other emerging technologies, life cycle assessment is difficult due to data limitations. Additional uncertainty is introduced in this case because very few full life cycle assessments have been conducted on aquaponics systems. The reported LCA studies are based in Europe or the United States, not Canada. This is a major gap, because as described in the previous sections, climate can significantly affect system operation by influencing heating and lighting requirements, system design, and even species. However, some results can be generalized and have been consistent across all studies. For example, all reviewed aquaponics LCA studies highlight energy consumption as a major contributor to environmental impacts. The studies conducted for cold-climate systems also found that energy inputs were significant and that renewable energy should be considered a necessity (Cohen et al., 2018; Forchino et al., 2018; Forchino et al., 2017; Maucieri et al., 2017). Furthermore, while most of the studies used the same species of fish and plants, some of them indicated the importance of product selection for both profitability (Goddek et al., 2015; Maucieri et al., 2017) and market acceptance (Forchino et al., 2017; Ghamkhar et al., 2019). Despite a keen awareness of how life cycle operations affect profit, only the study by Forchino et al. (2018) included life cycle cost analysis, concluding that profitability is only possible with a comprehensive understanding of market conditions. Overall, despite the consistency among results, some major differences arise as well, especially in terms of the assumptions made. The studies conducted, their locations, and major assumptions are summarized in *Table 2-1*.

Table 2-1: Summary of Assumptions Made in Reviewed Aquaponics LCA Literature

Location	Boundaries	Functional Unit	Allocation	Study
United States	Cradle-to-Gate	1 kg of combined product	None	Ghamkhar et al. (2019)
Belgium	Cradle-to-Gate	1 kg plants	Mass	Forchino et al. (2018)
France	Cradle-to-Gate	1 kg plants	System Expansion	Jaeger et al. (2018)
Switzerland	Cradle-to-Gate	1 tonne fish	Mass	Cohen et al. (2018)
Italy	Cradle-to-Gate	1 kg plants	Mass	Forchino et al. (2017)
St. Croix	Cradle-to-Gate	1 tonne fish	System Expansion	Boxman et al. (2017)
United States	Cradle-to-Gate	1 kg fish or 1 kg plants	Mass	Xie & Rosentrater (2015)
Indonesia	Cradle-to-Gate	640 kg combined product	Mass	Hindelang et al. (2014)

In terms of system boundaries, all the studies consider activities from cradle to system gate, making the results comparable, but the study conducted by Ghamkhar et al. (2019) is the only one that considers the equipment itself. While others often exclude it, this study makes the case that equipment accounts for a non-negligible portion of impacts and should be considered.

Functional unit selection is problematic in aquaponics studies. As seen in *Table 2-1*, mainly mass-based functional units are used, but there are studies which consider fish the main product, ones that consider plants the main product, and finally, ones that consider aggregate products. This implies that there is not yet consensus on what is considered the main product of aquaponics systems, which poses a problem in life cycle assessment because functional unit selection affects results. In fact, Ghamkhar et al. (2019), through the use of sensitivity analysis, found that overall results varied greatly depending on whether fish or plants were selected as the functional unit in aquaponics studies. Another problem is posed by the lack of diversity in allocation methods used in aquaponics studies. Future aquaponics LCAs would benefit from dividing aquaponics production into its unit operations of aquaculture and hydroponics in order to capture impacts of each product more accurately.

2.4 Economic Implications

Like any emerging technology, rationale for implementing aquaponics systems goes beyond environmental benefits and food production demands and should include potential economic gains. Based on the lower resource requirements, researchers predict lower input costs for both water and fertilizer (Rizal et al., 2018; Somerville et al., 2014; Tyson et al., 2011). However, one major limitation is that most aquaponics companies are private, with little incentive to share their economic data (Goddek et al., 2015). Even more limiting is that there are few studies covering economic performance. The ones that do, focus on warm climates outside of Canada that face entirely different economic, environmental, and policy barriers. The exploratory study by Tokunaga et al. (2015) is by far the most comprehensive and robust study of the economic feasibility of aquaponics in a warm climate. Their overall finding was that despite the potential for profitability, high capital expenses, labour, and feed costs were large barriers (Tokunaga et al., 2015). This reiterates similar findings that profitable conditions are fickle and highly dependent on variables like market demand and price (Bosma et al., 2017; Forchino et al., 2018; Forchino et al., 2017; Tokunaga et al., 2015; Xie & Rosentrater, 2015).

Despite these challenges, a number of options for reducing costs have been highlighted in literature. Many of these options include design or operation changes, such as the use of on-site renewable energy sources (Forchino et al., 2018; Tokunaga et al., 2015), the automation of labour (Tokunaga et al., 2015), the use of existing buildings to cut infrastructure costs (Junge et al., 2017), and even exploitation of economies of scale (Quagrainie et al., 2017). The most commonly suggested option is to ensure that the price of products is as high as possible by seeking organic certification (Asciuto et al., 2019; Quagrainie et al., 2017; Tokunaga et al., 2015). Janker et al. (2018) criticize this approach due to potential obstacles that exist in obtaining certification. Furthermore, due to gaps in literature, there is very little evidence that these measures will actually improve the economic performance of aquaponics systems. In summary, the current strategy for boosting economic profitability is to increase efficiency in system operation and to use quality-based certifications to increase product value, but significant further research is required to determine the effectiveness of these methods.

2.5 Life Cycle Cost Analysis

As mentioned above, economic performance is a key aspect that must be studied in order to ensure overall success in aquaponics systems. Life cycle cost (LCC) analysis is one way to determine economic productivity throughout the life cycle of a product or system. LCC is defined by Rebitzer & Hunkeler (2003) as "an assessment of all costs associated with the life cycle of a product." Similar to life cycle assessment, what sets LCC apart from other economic assessment methods is its inherent interest in the entire life cycle of a product. LCC is mainly used as an internal tool to assess a company's cost management over a product or system life cycle, rather than a tool that can determine economic value or be used for financial accounting (Kádárová et al., 2015; Rebitzer & Hunkeler, 2003). This is mainly because LCC captures steady state costs and neglects any changes in markets that could affect the value of the product (Luo et al., 2009). Instead, LCC is often used to optimize costs by a number of industries (Savić et al., 2019; Smit, 2012). Researchers have found that in the area of food and agriculture, there is much room left for improvement in terms of methods and applicability (De Menna et al., 2018; Savić et al., 2019). Furthermore, researchers also argue that despite the tendency for LCC to focus on business goals rather than environmental ones, environmental goals are necessary all same for well-rounded sustainable development (Rebitzer & Hunkeler, 2003; Savić et al., 2019). Therefore, it can be concluded from literature that in order to achieve such goals, LCC should be employed alongside environmental LCA.

In terms of application, LCC methodology follows closely with LCA. Typically, the same goal and scope will be used to frame an LCC study, including the boundaries, time periods, and data quality requirements (Kádárová et al., 2015; Moreau & Weidema, 2015; Rebitzer & Hunkeler, 2003). Furthermore, similarly to LCA, there is a need to identify the purpose and application of results to ensure that any findings are meaningful and introduce value to the intended audience (Smit, 2012). Then, instead of quantifying the flows by physical characteristics like in LCA, cash flows, adjusted by inflation and interest rates, are used in LCC (Saeid Mohamad et al., 2014). Furthermore, like LCA, all material and energy flows throughout the life cycle of a product must be included (De Menna et al., 2018; Saeid Mohamad et al., 2014). Therefore, it can be said that the life cycle cost of a product is the sum of all direct costs, which are associated with primary material and energy flows, and indirect costs, which are related to business operations rather than production (Smit, 2012). Additionally, especially for agriculture, researchers have found that indirect costs in an LCC study should include government funding and subsidies (Baquero et al., 2011). Allocation is necessary for these indirect costs (De Menna et al., 2018) and can be applied in the following ways: weight-based, usage rate, other specific rates based on physical or economic criteria (De Menna et al., 2018; Luo et al., 2009). Overall, while it is important to keep these fundamental components of LCC in mind, in practice, application can vary greatly.

In general, the application of LCC is much less standardized than LCA, resulting in a number of differing strategies applied throughout literature. In fact, De Menna et al. (2018) found through an assessment of LCC studies that distinctions between application approaches are rarely fully described or reported, making replication difficult. This is especially challenging because within different fields, such as agriculture, there is very little consensus on which methodology is most appropriate. Furthermore, Miah et al. (2017) also argue that because connections and similarities between the various approaches are unclear, potential integrated methods are left uninvestigated. There have been a few attempts by researchers to summarize and integrate various LCC frameworks, including Miah et al. (2017) who used multi-objective linear programming and Baquero et al. (2011) who used cost-benefit analysis to consolidate the approaches. Regardless of these variations in method, the basic calculation of summing sum the net prevent value (NPV) of all flows using the appropriate interest rate can be observed in multiple studies (Cleary et al., 2015; De Menna et al., 2018; Langdon, 2005; Miah et al., 2017; Spickova & Myskova, 2015). Therefore, future LCC studies should focus on standardizing calculations and methodology to ensure comparability and reliability between results.

2.6 Key Themes and Research Implications

Most of the literature reviewed here is from the past ten years, making aquaponics a relatively young field with growing interest and potential. Researchers have identified one major need across all studies. This is the need for optimization within aquaponics to reduce operation and start-up costs, improve environmental performance, and increase production yields. Specifically, the need for optimization has been highlighted with respect to environmental impact, system design, and symbiosis. Furthermore, researchers have consistently pointed out environmental hotspots related to energy use for all climates. Within the field of aquaponics LCA, a number of other gaps have been identified. These include dealing with co-products, allocation, and finally, functional unit selection and justification.

Due to the complex and ever evolving nature of these variables, there is no “one size fits all” solution. However, a number of options for improving operation from an environmental and economic standpoint have been identified. The next steps for aquaponics research are to eliminate some of the uncertainty surrounding cold climate operations as aquaponics gains popularity around the world (Villarroel et al., 2016). Especially in Canada, aquaponics systems need more guidance because the Canadian climate and market introduce different demands and conditions that need to be met for productivity. In the process of optimizing these systems, it is more important than ever to maintain environmental sustainability to ensure that these technologies remain viable alternatives to traditional agriculture. In conducting research such as this, sustainable pathways for aquaponics in Canada can effectively be identified.

Chapter 3 Contributions

The contributions for this chapter are as follows: I, Gayathri Valappil, conducted analysis and wrote the content, while Dr. Goretty Dias and Dr. Christine Moresoli provided guidance and revisions.

Chapter 3 Life Cycle Assessment of Aquaponics Production: A Canadian Case Study

3.1 Abstract

Global population growth is putting pressure on food production systems to meet growing nutritional demands. Therefore, methods of controlled-environment food production are frequently suggested as food security solutions as well as means to fill gaps in current production. Aquaponics is one such technology that combines recirculating aquaculture with hydroponics to simultaneously produce fish and vegetables, but is known for its energy intensity, especially in cold climates. This study splits aquaponics production into individual unit processes of aquaculture and hydroponics and uses a cradle-to-gate life cycle assessment to investigate the environmental barriers faced by small-scale, Canadian aquaponics systems. It was concluded that energy consumption for artificial lighting and heating was the biggest environmental hotspot due to the large percentage of fossil-based energy used by the local grid. This resulted in a global warming potential of 68 kg CO_{2eq}/kg live fish and 50 kg CO_{2eq}/kg leafy greens. All other input flows contributed to an average of 2% of total impacts. Energy efficiency improvements and renewable energy are suggested, but other input flows, including infrastructure and fish feed, could also be altered to improve environmental performance. The findings of this study are posed to support future businesses and researchers in making aquaponics operations and technologies more environmentally viable.

Keywords: life cycle assessment, cold climate agriculture, energy use, indoor aquaculture, Canada

3.2 Introduction

As the impacts of climate change become more prominent, the global agriculture industry will be under pressure to meet rising nutritional demands. In 2003, the Standing Senate Committee on Agriculture and Forestry issued a report that outlined the need for increased resiliency in Canadian agriculture due to expected changes in climate conditions, such as increased frequency of extreme weather events and pests, changes to Canada's growing zones, and the economic effect of changes in global agricultural productivity (Oliver & Wiebe, 2003). These changing climate conditions have already put strains on agricultural production around the world and have led to significant crop loss (Calicioglu et al., 2019; Eigenbrod & Gruda, 2015; Goodman & Minner, 2019). Furthermore, research also indicates the importance of shifting production towards currently under-produced goods, including seafood, nuts and legumes, and fruits and vegetables in order to make the food system as a whole more sustainable and capable of supporting a growing population (Bahadur KC et al., 2018). Therefore, restructuring the agriculture industry in Canada to accommodate climate change-related challenges and population growth is an important issue.

In response to these challenges, controlled-environment food production systems (CEFPS) are growing in popularity. CEFPS are climate-controlled, often indoor systems, in which ideal growing conditions can be maintained year-round (Benke & Tomkins, 2017; Despommier, 2011; Goodman & Minner, 2019; Shamshiri et al., 2018). They are especially important in urban areas and in cold regions because they open up the possibility of local produce being accessible year-round, rather than having to rely on imported goods. These systems are sometimes impervious to extreme weather events as well as the shorter growing periods in cold climates. Additionally, due to the level of control offered by CEFPS technologies, reduced resource use is often touted as a potential environmental and economic benefit (Benke & Tomkins, 2017; Despommier, 2011). For these reasons, CEFPS technologies are often thought of as a solution to food production barriers in urban areas and cold regions. However, they are often placed in converted warehouses and barns (Chance et al., 2018; Love et al., 2015) without consideration of how inadequate building envelopes can increase energy consumption in cold climates.

Of these CEFPS technologies, aquaponics is one particular type that combines aquaculture and hydroponics for simultaneous fish and vegetable production. These systems are typically closed loops that cycle water between the aquaculture and hydroponics systems with the help of biofilters (Danner et al., 2019; Goddek et al., 2015; Yep & Zheng, 2019). The water output from the aquaculture unit contains nutrients from the fish waste that eliminate or reduce the need for additional fertilizers in the input to the hydroponics unit (Goddek et al., 2015; Yep & Zheng, 2019). A common set-up for small-scale commercial aquaponics systems is to pair recirculating aquaculture systems (RAS) with deep-water culture (DWC) hydroponics systems (Goddek et al., 2015; Palm et al., 2018). In RAS, water output from the aquaculture system is treated using biofilters to convert harmful ammonia into a useful form of nitrogen before being sent to the hydroponics system and eventually returning to the aquaculture tanks (Delaide et al., 2016; Monsees et al., 2017). At the same time, DWC systems, also known as raft hydroponics, allow plants to sit on rafts that float directly atop nutrient rich water, eliminating the need for soil (Goddek et al., 2015; Sayadi-Gmada et al., 2019; Somerville et al., 2014; Yep & Zheng, 2019). In addition to reduced fertilizer and soil needs, aquaponics systems also require very little water beyond the initial filling due to the water recycling operations that take place (Danner et al., 2019; Goddek et al., 2015). Therefore, there is growing interest in these technologies to address challenges in the food system.

However, aquaponics systems are not without drawbacks. A number of life cycle assessments (LCA) exist for aquaponics systems, most of which highlight energy use to be the most significant hotspot for indoor operations (Forchino et al., 2018; Ghamkhar et al., 2019; Hindelang et al., 2014; Xie & Rosentrater, 2015). Furthermore, fish feed is found to be impactful due to the use of fishmeal and fish oil in many commercial operations (Cohen et al., 2018; Hindelang et al., 2014; Maucieri et al., 2017). However, the majority of these LCAs are based on warm or Mediterranean climates with very few that focus on cold climates, and none that look specifically at Canadian aquaponics systems. The few studies on cold regions have found that long winters introduce the need for additional heating and artificial lighting such that energy use is the primary concern (Ghamkhar et al., 2019; Wu et al., 2019). However, factors specific to Canada, such as composition of the electricity grid, materials and infrastructure requirements, markets for specific fish species and crop varieties, and length of the growing period can all affect LCA results. As a result, the need for Canadian perspectives on the life cycle assessment of indoor aquaponics systems is clear. Therefore, the purpose of this study was to identify the environmental barriers that are faced by small-scale, indoor Canadian aquaponics systems located in converted warehouses or barns by conducting a life cycle assessment. Additionally, a known challenge in aquaponics LCA studies, and in any LCA of a multifunctional system with multiple products including a primary product and coproducts, is how to partition impacts between products. Therefore, a secondary purpose of this study was to evaluate how coproduct treatment affects the final impact results for each product in the aquaponics system.

3.3 Methodology

This study followed the standard procedure for a life cycle assessment (LCA) outlined in the ISO 14044 framework. As per the guidelines, the study includes goal and scope definition, life cycle inventory, life cycle impact analysis, and interpretation (*CAN/CSA-ISO 14040*, 2006). Details regarding these methods are described in the following sections.

3.3.1 System Description

The aquaponics system of interest is a small-scale commercial facility located in Halifax, Nova Scotia, Canada. It consistently produced rainbow trout (*Oncorhynchus mykiss*) and striped bass (*Morone saxatilis*) year-round, while plant production rotated between a variety of leafy greens, including Swiss chard (*Beta vulgaris*), arugula (*Eruca vesicaria*), butter lettuce (*Lactuca sativa*), Vulcan hybrid lettuce (*Lactuca sativa*), and basil (*Ocimum basilicum*) depending on market value and demand (*Design Parameters Optimization and Economics of a Commercial Aquaponics*, 2018). The target market of this system were customers in Atlantic Canada and Ontario, but the venture ultimately shut down after five years due to the various uncertainties surrounding Canadian aquaponics practice.

The system consisted of three 6 m^2 Styrofoam stacked grow beds, a 0.75 m^3 high density polyethylene (HDPE) plastic fish tank, settling tank, mineralization tank, water filters and a biofilter, two water pumps (45-W each), two aerators (25-W each), and 90 T-8 fluorescent bulbs (32-W each) (*Design Parameters Optimization and Economics of a Commercial Aquaponics*, 2018). Because the system was located in a windowless room, all of the lighting required for plant growth needed to be provided artificially, resulting in a frequent bulb replacement rate. Further details regarding each of these components, including the lifespans for the main materials and the size are given in *Appendix A: Life Cycle Inventory Data*.

The hydroponics unit was a form of deep-water culture (DWC), while the aquaculture unit was a recirculating aquaculture system (RAS) which meant that the roots of the plants sat directly atop the nutrient-rich water that cycled back and forth between the systems. Each hydroponic grow bed had a volume of 1 m^3 and was able to hold 200 plants, resulting in a total system capacity of 600 plants. The total water capacity was 4 m^3, with 3 m^3 used by the hydroponics system and 1 m^3 used by the aquaculture system. Of this total volume, 0.01% was replaced each week. In terms of energy input, the system used minimal heating from October to March as well as fluorescent grow lights that operated for 12 hours a day year-round. The electricity requirement for the hydroponics system was determined based on use of 80 32-W lighting fixtures, while the remaining 10 fixtures were used by the aquaculture system. The heating was provided with electrical space heaters. Heating was therefore divided based on the area taken up by each process, meaning that 35% of heating was used for the hydroponics unit, based on a 6 m^2 area, and 65% was used for the aquaculture unit, based on a 13 m^2 area. Overall, the system took up 19 m^2 and could produce 64 kg of fish and 300 kg of produce each year, making this a multifunctional system. A not-to-scale diagram of the system is shown in *Figure 3-1*.

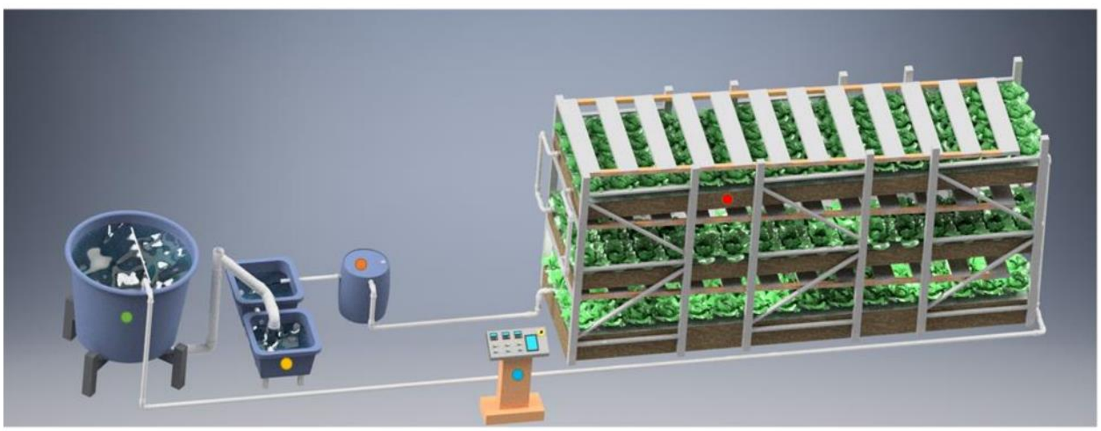

Figure 3-1: Depiction of aquaponics system.

Because aquaponics produces both fish and leafy greens, there is a main product and a coproduct. According to the ISO standards, the preferred way to deal with a multifunctional system is to subdivide the "black box" that produces the two products into its unit processes, where each unit process has an output of one product (*CAN/CSA-ISO 14040*, 2006). This means that all input flows and impacts were divided according to how they were used to generate each product. For an aquaponics system, the production operation can be seen as an integration of the aquaculture and hydroponics sub-systems, as shown in *Figure 3-2*. As a result, the need for allocation or system expansion was eliminated.

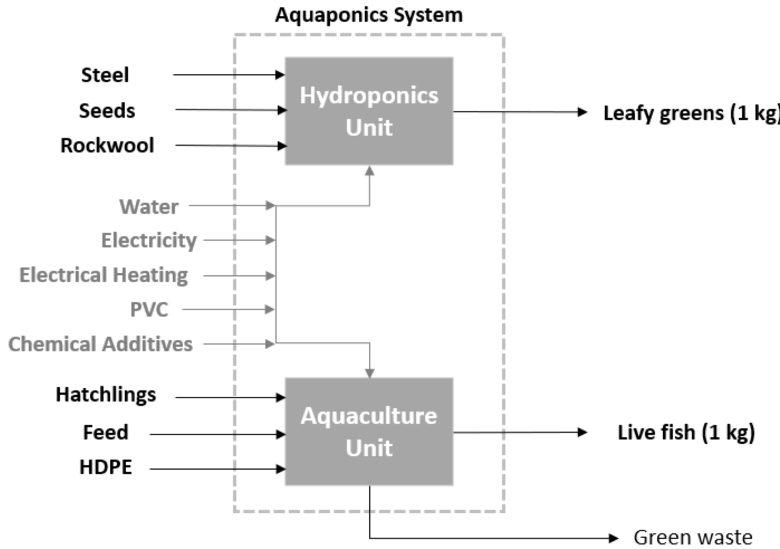

Figure 3-2: Flow diagram for unit process approach.

3.3.1.1 Climate Considerations

Nova Scotia is a Maritime province located on the east coast of Canada. Halifax is its capital. Proximity to the Atlantic Ocean gives Nova Scotia a milder climate than landlocked regions in Canada. This means that Halifax typically experiences mild summers and winters, with occasional periods of extreme heat and humidity or extreme cold (Environment Canada, 2021). During the cold season when heating was required (October to March), outdoor temperatures of -9°C and 14°C are typical, while the warm season has temperatures ranging between 17°C and 25°C (Environment Canada, 2021).

3.3.2 Goal and Scope

3.3.2.1 Goal and Application

The goal of this LCA was to explore the environmental impacts and resource consumption of small-scale aquaponics systems in Canada and to extend findings to other cold regions. Additionally, through the application of the unit process model described above, this research aimed to address gaps in current aquaponics LCAs which have generally applied allocation to partition impacts between co-products. The overarching aim was to evaluate the potential for aquaponics to be a responsible and sustainable production method for the Canadian food system.

The results of this study will be beneficial in several regards. Primarily, its findings will be able to guide existing and future aquaponics farmers in Canada to improve their environmental performance by identifying hotspots in operation and enabling their correction. This will guide system improvements and operational decision-making that will ultimately help to ensure that aquaponics facilities are environmentally sustainable. The intended audience for the study is therefore operators and owners of aquaponics systems, but also policy-makers and researchers who are looking for key areas of food production that should be targeted to achieve sustainability.

3.3.2.2 Functional Unit

As discussed previously, the aquaponics system of interest in this study provided a controlled environment for the simultaneous production of both fish and leafy greens. In LCA, this implies that it is a multi-functional system, however, one output must be selected as the main product, with the other being referred to as the co-product. Then, the function of the system can be described with respect to the main product, such as per unit of fish or per unit of leafy greens. In general, many aquaponics LCAs tend to select fish as the primary product and, in order to manage the co-product of plants, use mass allocation to partition impacts (Cohen et al., 2018; Forchino et al., 2017, 2018). However, allocation is not a desirable approach according to ISO guidelines (*CAN/CSA-ISO 14044*, 2006), so to avoid it, the unit process approach described in *Section 3.3.1* was instead applied in this study. Therefore, the two functional units selected for this study are: 1 kg of live fish for the aquaculture unit and 1 kg of leafy greens for the hydroponics unit over the period of one year of system operation.

