SUSTAINABLE SHRIMP PRODUCTION CHAIN IN THE MIDWESTERN UNITED STATES

by

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First and foremost, I owe my sincerest gratitude to Allah the Almighty for his endless blessing in my life.

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ABSTRACT

With the increasing global population, providing sufficient food to meet the rising demand has become a great challenge to food-producing sectors. Aquaculture is one of the food sources which produces varieties of seafood. Shrimp is the most popular seafood in the US, and its production plays an important role in the aquaculture industry. However, shrimp farming causes various types of pollution to damage the environment and aquatic biodiversity, the associated impacts must be mitigated to ensure the sustainability of shrimp production. This study performed a life cycle assessment (LCA) on different shrimp production chains from cradle to the market in Midwestern US covering three farming systems and eight shrimp feed formulas. Midpoint environmental impacts including acidification potential (AP), eutrophication potential (EP) and global warming potential (GWP) were determined. Feed production was identified as the main contributor to the AP and GWP for both the intensive and semi-intensive production systems (SPS), regardless of the feed formula. While the environmental performance of feed production highly depended on the feed conversion ratio, feed ingredient was another determining factor in which animal protein sources, including poultry by-product meal and fishmeal, showed high contributions to the AP and GWP. However, plant proteins such as soybean, wheat, and corn gluten meals produced higher EP, therefore, substituting plant-based ingredients for animal-based ones in shrimp feeds did not all result in positive environmental consequences. Shrimp farming was the hotspot of all the three impacts, especially accounting for the highest EP. Among the three farming systems studied here, the SPS caused the highest environmental burdens due to the intensive uses of chemicals and fertilizers. On the contrary, the extensive farming was found to be the most sustainable system because no inputs of feeding and additional materials and energy are required for its operation. The LCA model developed in this study is expected to serve as US shrimp farmers' decision-making guidelines to adapt farming practices with lower environmental footprint.

CHAPTER 1. INTRODUCTION

1.1 Overview

By 2050, the global population is expected to increase to 9.7 billion (UNDESA, 2015). This increase will create a significant challenge to food-producing sectors in terms of sufficient food production for the rising food demand. Therefore, diversification of food sources is essential to ensure food security. Aquaculture produces all sorts of seafood and plays an important role in supporting food security. In September 2015, United Nations (UN) member states adopted the 2030 Agenda for Sustainable Development, which defines a goal that fisheries and aquaculture should contribute towards food security and nutrition, with the use of natural resources aiming to ensure sustainable development in economic, social and environmental terms (FAO, 2016).

Figure 1.1 shows the evolution of global capture fisheries and aquaculture production. The world capture fisheries production increased from 69 to 93 million tonnes over the last three decades, in the meantime, the global aquaculture production jumped from approximately 5 to 63 million tonnes (FAO, 2016). The world average, per capita consumption of aquatic food increased from 9.9 kg in the 1960s to 14.4 kg in the 1990s, and the increase continued to reach 19.7 kg in 2013, which mainly results from rising household incomes and urbanization (FAO, 2016). In addition, growing international trade has provided consumers with more options of aquatic food (FAO, 2016). The increasing consumption of aquatic food nutritionally enhances human diets around the world because it is rich in protein and essential amino acids, and also provides essential fats, vitamins, and minerals (FAO, 2016). In 2013, aquatic food accounted for 6.7% of global protein consumption and 17% of animal protein consumption (Quaas et al., 2016).

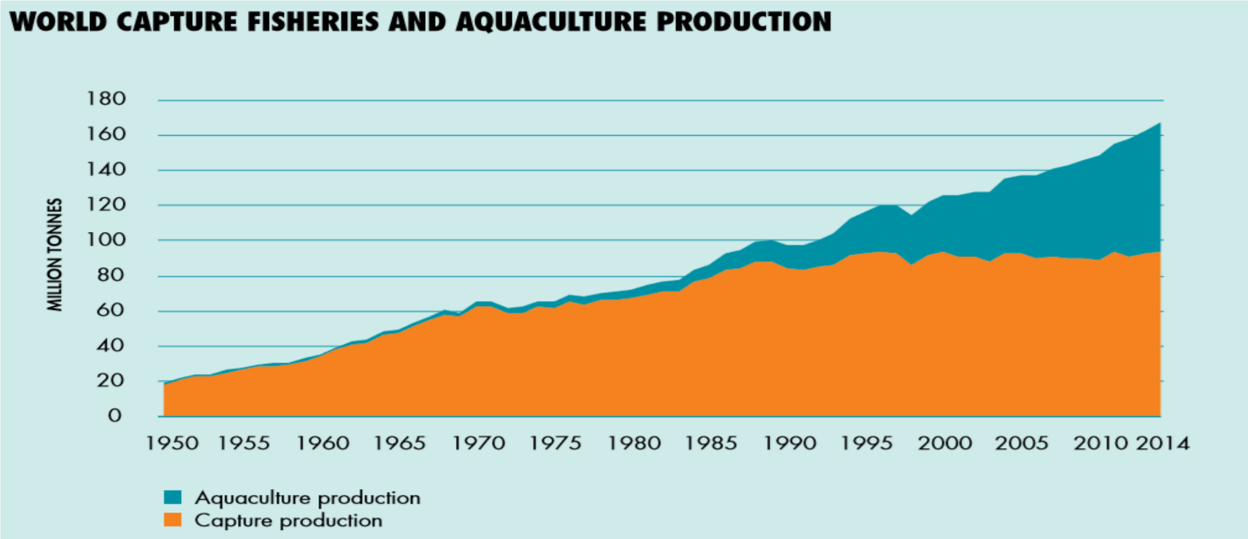


Figure 1.1. Evolution of global capture fisheries and aquaculture production (FAO, 2016).

Although aquaculture provides human with more dietary choices, the related activities can adversely affect the environment (Pillay, 2007). First, aquaculture needs space on land, or in lake or sea. Also, cultivation of aquatic animals needs oxygenated water. For some farming systems, feed is used to increase production yield. Energy is required for water pumping, aeration and temperature control. Besides, waste like uneaten food, animal faces and chemicals need to be removed and generally released to the environment. All these inputs of materials and energy, as well as emissions can increase the environmental burdens such as acidification, eutrophication, and climate change (Beveridge & Brummett, 2016), which highly depend on aquaculture species, location, farming system and management (Beveridge & Brummett, 2016). These environmental impacts are expected to become more severe while aquaculture production continuous to increase due to the growing number of farms and development of new farming technologies. Since the global seafood demand cannot be met without aquaculture (Tucker, Hargreaves, & Boyd, 2008), the trade-offs between food security and the environment have to be carefully assessed to lead the governments to examine their policies of sustainable development (Pillay, 2007).

1.2 Aquaculture

Wild aquatic animals are in limited supply, which, cannot keep up with the demand along with the growing global population. Furthermore, excessive capture of marine animals will adversely affect the sustainability of our environment. Therefore, aquatic animal farming, i.e., aquaculture, is needed to meet the increasing food demands while ensuring the sustainability of wild aquatic animals (Shrestha, A. & Shrestha, R., 2017). Aquaculture is rearing aquatic organisms, including fish, mollusks, crustaceans, and aquatic plants under controlled or semi-controlled conditions (Othmer, Kirk, & Stickney, 2004). Aquaculture is considered as the fastest-growing animal food source over the last five decades. In 1974, aquaculture provided 7% of aquatic food for human consumption, which increased to 26% in 1994, and 39% in 2004 (FAO, 2016). In 2016, global fishery production was 171 million tonnes, and aquaculture represented 47%, which is expected to reach 52% in 2025, as shown in Figure 1.2 (FAO, 2018).