3.3.2.3 System Boundaries

When modeling the life cycle, cradle-to-gate boundaries were applied. This meant that all aspects of the life cycle up to the point where products left the facility were considered. In particular, this included raw material extraction (ores, fuels, etc.), refining and manufacturing (plastics, steel refining, rockwool, feed, etc.), on-site activities (water and electricity use, etc.), as well as transport between these steps. Note that for the fish feed used in the aquaculture unit, while milling of crop products was included, energy for blending and its infrastructure were neglected. Similarly, the packaging materials used for the fish and leafy greens were excluded for this LCA screening due to its assumed minor influence on environmental impacts. Since activities that occur before or after these are not directly dependent on the operation of this aquaponics system, they were not of interest in this study. This includes cleaning and packaging of the fish and leafy greens, consumption, and disposal of products and system infrastructure, as well as any processes needed for the construction of capital buildings used at any stage in the life cycle. In terms of geographical boundaries, wherever possible Canadian and American data were given preference over European data to ensure that results are applicable to a wide range of Canadian aquaponics facilities. Additionally, data from daily operations exists for a one-year period, however the results of the assessment should be applicable over a suitable period where technological change is expected to be minor. The actual lifespan of aquaponics systems is debated in literature due to the varying lifespans of the materials used. Some studies have chosen a 20-year lifespan due to the breadth required for planning and predicting finances needed for capital projects (Bosma et al., 2017), while others have performed sensitivity analysis on various lifespans of the materials (Ghamkhar et al., 2019). It has been reported that shorter equipment lifespans tend to increase environmental impacts and that infrastructure is a highly sensitive area that should be included in aquaponics LCAs (Ghamkhar et al., 2019). For this study, a lifespan of 5 years was chosen because aquaponics is an emerging and rapidly evolving technology that is likely to have various environmental considerations in the near future.

3.3.2.4 Impact Categories and Impact Assessment

In order to model the system, openLCA 1.10 was used with information available in the ecoinvent 3.5 database. Modeling of the environmental impacts was done using TRACI 2.1 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts), which is the method developed by the United States Environmental Protection Agency. The impact categories chosen for this study were determined by the types of impacts incurred by aquaponics facilities but also follow closely with existing studies in order to allow for comparison between results. These categories are acidification, eutrophication, global warming potential and fossil fuel depletion.

Acidification potential captures the possibility of airborne emissions altering the pH of both soil and water and can be measured through sulfur dioxide, or equivalent, emissions (La Rosa, 2016). It is relevant to aquaponics production due to the emissions created in energy generation and plastic manufacturing (Forchino et al., 2017; Goddek et al., 2015), both of which are vital to the operation of the facility. Next, eutrophication potential indicates the possibility of excess nutrients being added to water to the point where algal blooms interfere with existing aquatic and terrestrial life (Morelli et al., 2018). Consideration of this impact is relevant to aquaponics operation due to its water usage and to compare impacts of other aquatic agriculture where eutrophication concerns are high (Morelli et al., 2018). Global warming potential is directly linked to energy usage and emissions of carbon dioxide and other greenhouse gases that result from it (La Rosa, 2016). Not only do most, if not all, aquaponics LCAs include this impact category, energy consumption often results in the largest impacts, making this category vital to the validity of this study. Furthermore, this is related to fossil fuel depletion because it directly connects non-renewable fuel use to the impacts of the system.

3.3.2.5 Data Quality Requirements

In order to ensure validity of results, defining data quality requirements is crucial for selection of relevant data. For the most part, the data used in this screening was obtained from the ecoinvent 3.5 database, which means not everything was directly applicable to this product system. Therefore, the data quality requirements given in *Table 3-1* were used to ensure that data used in the model would be temporally, geospatially, and technologically relevant to this study. Then, with these requirements in mind, a data quality matrix, such as the one developed by Weidema & Wesnæs (1996), was used to quantify the quality of a set of data at the interpretation phase. The matrix and data quality scores are provided in *Appendix B*: *Data Quality*.

Table 3-1: Data Quality Requirements

Data Quality Category	**Requirement**
Temporal	All data should be from within five years of 2018, which is the year the facility was operated.
Geospatial	Operation data should be appropriate for Canadian or similar northern regions. This is to ensure that cold climate considerations are made.
Technological	The most commonly used/available technology for upstream production processes will be accepted, but system data should be relevant for Canadian operations.

3.3.3 Life Cycle Inventory

As discussed previously, aquaponics systems have multiple input and output flows that must be accounted for in LCA. These consist of the basic consumable inputs, including seeds, hatchlings, water, feed, chemical additives, and energy, as well as infrastructure components of PVC, HDPE, Rockwool, steel, and polystyrene foam slabs. The output flows are the live fish and leafy greens. Each input or output flow value must be divided by the amount of functional unit produced. The normalized values for each input and output flow for the unit process approach are given in *Table 3-2* along with assumptions and sources for input values. Further information regarding material lifespan and infrastructure mass can be found in *Appendix A: Life Cycle Inventory* Data.

Table 3-2: Calculated Input and Output Flows, per Functional Unit for Aquaculture Unit and Hydroponics Unit

Flow	**Quantity**		**Unit**	**Assumptions & Sources[1]**
	Aquaculture Unit	*Hydroponics Unit*		
INPUTS				
Hatchlings	0.24	-	kg	Adult trout production, conservative approach
Seeds	-	2.4E-4	kg	
Water	19.78	9.15	kg	Tap water production in Quebec
Electricity	9.58	44.09	kWh	Grid composition used in Nova Scotia in 2018, see *Figure A-1*
Heating	61.80	6.97	kWh	Electrical heating used, compared to natural gas and biogas
Potassium	1.2E-4	2.5E-5	L	

Calcium	1.2E-4	2.5E-5	L	
Iron	6.3E-5	1.3E-5	L	
Feed				Energy required for blending feed components neglected
Soybean meal	0.65	-	kg	
Wheat	0.28	-	kg	
Corn/maize	0.28	-	kg	
Fishmeal and fish oil	0.09	-	kg	
Infrastructure				Based on 20-year lifespan, after which replaced
PVC	0.007	0.002	kg	
HDPE	0.041	-	kg	
Steel	-	0.019	kg	
Rockwool	-	0.048	kg	Annual replacement, from (De La Hera et al., 2016)
Polystyrene slabs	-	0.38	kg	Annual replacement, 100% virgin materials
OUTPUTS				
Live fish	**1**	-	kg	Rainbow Trout and Striped Bass
Leafy greens	**-**	**1**	kg	Various lettuces, chard, basil

[1]All unit processes from ecoinvent 3.5 database. Values obtained from Nova Scotia facility unless otherwise specified.

3.3.4 Assumptions and Limitations

A limitation of this study is the relative scarcity of Canadian life cycle inventory data (Ayer & Tyedmers, 2009). In fact, a significant portion of data on background processes is only available based on European conditions (Rebitzer et al., 2004), which means it may not be directly applicable to Canadian analyses (Weidema & Wesnæs, 1996). For processes occurring within Canada, use of data from non-Canadian locations can cause problems due to variations in the type of electricity grids and other manufacturing processes. Additionally, some data from the Nova Scotia facility was only provided in terms of Canadian dollar values, which are likely to have fluctuated from the time of operation to the time of the study. This included heating data, where only the electricity expenses were provided, rather than the amount of kilowatt hours of electrical heating used. Therefore, estimations were made using the cost of energy per kilowatt hour in Nova Scotia in 2018 to determine the consumption in kilowatt hours. Also, the production of hatchlings in Canada was unavailable in ecoinvent 3.5, so the process was approximated using data for fully grown trout produced in South America.

Assumptions had to be made on the materials used in the infrastructure and their amounts, the lifetime of equipment, the composition of the feed, and the amount of green waste produced on site. Firstly, many aquaponics life cycle assessment studies have suggested that infrastructure related impacts are negligible and often neglect it from analysis (Forchino et al., 2017; Ghamkhar et al., 2019). However, because waste from indoor agriculture has been found to be significant in other contexts (Egea et al., 2018), it was deemed relevant for this study. It was assumed that the major components that make up the aquaponics system, including the tanks, the piping, the racks, and the hydroponics growth supports, would be included within the scope of infrastructure. The materials of these components, as well as their replacement rates, are given in *Appendix A*: *Life Cycle Inventory Data*. However, other components, such as pumps, light bulbs, and the building housing the aquaponics system were left out for simplicity.

The manufacturer's website did not state the exact ratio of feed components; however, the ratio of proteins, fats, and carbohydrates was provided. Therefore, using this ratio and comparing to feed ratios and compositions provided in the work by Ghamkhar et al. (2019), an approximate feed composition was estimated, as shown in *Table 3-2*. Similarly, since the Rockwool production process was unavailable in ecoinvent 3.5, a life cycle inventory and emissions record from De La Hera et al. (2016) was used based on its similarity to Canadian manufacturing processes (*Rockwool Production Process*, 2020). Finally, the production of green waste on site was not considered. This green waste included leftover plant parts, such as leaves and roots.

Lastly, while the amount of electricity for lighting and pumping consumed by the aquaponics system was recorded in terms of kilowatt hours, the amount of heating was only available in terms of Canadian dollar values. To determine how much heating each unit process used, area-based allocation was used. The amount of heating used by the entire warehouse in which the aquaponics system was housed was given, so using the overall area of the building and the area specific to the aquaponics system, the amount of heating used by the aquaponics system was determined. Similarly, the ratio of area used by the aquaculture unit (13 m^2) to the hydroponics unit (6 m^2) was used to determine the heating specific to each unit process. This meant that 4000 kWh/year of heating was used for aquaculture and 2000 kWh/year was used for hydroponics. Next, the composition and quantity of additives were determined based on available liquid fertilizers targeted for aquaponics systems from Canadian suppliers. Finally, since the exact quantity of PVC piping was unknown, a quantity from literature for an aquaponics system exactly double the size of this one (Hindelang et al., 2014) was halved for this model.

3.3.5 Sensitivity Analysis

Sensitivity analysis was conducted to determine the impact of the coproduct treatment method on the final impact results associated with fish and leafy greens. As mentioned above, for the main analysis, the aquaponics system was split into individual unit processes of aquaculture production and hydroponics production. This is the ISO recommended approach for dealing with systems that have multiple outputs, known as multifunctional systems (*CAN/CSA-ISO 14044*, 2006). The other recommended approach is to use system expansion, where impacts of the co-product are subtracted from the system being studied based on known values from other life cycle assessments. However, because system expansion is based on the inherent assumption that the market will change in order to accommodate a displacement of production, it has been argued that system expansion is more suited to consequential LCAs which are fundamentally interested in how production changes affect the global share of environmental burdens (Pelletier et al., 2015). Attributional LCA, which is conducted in this study, is interested in the absolute impacts of a product or system, so system expansion is less suitable in this context. However, while best efforts can be taken to split the inputs according to unit process, the division of some inputs is not straightforward, introducing the need for this sensitivity analysis.

The inputs to the aquaponics system where uncertainty is introduced are electricity, water, PVC piping, chemical additives, and heating. For these input flows, adequate documentation outlining how they were divided during operation was not available. Instead, assumptions were made regarding their division. For electricity, water, and PVC piping, inferences based on equipment specifications were made. This included the electrical demand of pumps and the liquid capacity of the aquaculture and hydroponics tanks. On the other hand, the chemical additives were assumed to be shared equally and were split in half. Finally, heating was split based on the footprint of each unit process, as discussed in *Section 3.3.4*. This splitting of input flows represents a significant area of uncertainty. Therefore, in order to assess the sensitivity of modelling the system as unit processes, sensitivity analysis was conducted by modelling the system as a black box. For this black box approach, depicted as a flow diagram in *Figure 3-3,* allocation was used to partition impacts between the coproducts of live fish and leafy greens.

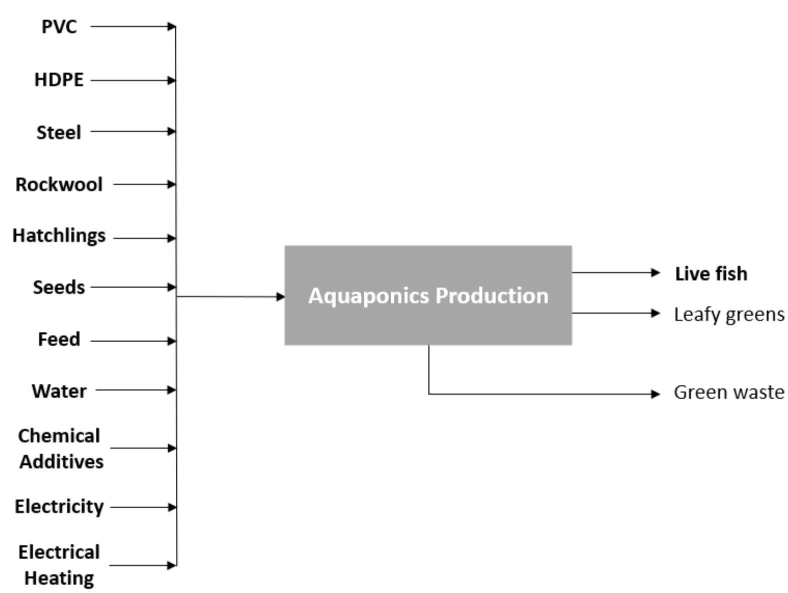

Figure 3-3: Process flow diagram for aquaponics facility, black box approach.

Allocation was applied for mass, energy, and protein contributions. *Table 3-3* shows the allocation ratios of impacts to fish and impacts to leafy greens for each allocation method, while the life cycle inventory values for the black box approach are given in *Table A-3*. For mass allocation, the ratio was simply determined based on the output mass of both individual processes over a one-year period. Similarly, energy or calorie allocation was conducted based on the caloric value of both fish and leafy greens. In this way, allocation is representative of one of the functions of food systems, which is to provide energy to the consumer (Notarnicola et al., 2017). Calorie allocation makes the most sense when 1 kg of live fish is selected as the functional unit, however, because leafy greens are typically consumed for nutrients rather than for calories, energy allocation may not make sense for a functional unit based on leafy greens. Finally, allocation by protein was also investigated to highlight the value of aquaponics as a protein-production system, given the interest in less-impactful protein sources (Bahadur KC et al., 2018; Specht et al., 2019). By switching from mass to energy to protein, the portion of impacts allocated to fish increases significantly, which highlights the importance of allocation in LCA and the limitations of many aquaponics studies solely relying on mass allocation.

Table 3-3: Allocation Ratios for Mass, Energy/Calorie, and Protein Allocation

Allocation Property	Impacts to Fish (%)	Impacts to Leafy Greens (%)
Mass	18	82
Energy/Calorie	80	20
Protein	90	10

3.4 Results

The results are presented for the impact contribution of the aquaculture and hydroponics units to various impact categories, the sensitivity analysis of the coproduct treatment methods, and a comparison of the environmental performance of this system to similar ones in literature.

3.4.1 Aquaponics as Two Individual Process: Aquaculture and Hydroponics

The contribution analysis for the aquaculture unit is illustrated in *Figure 3-4*. Heating, which was supplied by electricity, contributed up to 83% of impacts across all impact categories. Electricity used for lighting and pumping contributed up to 12% of the total impacts. This is a result of the average annual energy requirement for the aquaculture unit of 72 kWh per kilogram of fish and the fact that the electricity grid in Nova Scotia in 2018 was primarily composed of coal and other fossil-based energy, as shown in *Figure A-1*. As a result, a GWP of 68 kg CO_{2eq} per kg of live fish was measured. The other inputs combined contributed to between 0.001% and 2% of all impact categories investigated.

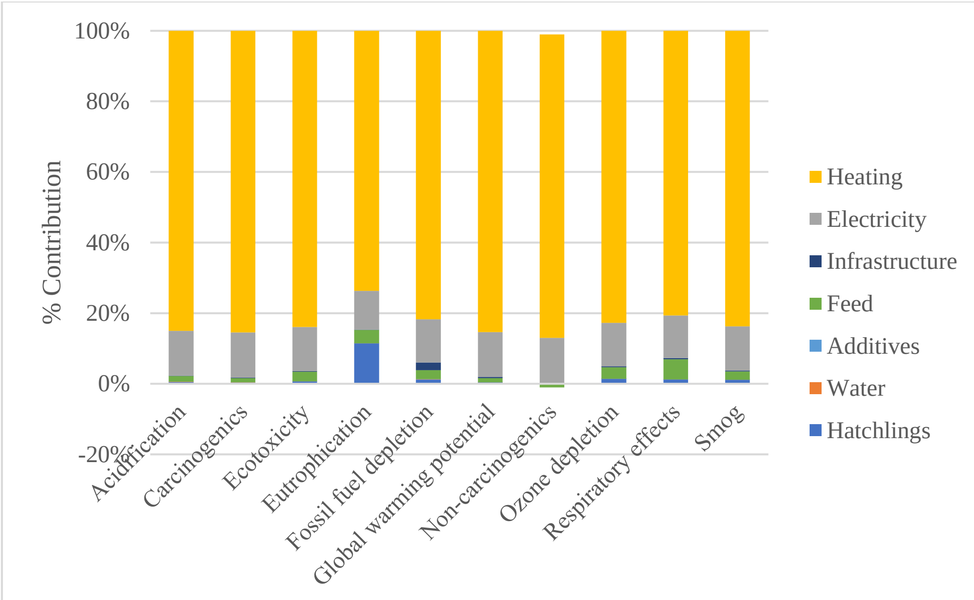

Figure 3-4: Relative contribution of input flows according to impact category for aquaculture unit.

In addition to heating, the production of hatchlings was particularly significant for the impact category of eutrophication. However, this value is a conservative estimation because the process was approximated using ecoinvent 3.5 data for fully grown trout due to the lack of data on hatchling production. Conservative estimations are typically preferred in LCA studies because they result in an overestimation of impacts, rather than an underestimation (Finnveden et al., 2009). Further details regarding the data quality of this process are given in *Appendix B: Data Quality*.

Finally, fish feed was also a notable input flow. While in this analysis fish feed contributed on average to 2% of the overall impacts, previous LCA studies on aquaponics and aquaculture have found fish feed to be a significant hotspot (Cohen et al., 2018; Hindelang et al., 2014; Maucieri et al., 2017), including those conducted in Canada (Ayer & Tyedmers, 2009; Pelletier et al., 2009). This difference may be due to the significantly lower content of fishmeal and fish oil in the fish feed used in this study compared to conventional, commercial feeds considered in the previous studies. For example, in the study conducted by Hindelang et al. (2014), the fish feed contributed to 90% of eutrophication, 60% acidification, and 25% global warming potential, rather than the average 2% observed here. The fish feed used in the study by Hindelang et al. (2014) consisted of 23% fishmeal and fish oil, while the feed used in the current study consisted of only 7% for an annual usage of 0.09 kg fishmeal and fish oil per kg of live fish. Furthermore, as shown in *Figure 3-5*, soybean meal was the largest contributor to the impacts of fish feed in this study, while fishmeal only contributed 6%.

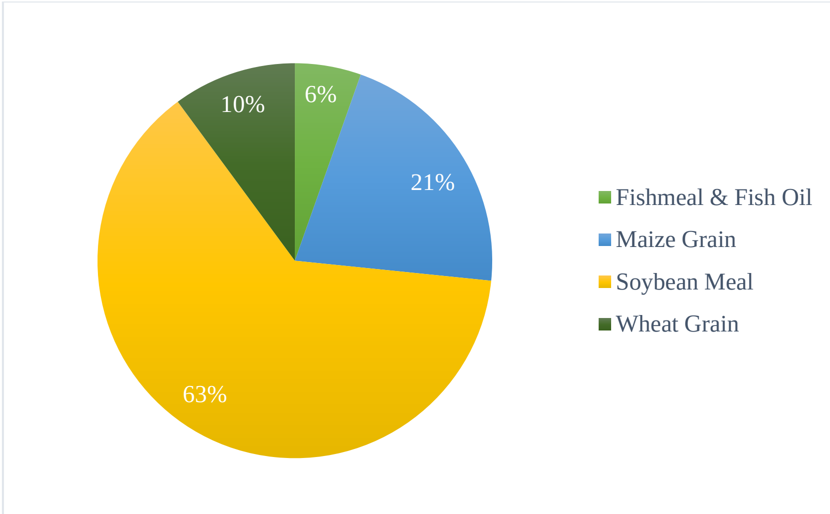

Figure 3-5: Average contribution of feed ingredients to environmental impact of fish feed.

The relative contribution of input flows according to impact category for the hydroponics unit is provided in *Figure 3-6*. When compared to aquaculture, the highest contribution to impacts from the hydroponics unit came from electricity for lighting. This is due to the daily requirement of 12 hours of artificial lighting, equating to 44 kWh per kilogram of leafy greens. Furthermore, fluorescent bulbs were used in the system, which consume more electricity than most newer lighting technologies (Rehman et al., 2017; Wolsey, 1993). Heating was also important, contributing to 13% of overall impacts on average. As a result, a GWP of 50 kg CO_{2eq} per kg of leafy greens was observed. Together, heating and electricity consumption for the hydroponics unit was 51 kWh/kg of leafy greens, compared to 71 kWh/kg of live fish in the aquaculture unit.

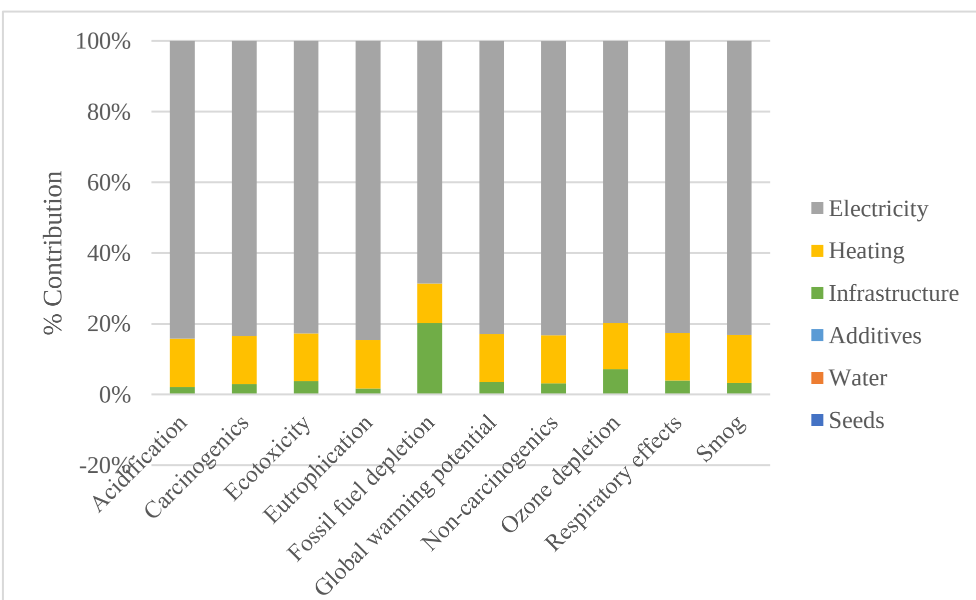

Figure 3-6: Relative contribution of input flows according to impact category for hydroponics unit.

Hydroponics infrastructure contributed to around 5% of impacts, which was more than water, seeds, and chemical additives. Specifically, the largest share (65%) of the infrastructure impacts, as shown in *Figure 3-7*, came from the polystyrene foam slabs used to support plants and which need to be replaced at a rate of 23 kg per year. The steel racks were also an important contributor due to the large energy use for virgin steel production. Therefore, infrastructure requires further consideration to reduce environmental impacts in aquaponics systems.

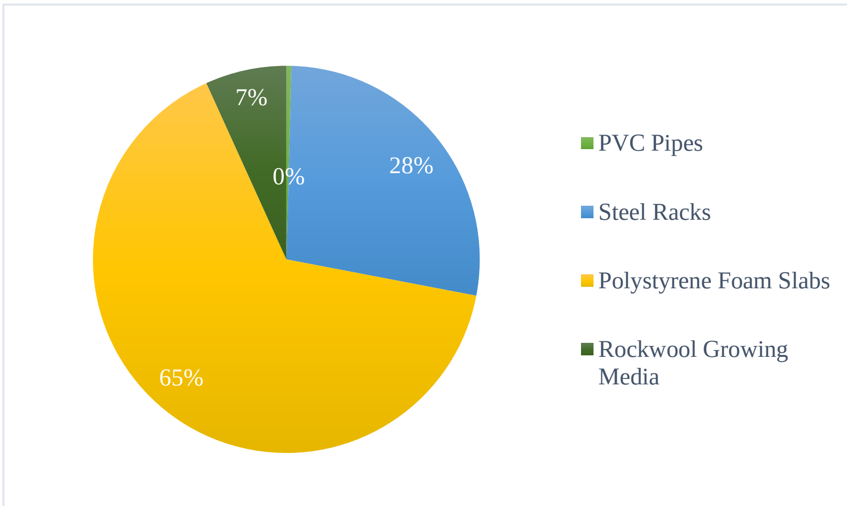

Figure 3-7: Average contribution of infrastructure components to total environmental impact of infrastructure.

3.4.2 Sensitivity Analysis of the Impact Partitioning for Aquaponics System

As discussed previously, a significant limitation of LCA application is having to partition impacts for systems that have multiple outputs, such as with an aquaponics system that produces both fish and leafy greens. By splitting the aquaponics system into its individual unit processes of aquaculture and hydroponics, allocation was avoided in this study. However, the unit process approach still required allocation of some inputs, including heat, certain infrastructure components, and additives, because the division of these input flows was not accurately measured. For this reason, a sensitivity analysis was conducted to determine impacts when mass, energy, and protein allocation were applied. The contribution of each input flow to the impact of global warming potential for the three different types of allocation is presented in *Figure 3-8*.