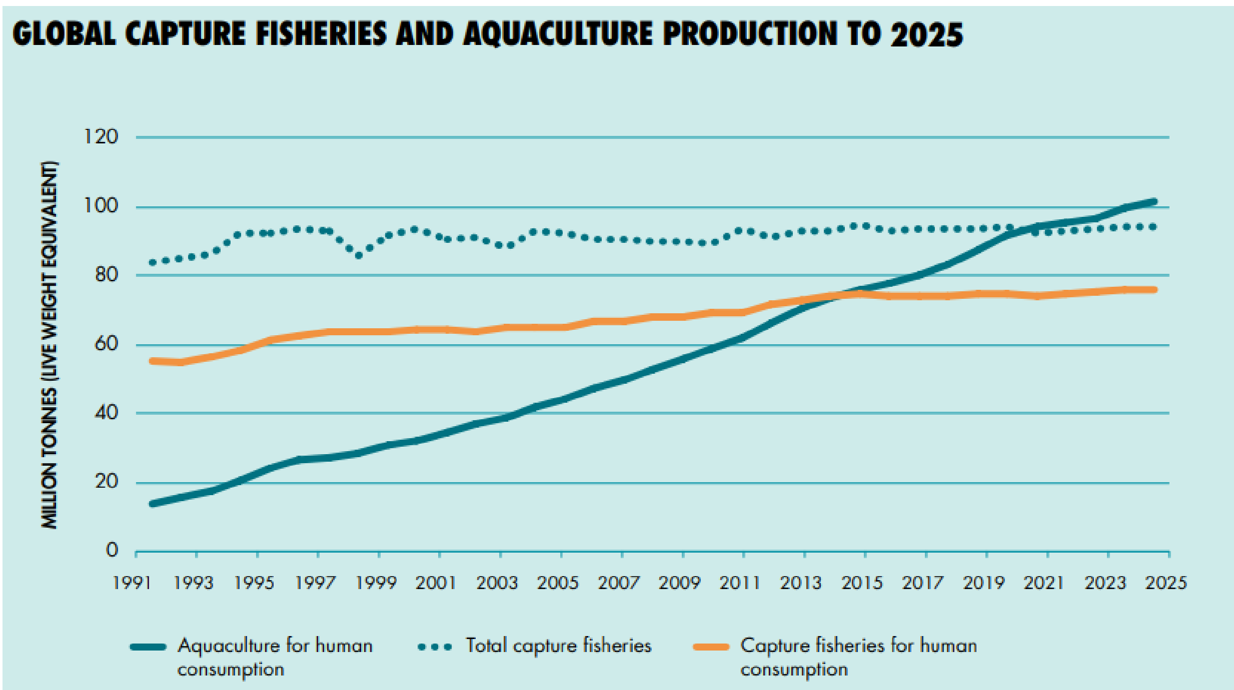


Figure 1.2. Global trajectories of capture fisheries and aquaculture production for human consumption (FAO, 2018).

Aquaculture is less environmentally demanding because it requires fewer resource inputs compared to other animal products. For example, with the same land area, the food produced via aquaculture is ten times or more of that from cattle and pig rearing (Shrestha, A. & Shrestha, R., 2017). Therefore, aquaculture is an important economic activity in many countries where arable land is scarce, especially in Asia. In China, between 1980 and 1997, aquaculture production grew at an annual rate of 16.7%, from 1.9 to around 23 million tonnes (Shrestha, A. & Shrestha, R., 2017). Moreover, the livelihoods of 10−12% of the world population are supported by fisheries and aquaculture, which provided jobs for 60 million people in 2012 (UN, 2014). Table 1.1 summarizes the major species and systems of aquaculture production in different regions for human consumption in 2014.

Table 1.1. Global aquaculture production of different species and systems in 2014 (FAO, 2016).

Region	Species	Inland aquaculture (Tonne)	Marine and coastal aquaculture (Tonne)	Total (Tonne)
Africa	Finfish	1,682,039	12,814	1,694,853
	Molluscs	-	3,708	3,708
	Crustaceans	7,240	5,108	12,348
	Other animals	-	1	1
Americas	Finfish	1,076,073	1,018,460	2,094,533
	Molluscs	-	539,989	539,989
	Crustaceans	63,915	652,610	716,525
	Other animals	567	-	567
Asia	Finfish	40,319,666	3,388,124	43,707,790
	Molluscs	277,744	14,545,398	14,823,142
	Crustaceans	2,673,159	3,507,019	6,180,178
	Other animals	520,244	370,538	890,782
Europe	Finfish	477,051	1,820,109	2,297,160
	Molluscs	-	631,789	631,789
	Crustaceans	74	241	315
	Other animals	39	824	863
Oceania	Finfish	4,432	63,124	67,556
	Molluscs	149	114,566	114,715
	Crustaceans	-	5,558	5,558
	Other animals	-	1,354	1,354
World	Finfish	43,559,260	6,302,631	49,861,891
	Molluscs	277,744	15,835,450	16,113,194
	Crustaceans	2,744,537	4,170,536	6,915,073
	Other animals	520,850	372,718	893,568
	Total	47,102,391	26,681,334	73,783,725

1.3 Aquaculture Systems

There are three major types of aquaculture system: open system, semi-closed system, and closed system, which have different levels of control of cultivation conditions, in terms of oxygen, temperature, and waste removal, the three critical elements to aquaculture (Tidwell, 2012). The following sections introduce these systems in detail and compare their advantages and disadvantages.

1.3.1 Open (Extensive) System

The open system is the oldest method for aquaculture, in which the dissolved oxygen content and temperature of water, as well as removal of biological waste are controlled solely by natural environment (Folke & Kautsky, 1989). For example, natural water flow can enhance dissolution of oxygen into water and remove feces of aquatic animals. Moreover, food for aquatic animals, like algae and phytoplankton, is provided naturally, which decreases the operating cost. However, the low growth rate and thus mass of aquatic animals harvested per area are the disadvantages of this system (Tidwell, 2012).

Depending the animal species raised, open system can be operated in several ways (Tidwell, 2012), including:

(i) Bivalve culture (floats, trays, and rafts; Figure 1.3): Bivalve culture method is commonly used in many countries across temperate and tropical regions like North America and Australia (Quayle & Newkirk, 1989). This method is used particularly for benthic animals by placing animals inside containers that are suspended off the bottom. In addition to preventing predation, this method allows animals to be cultivated at a specific depth where they can secure phytoplankton as the main nutrient source with the maximum density. (Tidwell, 2012). This method is environmentally friendly because it does not need feeding which can cause marine eutrophication (Gibbs, 2007; Sanz-Lazaro et al., 2018).

Figure 1.3. Open aquaculture system: bivalve culture of geoduck (nap.edu, 2010).

Cage and net pens (Figure 1.4): This method is for finfish and sometimes for crustaceans, which uses fixed cages in shallow waters like bay or lake with appropriate muddy bottoms, or net pens floated in rafts and anchored to lake/reservoir/river bottom (Tidwell, 2012).

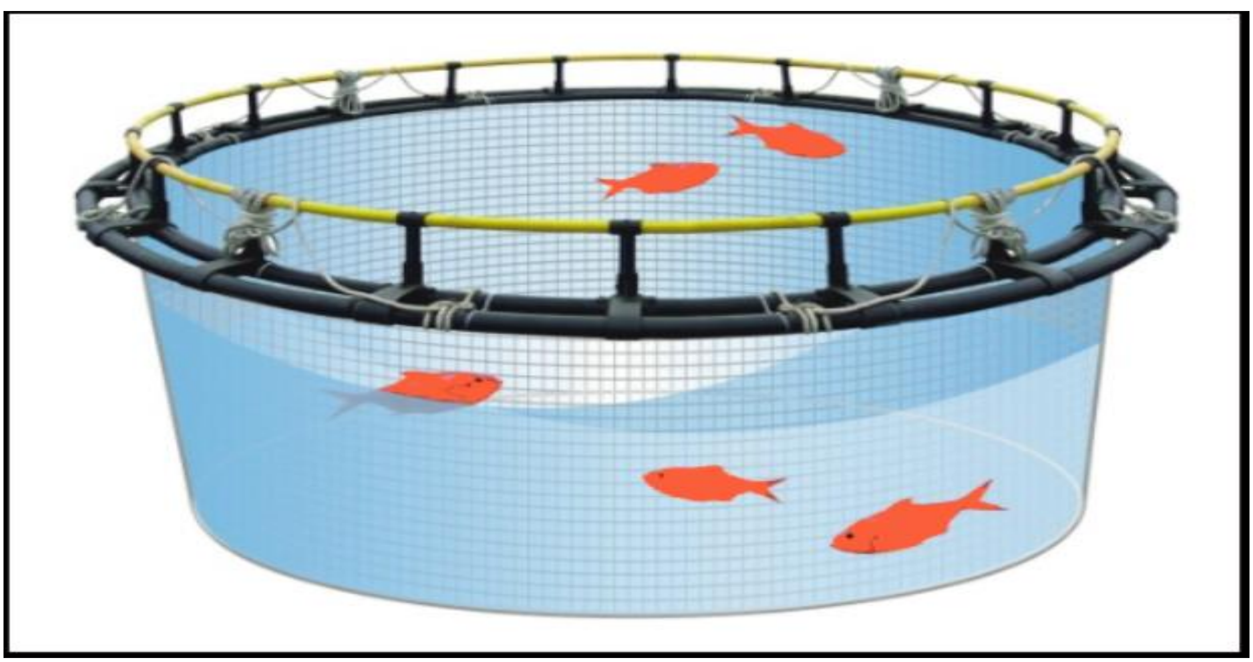


Figure 1.4. Open aquaculture system: cage and net pens (goodfishbadfish.com.au)

1.3.2 Semi-Closed (Semi-Intensive) System

Semi-closed system is operated in constructed production units using water from rainfall, spring, or river, hence the quality of cultivating water (i.e., oxygen, temperature, and waste) is regulated mainly by nature environment. This system has many advantages over open system. First, cultivation using prepared feed is more efficient. Besides, monitoring of water quality and detection of animal diseases are easier (Tidwell, 2012). However, semi-closed system needs more human control over the production compared to open system, like feeding and water management (Tidwell, 2012). For example, the water for cultivation can be used for one time then discharged, or regularly cleaned before reoxygenated by natural processes (Tidwell, 2012). Furthermore, the construction and equipment used for this system are costly, and the demands for energy and feed are greater (Tidwell, 2012).

Semi-closed system can be divided in two major types:

(i) Raceway (Figure 1.5): The production units are human-made, earthen or concrete troughs. The cultivating water comes from groundwater like springs or surface water like melted snow or rainwater runoff from high elevations, which can bring oxygen and remove waste away from units (Jerbi et al., 2012; Tidwell, 2012). Raceway system is more intensive, which can produce more than 300 tonnes of fish per hectare of land per year (Tidwell, 2012). However, raceway has a high water demand, for example, producing 1 kg of trout needs 98,000 L of water. Therefore, this method is only used in regions with sufficient water supply at required temperature throughout the year (Badiola et al., 2017; Tidwell, 2012).

Figure 1.5. Semi-closed aquaculture system: raceway (ussoy.org, 2018)

(ii) Pond: Pond system is prevalent, which requires sufficient high-quality water. This system has two main types: watershed (Figure 1.6) and levee (Figure 1.7), depending on the source of water. Watershed pond is suitable in the areas with sufficient rainfall to fill the pond, while levee pond works for the areas where groundwater is the primary water source (Freshwater-Aquaculture, 2019). The size of pond depends on the type of animal species cultivated. For example, prawn rearing needs 0.1−0.2 ha but cultivating catfish consumes more than 8 ha. Without supplement feeding, the biomass density of pond system is around 500 kg/ha, which can increase to 1,500 kg/ha with 30−40 kg/ha/day of supplement feed. However, increasing biomass density can decrease the amount of dissolved oxygen in pond, which can thus limit the harvest if the oxygen of the system only comes from photosynthetic phytoplankton. Therefore, incorporation of mechanical aeration can provide additional oxygen, allowing to increase feeding to 100 kg/ha/day in order to increase the production to more than 4,500 kg/ha (Tidwell, 2012). Solid waste generated in pond system is naturally degraded by heterotrophic bacteria and detritivores. Ammonia (NH_3) produced by aquatic animals can be directly absorbed by algae, or converted to nitrite (NO_2^-) by *Nitrosomonas* bacteria then further converted to nitrate (NO_3^-) by *Nitrobacter* bacteria, which can also be absorbed by algae. Therefore, increasing the numbers of algae and nitrification bacteria is important for nitrogen removal in the pond system (Tidwell, 2012).

Figure 1.6. Semi-closed aquaculture system: watershed pond (iowaenvironmentalfocus.org).

Figure 1.7. Semi-closed aquaculture system: levee pond (Avery, 2010)

1.3.3 Closed (Intensive) System

Closed system has full human control over the cultivation to minimize environmental interventions (Tidwell, 2012). The advantages of closed system include minimal exchange of water (hence minimum water demand) (Lucas, Southgate, & Tucker, 2012), and high yield. However, closed system has high construction and operating (electricity and maintenance) costs, and it has to be operated by well-trained personnel (Lucas, Southgate, & Tucker, 2012). Different closed systems include:

(i) Recirculating aquaculture system (RAS) (Figure 1.8): RAS is suitable for harsh areas with arid climatic conditions (Al-Hafedh & Alam, 2007). In RAS, the same batch of water is used repeatedly to minimize water consumption and reduce waste discharge (Badiola et al., 2017). To ensure the water quality, the level of dissolved oxygen is regulated by aeration/oxygenation. Moreover, mechanical filters are applied to remove solid waste, and nitrogenous waste generated by aquatic animals is detoxified to nitrite then nitrate by nitrifying bacteria, which are cultured in separate vessels as biofilters with water circulation (Tidwell, 2012).