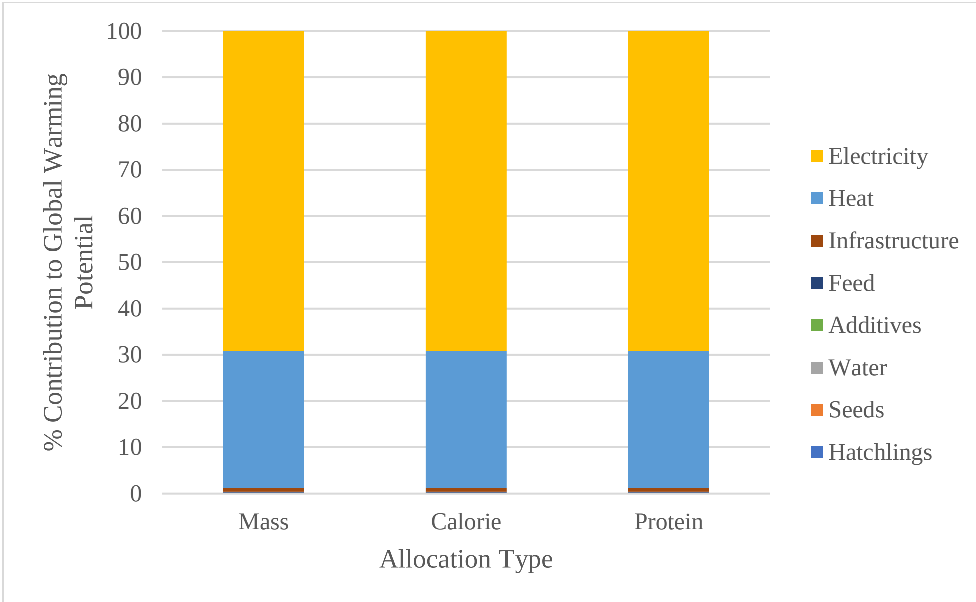

Figure 3-8: Comparison of contribution of input flows to global warming potential for mass, calorie, and protein allocation.

In all three allocation types, heating and electricity were the most impactful input flows, accounting for 98% of the total global warming potential. This is the case for all the other impact categories considered in this study, with heat and electricity contributing to an average of 90% of the total impact for each allocation type. This is important because it reinforces that heating and electricity are the most significant hotspots in operation for cold-climate aquaponics systems, as found in the unit process approach for both aquaculture and hydroponics.

The absolute magnitudes of the global warming potential and eutrophication potential impact categories by allocation method are presented in *Figure 3-9*. The impacts are given for the functional unit of 1 kg of fish and are partitioned based on the values in *Table 3-3*. Additionally, the global warming potential for the aquaculture unit, based on the unit process approach applied previously, was also provided as a reference. *Figure 3-9* indicates that the share of impacts attributed to fish is highest for protein allocation and lowest for mass allocation when compared to energy allocation. Specifically, the impact was approximately 4 times higher for protein allocation and 3.5 times higher for energy allocation when compared to mass allocation. Furthermore, the impacts of the aquaculture unit were similar to the impacts observed for mass allocation, but significantly different compared to calorie and protein allocation. This shows that while the contribution of input flows is not affected by impact partitioning methods, the actual value of impacts per functional unit varies greatly. How to allocate impacts, both in aquaponics research and in life cycle assessments in general, is heavily debated for this reason (Finnveden, 2000; Pelletier et al., 2015; Reap et al., 2008b).

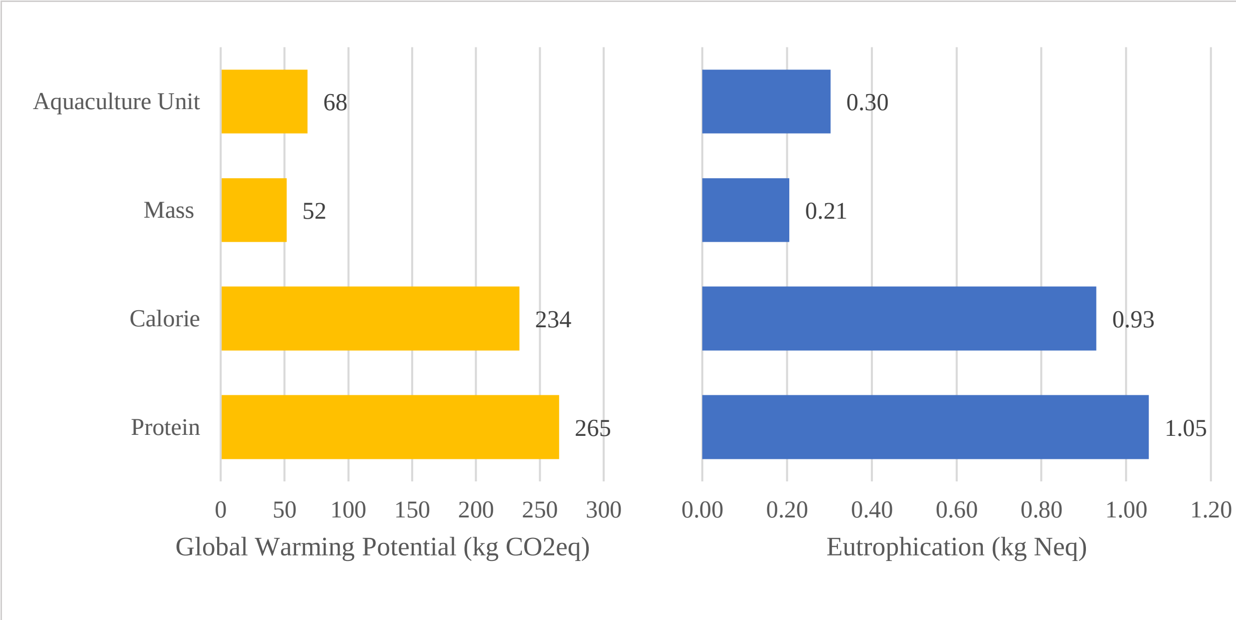

Figure 3-9: Changing magnitude of impacts by allocation method for global warming potential and eutrophication.

3.5 Perspectives and Recommendations

3.5.1 Insights from Literature

Much of the work done in this study is meant to support cold-climate aquaponics systems due to the fact that the majority of existing research is concentrated on systems in tropical and mild climates. This study aimed to determine the environmental barriers that are faced by small-scale aquaponics systems located in Canada. It was found that the hotspots uncovered here, namely energy for heating and lighting, were also frequently mentioned in literature for warm-weather systems but exasperated in this context of aquaponics operated in a cold climate. For example, energy consumption is often the most significant hotspot in all aquaponics research, but especially for systems located outside of tropical zones. The studies by Hindelang et al. (2014) in Thailand, Boxman et al. (2017) in St. Croix, and Barbosa et al. (2015) in Arizona, USA, despite having consistent, warm temperatures year-round, all found energy use for pumping and lighting in aquaponics production to be impactful. Other systems, such as those studied by Ghamkhar et al. (2019) in midwestern USA and Forchino et al. (2018) in Belgium, found that heating requirements in the winter greatly contributed to the environmental impacts. In the case of Ghamkhar et al. (2019), heating-related impacts were mainly caused by a reliance on natural gas, while the study by Forchino et al. (2018) used electrical heating powered by a mixture of renewable and non-renewable sources. In general, recirculating aquaculture systems (RAS), which is the type used in this study and the aforementioned aquaponics systems, have the greatest environmental impacts even when renewable energy sources are introduced (Ayer & Tyedmers, 2009). Therefore, the inherent energy demand of aquaponics systems hinders its environmental sustainability.

For the aquaponics LCAs mentioned above that selected fish to define functional unit, a comparison of the global warming potential (GWP) is provided in *Figure 3-10*. It is observed that the GWP of the system studied here at 52 kg CO_{2eq}, while over 20 times higher than the lowest GWP observed in the study by Hindelang et al. (2014), is still almost four times less than the worst impact, which was observed in the study by Ghamkhar et al. (2019). As mentioned previously, the reason the studies by Boxman et al. (2017) and Hindelang et al. (2014) have much lower impacts than the system in this study and the one studied by Ghamkhar et al. (2019) is that they are located in warm or mild climates and therefore have much lower energy requirements than the ones located in cold climates. While the system studied by Forchino et al. (2018) was not located in a warm region, its heating impacts were reduced through the use of renewable energy sources. This is in contrast to the study by Ghamkhar et al. (2019) where a higher quantity of natural gas-powered heating was required. As a result, the global warming potential is significantly higher, highlighting the influence the electricity grid and its composition can have on the environmental impact of cold-climate aquaponics systems.

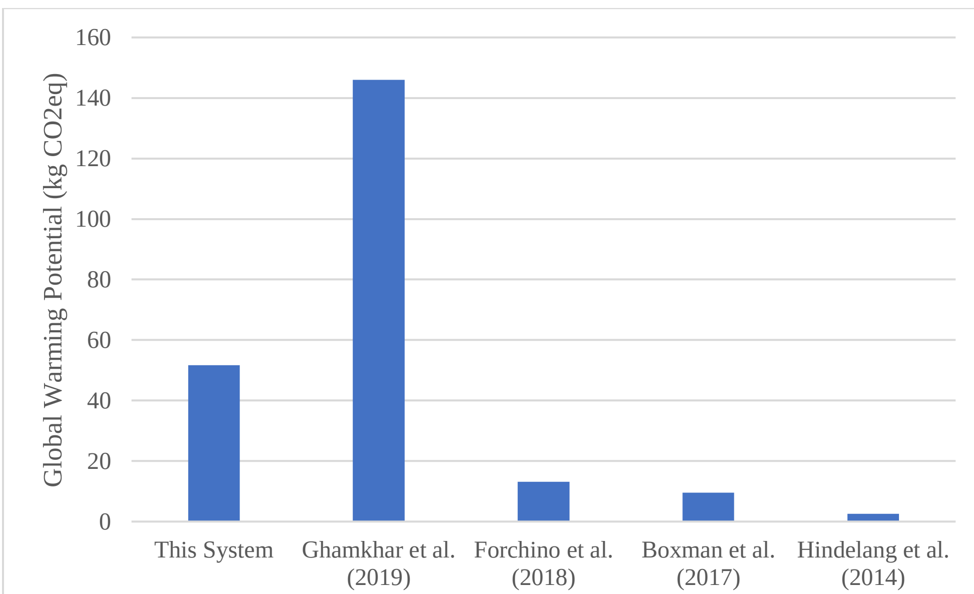

Figure 3-10: Comparison of global warming potential of aquaponics system in this study to aquaponics systems in literature (Boxman et al., 2017; Forchino et al., 2018; Ghamkhar et al., 2019; Hindelang et al., 2014)

In contrast, certain results from this study were quite different from patterns reported in literature. In previous studies, fish feed was typically determined to be an environmental hotspot (Ayer & Tyedmers, 2009; Cohen et al., 2018; Hindelang et al., 2014; Pelletier et al., 2009). The primary cause of this is the heavy dependence on fishmeal and fish oil-based feeds. In this study, fishmeal and fish oil made up 7% of the overall composition of fish feed, while in other studies fishmeal and fish oil were reported to make up

12-23% (Hindelang et al., 2014; Mungkung et al., 2013; Pelletier et al., 2009) and up to 50% (Ghamkhar et al., 2019) of commercial fish feed. The processes involved in obtaining fishmeal and fish oil typically result in eutrophication and other negative environmental impacts (Cohen et al., 2018; Malcorps et al., 2019). Furthermore, the cost of fishmeal and fish oil is expected to increase by up to 70% in the next ten years (Goddek et al., 2019). Therefore, switching to plant-based feed ingredients has been deemed valuable by much of the academic community. Additionally, infrastructure is often neglected in aquaponics LCAs because its impacts are generally assumed to be insignificant (Forchino et al., 2017; Ghamkhar et al., 2019). Hydroponics infrastructure, namely polystyrene foam slabs, contributed greatly to environmental impacts, which could be drastically reduced with the use of recycled polystyrene. In this study, while infrastructure was not nearly as impactful as energy consumption, it was an important input flow in the hydroponics unit, particularly under the fossil fuel depletion impact category. Overall, this study has shown that both fish feed and infrastructure are aspects of aquaponics studies that should be examined in detail despite the obvious and overshadowing issue of energy consumption.

3.5.2 Recommendations

Based on the findings of this study, a number of recommendations can be made both for improvement of the methodology and improvement of system performance. In terms of methodology, the splitting of the aquaponics system into unit processes was a better indication of the aquaponics production process because input flows were able to be split according to which product they contributed to. It was found that the type of allocation method applied, either mass, calorie, or protein, had a significant effect on the magnitude of the impacts. Furthermore, because mass allocation resulted in fewer impacts associated with fish when compared to the unit process approach, existing studies that have applied mass allocation may be slightly underreporting the implications of aquaponics production. Because of this, it is suggested that aquaponics LCAs model operation as the unit processes of aquaculture and hydroponics to better capture the reality of production. Additionally, other life cycle stages not examined here, such as transportation, packaging, and waste treatment should also be considered in future studies. Many existing studies are limited to cradle to system gate boundaries, but as determined here, neglected processes can play a significant role and are worth exploring. Therefore, future studies should expand methodologies beyond the basics, in addition to exploring different types of aquaponics systems and different regions of operation.

In terms of the improvement of system performance, the following suggestions should be considered. In general, it was determined that energy consumption contributed to the majority of impacts, which was the case throughout aquaponics literature as well. Furthermore, because cooling was not applied in the summer months, there was a resulting loss of fish during extreme heat episodes. This implies that, despite the significant amount of energy already consumed by the system, more energy would be required for addressing the extreme temperature fluctuations over the year. Therefore, optimization of heating and cooling in aquaponics systems should be considered to both reduce energy consumption and reduce the amount of fish loss. In the current study, the aquaponics system was located in an old warehouse, with a low-efficiency HVAC system and no windows, both of which contributed to its enormous energy consumption. This is a potential barrier to the environmental sustainability of aquaponics production because more and more urban agriculture systems are being set-up in existing spaces such as this. Consideration of buildings with efficient HVAC technologies and certification by a building energy board, such as LEED or Energy Star, could allow for optimization of energy consumption. If an existing certified site is not available, alternative options, such as retrofitting to LED lighting, improving insulation quality, and incorporating renewable energy sources are recommended. Furthermore, selection of climate-appropriate crops and fish, such as cold-resistant crops for winter operation and warm water fish for summer operation, should also be considered to ensure productivity and reduce energy demand. These options will be explored in further depth in the following chapter.

3.6 Conclusions

In summary, this study conducted life cycle assessment on a small-scale Canadian aquaponics system that operated year-round in Nova Scotia. It highlighted challenges specifically faced by systems located in cold climates as well as the environmental consequences of intensive energy consumption. Furthermore, a novel approach of splitting the aquaponics system into its unit operations of hydroponics and aquaculture helped to address methodological challenges faced in the LCA of multi-functional systems. It can be concluded that the methodology was effectively able to highlight hotspots of concern without the consequence of impact partitioning and that future research should aim to continually expand LCA methodology to fit system complexity.

It was found that electricity consumption, for both lighting and heating, was the most significant contributor to environmental impacts. While the aquaculture unit was most impacted by heating use, hydroponics dominated in energy consumption due to the need for artificial lighting to support plant growth. This is potentially a challenge all systems operating through winter can expect to face due to shortened daylight hours and low temperatures. Furthermore, the Nova Scotia electrical grid at the time of operation was fossil-fuel heavy, exasperating environmental impacts of energy consumption. Improvements, such as LED lighting, insulation, and renewable energy sources, are recommended areas of further research.

Moreover, other inputs which were not typically believed to have impacts on operation were also uncovered in this study. While when compared to energy consumption these input flows were insignificant, they also represent simple improvements that can be made with relatively no effect on operation. Specifically, infrastructure was found to be influential on the fossil fuel depletion potential of hydroponics operation. Switching to recycled materials and aiming to lengthen their lifespan are both simple, low-cost solutions to these problems. Additionally, while the impacts of fishmeal-based fish feeds are typically quite high, it can be concluded based on findings from this study that switching to plant-based feeds can drastically reduce the impact of commercial fish feeds.

Overall, while aquaponics systems help to address gaps in the food system by producing both vegetables and a high-quality protein source, their environmental impacts should not be ignored. Energy consumption is of primary concern and in their current state, aquaponics systems located in cold climates would contribute greatly to environmental degradation. Furthermore, other factors not included in this chapter, such as economic performance and social implications, should also be considered to ensure all pillars of sustainability are addressed. Consideration of the recommendations made here will be necessary for aquaponics to become a viable, wide-spread technology.

Chapter 4 Contributions

The contributions for this chapter are as follows: I, Gayathri Valappil, conducted analysis and wrote the content, while Dr. Goretty Dias, Dr. Christine Moresoli, and Dr. Jeffrey Wilson provided guidance and revisions.

Chapter 4 Exploration of Environmental and Economic Improvement Pathways: Life Cycle Cost and Scenario Analysis

4.1 Abstract

Aquaponics, which combines recirculating aquaculture and hydroponics to simultaneously produce fish and vegetables, is an emerging form of controlled-environment food production. These technologies are growing in popularity and are often suggested to be solutions to urban food insecurity and production gaps in the food system. However, especially in cold climates, much remains to be understood regarding the economic performance and environmental impact of aquaponics systems. This study uses life cycle assessment (LCA) and life cycle cost (LCC) analysis to determine how various alternative scenarios, including energy efficiency measures, renewable energy, and insect-based fish feed, affect environmental and economic sustainability of a small-scale Canadian aquaponics system. It was concluded that pairing increased energy efficiency with wind electricity resulted in a GWP reduction of 97% and an LCC reduction of 5%. Other measures, such as insect-feed and on-site biogas heating, increased costs drastically despite a reduction in environmental impacts. Future aquaponics studies should examine these and other improvement scenarios in more detail by considering other forms of economic analysis and including social impact assessment.

Keywords: aquaponics, life cycle assessment, life cycle cost, cold climate agriculture, energy use, indoor aquaculture, Canada

4.2 Introduction

Controlled-environment food production systems (CEFPS) are frequently suggested as solutions to many problems faced by the food industry today. They are a group of technologies characterized by their ability to moderate food production conditions, optimize yields, and minimize the influence of external factors, such as temperature and weather (Eigenbrod & Gruda, 2015; Lakhiar et al., 2018; Specht et al., 2014). However, the results from the previous chapter show that without proper consideration of energy-related challenges, CEFPS can instead pose other challenges. Winter conditions in Nova Scotia, including temperatures ranging between -9°C and 1°C and reduced sunlight (Environment Canada, 2021), as well as Nova Scotia's reliance on coal power (*Today's Energy Stats*, 2020), contribute to environmental impacts. It was concluded that the energy demand and energy source of indoor farming systems located in cold regions contributed greatly to environmental impacts beyond that of systems located in warm or mild climates.

Aquaponics is a specific form of CEFPS that combines aquaculture and hydroponics to simultaneously produce fish and vegetables. These systems may help to reduce resource use, especially water and fertilizer, when compared to conventional agriculture. However, much about the operation and impacts of aquaponics systems are still unknown. There are multiple studies that use LCA to examine the environmental implications of aquaponics, however most of them are geographically centered around Europe or the United States. The consensus from these studies is that intensive energy consumption is the biggest environmental barrier faced by aquaponics systems (Forchino et al., 2018; Ghamkhar et al., 2019; Xie & Rosentrater, 2015; Yep & Zheng, 2019). Countries like Canada, which experience long, harsh winters, are rarely the focus of environmental assessments which means that caveats of winter operation, such as increased heating and lighting demands, have not yet been assessed. Methods of reducing these demands and impacts, such as use of energy efficient appliances and renewable energy technologies, also have yet to be examined through LCA. As a result, much is left to be understood regarding the performance of aquaponics in Canadian markets.

The economic performance of cold-climate aquaponics systems has also rarely been addressed. Some studies have assessed their viability in specific markets, typically located within tropical zones or mild climates. In general, these studies have concluded that aquaponics can only be commercially viable in areas where niche markets, such as those for ornamental fish, exist (Bosma et al., 2017; Greenfeld et al., 2019; Janker et al., 2018; Tokunaga et al., 2015). These studies also state that the biggest cause for this is the high cost of operation which raises the cost of goods substantially. This also means that areas with easily accessible aquaculture and fishery products may not be able to support aquaponics production because the price of goods would not be competitive. Furthermore, many aquaponics facilities located across the United States ultimately failed after a few years of operation (Quagrainie et al., 2017). However, government funding can also motivate and support the operation of aquaponics systems. Therefore, understanding the economic barriers and policy incentives that affect the success of aquaponics businesses will prove useful in the future.

Of the existing economic assessments described above, the following trends can be observed. Two important aquaponics studies were limited to a qualitative assessment, where a cursory examination of economic performance was considered (Bosma et al., 2017; Rizal et al., 2018). These studies were particularly useful in the early stages of the field for gaining a preliminary understanding and to highlight potential improvement pathways. Additionally, a few quantitative assessments, such as cost benefit analysis (CBA) (Bosma et al., 2017; Gibbons, 2020) and techno-economic analysis (TEA) (Xie & Rosentrater, 2015) also exist, but are rare and restricted to specific geographies. While both CBA and TEA are powerful quantitative tools, they focus mainly on the profit gained from specific products (Bosma et al., 2017; Rizal et al., 2018) and technological performance based on system design (Xie & Rosentrater, 2015), respectively. In order to capture all costs incurred across the lifespan of aquaponics systems, life cycle cost (LCC) analysis should be conducted. However, LCC has rarely been used for quantitative assessment for aquaponics systems. One study has been conducted in Belgium (Forchino et al., 2018) but none exist for the Canadian market, which limits the ability for aquaponics businesses in Canada to understand economic hotspots across the full life cycle of operation.

The purpose of this study was therefore to examine alternative scenarios by targeting the hotspots identified from the LCA of a cold-climate aquaponics system located in Nova Scotia, Canada and to conduct LCC analysis for the original and alternative scenarios. The alternative scenarios were based on three themes: energy efficiency, energy source, and fish feed composition. The results include the environmental life cycle impacts of applying various alternative scenarios, followed by the LCC results of both the original and alternate systems. Recommendations regarding which measures are most worthy of pursuing are made to support policy makers and aquaponics businesses and researchers in Canada.

4.3 Methodology

This study used LCA and LCC analysis to examine a variety of alternative scenarios for both environmental and economic improvement. These scenarios included switching from fluorescent to LED lighting, upgrading insulation thickness and technology, using wind and biogas energy, and using insect-based fish feed to replace fishmeal and fish oil. The LCA methodology followed ISO guidelines. Details of the system description, boundaries, functional unit, and impact categories are provided in *Section 3.3.* Similarly, the fundamental motivation behind life cycle cost analysis is discussed in *Section 2.5*. The life cycle cost analysis methodology is described in depth in the following section.

4.3.1 LCA & LCC Scenarios

Alternative scenarios were explored to determine pathways for improvement of cold-climate aquaponics systems. The alternative scenarios investigated in this study focused on energy efficiency, energy source, and fish feed composition. Briefly, the energy efficiency scenarios examined measures that can be taken to reduce the amount of energy required by the system, thereby reducing both costs and environmental impacts. Then, the energy source scenarios built upon the efficiency scenarios to look at renewable sources of energy, which could further reduce the environmental impacts but may not necessarily reduce costs. Finally, the fish feed scenarios looked at both the environmental and economic implications of switching from fishmeal-heavy fish feeds to insect-meal based ones, which are frequently touted in literature as a potential solution to the environmental impacts of using fishmeal-based feeds (Junge et al., 2017; Smetana et al., 2016; Specht et al., 2019). The specific values and methods applied to model these scenarios are described in detail below.

4.3.1.1 Energy Efficiency Scenarios

As mentioned, the energy efficiency scenarios focused solely on reducing the amount of electricity used without considering the source of energy itself. There were two main improvement measures examined, LED lighting and improved insulation. In the existing system, fluorescent T-8 bulbs were used in all fixtures, including the ones that supplied artificial lighting for the plants. These bulbs were 2.54 cm in diameter, 30 cm in length, and had a wattage of 32 W (*Uline T-8 LED Bulbs*, 2021). Lighting was provided for 12 hours per day, 365 days per year. By switching to LED T-8 bulbs, energy usage for electricity was assumed to be lowered by 40%, as per the study by Katzin et al. (2021). Katzin et al. (2021) also suggested that switching to LEDs would result in a higher heating demand due to the amount of heat usually emitted by the fluorescent bulbs, but this phenomenon was not considered in this study. In terms of the life cycle inventory, the cost of LED bulbs was determined based on the bulk cost of 90 fixtures and a replacement rate of 3 years (*Uline T-8 LED Bulbs*, 2021), while the cost of energy was adjusted based on the improved lighting efficiency. These costs are provided in *Table 4-2*.

The other energy efficiency alternative was the improvement of insulation within the building that the aquaponics system operated. The building was relatively old and lacked an efficient HVAC system, which meant heating was provided through electric space heaters. Furthermore, because there was little existing insulation, a large portion of heating energy was lost each winter. This alternative scenario was based on increasing the thermal resistance by using a spray foam insulation to achieve R-13 insulation in the walls and R-19 in the roof, as per recommendations found in ASHRAE standards (*ASHRAE 90.1*, 2004). This was assumed to reduce heating requirements by 15% (*US Department of Energy*, 2020). The costs for insulation were determined based on the average material and installation costs in Canada, as shown in *Table 4-2*. However, since the range of costs is significant, sensitivity analysis was conducted to determine the impact of the upper and lower prices.