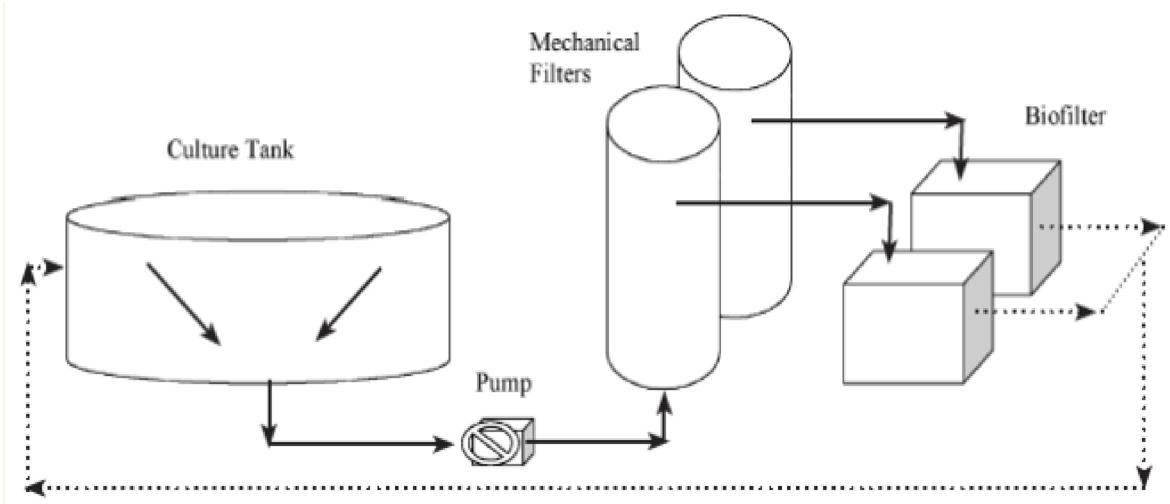


Figure 1.8. Closed aquaculture system: recirculating aquaculture system (Al-Hafedh & Alam, 2007).

(ii) Biofloc system (Figure 1.9): The main difference between RAS and biofloc system is that the heterotrophic bacteria used in biofloc system live with aquatic animals in the same tank. In the biofloc system, nitrogenous waste is converted to bacterial biomass, and solid waste retained in the tank is colonized with heterotrophic bacteria then becomes a great source of protein for aquatic animals. However, this system has a high demand for oxygen due to the presence of a large number of bacterial colonies.

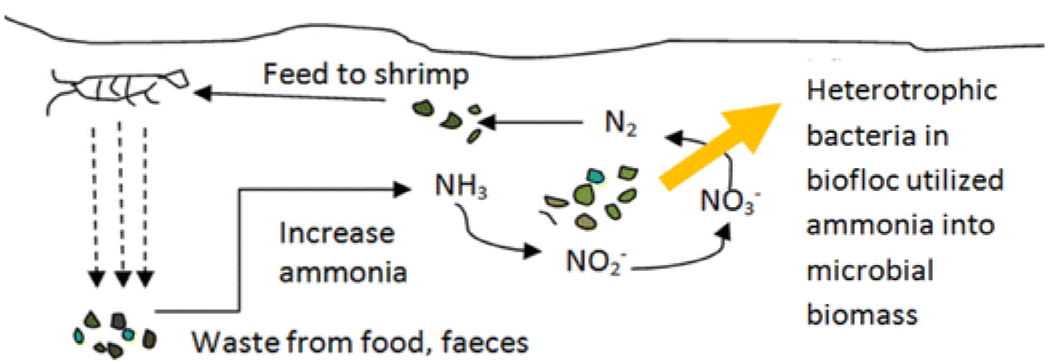


Figure 1.9. Closed aquaculture system: biofloc system (Manan et al., 2016).

(iii) Aquaponics (Figure 1.10): Aquaponics is a combination of two food productions, aquaculture and hydroponics (cultivating plants in water without soil), within a closed recirculating system (FAO, 2016). The plants in aquaponics system act as biofilters, their roots can absorb nitrogenous waste and maintain the water quality required by aquatic animal cultivation (FAO, 2016). Aquaponics has high production yield with low inputs of land, manpower and chemicals. Furthermore, aquaponics does not need fertilizers or pesticides, so it is an useful production method in arid regions where the soil is not suitable for plant cultivation (FAO,2016).

Table 1.2 summarizes the features of different aquaculture systems.

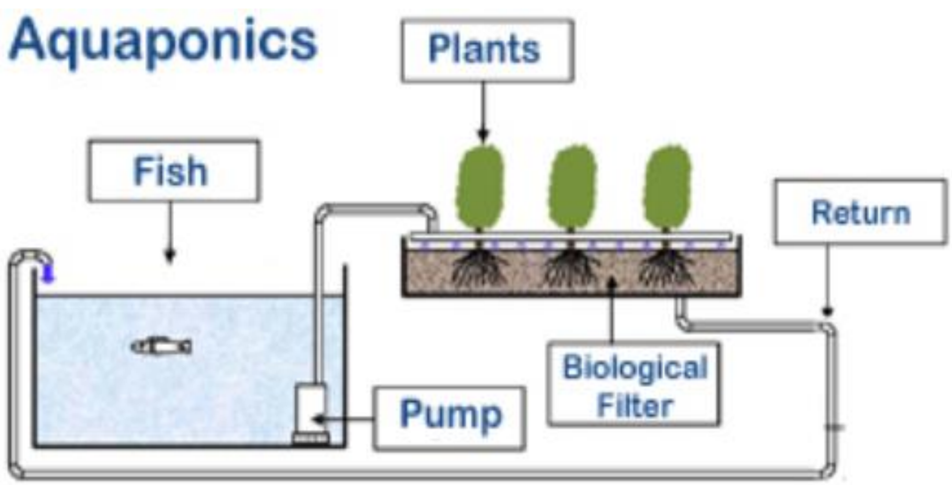


Figure 1.10. Closed aquaculture system: aquaponics (appropedia.org)

Table 1.2. Features of major aquaculture systems.

System	Species	Region	Advantage	Disadvantage
Extensive system				
Bivalve culture	Benthic animals	Coast, lake	Environmentally friendly Natural feeding	Only applicable to few species
Cage and net pens	Finfish, crustaceans	Bay, lake	Very low energy demand Low cost Minimum human control required	Low yield
Semi-intensive system				
Raceway	Suitable for many species	Areas where water runoff from high elevations	Low feed conversion ratio (FCR)	High cost for construction High demand for water Discharge of harmful waste to the environment
Pond		Areas where water is available throughout the year from rivers, lakes, or rain	Low FCR High yield Better control over the water quality and feed	High cost for construction Possible discharge of harmful waste to the environment
Intensive system				
RAS	Suitable for many species.	Suitable for any areas especially in arid regions	Low demand for water High yield with low land use	High energy demand

Biofloc	Low demand for water High yield with low land use Lower FCR than RAS
Aquaponics	Benefit exchange between cultivations of vegetables and aquatic animals No need for chemicals or fertilizers High yield with low land use

1.4 Shrimp

1.4.1 Shrimp Production

Shrimp is a species of Decapoda, which is an order of crustaceans with five pairs of legs like lobster and crab (Ackefors, 2009). There are hundreds of shrimp species found in fresh, brackish, and sea waters, but most of these species are unused for human consumption (Dore & Frimodt, 1991). Whiteleg shrimp (*Litopenaeus vannamei*; Figure 1.10) is one of the commercial shrimps and also the dominant farmed species (Ackefors, 2009). Whiteleg shrimp is native to the Eastern Pacific coast and lives in tropical marine areas, where the water temperature is over 20 ºC throughout the year. Adult shrimp lives in the ocean and each shrimp can spawn 100,000−250,000 eggs of approximately 0.22 mm in diameter. After 16 hours of spawning, eggs are hatched to nauplii (the first stage of larvae). Nauplii do not require feeding but absorb the yolks in their ventrally attached sacs. At the following larval stages (protozoea, mysis, and early postlarvae), larvae feed on phytoplankton and zooplankton. Postlarvae migrate inshore with tidal currents to spend their juvenile and pre-adult stages in freshwater areas. Postlarvae start to feed on benthic detritus, worms, bivalves, and crustaceans (FAO, 2009). After 6−7 months, the weights of mature shrimp are around 20 and 28 g for male and female, respectively.

Figure 1.11. White shrimp (*Litopenaeus vannamei*) (Mustapha, 2018).

Shrimp is a great source of protein, 100 g of cooked shrimp provides 24 g of protein (FDA, 2008). Shrimp is one of the most popular seafood in the world (Mahmoud, 2009). The global shrimp aquaculture production increased rapidly from less than 9000 tonnes in 1970 to 3.5 million tonnes in 2009, while the capture shrimp was 3 million tonnes (Asche et al., 2011; Cao et al., 2001), as shown in Figure 1.12. In 2018, its production reached around 4 million tonnes, with an increase of 3−5% over 2017 (FAO, 2019). The US is the main market for shrimp, which imported around 477,000 tonnes in 2005 (FAO, 2009). To meet the high demand for shrimp (2 kg/capita in 2018), the import of whole shrimp to the US increased by 5.1% in 2017, with 36% from India, 19% from Indonesia, 11% from Ecuador, 8% from Vietnam, and 7% from each China and Thailand 7% from each, while 160,000 tonnes of processed shrimp was imported mainly from China, Vietnam, Thailand, and Indonesia (FAO, 2019). Most of the imported shrimp comes from aquaculture production (Asche et al., 2011). In contrast, the market share of domestic shrimp in the US was 43% in 1980, which decreased to 12% in 2001. Furthermore, the US has a large wild shrimp fishery with 80% caught in the Gulf of Mexico (Asche et al., 2011). In 2012, the state of Indiana had around 50 aquaculture farms with a total of $15 million in sales (in.gov, 2015). Moreover, there are 11 shrimp farms in Indiana that sell their products directly to consumers or nearby restaurants (iiseagrant.org, 2016).

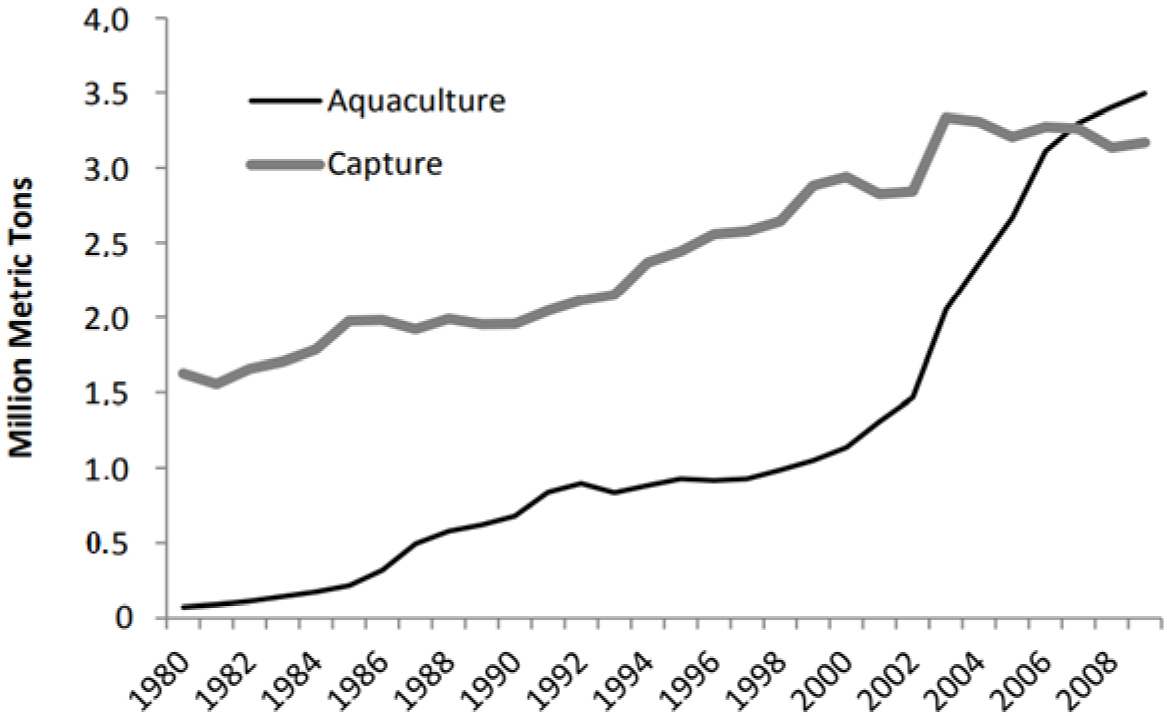


Figure 1.12. Global aquaculture and capture shrimp production (Asche et al., 2011).

1.4.2 Shrimp Farming

Shrimp can be farmed using the three main aquaculture systems. In the extensive systems, shrimp is farmed in open wet areas like mangroves and feeds mainly on food from the environment. This system has a low density of postlarvae (4−10/m^2), and thus produces low yield (FAO, 2006). Farming shrimp in semi-intensive systems uses natural food supplemented with feeding. The density of postlarvae is higher than extensive system, of (10−30/m^2), resulting in a higher yield (FAO, 2006). Intensive systems can produce shrimp with an even higher yield than semi-intensive systems in a small area (0.1−1.0 ha), because of its high postlarvae density (60−300/m^2). However, the feed conversion ratio (FCR), the amount of feed it takes to grow a kilogram of shrimp, is higher than other systems (FAO, 2006).

Compared to large land animals, shrimps have a lower FCR, between 1.0 and 2.4 depending on feed ingredients, because shrimps are ectotherm and need less energy to regulate their body temperatures (Fry et al., 2018). The primary nutrient in shrimp feed is protein. Each 100 g of shrimp feed contains 25−45 g of protein and 225− 433 calories (Fry et al., 2018). Fishmeal is considered as a great source of protein (amino acids), essential fatty acids, vitamins, and minerals (Suarez et al., 2009) which commonly accounts for 25−50% of shrimp feed. Formulating feed with fishmeal increases its production cost, hence it is important for animal feed industry to find alternative feed ingredients to reduce the demand for fishmeal by including land animal by-products or plant crops like soybean, wheat, corn, etc. (Amaya, Davis, & Rouse, 2007) as protein sources. However, plant-sourced ingredients are less suitable for shrimp feed because they contain larger amounts of carbohydrates and fat with relatively low protein content (Alam et al., 2005).