4.3.1.2 Energy Source Scenarios

Building upon the previous section, the energy source scenarios examined the effect of replacing fossil-based energy with renewable energy on the environmental and economic performance. It was assumed that energy efficiency was first reduced through the use of LED lighting and improved insulation before varying the energy source. While replacing fossil-based energy was expected to reduce environmental impacts, particularly within the fossil fuel depletion and global warming potential (GWP) impact categories, the overall life cycle cost was expected to increase due to the limited access to off-site renewable electricity in Nova Scotia.

The original scenario operated with electricity provided by the grid in Nova Scotia. The composition of this grid was fossil-fuel heavy, consisting of 63% coal and coke and an overall non-renewable energy contribution of 76% (*Today's Energy Stats*, 2020). The remaining fractions of the grid can be found in *Figure A-1*. Therefore, two energy source alternative scenarios were examined. The first alternative scenario considered 100% onshore wind energy to reflect the growing proportion of wind farming on the eastern coast of Canada and that the Nova Scotia grid is shifting towards more renewable sources of energy (*Today's Energy Stats*, 2020). While the original scenario used electrical heating, natural gas heating is more commonly used in Nova Scotia, so both options of heating source were evaluated. The pricing for the wind electricity scenario was based on the Canadian company Bullfrog Power that allows for the purchase of renewable energy credits. Their business model was based on investing in renewable energy projects to offset the amount of non-renewable energy used by their customers (*Bullfrog Power Canada*, 2021). Therefore, they charge an additional 2 cents per kWh for electricity. This is reflected in the LCI provided in *Table 4-2*.

The second alternative energy source scenario considered the use of biogas energy from anaerobic digestion. The basic premise of this scenario was to partner aquaponics facilities with other agricultural facilities, specifically dairy farms, that produced enough waste to share excess biomass energy. Dairy farms in Canada are most equipped for having on-site anaerobic digesters due to their size and economic profitability and often only use the biomass for electricity, implying that some amount of heat gets wasted (Law et al., 2012; Purdy et al., 2018; Zhang et al., 2013). Therefore, there is potential for aquaponics systems to capture this waste heat. In this case, it was assumed that the aquaponics facility would use anaerobic digestion solely for the purpose of heating over the months of October to March and continue to use wind or grid-powered electricity for all other energy needs.

From here, two implementation options for biogas energy were considered. The first was that at the expense of the aquaponics business, a small-scale combined heat and power (CHP) system would be installed on site, assuming the partner facility would have its own existing anaerobic digester. Due to this partnership between facilities, there would be no additional cost for the biogas, but excess waste heat could be used instead of lost. The cost of a small-scale CHP system is also an area where sensitivity analysis was conducted since larger CHP systems are more prevalent in the current market, making the cost of small ones unpredictable (Darrow et al., 2015). The second implementation option was to purchase credits for renewable biogas through Bullfrog Power, as described for the wind energy scenario. In this way, the capital cost of a CHP system could be avoided. Furthermore, this represents a feasible option for existing aquaponics facilities not located near dairy farms. Both of these options were explored with respect to environmental impacts and economic performance.

4.3.1.3 Fish Feed Scenarios

The fish feed scenarios focused on the impacts associated with the use of fishmeal and fish oil in fish feed. Fishmeal and fish oil, obtained from lower trophic level fish, are often the main ingredient in fish feed formulations for aquaculture (Ghamkhar et al., 2019; Maiolo et al., 2020; Roffeis et al., 2017). Because of the significant impacts and costs of these feed components, other protein sources, including soybean meal or insect meal are introduced (Roffeis et al., 2017). Furthermore, LCA studies conducted by Le Féon et al. (2018) and Roffeis et al. (2017) have shown that substituting insect meal in fish feed for aquaculture can be environmentally beneficial, while not totally economically different. The original scenario used a soybean-heavy fish feed, which meant that the impacts were not as significant as other aquaponics systems from literature (Ghamkhar et al., 2019; Yep & Zheng, 2019), but room for improvement exists. Therefore, understanding how the use of insect meal in fish feed compares to the current fish feed would be useful. However, only the effect on environmental impact and life cycle cost were considered in this study. The effect on fish productivity, such as growth and weight gain, were not considered. The study by Roffeis et al. (2017) was used as the baseline for insect-based feed (IBF) production and impacts, as shown in *Table* A-4.

In terms of LCC, uncertainty is introduced because the cost of IBF is ambiguous in the current market. While there has been significant research conducted on the use of and resulting productivity of IBF, there are only a few companies that sell it at a commercial scale. Furthermore, the ones that do often use insect meal as a supplement or additive, rather than a replacement for fishmeal and fish oil (Pulina et al., 2018). However, it was possible to estimate a range of prices based on current trends in the insect meal market. As shown in *Table 4-2*, three prices were selected: \$370/year, \$740/year, and \$1500/year. The lower price is based on the current price of commercial fish feed, assuming that future process improvements would allow for competitive pricing of insect-meal products (Pulina et al., 2018). The intermediate price is a more realistic estimate for the cost of these goods in the European market in the near future based on the study by Pulina et al. (2018) and was therefore used in this study. Finally, the high price is based on costs of specialty feeds, such as pet food (Pulina et al., 2018). Sensitivity analysis was conducted to determine implications of this uncertainty in IBF pricing. One of the limitations of this scenario is that the effect on fish health and growth was not considered. Further research must be done to assess the productivity in aquaculture and aquaponics systems using IBF to improve the quality of the LCC estimates.

The various alternative scenarios are summarized in *Table 4-1*. Note that the addition of an A or H to any of the short forms listed refer to aquaculture and hydroponics, respectively.

Table 4-1: LCC Scenario Descriptions and Naming

Scenario Theme	**Scenario Description**	**Short Form**

Original	*Original system operation, grid pricing*	O
	Original energy usage, natural gas heating, grid pricing	O-NG
Energy Efficiency	*Insulation at average price*	INS
	LED lighting	LED
	Efficiency measures combined (average price insulation & LEDs)	EFF
Energy Source	*Wind electricity, efficiency measures, Bullfrog pricing*	W
	Biogas heating, efficiency measures, wind electricity, Bullfrog pricing	BG
	Off-site biogas heating, efficiency measures, wind electricity, Bullfrog pricing (LCC only)	OFF-BG
	On-site biogas heating, efficiency measures, wind electricity, Bullfrog pricing (LCC only)	ON-BG
Fish Feed	*Wind electricity, efficiency measures, insect-based feed, Bullfrog pricing*	IBF

4.3.1 Life Cycle Cost Analysis (LCC)

Like LCA, LCC requires the definition of a goal and scope and collection of inventory data. Boundaries, time period of data validity, data quality, among others, are all aspects that must be defined clearly (Kádárová et al., 2015; Moreau & Weidema, 2015; Rebitzer & Hunkeler, 2003). In this study, all aspects of the goal and scope, including the system description defined in *Section 3.3* for the LCA remain the same for the LCC, but the life cycle inventory is different. In LCC, monetary values are of primary interest. Therefore, costs associated with investment, maintenance, operation, and energy, as well as all other expenses incurred throughout the life cycle of a product system, were considered (Cleary et al., 2015; Langdon, 2005).

4.3.1.1 Economic Life Cycle Inventory

The costs considered for the LCC are provided in *Table 4-2*. The costs pertinent to the original operation and additional values for Bullfrog pricing, insulation, insect-based feed, and combined heat and power systems are provided for the alternative scenarios of the aquaponics system. All data was collected from system operation, unless otherwise specified.

Table 4-2: Economic Life Cycle Inventory for Original Scenario and Alternative Scenarios of the Aquaponics System

Item	Cost	Notes and Source
Energy		
Electricity Rate	8.353 ¢/kWh	(*Rates & Tariffs*, 2020)
Natural Gas Rate	$0.07/kWh	(*Rates & Tariffs*, 2020)
Bullfrog Electricity Rate	10.353 ¢/kWh	(*Bullfrog Power Canada*, 2021)
Bullfrog Renewable Natural Gas Rate	$0.08/kWh	(*Bullfrog Power Canada*, 2021)

Lighting		
Fluorescent Bulbs	$234/year	(*Uline Bulk T-8 Bulbs*, 2020)
LED Bulbs	$358/year	(*Uline T-8 LED Bulbs*, 2021)
Insulation and Installation		Based on the range of costs of insulation materials in Canada from (*Great Northern Insulation*, 2020) and thickness requirements from ASHRAE (*ASHRAE 90.1*, 2004)
Low Cost	$780	
Average Cost	$1700	
High Cost	$2600	
Consumables		From confidential business report and cost projections (Wilson et al., 2018)
Water	$190/year	
Seeds	$140/year	
Rockwool Growing Media	$560/year	
Hatchlings	$480/year	
Chemical Additives	$200/year	
Feed		
Original Feed	$370/year	
Low-Cost Insect Feed	$370/year	(Pulina et al., 2018)
Average-Cost Insect Feed	$740/year	(Pulina et al., 2018)
High-Cost Insect Feed	$1500/year	(Pulina et al., 2018)
Combined Heat & Power (CHP)		System equipment and maintenance costs (San Martín et al., 2008)
Low-Cost	$2600	
Average-Cost	$5700	
High-Cost	$8900	

The discount rate is an important factor in LCC calculations. It is a rate describing the change of the value of money over time (Langdon, 2005). In terms of LCC, the discount rate is used to determine the present value of all input costs and output revenues over the lifetime of the product or system so that all cash flows can be summed up within an equivalent time frame. In this study, three discount rates were considered to understand their effect on LCC. First, the rate for determining net-present values of economic flows in Canada (8%), which is based on the economic opportunity cost of capital, was considered (Jenkins & Kuo, 2007). Additionally, another accepted discount rate proposed by Canadian researchers (10%) (Jenkins & Kuo, 2007) and the more recent social discount rate approved by the Canadian treasury board (3.5%) (Boardman et al., 2010) were also selected. The discount rate of 8% represents the most likely scenario for a business undertaking an aquaponics project and was therefore used throughout the analysis. In contrast, the social discount rate reflect the social opportunity cost of capital and can be applied to the aquaponics facility because it represents a project that has inherent social value, such as supporting urban food security. Therefore, the effect of the selecting a different discount rate was examined through the use of a sensitivity analysis in *Section 4.4.4*.

4.3.1.2 LCC Methodology

LCC involves taking values from the life cycle inventory, applying the discount rate, and summing them up over a given period of time; however much of LCC methodology has not yet been standardized (De Menna et al., 2018; Miah et al., 2017). In this study, the life cycle cost was determined by summing the net present value (NPV) of all expense cash flows over a 20-year period. The timespan was selected based on the expected lifespan of the aquaponics system and its major infrastructure components. This is described in Equation 1, where *t* represents the year, C_t represents the cash flow at year *t* including both costs and revenues, and *i* represents the discount rate.

$$LCC = \sum_{t=1}^{20} \left(\frac{C_t}{(1+i)^t} \right) \tag{1}$$

Furthermore, the inflation rate in Canada at the time of the study (2%) was applied to determine the value of each cash flow over the 20-year period (*Bank of Canada Interest Rates*, 2019). This was calculated as shown in Equation 2 below, where *f* represents the inflation rate.

$$C_t = C_{t-1} \times (1+f) \tag{2}$$

In addition to the life cycle cost, the internal rate of return (IRR) was also calculated. This value is useful because it allows for a comparison between projects. When the IRR is low, it means that there is a lower return on investment, usually implying that the high capital and operation costs outweigh profits (Langdon, 2005). Therefore, higher IRR values are desired because they imply higher cash returns. IRR is estimated by solving for the value of *i* after setting Equation 1 to zero and substituting values for C_t and *t*. These two values of LCC and IRR were of main interest in this study and are discussed in *Section 4.4.3*.

4.4 Results

The results are presented for the impact comparison of the alternative scenarios, contribution analysis for the alternative scenarios, comparison of the life cycle costs and internal rate of return, and the sensitivity analysis conducted on the LCC.

4.4.1 Alternative Scenarios Impact Comparison

The alternative scenarios focused on areas that were environmental hotspots in the original scenario (O, O-NG). Since energy consumption had the greatest environmental impact, energy efficiency (INS, LED, EFF) and energy source (W, BG) related scenarios were the main focus, along with a third alternative scenario related to fish feed (IBF).

The benefits and consequences of each alternative scenario explored in this study are presented in *Figure 4-1* and *Figure 4-2* for four impact categories: acidification, eutrophication, fossil fuel depletion, and global warming potential. First of all, for both aquaculture and hydroponics, the use of renewable biogas (BG) heating almost doubled the impacts of eutrophication and acidification due to ammonia storage practices, while significantly reducing fossil fuel depletion and global warming potential impacts. In contrast, the A-IBF scenario and the H-W scenario resulted in the most significant reductions across all impact categories. In fact, each impact was reduced by an average of 80%, making these the most promising scenarios from an environmental perspective. Specifically, they reduced the GWP of aquaculture from 68 kg CO_{2eq}/kg live fish to 3 kg CO_{2eq}/kg of live fish and reduced the GWP of hydroponics from 50 kg CO_{2eq}/kg leafy greens to 3 kg CO_{2eq}/kg leafy greens. This analysis highlights that energy efficiency measures alone cannot significantly reduce environmental impacts of aquaponics systems, but pairing such measures with a renewable source of electricity, such as wind, can drastically reduce impacts. The absolute impact values for the remaining impact categories are provided in *Appendix C: Life Cycle Impact Results*.

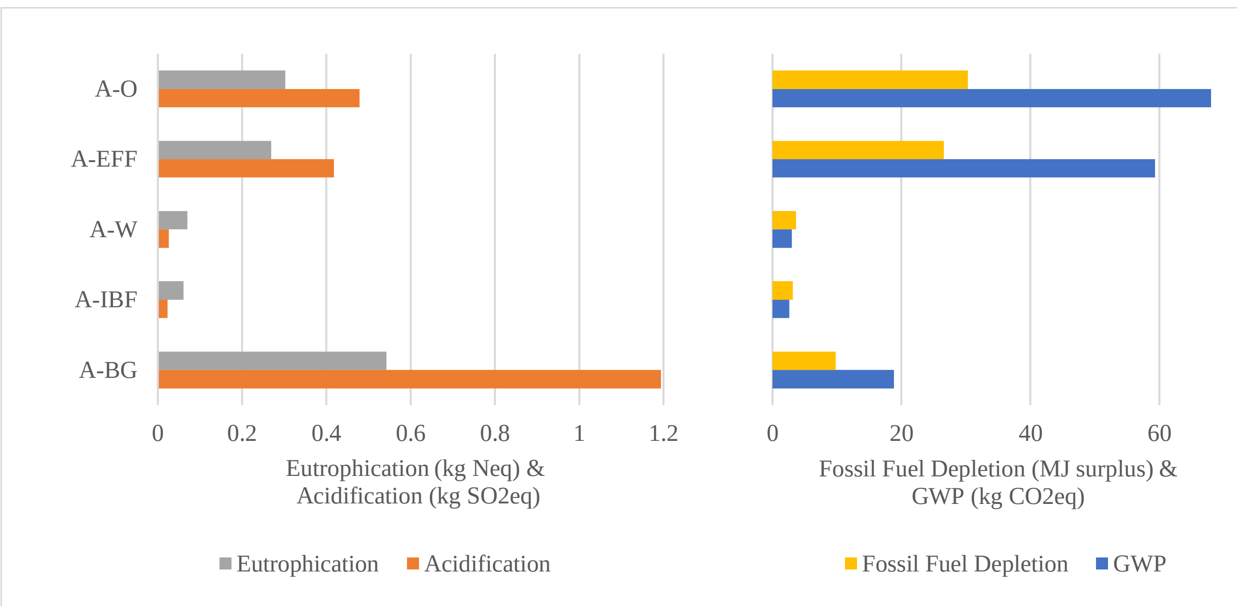

Figure 4-1: Alternative scenario comparison according to eutrophication, acidification, fossil fuel depletion, and GWP per kg of live fish for the aquaculture unit.

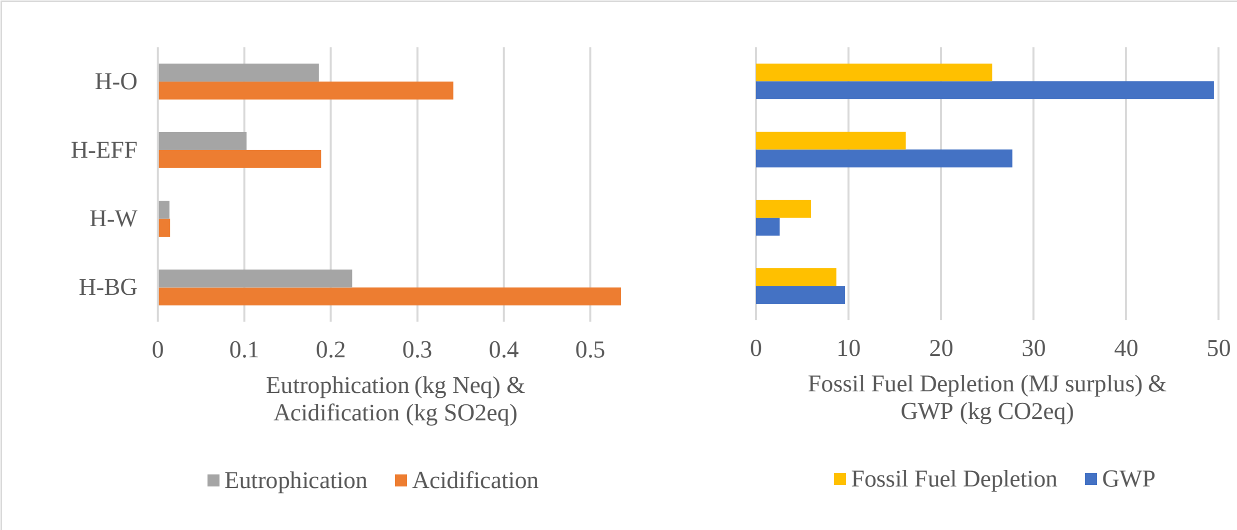

Figure 4-2: Alternative scenario comparison according to eutrophication, acidification, fossil fuel depletion, and GWP per kg of leafy greens for the hydroponics unit.

4.4.2 Alternative Scenarios Contribution Analysis

4.4.2.1 Energy Efficiency Alternative Scenarios

The energy efficiency alternative scenarios included: (1) switching from fluorescent bulbs to LED bulbs (LED), and (2) increasing the thickness and type of insulation to match ASHRAE standards (INS). Combined (EFF), these two alternatives were expected to significantly lower the energy consumed by the system. *Figure 4-3* shows the relative contribution of inputs for the aquaculture unit with increased insulation and LED lighting (A-EFF). When compared to *Figure 3-4*, which shows the contribution of input flows to impacts of the original aquaculture scenario (A-O), the overall contribution of each input flow did not change significantly, implying that electricity and heating were still the most significant contributors. Furthermore, the heat and electricity usage only changed from 71 kWh/kg of live fish in the original system to 62 kWh/kg of live fish with the improvements, resulting in a GWP and fossil fuel depletion reduction of 12%. This is because the greatest reduction in electricity came from the switch to LED lighting, of which the majority of usage was associated with the hydroponics unit, rather than the aquaculture unit. On top of this, the building in which the system operated was not selected with HVAC efficiency, access to windows, and building envelope in mind. Therefore, while the increased insulation quality does result in a heating reduction, a more significant heating reduction for the aquaculture system will require more dramatic changes, such as a full retrofit of the building.

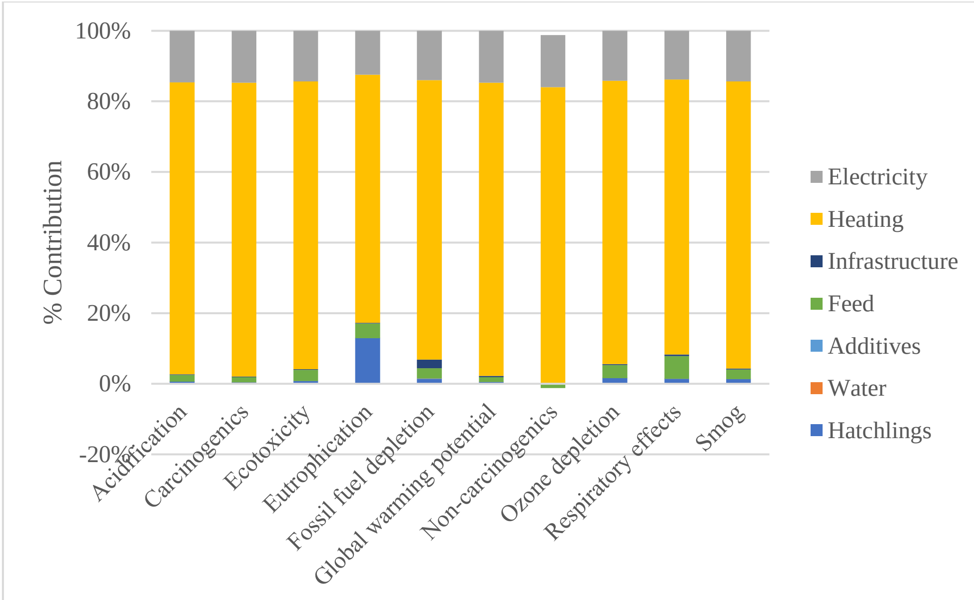

Figure 4-3: Relative contribution of input flows to impact category for the A-EFF scenario.

Figure 4-4 shows the contribution of the input flows to each impact category for the hydroponics unit after insulation improvements and LED lighting were applied (H-EFF). Like the aquaculture unit, the relative contribution did not change significantly from the original scenario for the hydroponics unit. However, because lighting played such a significant role in hydroponics' energy consumption, the electricity and heating demand changed from 51 kWh/kg of leafy greens to 27 kWh/kg leafy greens. This resulted in a 36% reduction in fossil fuel depletion and a 44% reduction in global warming potential. Overall, the energy efficiency scenarios resulted in more significant reductions in environmental impact for the hydroponics unit than the aquaculture unit, almost halving the electricity and heating demand and reducing fossil-fuel related impacts by up to 44%. However, the relatively similar contributions of input flows for EFF and O indicate that room for improvement exists for both aquaculture and hydroponics.

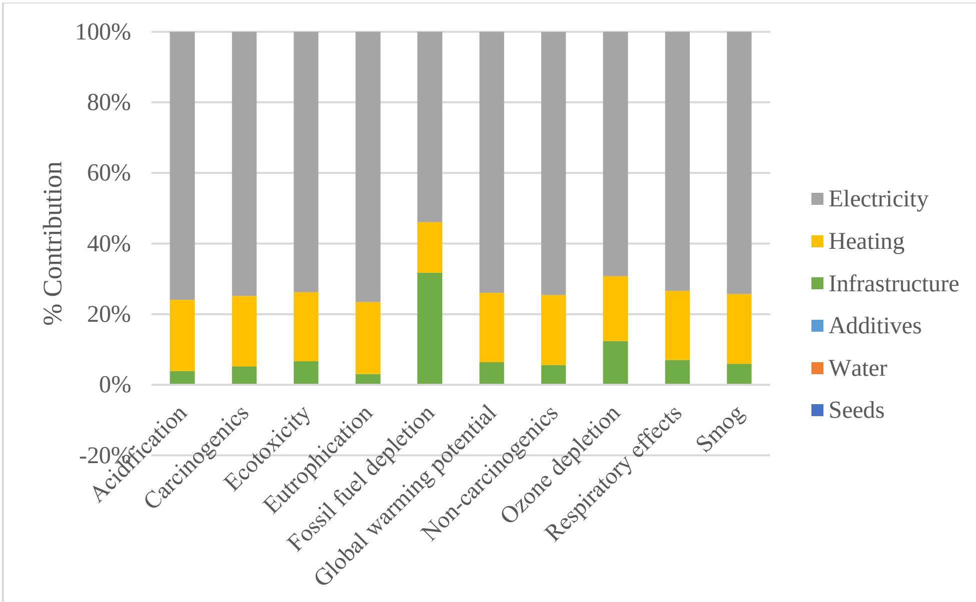

Figure 4-4: Relative contribution of input flows to impact category for the H-EFF scenario.

4.4.2.2 Energy Source Alternative Scenarios

The energy source alternative scenarios considered two different sources of energy. First, wind energy was considered to be a plausible option in Nova Scotia due to the many options for on and offshore wind energy and many coastal areas with high wind potential. This scenario, as discussed in *Section 4.3.1*, assumed that wind energy credits could be purchased to offset the impact of the fossil-based grid used in Nova Scotia.

Starting with the aquaculture unit, *Figure 4-5* shows the relative contribution of input flows to impact categories for the A-W scenario, where efficiency measures of LED lighting and improved insulation, as well as wind electricity, were applied. In contrast with A-EFF and H-EFF discussed previously, wind electricity shifted the relative contribution of other input flows dramatically. In fact, the use of wind energy resulted in a 95% reduction of GWP and an 88% reduction in fossil-fuel depletion, with similar reductions being observed for other impact categories. The absolute values of the GWP and fossil fuel depletion are provided in *Appendix C: Life Cycle Impact Results*. With such reductions, other input flows, such as fish feed, infrastructure, and hatchlings appeared to be much more influential. However, energy consumption for heat and electricity remained the largest hotspot.