1.4.3 Environmental Impacts of Shrimp Production

Increasing shrimp production, however, causes various negative environmental impacts. Shrimp production impacts occur in several stages: feed production and processing, larvae rearing, shrimp farming, processing and packaging, and transportation of final product to the market. Feed production and farming have been identified as the main stages causing environmental burdens (Badiola et al., 2017; Jonell & Henriksson, 2015; Henriksson, Mohan & Philips, 2017). Feed production, depending on the ingredients, can generate various environmental impacts such as global warming, acidification and eutrophication because of the high energy, fertilizers and pesticides used for agricultural activities (Henriksson, Mohan & Philips, 2017). For shrimp farming, intensive system is more energy-consuming, resulting in high global warming and acidification potentials (Badiola et al., 2017). The semi-intensive system can harm the environment through discharge of untreated wastewater which causes eutrophication (Jerbi et al., 2012). In extensive production, the uses of diesel for transportation and sometimes fertilizers are the hotspots of global warming, acidification and eutrophication (Jonell & Henriksson, 2015). Figure 1.13 shows the carbon emissions related to different food products. On the energy basis, shrimp has the highest carbon footprint compared to other animal-sourced foods (Chang et al., 2017).

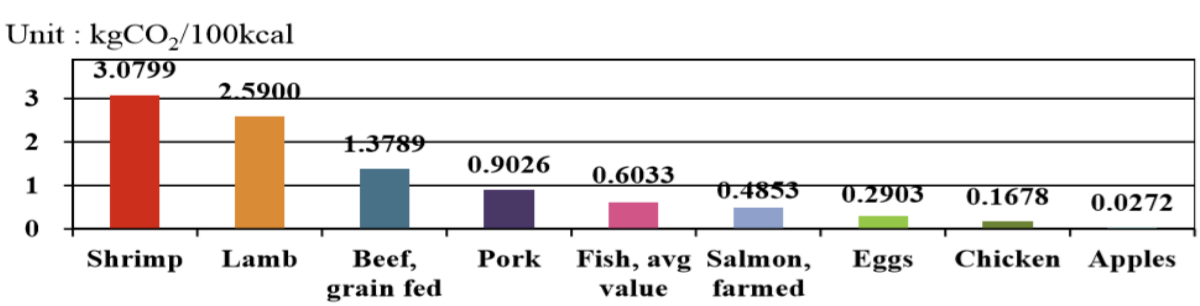


Figure 1.13. Carbon emissions of different foods production (Chang et al, 2017).

1.5 Life cycle assessment

The increasing environmental awareness leads many industries and businesses to evaluate how their activities affect the environment and adopt strategies to produce environmentally friendly products. Evaluating the environmental performance of a commercial product, process, or service is of importance to ensure its sustainability (Finnveden & Moberg, 2005). The traditional environmental assessment focuses on a single environmental impact, like energy usage or nutrient discharge. However, over the last two decades, there have been various methodologies developed to analyze multiple environmental impacts, for example, environmental impact assessment (EIA), risk assessment (RA), technological assessment (TA), environmental management system (EMS), environmental auditing (EA), ecological footprint (EF), and life cycle assessment (LCA) (Samuel-Fitwi, Schroeder, & Schulz, 2012). Among all these methods, LCA is considered as the most comprehensive and robust evaluation tool (Samuel-Fitwi, Schroeder, & Schulz, 2012).

LCA is a science-based approach to assess the environmental consequences and indicate the hotspots for determining the priority of actions (Buyle, Braet & Audenaert, 2012). The term "life cycle" refers to the significant activities of the life of a product, process, or service from raw material extraction and processing (cradle), through manufacturing, distribution and use, to recycling or final disposal (grave) (EPA, 2006). In addition to calculating the potential environmental impacts, LCA is an important tool for helping authorities, environmental science researchers, industries and policy-makers (1) compare among alternative products, processes, or services; (2) compare among alternative life cycles of a certain product or service; (3) indicate which parts of the life cycle can be improved; (4) document the overall environmental profile of a product, process, or service (EPA, 2006; Roy et al., 2009).

LCA has four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (Figure 1.14), which are standardized by the International Organization for Standardization (ISO) and particularly included in ISO 14040 (2006).

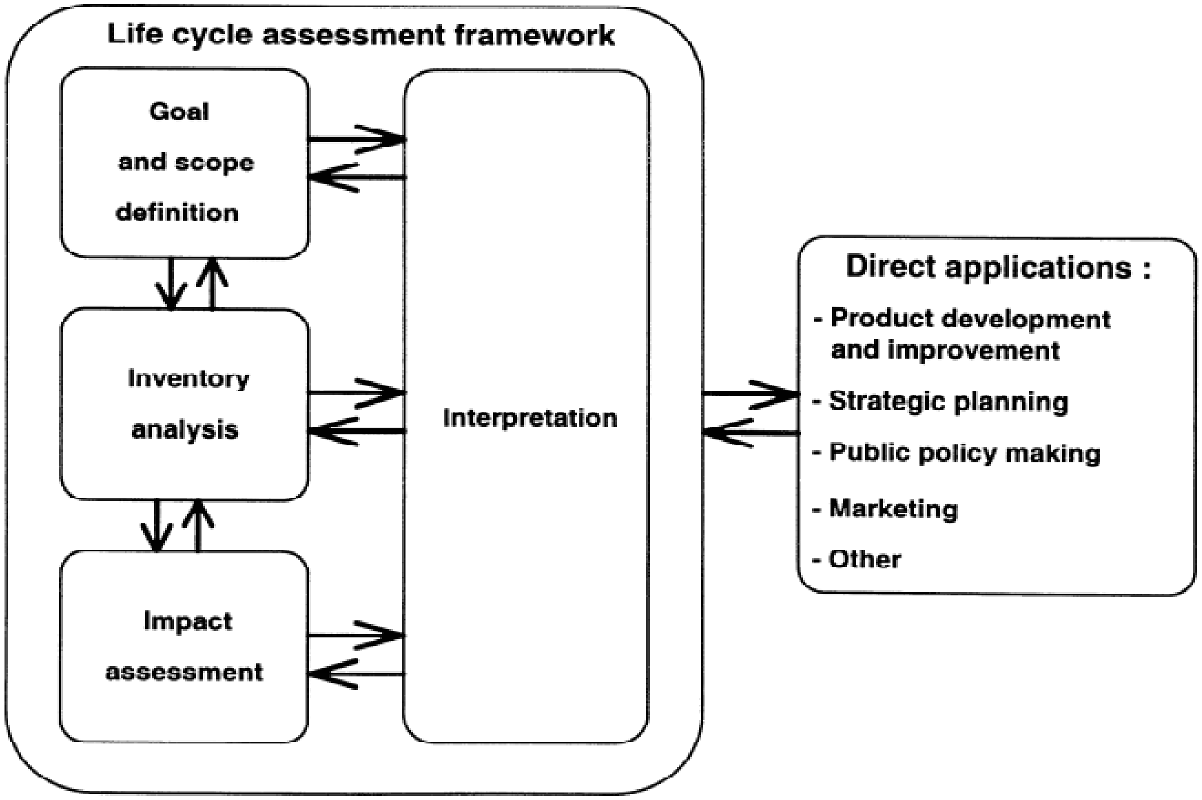


Figure 1.14. LCA framework (ISO 14040, 2006).

1.5.1 Goal and scope definition

Goal and scope definition is the most important phase of LCA because it defines the aim of the study, intended applications and audience, system boundaries, and functional unit, and related assumptions (EPA, 2006; Roy et al., 2009). The system boundary includes all the unit processes that relate to the target's life cycle with the general inputs and outputs of the studied system identified, as shown in Figure 1.15 (Roy et al., 2009). Functional unit (FU) provides a reference to which all the inputs and outputs are related, defining an appropriate FU is important to ensure the accuracy of LCA results (ISO 14040, 2006).

1.5.2 Inventory analysis

Inventory analysis phase is a process of quantifying the required inputs (water, energy, raw materials, etc.) and the outputs (air emissions, solid waste disposal, water discharges, etc.) generated throughout the target's life cycle (PSU.edu, 2018). Because of the collection of associated data, including primary and secondary data, building the life cycle inventory (LCI) is the most time-consuming step in a LCA study (Roy et al., 2009).

1.5.3 Impact assessment

The phase addresses the environmental issues defined in the goal and scope phase (ISO 14040, 2006). Based on the LCI, life cycle impacts assessment (LCIA) is to calculate the potential impacts of resource use (energy, water, and materials) and emissions to the environment throughout the target's life cycle (EPA, 2006). Environmental impacts that can be characterized range from global scale (global warming, ozone depletion), regional scale (acidification, eutrophication), to local scale (hazardous waste, solid waste) (Roy et al., 2009).

1.5.4 Interpretation

Interpretation phase is to evaluate a LCA study considering its completeness, consistency and sensitivity. This phase also analyzes and compares the results of LCI and LCIA (Roy et al., 2009), and provides conclusions and recommendations for decision makers to identify significant issues or select the best product, process, or system (ISO 14040, 2006).

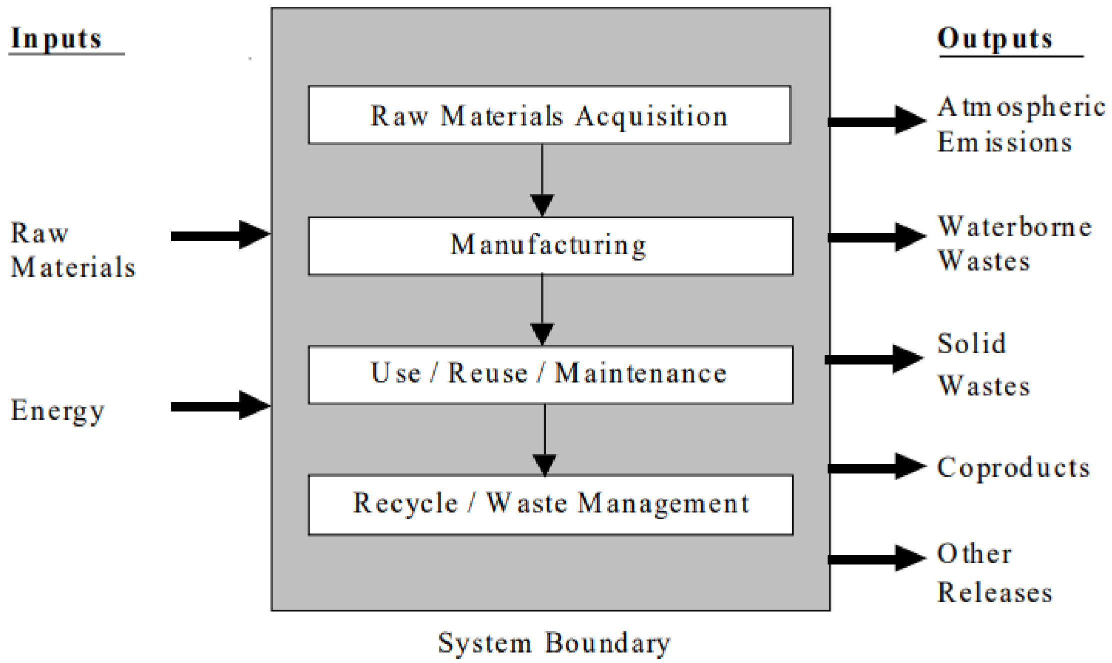


Figure 1.15. System boundary and inventory of LCA (nepis.epa.gov).

1.6 LCA applications in shrimp production

Some LCA studies have been performed on shrimp production to compare different production systems, and feed formulations and ingredients. Intensive shrimp farming was found to have an energy demand twice as high as semi-intensive farming (Cao, 2011). Moreover, using feeds with lower FCR reduced the environmental impacts of shrimp production (Cao, 2011). Jonell and Henriksson, (2015) reported that extensive mangrove farming generated lower acidification and eutrophication potentials than intensive and semi-intensive farming due to reduced uses of feed and chemicals. Electricity use in RAS for water temperature regulation was identified as the hotspot (Badiola et al., 2017). Silva et al. (2017) compared poultry by-product, soybean, and fishmeal as ingredients of aqua feeds and found that poultry by-product was the least environment-friendly option, because of the higher eutrophication and acidification potentials associated with its production (Henriksson, Mohan & Philips, 2017) Furthermore, compared to soybean meal production, fishmeal production for aqua feed had higher emissions that cause global warming mainly from fuel use for fishing boats. Feeds based on plant protein were found to have low environmental impacts (acidification, eutrophication, and global warming potentials) compared to those based on fishmeal, however, the results can be different depending on the LCA methodology, and ingredients and their sources (Samuel-Fitwi et al., 2013).

While LCA has been widely applied for aquaculture production in Asian and European countries, the specific knowledge of the environmental performance of intensive shrimp production in the US, the country with annual consumption of over a half-billion kilograms of shrimp (FAO, 2019), is still quite limited.

1.7 Objectives and structure of the thesis

To meet the growing demand for shrimp in the US, the fast expansion of its production has exerted severe damages to the ecosystems. Therefore, there is a strong need to develop and support the US intensive shrimp production with more sustainable farming systems to not only increase the productivity and quality of shrimp but also reduce associated environmental impacts. The thesis aims to evaluate the environmental performance of a closed biofloc shrimp farming system in the Midwestern US using the LCA approach. In addition to identifying the environmental hotspots of the current system, this study compared the environmental consequences of eight different shrimp feeds as well as the environmental profiles of three shrimp production chains using different farming systems. This study provides farmers and consumers with a deep and clear understanding of resource utilization and emissions resulting from shrimp production. The results obtained can help shrimp farmers adapt alternative farming practices to enhance the sustainability of their production, and promote consumers' awareness of choosing more environment-friendly shrimp products.

In the rest of the thesis, the LCA methodologies used for analyzing the shrimp production are described in Chapter 2. The environmental performance, in terms of midpoint impacts, of different production scenarios are reported and discussed in Chapter 3. The main findings of this study and recommendations for future studies are summarized in Chapter 4.

CHAPTER 2. LCA METHODOLOGY

2.1 Goal and scope definition

The goal of this LCA study was to assess the cradle-to-market environmental performance of intensive shrimp (*Litopenaeus vannamei*) production in the US through (i) identifying the environmental hotspots of a local shrimp farm in the state of Indiana with closed-system operation, (ii) examining the environmental consequences of eight alternative shrimp feeds, (iii) comparing the environmental profiles of three shrimp production chains operated with different farming systems. This study intended to help shrimp producers adopt more sustainable production chains, and increase social awareness of environmental issues of intensive aquaculture production. The intended audience included shrimp farmers in Indiana who are interested in improving the sustainability of their production, and consumers who are willing to purchase more sustainable farm-raised shrimp.