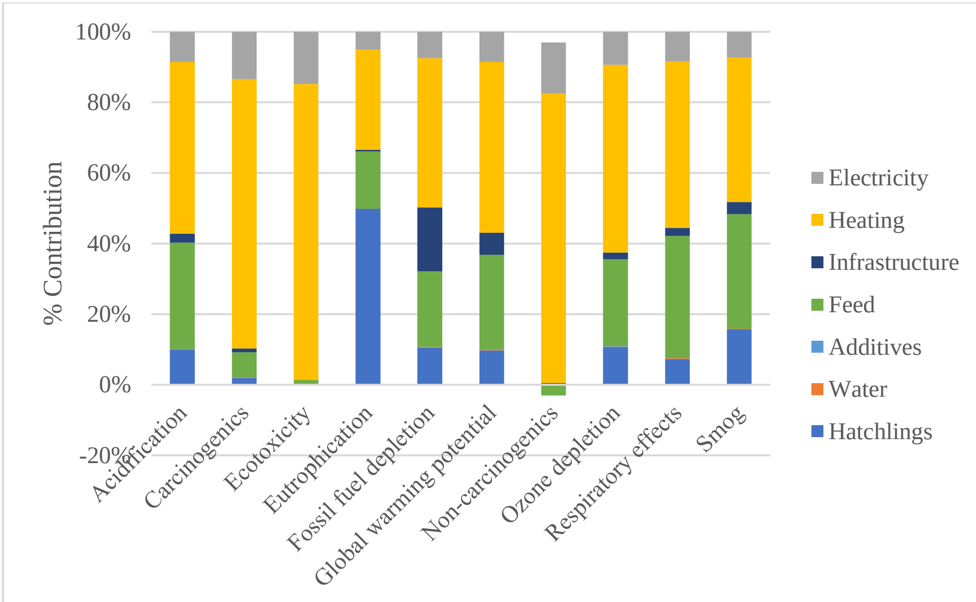

Figure 4-5: Relative contribution of input flows to impact category for the A-W scenario.

The contribution of the input flows to impact category for the H-W scenario is shown in *Figure 4-6*. It was observed that the contribution profile changed greatly compared to the original scenario, H-O. While in the original scenario, the input flow of infrastructure had a minor contribution to select impact categories, it is now dominant in many impact categories, including fossil fuel depletion, global warming potential, acidification, ozone depletion, and smog. Therefore, for the hydroponics system it is especially important that infrastructure aspects, such as materials, lifespans, and recycling options, be considered and improved on. However, because electricity was still the greatest contributor to environmental impacts, it can be concluded that the use of artificial lighting is a barrier to the environmental sustainability of hydroponics systems.

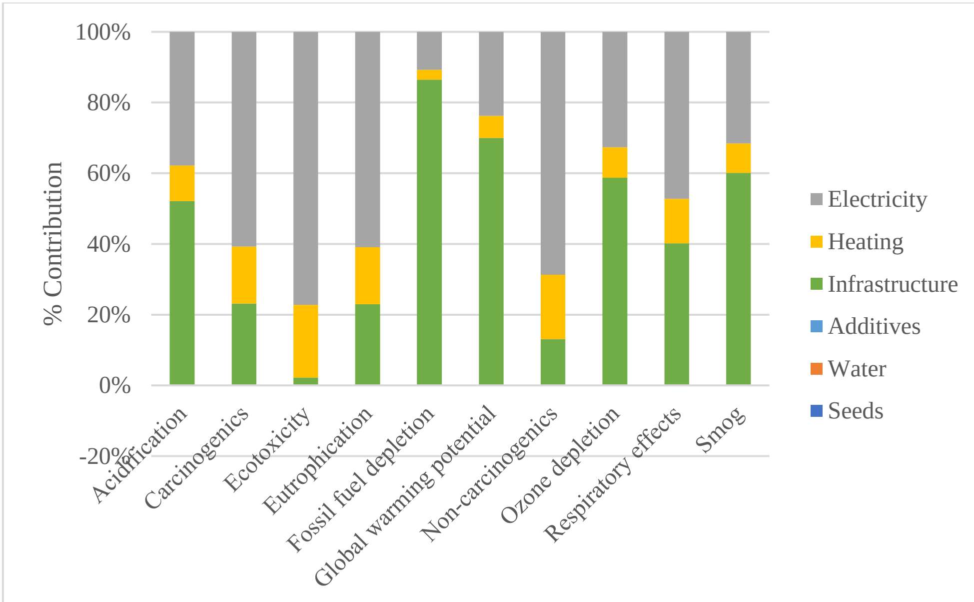

Figure 4-6: Relative contribution of input flows to impact category for the H-W scenario.

The second type of energy source scenario was the use of biogas heating. For these scenarios (A-BG and H-BG), biogas energy was used to replace electrical heating used in the original scenario, while the remaining electricity requirement was fulfilled with wind electricity. The relative contribution of the input flows to each impact category for the A-BG and H-BG scenarios are presented in *Figure 4-7* and *Figure* 4-8.

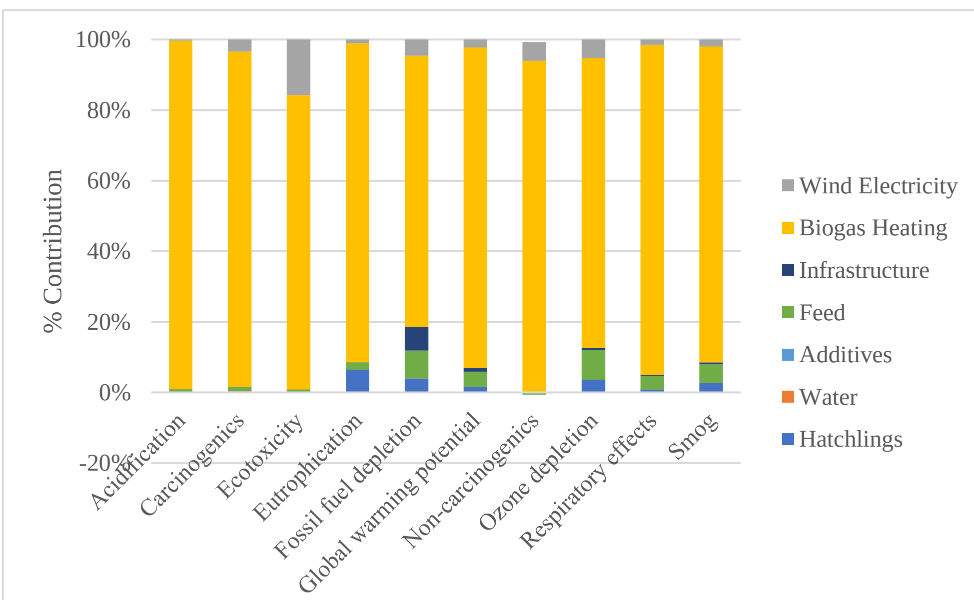

Figure 4-7: Relative contribution of input flows according to impact category for the A-BG scenario.

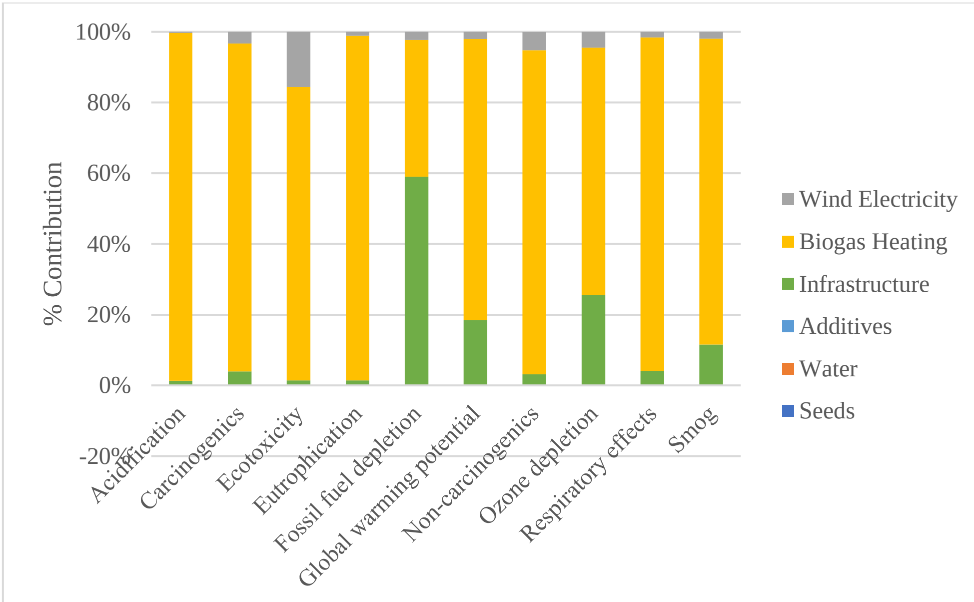

Figure 4-8: Relative contribution of input flows to impact category for the H-BG scenario.

In both the aquaculture unit and the hydroponics unit, the use of biogas heating resulted in the contribution of input flow to each impact category being shifted considerably from the original system. Now, with the notable exception of fossil fuel depletion in the hydroponics unit, the greatest contributor to every impact category was biogas heating. These results highlighted the burden of heating requirements for indoor cold-climate agriculture systems. Heating remains the largest contributor to all impact categories in the aquaculture unit even when renewable energy sources were used. Heating is now also the largest contributor to all impact categories in hydroponics unit, whereas previously, electricity for lighting was the greatest contributor. In fact, acidification and eutrophication potential were nearly doubled, despite over a 60% reduction in both global warming potential and fossil fuel depletion among both unit processes.

4.4.2.3 Fish Feed Alternative Scenario

In this alternative scenario, the type of fish feed used in the aquaculture unit was altered in addition to the previously described scenarios of energy efficiency and wind electricity. The typical commercial fish feed, consisting of fishmeal and fish oil, was replaced with an insect meal-based feed adapted from the study by Roffeis et al. (2017). The relative contribution of the input flows to each impact category is presented in *Figure 4-9* for the IBF scenario. When compared to the relative contribution for A-W shown in *Figure 4-5*, the contribution of the feed was significantly less for many impact categories, including eutrophication, smog, and respiratory effects. Note that in the original scenario, the fish feed used contained only 7% fishmeal, which is far less that the 25-50% fishmeal used in many conventional feeds (Ghamkhar et al., 2019; Hindelang et al., 2014). This implies that the effect of switching to IBF could be even more dramatic for systems using feeds with a larger proportion of fishmeal and fish oil. Therefore, additional research is required before embracing insect meal as a suitable alternative to fishmeal.

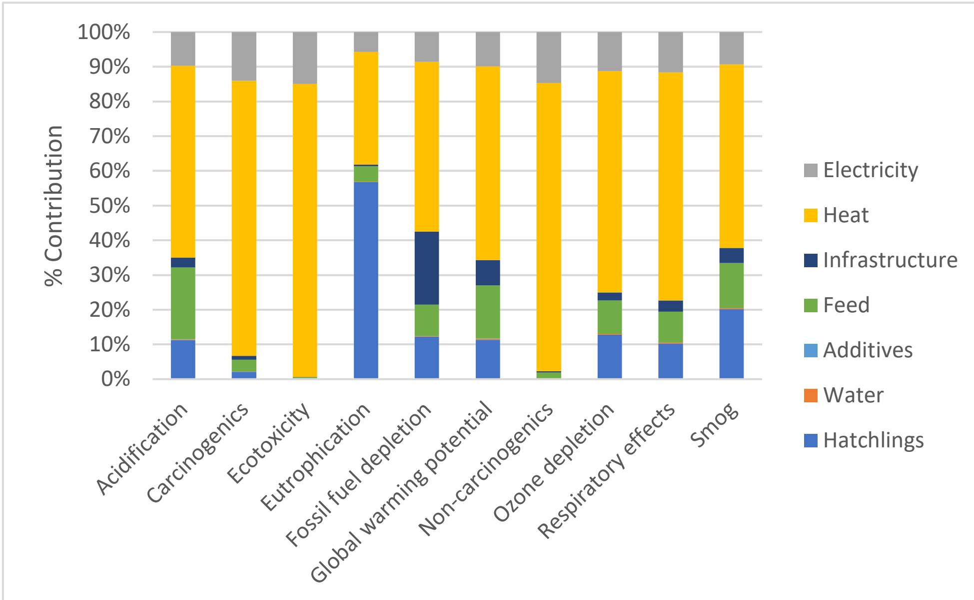

Figure 4-9: Relative contribution of input flows to impact category for the IBF scenario.

4.4.3 LCC

In addition to the LCA perspective discussed above, the LCC was also calculated for both the original scenario and the alternative scenarios. For these scenarios, a discount rate of 8% was selected and results are given over a 20-year period, rather than per the mass-based functional units used previously in the LCA analysis. This means that LCC was calculated for the overall aquaponics system, rather than for the unit processes of aquaculture and hydroponics. As with the LCA, electricity and heating costs, specifically for lighting, represented the largest economic hotspot regardless of alternatives. However, examination beyond LCC hotspots is relevant here because costs are expressed over the entire life cycle, allowing for effective comparison between scenarios. Therefore, the LCC and IRR of the original and alternative scenarios are provided in *Figure 4-10* for the naming convention presented in *Table 4-1*.

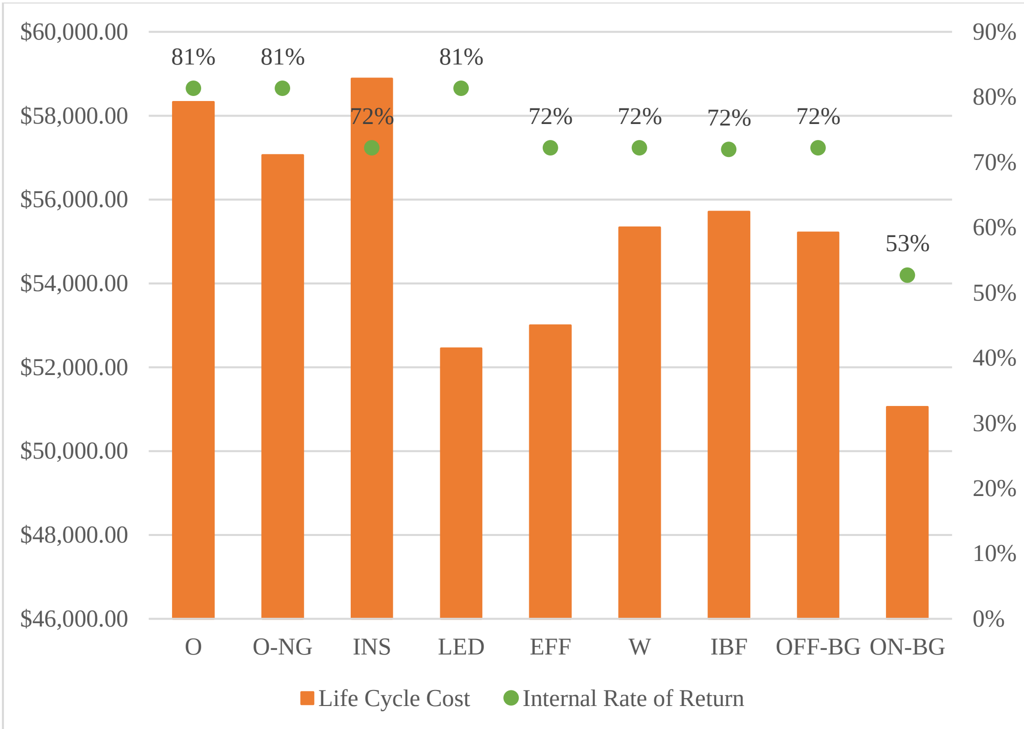

Figure 4-10: Life cycle cost and internal rate of return for scenarios described in Table 4-1.

Five scenarios (EFF, W, IBF, OFF-BG, ON-BG) had significantly lower LCC and lower IRR than the original scenario. The IRR was lowered because even though each of the five scenarios had the same revenue, the capital costs were higher than the original scenario, resulting in a lower return on investment. Furthermore, while the LCC was lower for these five scenarios, much of the reduction was due to the energy source alternatives, while all other alternative scenarios actually increased the overall operation and capital costs of the system. There was one notable exception to this, which was the scenario where only LED bulbs were considered. This is because the higher replacement costs of LED bulbs were offset by the significant reduction of overall lighting costs, resulting in a lower LCC as well as the highest IRR of the alternative scenarios. Moreover, because productivity changes associated with improvement scenarios were not considered, the actual IRR values may be different than shown here. In general, it can be concluded that higher capital costs tend to lower the IRR unless operating costs are reduced significantly.

It also appeared that when environmental burdens were reduced, LCC tended to decrease to different extents. For example, the alternative scenarios where wind energy was considered (W and IBF) had the highest reduction in environmental impacts, but LCC was only reduced by up to 5%. On the other hand, the LED scenario resulted in one of the lowest LCCs observed in *Figure 4-10* but only reduced environmental impacts slightly. When energy efficiency measures were combined (EFF), a small reduction in environmental impacts was observed as well as a reduction of LCC by 9%. The highest LCC reduction, 12%, was observed for the ON-BG scenario, however, this scenario also resulted in an overall increase in eutrophication and acidification potentials. Therefore, while a modest reduction in environmental burdens is associated with a significantly lower LCC, significant reductions in environmental burdens only led to modest reductions in LCC. This is because the scenarios that resulted in lower LCC tended to reduce energy demand but did not address the GHG emissions associated with Nova Scotia's reliance on coal. Therefore, the importance of considering both environmental and economic factors when making decisions is clear because alone, neither assessment is able to fully describe outcomes. This is further discussed through the use of eco-efficiency charts in *Section 4.5.1*.

4.4.4 Sensitivity Analysis for LCC

Sensitivity analysis was used to assess the uncertainty in the discount rate, the cost of insulation, the efficiency and cost of biogas heating, and the price of insect-based fish feed. Each of these are discussed in the following section, highlighting areas where further research is needed.

4.4.4.1 Discount Rate

As discussed in *Section 4.3.1*, the discount rates for this system were 3.5%, 8%, and 10%. For all previously discussed LCC values, 8% was applied because it represents an appropriate discount rate for economic analysis in Canada at the time of the study (Jenkins & Kuo, 2007). Additionally, 3.5%, which represents a social discount rate, and 10%, which is another accepted rate for calculating net present value, were also examined. *Figure 4-11* shows the effect each discount rate has on life cycle cost for each scenario. LCC values changed linearly for each scenario as the discount rate changed. On average, when a 3.5% discount rate was applied, there was a 38% increase from the original LCC, while the 10% discount rate resulted in an 11% decrease. Therefore, selection of discount rate is quite influential on the absolute magnitude of LCC values. Consequently, differences in these rates could have a significant impact on decision making throughout the planning and operation stages. However, in this study, the relative value of LCC was desired because the goal was to understand how LCC compares between the alternative scenarios.

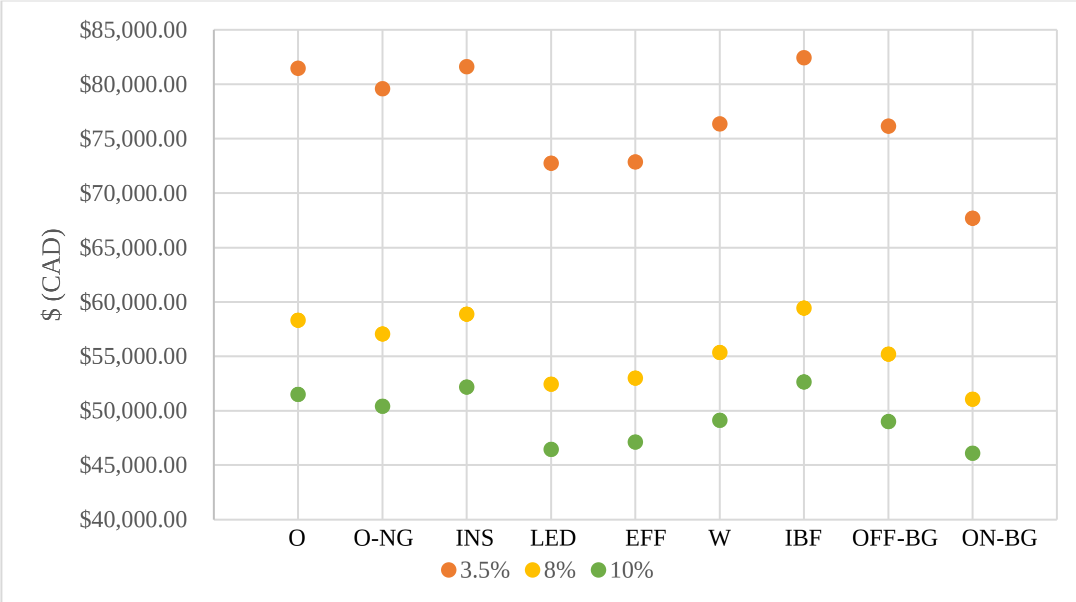

Figure 4-11: Sensitivity analysis showing effect of discount rate on life cycle cost.

4.4.4.2 Insulation Cost

Sensitivity analysis was conducted on the cost of insulation in Canada. The cost of insulation was based on the average range of spray foam insulation materials and installation because no direct quote for the aquaponics facilities was obtained. In this case, instead of the previously considered $1700 for insulation, costs could vary between $780 and $2500. However, because the LCC values were typically greater than $50,000, the one-time cost difference of $1000 for insulation did not play a significant role, especially because quality differences of the insulation from the different price points were not considered. Therefore, it can be concluded that this variation in insulation costs did not affect the robustness of the model or the validity of the results.

4.4.4.3 Biogas Heating Efficiency

The purpose of the sensitivity analysis conducted in this section was to determine how different assumptions regarding the efficiency of CHP systems affect the LCC of the ON-BG scenario. As discussed previously, this scenario assumed that a small-scale CHP system was installed on-site instead of purchasing credits from Bullfrog Power for renewable biogas energy. The uncertainty came from the varying efficiency of different CHP systems converting biogas to heat and electricity. All results discussed previously assumed an efficiency of 35/25, where 35% of output was electricity and 25% was heating, but the ratio of 40/20 is also possible for small-scale CHP systems (US Department of Energy, 2019; Uuemaa et al., 2014). For the ON-BG scenario with an efficiency of 35/25, the LCC was $51,000 and the IRR was 53%. However, when a 40/20 efficiency was considered, the LCC became $52,000 and the IRR remained at 53%. Therefore, similarly to the insulation cost, it can be concluded that the fluctuation of $1000 depending on the efficiency of the CHP system has very little impact on the overall LCC.

4.4.4.4 Insect Feed Pricing

Sensitivity analysis was conducted on the cost of insect-based feed to determine how uncertainty in the commercial rate for insect-meal based fish feeds (IBF) affected the LCC. As discussed in *Section 4.3.1*, the price of insect feed varies greatly due to the niche markets and inadequate production processes of existing facilities. In addition to the midrange cost of IBF of $740/year that was considered in the previous discussion of the IBF scenario, a low cost of $370/year (IBF-LOW) and a high cost of $1500/year (IBF-HI) are also possible. The change in LCC as the price of feed varied is presented in *Figure 4-12*. Compared to the insulation and biogas input flows where variations of around $1000 were observed, the variation for the change in IBF cost was much more significant, at over $10,000 over the lifespan of 20 years. The highest LCC of $68,000 observed for IBF-HI was higher than all other scenarios considered in this study, including the scenarios which incurred higher capital costs. Therefore, the uncertainty in insect feed pricing is an area of concern in this study and represents an area where large margins for error exist.

Figure 4-12: Sensitivity analysis on LCC for insect-based feed price variations.

4.5 Discussion

4.5.1 Eco-Efficiency Analysis

The previous sections indicate that environmental impacts and costs do not necessarily align with each other for the aquaponics system investigated in this study. There appears to be a need for trade-offs between reducing environmental impacts and reducing costs and it may be premature to make decisions based solely on environmental or economic analyses. Consideration of the environmental impacts and costs together may assist in providing a more complete picture of the overall implications of a product or system. One avenue to visualize potential relationships between environmental impacts and costs of a product or system is to use eco-efficiency charts. The purpose of eco-efficiency charts is to highlight the intersections between environmental and economic sustainability. In this case, the bottom left quadrant will identify scenarios that minimize both environmental impacts and LCC. The eco-efficiency chart for the global warming potential impact category is presented in *Figure 4-13* for each alternative scenario discussed in this chapter at a discount rate of 8%.

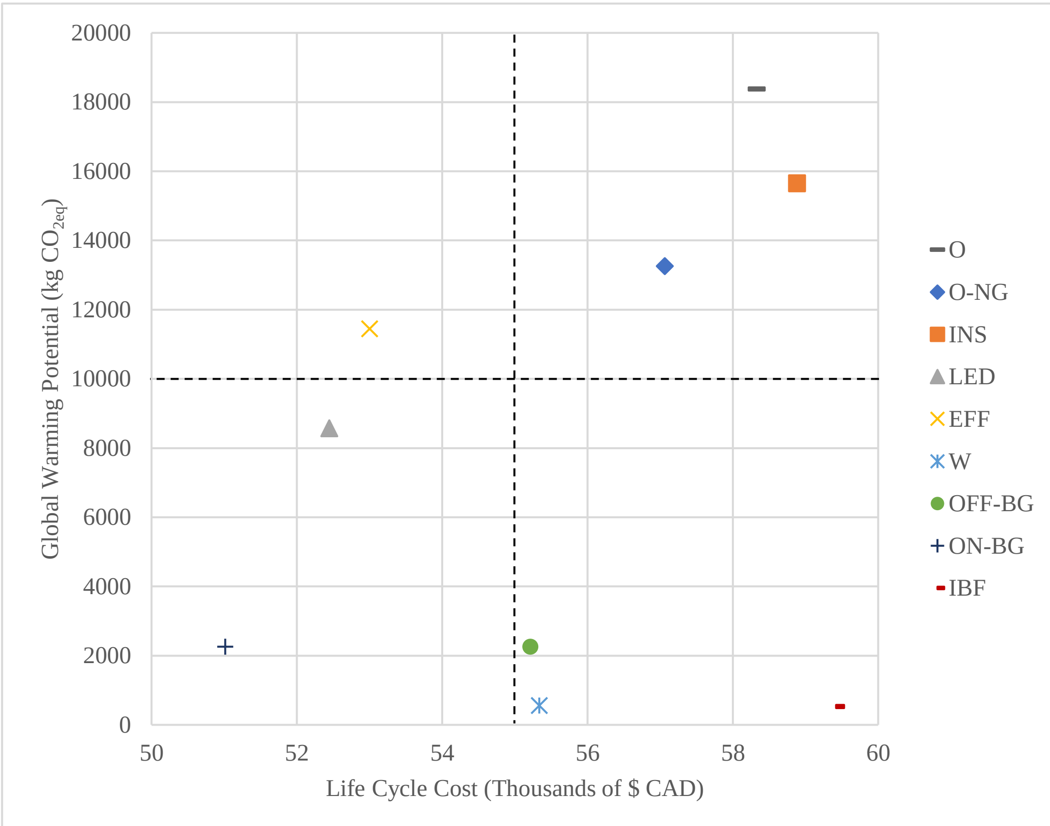

Figure 4-13: Eco-efficiency chart of all scenarios for global warming potential against LCC with an 8% discount rate.

The bottom left quadrant highlights two main scenarios where both costs and environmental impacts are reduced: the implementation of LED lighting (LED) and the use of on-site biogas heating paired with wind energy and efficiency measures (ON-BG). Lower environmental impacts are seen in the bottom right quadrant, which contains more costly scenarios (W, OFF-BG, and IBF) that have added energy costs through Bullfrog Power's renewable energy credit program. The top right quadrant contains those scenarios which are both expensive and did not lower environmental impacts, namely, the original (O), natural gas heating (O-NG), and the increased insulation scenario (INS), while the top left quadrant contains only the scenario where efficiency measures are applied (EFF) with a large reduction in life cycle cost but minor reduction in GWP. This classification indicates that the lowest cost scenarios are those that include energy efficiency improvements, but their ability to reduce environmental impacts remains marginal when compared to more expensive alternative scenarios, such as switching to renewable energy.

Similar eco-efficiency observations as those seen in *Figure 4-13* were made for the fossil fuel depletion, ozone depletion, respiratory effects, and smog impact categories. In contrast, the eco-efficiency charts for the acidification and the eutrophication impact categories were different. Those differences are illustrated in *Figure 4-14* for the acidification impact category. Now, two scenarios with energy efficiency improvements, LED and EFF, are located in the bottom left quadrant. The ON-BG scenario previously observed in this quadrant has moved to the top left quadrant, indicating higher acidification potential than the original scenario. A similar difference is observed for the OFF-BG scenario, which moved from the bottom right quadrant to the top right quadrant. This has to do with emissions associated with storing the liquid anaerobic digestate in open-air containers, reinforcing the existence of trade-offs for every improvement and the importance of considering multiple environmental impact categories. Except for the two BG scenarios and the EFF scenario, all other scenarios remain in the same quadrants observed previously. The eco-efficiency charts demonstrate that W is the most eco-efficient option in terms of both environmental impacts and economic performance for all impact categories assessed in this study.

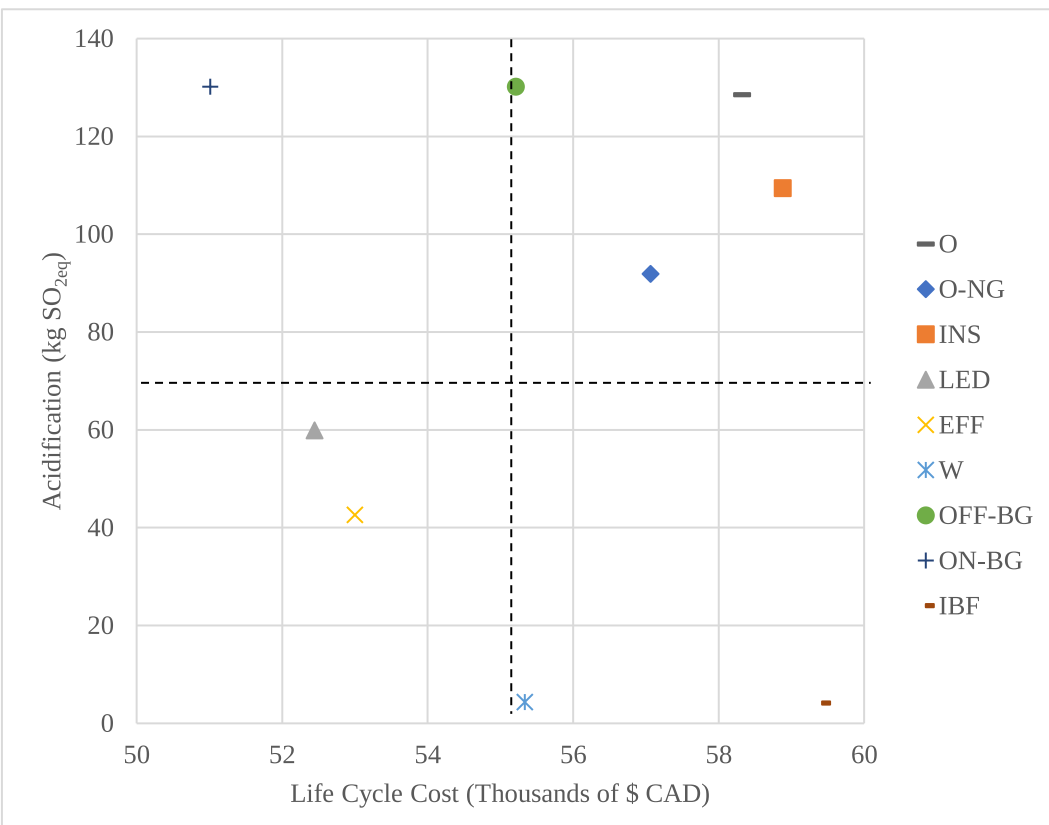

Figure 4-14: Eco-efficiency chart of all scenarios for the acidification impact against LCC with an 8% discount rate.

4.5.2 Comparison to Other Agricultural Systems

Throughout this chapter and the previous, the implications of this specific cold-weather aquaponics system located in Nova Scotia, Canada have been considered. Equally important is to understand how the performance of aquaponics systems compares to similar systems and to conventional means of producing fish and leafy greens. A comparison was done for the global warming potential and acidification impact categories to align with literature data available. The results of the comparison are presented according to each unit of the aquaponics system, namely the aquaculture unit and the hydroponics unit.

For the aquaculture unit, the comparison was made with the results from Ayer & Tyedmers (2009) for both a similar indoor-recirculating aquaculture system and a net-pen aquaculture system, along with results from Svanes et al. (2011) for long-line fishing. While the comparison to a similar recirculating system is crucial, the comparison to net-pen aquaculture and long-line fishing were selected because they represent two common means of obtaining fish in Canada (*Atlantic and Arctic commercial fisheries*, 2020). The comparison between the original scenario (A-O), the aquaculture scenario with wind energy, LED lighting, and improved insulation (A-W), and the published results is presented in *Figure 4-15*, where impacts are given per kilogram of fish.

The global warming potential and acidification impact of the original aquaculture unit (A-O) significantly exceeded those of all other reference systems, including the indoor recirculating aquaculture system studied in Ayer & Tyedmers (2009). In fact, the impacts of the A-O scenario ranged from twice to 30 times higher than the others. However, once wind energy, LED lighting, and improved insulation were considered (A-W), the impacts were considerably lower for both impact categories. In fact, the A-W was almost 90% less impactful in both categories when compared to the other indoor aquaculture system. Furthermore, the A-W scenario was much more comparable in terms of impacts to the long-line fishing and net-pen aquaculture systems. Therefore, this comparison indicates that indoor aquaculture systems in Canada are more environmentally impactful than common, cheaper means of fishing and aquaculture. Only by applying significant improvements, that would include both energy efficiency measures and renewable energy sources, can their impacts be reduced to levels comparable to alternative processes.

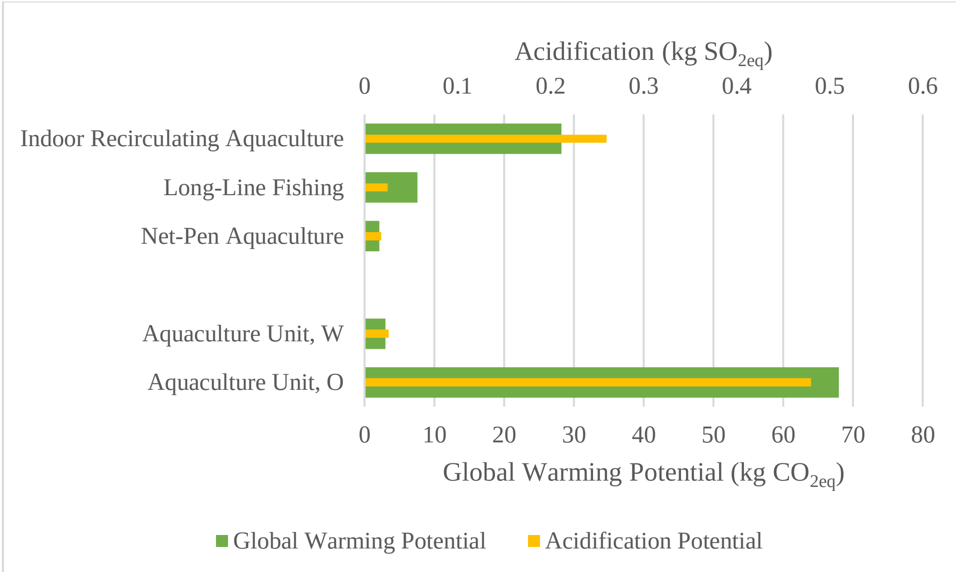

Figure 4-15: Comparison of the aquaculture unit (A-O and A-W) to indoor recirculating aquaculture, net-pen aquaculture (Ayer & Tyedmers, 2009), and long-line fishing (Svanes et al., 2011).

The comparison between the original scenario (H-O), the hydroponics scenario with wind energy, LED lighting, and increased insulation (H-W) and published results for greenhouse and open-field lettuce production is illustrated in *Figure 4-16* per kilogram of greens. As observed in the aquaculture unit comparison, the magnitude by which H-O exceeded the global warming potential and acidification impacts of conventional agriculture was quite large. These impacts were often 30 times higher than both greenhouse lettuce and open-field lettuce production for global warming potential and acidification. In contrast to the aquaculture unit, the use of wind energy, LED lighting, and increased insulation (H-W) did not improve operation of the hydroponics system to make it comparable to conventional farming. Given the significant amount of artificial lighting required by the hydroponics system, the higher impacts are not surprising. One point to note is that lettuce was used for the comparison to conventional farming systems, but lettuce tends to require less sunlight than greens such as basil (Avgoustaki, 2019). One could expect lower lighting needs, and therefore less energy-related impacts, if lettuce were the sole crop grown in this hydroponics system. The absence of natural light ultimately made the hydroponics unit, irrespective of improvements, much more environmentally impactful that conventional means of agriculture. Therefore, indoor operation of hydroponics systems is an energy intensive means of production, but there remains opportunity to couple production with indoor aquaculture in order to reduce environmental impacts.

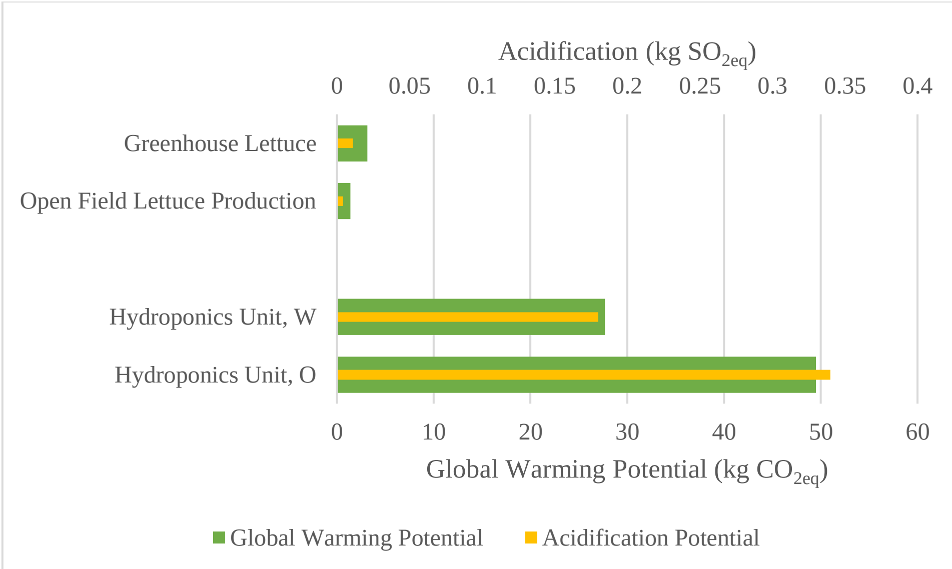

Figure 4-16: Comparison of hydroponics unit (H-O and H-W) to compact greenhouse lettuce and open field lettuce production (Khandelwal, 2020).

In the context of the economic perspective, few full life cycle cost studies exist on the subject. The LCC study by Forchino et al. (2018) for an indoor aquaponics system located in Belgium that produced 700 kg of fish and 4000 kg of leafy greens determined LCC to be €77,000, which is equivalent to $120,000 CAD at the time of the study. On the other hand, the aquaponics system considered here was over 10 times smaller and still cost $58,000 CAD. Both the system considered in this study and the one in the study by Forchino et al. (2018) were located in zones with a winter season, used similar system boundaries of cradle to system gate, and used artificial lighting-supported deep-water culture (DWC) as the method for hydroponics production. Seeing as the cost was only around double but production was tenfold higher, this could indicate that an economy of scale exists for aquaponics, such that larger systems could have lower production costs than smaller systems. However, a comparison between two studies alone is insufficient to make claims on the overall economic performance of aquaponics systems. Therefore, significant research is still needed on this subject to both highlight economic hurdles and make recommendations for improvement. Especially for cold climates, additional economic assessment of aquaponics systems would help to address challenges related to the cost of energy, matching market demand, and to determine whether economies of scale exist for aquaponics production.

4.6 Recommendations and Conclusions

The LCA and LCC of an existing aquaponics system located in Nova Scotia, Canada was assessed for alternative scenarios aimed at reducing environmental impacts and economic burdens. Based on this analysis, recommendations for future research and decision-makers are made. First of all, the use of energy efficiency measures reduced environmental impacts and life cycle costs. Therefore, it is recommended that cold-climate aquaponics systems invest in energy efficient lighting, upgrade insulation, and consider operation in greenhouses or locations with natural light to reduce energy demands. Especially in the case of LED lighting, despite having initially higher investments, operating costs can be greatly reduced due to an increase in energy efficiency.

The second recommendation is to consider renewable sources of energy, such as wind. The use of wind energy, while being a slightly more costly option than other scenarios examined, had the highest reduction in environmental impacts. As the use of wind energy and other renewable energy technologies increases, it is likely that costs will be reduced, making scenarios that include both efficiency measures and renewable energy more favourable for cold-climate systems. In contrast, the use of biogas heating reduced global warming potential and fossil fuel depletion impacts dramatically, but significantly increased acidification and eutrophication impacts. This increase in acidification and eutrophication potential is likely due to ammonia emissions associated with the open-air storage of the liquid anaerobic digestate (Fusi et al., 2016; Jamaludin et al., 2018). Options for mitigation may exist, such as ammonia scrubbing (Jamaludin et al., 2018) and closed storage. Furthermore, uncertainty exists around the efficiency of energy production in small-scale CHP systems used for anaerobic digestion, as well as their costs (Darrow et al., 2015). The ON-BG scenario therefore remains incomplete and requires more detailed analysis on cost, efficiency of energy production, and environmental impact. In addition to selecting traditional sources of renewable energy, other options for energy and heat recovery through industrial symbiosis should also be explored to reduce the environmental burdens and costs of aquaponics operation in cold climates.

The use of insect-based feed (IBF) was found to reduce environmental impacts compared to the original scenario. There remains a significant amount of uncertainty surrounding impacts of production because most available data on IBF is based on studies conducted in Africa, rather than Europe or North America. The cost of IBF is also an area of uncertainty which was found to influence the LCC by 7% to 15%. Moreover, IBF is often suggested to eliminate impacts of the harmful aquaculture practices associated with fishmeal and fish oil, like overfishing (Maiolo et al., 2020; Malcorps et al., 2019; Springmann et al., 2018), but other impacts of IBF have not been considered here, such as influence on fish growth and productivity. Therefore, additional research is required before embracing insect meal as a suitable alternative to fishmeal. The emerging nature of IBF and its contribution to impacts and costs mean that significant work is required to understand its use in aquaponics systems.

Eco-efficiency charts were used to compare alternative scenarios and identify those scenarios that reduced both environmental impacts and economic burdens of aquaponics systems. The scenarios with improved energy efficiency measures and wind electricity were among the most eco-efficient, with lower environmental impacts and lower LCC. However, few other LCC studies have been conducted on aquaponics systems, which means that patterns in economic burden are difficult to identify. Therefore, additional LCC studies, especially those for aquaponics systems that vary in system size and geographical location, are required for a more in-depth understanding.

In this study, the environmental and economic pillars of sustainability of aquaponics systems for cold climate conditions were investigated while no consideration was given to the social pillar of these systems. Therefore, it is recommended that the social implications of aquaponics systems located in cold climates be studied. By understanding the relationships and trade-offs that exist between the three pillars of sustainability, environment, economy, and society, optimized operation parameters can be determined for cold-climate aquaponics systems, building upon the key findings from this study.

Chapter 5 Conclusions and Recommendations

5.1 Conclusions

The purpose of this study was to identify the environmental and economic barriers faced by small-scale aquaponics systems in Canada and to identify pathways for reducing environmental impacts and operational costs. In order to do so, a life cycle assessment (LCA) and life cycle cost (LCC) analysis were conducted. The LCA focused on uncovering environmental hotspots from cradle to system gate of aquaponics production, while the LCC looked at all incurred costs over the system lifespan of 20 years. Scenario analysis was also conducted to determine methods of improving operation by focusing on hotspots identified in the LCA. It was found that the overarching challenge facing aquaponics systems, especially those located in cold climates, is their energy intensity. Energy consumption was the most significant environmental hotspot uncovered in this study. This impact was worsened by a reliance on coal in Nova Scotia. The significant energy consumption also made electricity and heating the highest expenses of the system even when alternative scenarios improving energy efficiency, such as LED lighting and increased insulation, were considered. Consequently, cold-climate aquaponics operations should include energy efficiency measures, as well as transition to renewable sources of energy to improve environmental and economic performance.

In this study, the alternative scenario using LED lighting and insulation paired with wind energy resulted in the greatest reduction of environmental impacts, including a 97% reduction in GWP and an 89% reduction in eutrophication potential, while also reducing the life cycle cost by 5%. However, while the use of wind energy was successful, biogas heating, another form of renewable energy considered in this study, was not as successful. The use of renewable biogas did offset fossil fuel depletion and global warming potential and reduce LCC by up to 12%, but it also increased acidification and eutrophication impacts by over 20%. Thus, certain operation parameters can reduce overall environmental impacts greatly without reducing LCC significantly, while others can reduce specific environmental impacts in order to reduce LCC to a greater extent. Trade-offs must therefore be considered when making decisions about energy source for aquaponics production systems.

Furthermore, the unit process approach of dividing the aquaponics production process into the operations of aquaculture and hydroponics was applied in this study. This resulted in a more accurate representation of how input flows contributed to the impacts of the two co-products of the system. When impacts were instead allocated between products by mass, calorie, or protein content, it was found that results varied greatly depending on the allocation method applied and that studies in literature using mass allocation may be slightly underreporting impacts per kg of fish. Therefore, future aquaponics LCAs should model production using the unit process approach in order to achieve a more accurate and realistic understanding of impacts incurred by each co-product of the system.

5.2 Recommendations

In addition to the above recommendations on energy efficiency and energy source, other changes to the operation of cold-climate aquaponics systems to support businesses, researchers, and policy makers should be considered. First of all, building design and envelope, such as adequate insulation, access to natural lighting, and efficient HVAC technology, should be taken into consideration when setting up energy-intensive indoor agriculture technologies in order to reduce energy demand. Furthermore, the optimization of infrastructure, such as the type of mechanical components, system design, and material lifespan, represents an important opportunity to both reduce impacts and costs while improving productivity. Additionally, climate-specific choices should be considered. In this study, the aquaponics system produced leafy greens year-round, but consideration should be given to crops that are more resistant to the cold for winter operation. Furthermore, opportunities for industrial symbiosis, such as industrial waste heat recovery, should be considered in order to share resources between processes, thereby reducing environmental impacts and costs. Finally, in addition to these environmental and economic-focused recommendations, it is also crucial to consider social drivers in the start-up and operation of aquaponics systems. As demonstrated in this study, aquaponics systems have many environmental issues that have yet to be sorted out and are not very profitable as stand-alone systems. That being said, there are many potential social benefits, including community engagement and supporting urban food security, that should be considered. Overall, a deeper understanding of the environmental, economic, and social factors that drive the sustainability of aquaponics is needed to ensure their success and productivity in cold climates.

References

Andrews, R., & Pearce, J. M. (2011). Environmental and economic assessment of a greenhouse waste heat exchange. *Journal of Cleaner Production*, *19*(13), 1446–1454. https://doi.org/10.1016/j.jclepro.2011.04.016

Andrić, I., Pina, A., Ferrão, P., Fournier, J., Lacarrière, B., & Le Corre, O. (2017). Approach for modelling anaerobic digestion processes of fish waste. *International Scientific Conference "Environmental and Climate Technologies."* https://doi.org/10.1016/j.egypro.2018.07.108

Asciuto, A., Schimmenti, E., Cottone, C., & Borsellino, V. (2019). A financial feasibility study of an aquaponic system in a Mediterranean urban context. *Urban Forestry & Urban Greening*, *38*, 397–402. https://doi.org/10.1016/j.ufug.2019.02.001

ASHRAE 90.1. (2004).

Atlantic and Arctic commercial fisheries. (2020). https://www.dfo-mpo.gc.ca/fisheries-peches/commercial-commerciale/atl-arc-eng.html

Atlason, R. S., Danner, R. I., Unnthorsson, R., Oddsson, G. V., Sustaeta, F., & Thorarinsdottir, R. (2017). Energy Return on Investment for Aquaponics: Case Studies from Iceland and Spain. *BioPhysical Economics and Resource Quality*, *2*, 1–12. https://doi.org/10.1007/s41247-017-0020-5

Avgoustaki, D. D. (2019). Optimization of Photoperiod and Quality Assessment of Basil Plants Grown in a Small-Scale Indoor Cultivation System for Reduction of Energy Demand. *Energies*, *12*(20), 3980. https://doi.org/10.3390/en12203980

Ayer, N. W., & Tyedmers, P. H. (2009). Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada. *Journal of Cleaner Production*, *17*(3), 362–373. https://doi.org/10.1016/j.jclepro.2008.08.002

Bahadur KC, K., Dias, G. M., Veeramani, A., Swanton, C. J., Fraser, D., Steinke, D., Lee, E., Wittman, H., Farber, J. M., Dunfield, K., McCann, K., Anand, M., Campbell, M., Rooney, N., Raine, N. E., Van Acker, R., Hanner, R., Pascoal, S., Sharif, S., … Fraser, E. D. G. (2018). When too much isn't enough: Does current food production meet global nutritional needs? *PLoS ONE*, *13*(10). https://doi.org/10.1371/journal.pone.0205683

Bank of Canada Interest Rates. (2019). https://www.bankofcanada.ca/rates/interest-rates/

Baquero, G., Esteban, B., Riba, J.-R., Rius, A., & Puig, R. (2011). An evaluation of the life cycle cost of rapeseed oil as a straight vegetable oil fuel to replace petroleum diesel in agriculture. *Biomass and Bioenergy*, *35*, 3687–3697. https://doi.org/10.1016/j.biombioe.2011.05.028

Barbosa, G., Gadelha, F., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G., & Halden, R. (2015). Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods. *International Journal of Environmental Research and Public Health*, *12*(6), 6879–6891. https://doi.org/10.3390/ijerph120606879

Benke, K., & Tomkins, B. (2017). Future food-production systems: Vertical farming and controlled-environment agriculture. *Sustainability: Science, Practice, and Policy*, *13*(1), 13–26. https://doi.org/10.1080/15487733.2017.1394054

Bianchi, M., Strid, A., Winkvist, A., Lindroos, A. K., Sonesson, U., & Hallström, E. (2020). Systematic evaluation of nutrition indicators for use within food LCA studies. *Sustainability (Switzerland)*, *12*(21), 1–18. https://doi.org/10.3390/su12218992

Boardman, A. E., Moore, M. A., & Vining, A. R. (2010). The social discount rate for canada based on future growth in consumption. *Canadian Public Policy*, *36*(3), 325–343.

https://doi.org/10.3138/cpp.36.3.325

Bohnes, F. A., & Laurent, A. (2019). LCA of aquaculture systems: methodological issues and potential improvements. *International Journal of Life Cycle Assessment*, *24*(2), 324–337. https://doi.org/10.1007/s11367-018-1517-x LK

Bong, C. P. C., Lim, L. Y., Lee, C. T., Klemeš, J. J., Ho, C. S., & Ho, W. S. (2018). The characterisation and treatment of food waste for improvement of biogas production during anaerobic digestion – A review. *Journal of Cleaner Production*, *172*, 1545–1558. https://doi.org/10.1016/j.jclepro.2017.10.199

Bosma, R. H., Lacambra, L., Landstra, Y., Perini, C., Poulie, J., Schwaner, M. J., & Yin, Y. (2017). The financial feasibility of producing fish and vegetables through aquaponics. *Aquacultural Engineering*, *78*, 146–154. https://doi.org/10.1016/j.aquaeng.2017.07.002

Boxman, S. E., Zhang, Q., Bailey, D., & Trotz, M. A. (2017). Life Cycle Assessment of a Commercial-Scale Freshwater Aquaponic System. *Environmental Engineering Science*, *34*(5), 299–311. https://doi.org/10.1089/ees.2015.0510

Bullfrog Power Canada. (2021). https://www.bullfrogpower.com/

Calicioglu, O., Flammini, A., Bracco, S., Bellù, L., & Sims, R. (2019). The Future Challenges of Food and Agriculture: An Integrated Analysis of Trends and Solutions. *Sustainability*, *11*(1), 222. https://doi.org/10.3390/su11010222

Campbell, B. M., Beare, D. J., Bennett, E. M., Hall-Spencer, J. M., Ingram, J. S. I., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J. A., & Shindell, D. (2017). Agriculture production as a major driver of the earth system exceeding planetary boundaries. *Ecology and Society*, *22*(4). https://doi.org/10.5751/ES-09595-220408

Chance, E., Ashton, W., Pereira, J., Mulrow, J., Norberto, J., Derrible, S., & Guilbert, S. (2018). The Plant - An experiment in urban food sustainability. *Environmental Progress & Sustainable Energy*, *37*(1), 82–90. https://doi.org/10.1002/ep.12712

Chen, P., Zhu, G., Kim, H. J., Brown, P. B., & Huang, J. Y. (2020). Comparative life cycle assessment of aquaponics and hydroponics in the Midwestern United States. *Journal of Cleaner Production*, *275*, 122888. https://doi.org/10.1016/j.jclepro.2020.122888

Cleary, J., Wolf, D. P., & Caspersen, J. P. (2015). Comparing the life cycle costs of using harvest residue as feedstock for small- and large-scale bioenergy systems (part II). *Energy*, *86*, 539–547. https://doi.org/10.1016/j.energy.2015.04.057

Cohen, A., Malone, S., Morris, Z., Weissburg, M., & Bras, B. (2018). Combined Fish and Lettuce Cultivation: An Aquaponics Life Cycle Assessment. *Procedia CIRP*, *69*, 551–556. https://doi.org/10.1016/j.procir.2017.11.029

Concha, D., Adams, M., Suárez, J., & Faxas, R. (2016). Fostering food and energy security through by-product valorization within agricultural and agro-industrial networks: study of the province of Santiago de Cuba. *International Journal of Sustainable Development and World Ecology*, *24*(2), 159–174. https://doi.org/10.1080/13504509.2016.1156035

Danner, R. I., Mankasingh, U., Anamthawat-Jonsson, K., & Thorarinsdottir, R. I. (2019). Designing Aquaponic Production Systems towards Integration into Greenhouse Farming. *Water*, *11*(10), 2123. https://doi.org/10.3390/w11102123

Darrow, K., Tidball, R., Wang, J., & Hampson, A. (2015). Technology Characterization – Reciprocating Internal Combustion Engines. *Catalog of CHP Technologies*, *2*.

De La Hera, G., Muñoz-Díaz, I., Cifrian, E., Ramón, V., Oskar, G., Martin, S., & Viguri, J. R. (2016).

Comparative environmental life cycle analysis of stone wool production using traditional and alternative materials. *Waste and Biomass Valorization*, *8*, 1505–1520. https://doi.org/10.1007/s12649-016-9660-8

De Menna, F., Dietershagen, J., Loubiere, M., & Vittuari, M. (2018). Life cycle costing of food waste: A review of methodological approaches. *Waste Management*, *73*, 1–13. https://doi.org/10.1016/j.wasman.2017.12.032

Delaide, B., Goddek, S., Gott, J., Soyeurt, H., & Jijakli, M. H. (2016). Lettuce (Lactuca sativa L. var. Sucrine) growth performance in complemented aquaponic solution outperforms hydroponics. *Water (Switzerland)*, *8*(10), 1–11. https://doi.org/10.3390/w8100467

Design Parameters Optimization and Economics of a Commercial Aquaponics (Issue March). (2018).

Despommier, D. (2011). The vertical farm: controlled environment agriculture carried out in tall buildings would create greater food safety and security for large urban populations. *Journal of Consumer Protection and Food Safety*, *6*, 233–236. https://doi.org/10.1007/s00003-010-0654-3

DEWALT Shelf Steel . (2020). The Home Depot Canada. https://www.homedepot.ca/product/dewalt-48-inch-h-x-50-inch-w-x-18-inch-d-3-shelf-steel-wire-deck-industrial-storage-rack-unit-in-yellow/1001406251

Dias, G. M., Ayer, N. W., Khosla, S., Van Acker, R., Young, S. B., Whitney, S., & Hendricks, P. (2017). Life cycle perspectives on the sustainability of Ontario greenhouse tomato production: Benchmarking and improvement opportunities. *Journal of Cleaner Production*, *140*, 831–839. https://doi.org/10.1016/j.jclepro.2016.06.039

Dorr, E., Sanyé-Mengual, E., Gabrielle, B., Grard, B. J. P., & Aubry, C. (2017). Proper selection of substrates and crops enhances the sustainability of Paris rooftop garden. *Agronomy for Sustainable Development*, *37*(5). https://doi.org/10.1007/s13593-017-0459-1

Egea, F. J., Torrente, R. G., & Aguilar, A. (2018). An efficient agro-industrial complex in Almería (Spain): Towards an integrated and sustainable bioeconomy model. *New Biotechnology*, *40*, 103–112. https://doi.org/10.1016/j.nbt.2017.06.009

Eigenbrod, C., & Gruda, N. (2015). Urban vegetable for food security in cities. A review. In *Agronomy for Sustainable Development* (Vol. 35, Issue 2, pp. 483–498). Springer-Verlag France. https://doi.org/10.1007/s13593-014-0273-y

Environment Canada. (2021). *Historical Climate Data*. https://climate.weather.gc.ca/historical_data/search_historic_data_e.html

Environmental management — Life cycle assessment — Principles and framework: CAN/CSA-ISO 14040 (Vol. 06). (2006). International Organization for Standardization (ISO).

Environmental management — Life cycle assessment — Requirements and guidelines: CAN/CSA-ISO 14044, 06 (2006).

Estimated Life Expectancy Chart. (2019). InterNACHI.

Fang, Y., Hu, Z., Zou, Y., Fan, J., Wang, Q., & Zhu, Z. (2017). Increasing economic and environmental benefits of media-based aquaponics through optimizing aeration pattern. *Journal of Cleaner Production*, *162*, 1111–1117. https://doi.org/10.1016/j.jclepro.2017.06.158

Fernandez-Mena, H., Nesme, T., & Pellerin, S. (2016). Towards an Agro-Industrial Ecology: A review of nutrient flow modelling and assessment tools in agro-food systems at the local scale. *Science of the Total Environment*, *543*, 467–479. https://doi.org/10.1016/j.scitotenv.2015.11.032

Finnveden, G. (2000). On the limitations of life cycle assessment and environmental systems analysis tools in general. *International Journal of Life Cycle Assessment*, *5*(4), 229–238. https://doi.org/10.1007/BF02979365

Finnveden, Göran, Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S. (2009). Recent developments in Life Cycle Assessment. In *Journal of Environmental Management* (Vol. 91, Issue 1, pp. 1–21). https://doi.org/10.1016/j.jenvman.2009.06.018

Forchino, A., Gennotte, V., Maiolo, S., Brigolin, D., Mélard, C., & Pastres, R. (2018). Eco-designing Aquaponics: A Case Study of an Experimental Production System in Belgium. *Procedia CIRP*, *69*, 546–550. https://doi.org/10.1016/j.procir.2017.11.064

Forchino, A., Lourguioui, H., Brigolin, D., & Pastres, R. (2017). Aquaponics and sustainability: The comparison of two different aquaponic techniques using the Life Cycle Assessment (LCA). *Aquacultural Engineering*, *77*, 80–88. https://doi.org/10.1016/j.aquaeng.2017.03.002

Fraccascia, L., Yazdanpanah, V., van Capelleveen, G., & Yazan, D. M. (2020). Energy-based industrial symbiosis: a literature review for circular energy transition. In *Environment, Development and Sustainability* (Issue 0123456789). Springer Netherlands. https://doi.org/10.1007/s10668-020-00840-9

Fusi, A., Bacenetti, J., Fiala, M., & Azapagic, A. (2016). Life cycle environmental impacts of electricity from biogas produced by anaerobic digestion. *Frontiers in Bioengineering and Biotechnology*, *4*(MAR), 181–193. https://doi.org/10.3389/fbioe.2016.00026

Ghamkhar, R., Hartleb, C., Wu, F., Hicks, A., & Baiocchi, G. (2019). Life cycle assessment of a cold weather aquaponic food production system. *Journal of Cleaner Production*, *244*. https://doi.org/10.1016/j.jclepro.2019.118767

Gibbons, G. M. (2020). *An Economic Comparison of Two Leading Aquaponic Technologies Using Cost Benefit Analysis: The Coupled and Technologies Using Cost Benefit Analysis: The Coupled and Decoupled Systems* [Utah State University]. https://digitalcommons.usu.edu/etd/7823

Gigliona, J. (2015). *Implementation of a biogas-system into aquaponics Determination of minimum size of aquaponics and costs per kWh of the produced energy*. https://www.diva-portal.org/smash/get/diva2:826751/FULLTEXT01.pdf

Goddek, S., Delaide, B., Mankasingh, U., Ragnarsdottir, K. V., Jijakli, H., & Thorarinsdottir, R. (2015). Challenges of sustainable and commercial aquaponics. *Sustainability (Switzerland)*, *7*(4), 4199–4224. https://doi.org/10.3390/su7044199

Goddek, S., Espinal, C. A., Delaide, B., Jijakli, M. H., Schmautz, Z., Wuertz, S., & Keesman, K. J. (2016). Navigating towards decoupled aquaponic systems: A system dynamics design approach. *Water*, *8*(7), 303. https://doi.org/10.3390/W8070303

Goddek, S., Joyce, A., Kotzen, B., & Burnell Editors, G. M. (Eds.). (2019). *Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future*.

Goddek, S., & Körner, O. (2019). A fully integrated simulation model of multi-loop aquaponics: A case study for system sizing in different environments. *Agricultural Systems*, *171*, 143–154. https://doi.org/10.1016/j.agsy.2019.01.010

Goldstein, B., Hauschild, M., Fernandez B, J., Birkved, M., Fernández, J., & Birkved, M. (2016). Testing the environmental performance of urban agriculture as a food supply in northern climates. *Journal of Cleaner Production*, *135*, 984–994. https://doi.org/10.1016/j.jclepro.2016.07.004

González-García, S., Gomez-Fernández, Z., Dias, A. C., Feijoo, G., Moreira, T., & Arroja, L. (2014). Life Cycle Assessment of broiler chicken production: a Portuguese case study. *Journal of Cleaner*

Production, *74*, 125–134. https://doi.org/10.1016/j.jclepro.2014.03.067

Goodman, W., & Minner, J. (2019). Will the urban agricultural revolution be vertical and soilless? A case study of controlled environment agriculture in New York City. *Land Use Policy*, *83*(June 2018), 160–173. https://doi.org/10.1016/j.landusepol.2018.12.038

Great Northern Insulation. (2020). https://www.gni.ca/insulation-faqs/insulation-cost

Greenfeld, A., Becker, N., McIlwain, J., Fotedar, R., & Bornman, J. F. (2019). Economically viable aquaponics? Identifying the gap between potential and current uncertainties. *Reviews in Aquaculture*, *11*(3), 848–862. https://doi.org/10.1111/raq.12269

Halloran, A, Hanboonsong, Y., Roos, N., & Bruun, S. (2017). Life cycle assessment of cricket farming in north-eastern Thailand. *Journal of Cleaner Production*, *156*, 83–94. https://doi.org/10.1016/j.jclepro.2017.04.017

Halloran, Afton, Roos, N., Eilenberg, J., Cerutti, A., & Bruun, S. (2016). Life cycle assessment of edible insects for food protein: a review. *Agronomy for Sustainable Development*, *36*(57). https://doi.org/10.1007/s13593-016-0392-8

Hallström, E., Davis, J., Woodhouse, A., & Sonesson, U. (2018). Using dietary quality scores to assess sustainability of food products and human diets: A systematic review. *Ecological Indicators*, *93*(February), 219–230. https://doi.org/10.1016/j.ecolind.2018.04.071

Hannon, C., Officer, R. A., & Le Dorven, J. (2013). Review of the technical challenges facing aquaculture of the European abalone Haliotis tuberculata in Ireland. *Aquaculture International*, *21*, 243–254. https://doi.org/10.1007/s10499-012-9584-7

Hayashi, K., Gaillard, G., Nemecek, T., & Fal Reckenholz, A. (2005). Life Cycle Assessment of Agricultural Production Systems: Current Issues and Future Perspectives. *Good Agricultural Practice (GAP) in Asia and Oceania*.

Henriksson, P. J. G., Belton, B., Murshed-E-Jahan, K., & Rico, A. (2018). Measuring the potential for sustainable intensification of aquaculture in Bangladesh using life cycle assessment. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(12), 2958–2963. https://doi.org/10.1073/pnas.1716530115

Hindelang, M., Gheewala, S. H., Mungkung, R., & Bonnet, S. (2014). *Environmental Sustainability Assessment of a Media Based Aquaponics System In Thailand*.

Hochman, G., Hochman, E., Naveh, N., & Zilberman, D. (2018). The Synergy between Aquaculture and Hydroponics Technologies: The Case of Lettuce and Tilapia. *Sustainability*, *10*(10), 3479. https://doi.org/10.3390/su10103479

Jaeger, C., Foucard, P., Tocqueville, A., Nahon, S., & Aubin, J. (2018). Mass balanced based LCA of a common carp-lettuce aquaponics system. *Aquacultural Engineering*, *84*, 29–41. https://doi.org/10.1016/j.aquaeng.2018.11.003

Jamaludin, Z., Rollings-Scattergood, S., Lutes, K., & Vaneeckhaute, C. (2018). Evaluation of sustainable scrubbing agents for ammonia recovery from anaerobic digestate. *Bioresource Technology*, *270*(September), 596–602. https://doi.org/10.1016/j.biortech.2018.09.007

Janker, J., Reinhardt, T., Villarroel, M., & Junge, R. (2018). Analysis of aquaponics as an emerging technological innovation system. *Journal of Cleaner Production*, *180*, 232–243. https://doi.org/10.1016/j.jclepro.2018.01.037

Jenkins, G., & Kuo, C.-Y. (2007). *The Economic Opportunity Cost of Capital for Canada - An Empirical Update*.

Junge, R., König, B., Villarroel, M., Komives, T., & Jijakli, M. (2017). Strategic Points in Aquaponics. *Water*, *9*(3), 182. https://doi.org/10.3390/w9030182

Kádárová, J., Kobulnický, J., & Teplicka, K. (2015). Product Life Cycle Costing. *Applied Mechanics and Materials*, *816*, 547–554. https://doi.org/10.4028/www.scientific.net/AMM.816.547

Kalhor, T., Rajabipour, A., Akram, A., & Sharifi, M. (2016). Environmental impact assessment of chicken meat production using life cycle assessment. *Information Processing in Agriculture*, *3*, 262–271. https://doi.org/10.1016/j.inpa.2016.10.002

Kang, J. H., Krishnakumar, S., Louise, S., Atulba, S., Jeong, B. R., & Hwang, S. J. (2013). Light Intensity and Photoperiod Influence the Growth and Development of Hydroponically Grown Leaf Lettuce in a Closed-type Plant Factory System Introduction. *Horticulture, Environment, and Biotechnology*, *54*(6), 501–509. https://doi.org/10.1007/s13580-013-0109-8

Katzin, D., Marcelis, L. F. M., & van Mourik, S. (2021). Energy savings in greenhouses by transition from high-pressure sodium to LED lighting. *Applied Energy*, *281*(July 2020), 116019. https://doi.org/10.1016/j.apenergy.2020.116019

Khandelwal, G. (2020). *Growing Compact and Going Compact*. University of Waterloo.

Kloas, W., Groß, R., Baganz, D., Graupner, J., Monsees, H., Schmidt, U., Staaks, G., Suhl, J., Tschirner, M., Wittstock, B., Wuertz, S., Zikova, A., & Rennert, B. (2015). A new concept for aquaponic systems to improve sustainability, increase productivity, and reduce environmental impacts. *Aquaculture Environment Interactions*, *7*(2), 179–192. https://doi.org/10.3354/aei00146

Knaus, U., & Palm, H. (2017). Effects of the fish species choice on vegetables in aquaponics under spring-summer conditions in northern Germany (Mecklenburg Western Pomerania). *Aquaculture*, *473*, 62–73. https://doi.org/10.1016/j.aquaculture.2017.01.020

Konig, B., Junge, R., Bittsanszky, A., Villarroel, M., & Komives, T. (2016). On the sustainability of aquaponics. *Ecocycles*, *2*(1), 26–32. https://doi.org/10.19040/ecocycles.v2i1.50

La Rosa, A. D. (2016). Life cycle assessment of biopolymers. In *Biopolymers and Biotech Admixtures for Eco-Efficient Construction Materials* (pp. 1–465). Elsevier Inc. https://doi.org/10.1016/C2014-0-02075-8

Lages Barbosa, G., Daiane, F., Gadelha, A., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G. M., Halden, R. U., Bhamidiammarri, R., Tota-Maharaj, K., Barbosa, G. L., Almeida Gadelha, F. D., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G. M., & Halden, R. U. (2015). Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods. *International Journal of Environmental Research and Public Health*, *12*(6), 6879–6891. https://doi.org/10.3390/ijerph120606879

Laidlaw, J., & Magee, L. (2014). Towards urban food sovereignty: the trials and tribulations of community-based aquaponics enterprises in Milwaukee and Melbourne. *The International Journal of Justice and Sustainability*, 1469–6711. https://doi.org/10.1080/13549839.2014.986716

Lakhiar, I. A., Gao, J., Syed, T. N., Chandio, F. A., & Buttar, N. A. (2018). Modern plant cultivation technologies in agriculture under controlled environment: A review on aeroponics. *Journal of Plant Interactions*, *13*(1), 338–352. https://doi.org/10.1080/17429145.2018.1472308

Langdon, D. (2005). *Literature review of life cycle costing (LCC) and life cycle assessment (LCA)* (Issue June).

Law, R., Harvey, A., & Reay, D. (2012). Opportunities for low-grade heat recovery in the UK food processing industry. *Applied Thermal Engineering*, *53*, 188–196. https://doi.org/10.1016/j.applthermaleng.2012.03.024

Le Féon, S., Thévenot, A., Maillard, F., Macombe, C., Forteau, L., & Aubin, J. (2018). Life Cycle Assessment of fish fed with insect meal: Case study of mealworm inclusion in trout feed, in France. *Aquaculture*, *500*, 82–91. https://doi.org/10.1016/j.aquaculture.2018.06.051

Legorburu, G., & Smith, A. D. (2018). Energy modeling framework for optimizing heat recovery in a seasonal food processing facility. *Applied Energy*, *229*, 151–162. https://doi.org/10.1016/j.apenergy.2018.07.097

Lopez-Andres, J. L., Alfonso Aguilar-Lasserre, A., Fernando Morales-Mendoza, L., Azzaro-Pantel, C., Raúl erez-Gallardo, J. P., & Octavio Rico-Contreras, J. (2017). Environmental impact assessment of chicken meat production via an integrated methodology based on LCA, simulation and genetic algorithms. *Journal of Cleaner Production*, *174*, 477–491. https://doi.org/10.1016/j.jclepro.2017.10.307

Love, D. C., Uhl, M. S., & Genello, L. (2015). Energy and water use of a small-scale raft aquaponics system in Baltimore, Maryland, United States. *Aquacultural Engineering*, *68*, 19–27. https://doi.org/10.1016/j.aquaeng.2015.07.003

Luo, L., Van Der Voet, E., & Huppes, G. (2009). Life cycle assessment and life cycle costing of bioethanol from sugarcane in Brazil. *Renewable and Sustainable Energy Reviews*, *13*, 1613–1619. https://doi.org/10.1016/j.rser.2008.09.024

Main Methods of Hydroponics. (2019). https://www.btlliners.com/the-main-methods-of-hydroponics

Maiolo, S., Parisi, G., Biondi, N., Lunelli, F., Tibaldi, E., & Pastres, R. (2020). Fishmeal partial substitution within aquafeed formulations: life cycle assessment of four alternative protein sources. *International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-020-01759-z

Malcorps, W., Kok, B., van't Land, M., Fritz, M., van Doren, D., Servin, K., van der Heijden, P., Palmer, R., Auchterlonie, N. A., Rietkerk, M., Santos, M. J., & Davies, S. J. (2019). The sustainability conundrum of fishmeal substitution by plant ingredients in Shrimp Feeds. *Sustainability (Switzerland)*, *11*(4), 1–19. https://doi.org/10.3390/SU11041212

Martin, M., & Molin, E. (2019). Environmental Assessment of an Urban Vertical Hydroponic Farming System in Sweden. *Sustainability*, *11*(15), 4124. https://doi.org/10.3390/su11154124

Maucieri, C., Forchino, A. A., Nicoletto, C., Junge, R., Pastres, R., Sambo, P., & Borin, M. (2017). Life cycle assessment of a micro aquaponic system for educational purposes built using recovered material. *Journal of Cleaner Production*, *172*, 3119–3127. https://doi.org/10.1016/j.jclepro.2017.11.097

Miah, J. H., Koh, S. C. L., & Stone, D. (2017). A hybridised framework combining integrated methods for environmental Life Cycle Assessment and Life Cycle Costing. *Journal of Cleaner Production*, *168*, 846–866. https://doi.org/10.1016/j.jclepro.2017.08.187

Monsees, H., Kloas, W., & Wuertz, S. (2016). Comparison of coupled and decoupled aquaponics: Implications for future system design. *European Aquaculture Society*. https://www.researchgate.net/publication/314305063

Monsees, H., Kloas, W., & Wuertz, S. (2017). Decoupled systems on trial: Eliminating bottlenecks to improve aquaponic processes. *PLoS ONE*, *12*(9), 1–18. https://doi.org/10.1371/journal.pone.0183056

Moreau, V., & Weidema, B. P. (2015). The computational structure of environmental life cycle costing. *The International Journal of Life Cycle Assessment*, *20*(10), 1359–1363. https://doi.org/10.1007/s11367-015-0952-1

Morelli, B., Hawkins, T. R., Niblick, B., Henderson, A. D., Golden, H. E., Compton, J. E., Cooter, E. J., & Bare, J. C. (2018). Critical review of eutrophication models for life cycle assessment. *Environmental Science and Technology*, *52*(17), 9562–9578. https://doi.org/10.1021/acs.est.8b00967

Moreno, D., Lopez-Berenguer, C., Martinez-Ballesta, C., Carvajal, M., & Garcia-Viguera, C. (2007). Basis for the new challenges of growing broccoli for health in hydroponics. *Journal of the Science of Food and Agriculture*, *1243*(January), 1237–1243. https://doi.org/10.1002/jsfa

Mungkung, R., Aubin, J., Prihadi, T. H., Slembrouck, J., Van Der Werf, H. M. G., & Legendre, M. (2013). Life cycle assessment for environmentally sustainable aquaculture management: A case study of combined aquaculture systems for carp and tilapia. *Journal of Cleaner Production*, *57*, 249–256. https://doi.org/10.1016/j.jclepro.2013.05.029

Notarnicola, B., Sala, S., Anton, A., McLaren, S. J., Saouter, E., & Sonesson, U. (2017). The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. *Journal of Cleaner Production*, *140*, 399–409. https://doi.org/10.1016/j.jclepro.2016.06.071

Oliver, D., & Wiebe, J. (2003). *Climate Change: We Are at Risk* (Issue Standing Senate Committee on Agriculture and Forestry).

Olsen, R. L., & Hasan, M. R. (2012). A limited supply of fishmeal: Impact on future increases in global aquaculture production. *Trends in Food Science and Technology*, *27*(2), 120–128. https://doi.org/10.1016/j.tifs.2012.06.003

Palm, H. W., Knaus, U., Appelbaum, S., Goddek, S., Strauch, S. M., Vermeulen, T., Haïssam Jijakli, M., & Kotzen, B. (2018). Towards commercial aquaponics: a review of systems, designs, scales and nomenclature. *Aquaculture Environment Interaction*, *26*, 813–842. https://doi.org/10.1007/s10499-018-0249-z

Pattillo, D. (2017a). An Overview of Aquaponic Systems: Aquaculture Components. In *North Central Regional Aquaculture Centre Technical Bulletins*. http://lib.dr.iastate.edu/ncrac_techbulletins/20

Pattillo, D. (2017b). An Overview of Aquaponic Systems: Hydroponic Components. In *Technical Bulletins North Central Regional Aquaculture Center*. http://lib.dr.iastate.edu/ncrac_techbulletins/19

Pelletier, N., Ardente, F., Brandão, M., De Camillis, C., & Pennington, D. (2015). Rationales for and limitations of preferred solutions for multi-functionality problems in LCA: is increased consistency possible? *International Journal of Life Cycle Assessment*, *20*(1), 74–86. https://doi.org/10.1007/s11367-014-0812-4

Pelletier, N., Tyedmers, P., Sonesson, U., Scholz, A., Ziegler, F., Flysjo, A., Kruse, S., Cancino, B., & Silverman, H. (2009). Not all salmon are created equal: Life cycle assessment (LCA) of global salmon farming systems. *Environmental Science and Technology*, *43*(23), 8730–8736. https://doi.org/10.1021/es9010114

Pennisi, G., Orsini, F., Blasioli, S., Cellini, A., Crepaldi, A., Braschi, I., Spinelli, F., Nicola, S., Fernandez, J. A., Stanghellini, C., Gianquinto, G., & Marcelis, L. F. M. (2019). Resource use efficiency of indoor lettuce (Lactuca sativa L.) cultivation as affected by red:blue ratio provided by LED lighting. *Scientific Reports*, *9*(1), 1–11. https://doi.org/10.1038/s41598-019-50783-z

Plastic Drum. (2020). Uline. https://www.uline.ca/Product/Detail/S-11860/Drums/Plastic-Drum-with-Lid-30-Gallon-Open-Top-Blue?pricode=YD824&gadtype=pla&id=S-11860&gclid=CjwKCAjwkun1BRAIEiwA2mJRWfQnEWI22yW-BJHSeKbzu-PLpGdwlsip3D0isQRGG517B9jZ03DLaxoC6E0QAvD_BwE&gclsrc=aw.ds

Polyethylene Tanks. (2020). Fish Farm Supply Co. https://www.fishfarmsupply.ca/collections/tanks/products/polyethylene-tanks?variant=41950533006

Proksch, G., Ianchenko, A., & Kotzen, B. (2019). Aquaponics in the Built Environment. In *Aquaponics Food Production Systems* (pp. 523–558). Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6_21

Pulina, P., Arru, B., Madau, F. A., Furesi, R., & Gasco, L. (2018). *Insect Meal in the Fish Diet and Feeding Cost: First Economic Simulations on European Sea bass Farming by a Case Study in Italy*. 17.

Purdy, A., Pathare, P. B., Wang, Y., Roskilly, A. P., & Huang, Y. (2018). Towards sustainable farming: Feasibility study into energy recovery from bio-waste on a small-scale dairy farm. *Journal of Cleaner Production*, *174*, 899–904. https://doi.org/10.1016/j.jclepro.2017.11.018

Quagrainie, K., Manolio, R., Flores, V., Kim, H.-J., & Mcclain, V. (2017). Economic analysis of aquaponics and hydroponics production in the U.S. Midwest. *Journal of Applied Aquaculture*, *30*(1), 1–14. https://doi.org/10.1080/10454438.2017.1414009

Rates & Tariffs. (2020). Nova Scotia Power. https://www.nspower.ca/about-us/electricity/rates-tariffs

Reap, J., Roman, F., Duncan, S., & Bras, B. (2008a). A survey of unresolved problems in life cycle assessment. Part 1: Goal and scope and inventory analysis. *International Journal of Life Cycle Assessment*, *13*(4), 290–300. https://doi.org/10.1007/s11367-008-0008-x

Reap, J., Roman, F., Duncan, S., & Bras, B. (2008b). A survey of unresolved problems in life cycle assessment. Part 2: Impact assessment and interpretation. *International Journal of Life Cycle Assessment*, *13*(5), 374–388. https://doi.org/10.1007/s11367-008-0009-9

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W. P., Suh, S., Weidema, B. P., & Pennington, D. W. (2004). Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International*, *30*(5), 701–720. https://doi.org/10.1016/j.envint.2003.11.005

Rebitzer, G., & Hunkeler, D. (2003). Life cycle costing in LCM: Ambitions, opportunities, and limitations - Discussing a framework. *International Journal of Life Cycle Assessment*, *8*(5), 253–256. https://doi.org/10.1007/BF02978913

Rehman, M., Ullah, S., Bao, Y., Wang, B., Peng, D., & Liu, L. (2017). Light-emitting diodes: whether an efficient source of light for indoor plants? *Environmental Science and Pollution Research*, *24*(32), 24743–24752. https://doi.org/10.1007/s11356-017-0333-3

Rizal, A., Dhahiyat, Y., Andriani, Y., Handaka, A. A., & Sahidin, A. (2018). The economic and social benefits of an aquaponic system for the integrated production of fish and water plants. *IOP Publishing IOP Conf. Series: Earth and Environmental Science*, *137 012098*. https://doi.org/10.1088/1755-1315/137/1/012098

Robb, D. H. F., MacLeod, M., Hasan, M. R., & Soto, D. (2017). *Greenhouse gas emissions from aquaculture A life cycle assessment of three Asian systems*.

Rockwool Production Process. (2020).

Roffeis, M., Almeida, J., Wakefield, M., Valada, T., Devic, E., Koné, N., Kenis, M., Nacambo, S., Fitches, E., Koko, G., Mathijs, E., Achten, W., & Muys, B. (2017). Life Cycle Inventory Analysis of Prospective Insect Based Feed Production in West Africa. *Sustainability*, *9*(10), 1697. https://doi.org/10.3390/su9101697

Romeo, D., Vea, E. B., & Thomsen, M. (2018). Environmental impacts of urban hydroponics in Europe: A case study in Lyon. *Procedia CIRP*, 540–545. https://doi.org/10.1016/j.procir.2017.11.048

Ross, L. G., Martinez Palacios, C. A., & Morales, E. J. (2008). Developing native fish species for aquaculture: The interacting demands of biodiversity, sustainable aquaculture and livelihoods. *Aquaculture Research, 39*(7), 675–683. https://doi.org/10.1111/j.1365-2109.2008.01920.x

Sabzalian, M. R., Heydarizadeh, P., Zahedi, M., Boroomand, A., Agharokh, M., Sahba, M. R., & Schoefs, B. (2014). High performance of vegetables, flowers, and medicinal plants in a red-blue LED incubator for indoor plant production. *Agronomy for Sustainable Development, 34,* 879–886.

https://doi.org/10.1007/s13593-014-0209-6

Saeid Mohamad, R., Verrastro, V., Cardone, G., Bteich, M. R., Favia, M., Moretti, M., & Roma, R. (2014). Optimization of organic and conventional olive agricultural practices from a Life Cycle Assessment and Life Cycle Costing perspectives. *Journal of Cleaner Production*, *70*, 78–89. https://doi.org/10.1016/j.jclepro.2014.02.033

San Martín, J. I., Zamora, I., San Martín, J. J., Aperribay, V., & Eguía, P. (2008). Trigeneration systems with fuel cells. *Renewable Energy and Power Quality Journal*, *1*(6), 135–140. https://doi.org/10.24084/repqj06.245

Sanyé-Mengual, E., Gasperi, D., Michelon, N., Orsini, F., Ponchia, G., & Gianquinto, G. (2018). Eco-efficiency assessment and food security potential of home gardening: A case study in Padua, Italy. *Sustainability (Switzerland)*, *10*(7). https://doi.org/10.3390/su10072124

Sanyé-Mengual, E., Oliver-Solà, J., Montero, J. I., & Rieradevall, J. (2015). An environmental and economic life cycle assessment of rooftop greenhouse (RTG) implementation in Barcelona, Spain. Assessing new forms of urban agriculture from the greenhouse structure to the final product level. *International Journal of Life Cycle Assessment*, *20*(3), 350–366. https://doi.org/10.1007/s11367-014-0836-9

Sanyé-Mengual, E., Orsini, F., Oliver-Solà, J., Rieradevall, J., Montero, J. I., & Gianquinto, G. (2015). Techniques and crops for efficient rooftop gardens in Bologna, Italy. *Agronomy for Sustainable Development*, *35*(4), 1477–1488. https://doi.org/10.1007/s13593-015-0331-0

Savić, B., Milojević, I., & Petrović, V. (2019). Cost optimization in agribusiness based on life cycle costing. *Ekonomika Poljoprivrede*, *66*(3), 823–834. https://doi.org/10.5937/ekopolj1903823s

Savidov, N. A., Hutchings, E., & Rakocy, J. E. (2007). Fish and plant production in a recirculating aquaponic system: A new approach to sustainable agriculture in Canada. *Acta Horticulturae*, *742*, 209–222. https://doi.org/10.17660/actahortic.2007.742.28

Sayadi-Gmada, S., Rodríguez-Pleguezuelo, C. R., Rojas-Serrano, F., Parra-López, C., Parra-Gómez, S., García-García, M. del C., García-Collado, R., Lorbach-Kelle, M. B., & Manrique-Gordillo, T. (2019). Inorganic Waste Management in Greenhouse Agriculture in Almeria (SE Spain): Towards a Circular System in Intensive Horticultural Production. *Sustainability*, *11*(14), 3782. https://doi.org/10.3390/su11143782

Schrijvers, D. L., Loubet, P., & Sonnemann, G. (2016). Critical review of guidelines against a systematic framework with regard to consistency on allocation procedures for recycling in LCA. *International Journal of Life Cycle Assessment*, *21*(7), 994–1008. https://doi.org/10.1007/s11367-016-1069-x

Shamshiri, R. R., Kalantari, F., Ting, K. C., Thorp, K. R., Hameed, I. A., Weltzien, C., Ahmad, D., & Shad, Z. (2018). Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. *International Journal of Agricultural and Biological Engineering*, *11*(1), 1–22. https://doi.org/10.25165/j.ijabe.20181101.3210

Smetana, S., Palanisamy, M., Mathys, A., & Heinz, V. (2016). Sustainability of insect use for feed and food: Life Cycle Assessment perspective. *Journal of Cleaner Production*, *137*, 741–751. https://doi.org/10.1016/j.jclepro.2016.07.148

Smit, M. C. (2012). A North Atlantic Treaty Organisation framework for life cycle costing. *International Journal of Computer Integrated Manufacturing*, *25*, 444–456. https://doi.org/10.1080/0951192X.2011.562541

Somerville, C., Cohen, M., Pantanella, E., Stankus, A., & Lovatelli, A. (2014). Small-scale aquaponic food production. Integrated fish and plant farming. In *FAO Fisheries and Aquaculture*.

Specht, K., Siebert, R., Hartmann, I., Freisinger, U. B., Sawicka, M., Werner, A., Thomaier, S., Henckel, D., Walk, H., & Dierich, A. (2014). Urban agriculture of the future: An overview of sustainability aspects of food production in and on buildings. *Agriculture and Human Values*, *31*(1), 33–51. https://doi.org/10.1007/s10460-013-9448-4

Specht, K., Zoll, F., Schümann, H., Bela, J., Kachel, J., & Robischon, M. (2019). How Will We Eat and Produce in the Cities of the Future? From Edible Insects to Vertical Farming—A Study on the Perception and Acceptability of New Approaches. *Sustainability*, *11*(16), 4315. https://doi.org/10.3390/su11164315

Spickova, M., & Myskova, R. (2015). Costs Efficiency Evaluation using Life Cycle Costing as Strategic Method. *Procedia Economics and Finance*, *34*, 337–343. https://doi.org/10.1016/s2212-5671(15)01638-x

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., de Vries, W., Vermeulen, S. J., Herrero, M., Carlson, K. M., Jonell, M., Troell, M., DeClerck, F., Gordon, L. J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., … Willett, W. (2018). Options for keeping the food system within environmental limits. *Nature*, *562*(7728), 519–525. https://doi.org/10.1038/s41586-018-0594-0

Styrofoam Slab. (2020). https://www.homedepot.com/p/STYROFOAM-2-in-x-4-ft-x-8-ft-R-10-Scoreboard-XPS-Insulation-1578/202899754

Svanes, E., Vold, M., & Hanssen, O. J. (2011). Environmental assessment of cod (Gadus morhua) from autoline fisheries. *International Journal of Life Cycle Assessment*, *16*, 611–624. https://doi.org/10.1007/s11367-011-0298-2

Today's Energy Stats. (2020). Nova Scotia Power. https://www.nspower.ca/clean-energy/todays-energy-stats#

Tokunaga, K., Tamaru, C., Ako, H., & Leung, P. (2015). Economics of small-scale commercial aquaponics in hawai'i. *Journal of the World Aquaculture Society*, *46*(1), 20–32. https://doi.org/10.1111/jwas.12173

Tyson, R. V., Treadwel, D. D., & Simonne, E. H. (2011). Opportunities and challenges to sustainability in aquaponic systems. *HortTechnology*, *21*(1), 1–13. https://doi.org/10.21273/horttech.21.1.6

Uline Bulk T-8 Bulbs. (2020). https://www.uline.ca/Product/Detail/S-19983/Light-Bulbs/Fluorescent-Tubes-48-T8-Daylight?pricode=YE011&gadtype=pla&id=S-19983&gclid=Cj0KCQiAhs79BRD0ARIsAC6XpaW0ii4f69_tb3vo7CKPY39aGbtvh-Ys3ciWhJV4XIGbk5VAjYZcN94aAkphEALw_wcB&gclsrc=aw.ds

Uline T-8 LED Bulbs. (2021). https://www.uline.ca/Product/Detail/S-23706/Light-Bulbs/Sylvania-Glass-LED-Tubes-48-T8-Daylight

US Department of Energy. (2019). *Characterization of CHP Opportunities at U.S. Wastewater Treatment Plants*. *April*, 23.

US Department of Energy. (2020). *Insulation*. https://www.energy.gov/energysaver/weatherize/insulation

Uuemaa, P., Vigants, H., Blumberga, D., & Drovtar, I. (2014). Industrial CHP excess heat efficient usage for cooling. *Energetika*, *60*(2), 136–148. https://doi.org/10.6001/energetika.v60i2.2937

Villarroel, M., Junge, R., Komives, T., König, B., Plaza, I., Bittsánszky, A., & Joly, A. (2016). Survey of aquaponics in Europe. *Water (Switzerland)*, *8*(10), 3–9. https://doi.org/10.3390/w8100468

Weidema, B. P., & Wesnæs, M. S. (1996). Data quality management for life cycle inventories-an example of using data quality indicators. *Journal of Cleaner Production*, *4*(3–4), 167–174. https://doi.org/10.1016/S0959-6526(96)00043-1

Weidema, B., & Schmidt, J. (2010). Avoiding Allocation in Life Cycle Assessment Revisited. *Journal of Industrial Ecology*, *14*(2), 192–195. https://doi.org/10.1111/j.1530-9290.2010.00236.x

Wender, B. A., Foley, R. W., Hottle, T. A., Sadowski, J., Prado-Lopez, V., Eisenberg, D. A., Laurin, L., & Seager, T. P. (2014). Anticipatory life-cycle assessment for responsible research and innovation. *Journal of Responsible Innovation*, *1*(2), 200–207. https://doi.org/10.1080/23299460.2014.920121

Wilson, J., Carscallen, M., & Kierstead, P. (2018). *Confidential Business Plan & Cost Projections*.

Wolsey, R. (1993). T8 Fluorescent Lamps. *Lighting Answers Volume 1*, *Issue 1*.

Wu, F., Ghamkhar, R., Ashton, W., & Hicks, A. L. (2019). Sustainable Seafood and Vegetable Production: Aquaponics as a Potential Opportunity in Urban Areas. *Integrated Environmental Assessment and Management*, *15*(6), 832–843. https://doi.org/10.1002/ieam.4187

Xie, K., & Rosentrater, K. A. (2015). Life cycle assessment (LCA) and Techno-economic analysis (TEA) of tilapia-basil aquaponics. *Agricultural and Biosystems Engineering*, 2–32. https://doi.org/10.13031/aim.20152188617

Yan, M., & Holden, N. M. (2018). Life cycle assessment of multi-product dairy processing using Irish butter and milk powders as an example. *Journal of Cleaner Production*, *198*, 215–230. https://doi.org/10.1016/j.jclepro.2018.07.006

Yep, B., & Zheng, Y. (2019). Aquaponic trends and challenges – A review. *Journal of Cleaner Production*, *228*, 1586–1599. https://doi.org/10.1016/j.jclepro.2019.04.290

Yildiz, H., Robaina, L., Domínguez, D., Pirhonen, J., Mente, E., & Parisi, G. (2017). Fish welfare in aquaponic systems: Its relation to water quality with an emphasis on feed and faeces-A review. *Water (Switzerland)*, *9*(1). https://doi.org/10.3390/w9010013

Zhang, S., Bi, T., & Clift, R. (2013). A Life Cycle Assessment of integrated dairy farm-greenhouse systems in British Columbia. *Bioresource Technology*, *150*, 496–505. https://doi.org/10.1016/j.biortech.2013.09.076

Appendix A: Life Cycle Inventory Data

Table A-1: Infrastructure Weights

Component	Material	Weight (kg)	Quantity	Reference
210-gal tank	HDPE	22.7	1	(Fish Farm Supply Co, 2020)
50-gal tank	HDPE	11.3	2	(Fish Farm Supply Co, 2020)
32-gal tank	HDPE	7.3	1	(*Plastic Drum*, 2020)
Rack	Steel	30.4	~3.8	(*DEWALT Shelf Steel*, 2020)
Rockwool cube	Rockwool	0.0022	6528	(Ghamkhar et al., 2019)
Styrofoam slab	Polystyrene	8.58	6	(*Styrofoam Slab*, 2020)
Pipes	PVC	64	unknown	(Hindelang et al., 2014)

Table A-2: Infrastructure Materials and Lifespans

Component	Main Material	Lifespan (Years)	Reference
Rack	Steel	20	(*Estimated Life Expectancy Chart*, 2019)
Tanks	HDPE	20	(Pattillo, 2017a)
Pipes	PVC	20	(Proksch et al., 2019)
Fluorescent Bulbs	Not considered	2.5	(Wolsey, 1993)
LED Bulbs	Not considered	5	(Rehman et al., 2017)
Raft Trays	Polystyrene	3	(Ghamkhar et al., 2019)
Growing Media	Rockwool	1	(*Rockwool Production Process*, 2020)

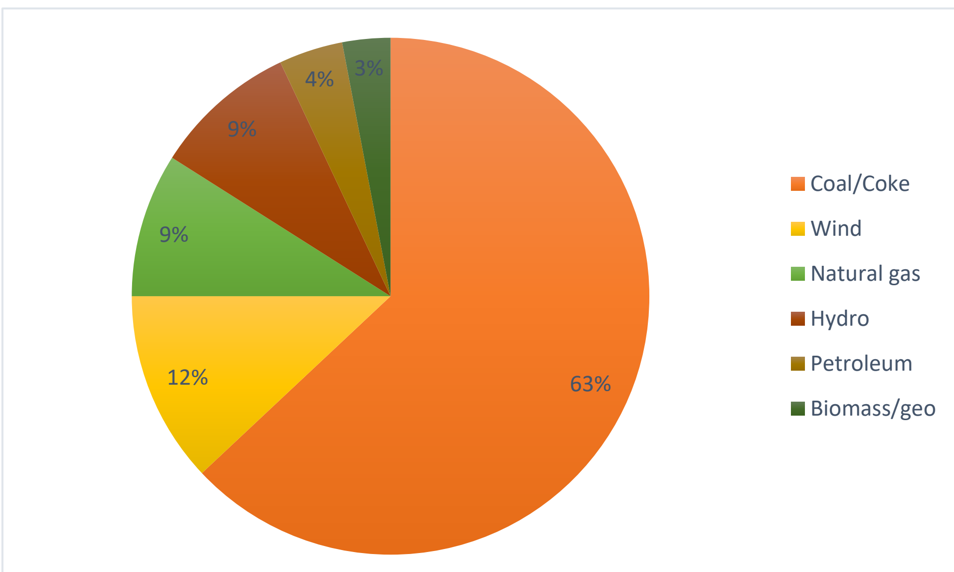

Figure A-1: Nova Scotia Grid Composition, 2018 (Today's Energy Stats, 2020)

Table A-3: Life Cycle Inventory for Black-Box Approach

Flow	Quantity	Unit	Assumptions and Sources[1]
	Black Box Approach		
INPUTS			
Hatchlings	0.24	kg	Adult trout production, conservative approach
Seeds	0.00011	kg	
Water	62.68	kg	Tap water production in Quebec
Electricity	216.26	kWh	Grid composition used in Nova Scotia in 2018, see *Figure A-1*
Heating	94.48	kWh	Electrical heating used, compared to natural gas and biogas
Potassium	0.012	L	
Calcium	0.012	L	
Iron	0.0065	L	
Feed			Energy required for blending feed components neglected
Soybean meal	0.65	kg	
Wheat	0.28	kg	
Corn/maize	0.28	kg	
Fishmeal and fish oil	0.09	kg	
Infrastructure			Based on 20 year lifespan, after which replaced
PVC	0.014	kg	
HDPE	0.032	kg	
Steel	0.018	kg	
Rockwool	0.226	kg	Annual replacement, from (De La Hera et al., 2016)
Polystyrene slabs	0.365	kg	Annual replacement, 100% virgin materials
OUTPUTS			
Live fish	**1**	kg	Rainbow Trout and Striped Bass
Leafy greens	4.69	kg	Various lettuces, chard, basil

[1]All unit processes from ecoinvent 3.5 database.

Table A-4: Life Cycle Inventory for Insect-Based Feed, from (Roffeis et al., 2017)

Flow	Quantity	Unit
INPUTS		
Land	0.05	m^2a
Built infrastructure	0.11	m^2a
Manure, dried	6.30	kg
Brewery waste	8.90	kg
Water	74.60	L
Natural gas	3.30	MJ
Transport by truck	0.10	km
OUTPUTS		
Wastewater	49.80	L

CH_4 to air	11.30	g
N_2O to air	0.20	g
NH_3 to air	2.10	g
Volatile solids to air	1.80	g
IBF	**1.00**	kg
Residue substrate	7.10	kg

Table A-5: Impact Categories and Units

Impact Category	Unit
Acidification	kg SO2 eq
Carcinogenics	CTUh
Ecotoxicity	CTUe
Eutrophication	kg N eq
Fossil fuel depletion	MJ surplus
Global warming potential	kg CO2 eq
Non-carcinogenics	CTUh
Ozone depletion	kg CFC-11 eq
Respiratory effects	kg PM2.5 eq
Smog	kg O3 eq

Appendix B: Data Quality

Table B-1: Data Quality Matrix, Adapted from (Weidema & Wesnæs, 1996)

Indicator score	**1**	**2**	**3**	**4**	**5**
Temporal correlation	Less than three years of different to year of study date	Less than six years difference	Less than 10 years difference	Less than 15 years difference	Age of data unknown or more than 15 years difference
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown are or area with very different production conditions
Technological correlation	Data from enterprises, processes, and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

Table B-2: Data Quality Scores

Inventory Flow	**Time Period**	**Geographic Region**	**Data Quality Scores**
Electricity Generation			
Coal	2013	Global	(2,2,1)
Wind	2013	Nova Scotia, CA	(2,1,1)
Hydro	2012	Switzerland	(2,2,3)
Natural Gas	2013	Nova Scotia, CA	(2,1,1)
Oil	2013	Global	(2,2,2)
Biomass	2014	Switzerland	(2,4,3)
Imports	2013	New Brunswick, CA	(2,1,1)
Composition	2018	Nova Scotia, CA	(1,1,1)
Infrastructure			
Steel	2005	Germany	(4,4,2)
Steel Manufacturing	2011	Quebec, CA	(3,3,2)
Polystyrene, Virgin	2003	Global	(4,4,4)
Polystyrene, 100% Recycled	2003	Global	(4,4,4)
Rockwool	2000	Switzerland	(5,4,5)
Hatchlings	2012	Peru	(2,5,4)
Feed			
Maize	2018	Quebec, CA	(1,2,2)
Wheat	2018	Quebec, CA	(1,2,2)
Soybean Meal	2011	Global	(3,4,2)
Fishmeal and Fish Oil	2016	Peru and Chile	(1,4,4)

Appendix C: Life Cycle Impact Results

For aquaculture, the functional unit (FU) is 1 kg live fish and for hydroponics, the FU is 1 kg live fish.

Table C-1: Impact Results for Scenario Analysis for Aquaculture and Hydroponics Units

Scenario	*Global Warming Potential (kg CO_{2eq}/FU)*		*Fossil Fuel Depletion (MJ surplus/FU)*		*Acidification (kg SO_{2eq}/FU)*		*Eutrophication (kg N_{eq}/FU)*	
Unit Process	Aquaculture	Hydroponics	Aquaculture	Hydroponics	Aquaculture	Hydroponics	Aquaculture	Hydroponics
O	68.02	49.52	30.30	25.52	0.48	0.34	0.30	0.19
EFF	59.36	27.71	26.60	16.21	0.42	0.19	0.27	0.10
W	3.02	2.55	3.63	5.95	0.03	0.01	0.07	0.01
BG	18.85	9.61	9.80	8.69	1.19	0.54	0.54	0.22
IBF	2.61	-	3.14	-	0.02	-	0.06	-