The functional unit (FU) used here was defined as 1000 kg of live shrimp ready for transportation at the farm gate. Figure 2.1 shows the system boundary of this cradle-to-market LCA study, which started from feed ingredients production through feed processing to shrimp farming with shrimp larvae reared separately. After growing to the market size (approximately 20 g), shrimp were harvested then processed and packaged before transportation to Chicago, IL. For the comparisons among different production chains and farming systems, the unit processes included in each system were slightly different, which were summarized in Table 2.1. It is important to note that food for shrimp cultivated in the open system was provided naturally and no feeding was applied. Furthermore, different from the production chains using semi-closed and open systems which froze the shrimp for transportation, the shrimp produced from the closed system was transported under refrigeration.

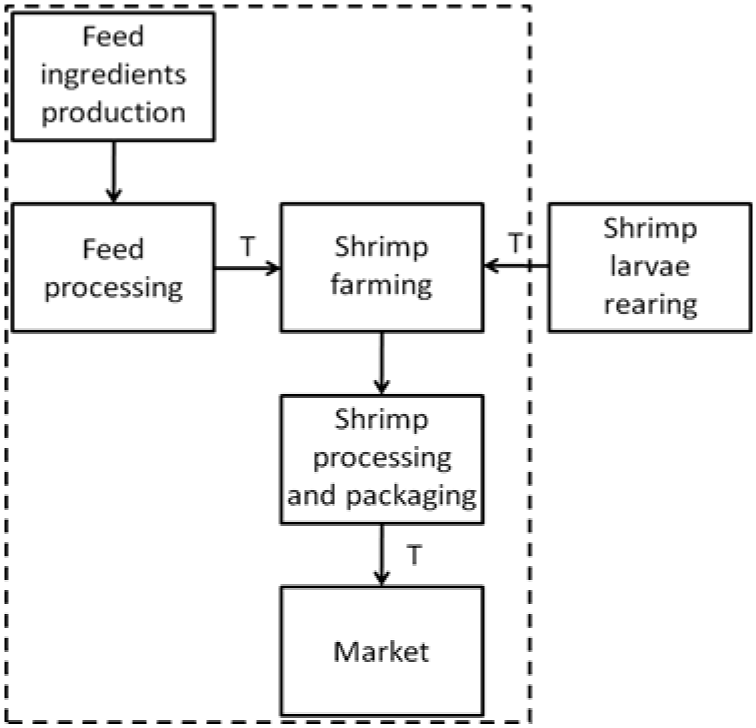


Figure 2.1. Process flow diagram of shrimp production. Dashed box refers to the system boundary, T refers to transportation.

Table 2.1. Unit processes included in different shrimp production chains.

Farming system	Closed	Semi-closed	Open
Feed processing facility location	Gardners, Pennsylvania, US	Angleton, Texas, US	None*
Larvae farm location	Marathon, Florida, US	Plantation Key, Florida, US	Tỉnh Cà Mau or surrounding provinces, Vietnam
Farm location	Fowler, Indiana, US	Gulf Shores, Alabama, US	Cà Mau, Vietnam
Processing	Packing manually	Washing and deheading	Washing and deheading
Transportation to Chicago	Refrigerated diesel truck	Freezer diesel truck	Freezer ocean freighter and diesel truck

*Feeding was not applied in open system

2.2 Life cycle inventory

This study used both primary and secondary data. The primary data collected from a shrimp farm located in Indiana which uses a closed biofloc system. The data on other shrimp feeds and production chains was adapted from related LCA studies. Furthermore, unless specified otherwise, the background inventory data (e.g., fertilizers, energy carriers, transportation modes, packaging materials, etc.) was collected from the ecoinvent database v3.0 (Wernet et al., 2016). The sources of life cycle inventory (LCI) data for all the scenarios studied are described in the following sections.

2.2.1 Shrimp feed

The local shrimp farm (closed system) in Indiana used a commercial shrimp feed, named as Feed C here. According to the farm manager, 1500 kg of feed was required for the shrimp to gain 1000 kg in weight, indicating that the feed conversion ratio (FCR) was 1.5. Because the complete formula of the commercial feed is confidential information, an approximate feed composition was used in this study based on the information provided by the farm manager and the formula reported by Rahman et al., (2017), as shown in Table 2.2.

For the production chain using semi-closed system, the feed (Feed S) had an FCR of 1.12, and the data on its composition was collected from Amaya et al. (2006), as shown in Table 2.2. Because of limited life cycle data available, some minor feed ingredients, including mold inhibitor, vitamin premix, mineral premix and Rovimix® Stay-C® 35, were aggregated as supplements.

The environmental feasibility of six alternative shrimp feeds mainly different in the protein source, named as Feed 1−6, were analyzed for the closed farming system. The formula of Feed 1 (FCR = 1.62) was based on Lebel et al. (2010) and Henriksson et al. (2017) with minor modifications, for example, squid meal was replaced by fishmeal because of the lack of life cycle data. The data on Feed 2 (FCR = 1.14) was collected from Muhammad et al. (2016) and Henriksson et al. (2017), in which shrimp by-product meal and squid meal were replaced by fishmeal here. Feeds 3, 4, 5 and 6 which had the same FCR of 1.8 were adapted from Moreno-Arias et al. (2018) with the minor ingredients (vitamin premix, mineral premix, choline chloride, butylated hydroxytoluene and sodium alginate) considered as supplements.

All the feed ingredients were processed into shrimp feeds in the processing facility. The inputs, including steam, electricity, freshwater, and land, required for feed processing were estimated based on Henriksson et al. (2017). The Feeds C and 1−6, and Feed S were then transported by diesel truck to the closed and semi-closed shrimp farms, respectively. The distances between the feed processing facilities and the farms (1006 km from Pennsylvania to Indiana; 904 km from Texas to Alabama) were estimated using Google Maps and summarized in Table 2.2.

Table 2.2. Compositions of shrimp feed for growing 1000 kg shrimp

Feed ingredient (kg)	Feed C	Feed S	Feed 1	Feed 2	Feed 3	Feed 4	Feed 5	Feed 6
Fish meal	450	33.6	469.8[2]	216.6[3]	0	180	360	540
Poultry by-product meal	75	179.2	32.4	34.2	0	0	0	0
Soybean meal	300	416.304	372.6	342	1287	971.64	655.02	342
Corn gluten meal	0	35.504	0	22.8	252	188.1	252	658.98
Wheat meal	0	0	0	0	90	270	270	90
Sorghum	0	362.096	0	0	9	18	92.7	18.54
Corn grains	0	0	162	114	0	0	0	0
Distillers dried grains with solubles	0	0	0	22.8	0	0	0	0
Wheat flour	450	0	453.6	22.8	0	0	0	0
Wheat bran	0	0	0	114	0	0	0	0
Rice brokens	0	0	64.8	0	0	0	0	0
Rice bran	75	0	0	102.6	0	0	0	0
Cassava	0	0	0	57	0	0	0	0
Fish oil	45	50.064	0	22.8	70.02	80.28	78.3	58.5
Palm oil	0	0	16.2	11.4	0	0	0	0
Soybean lecithin	45	0	0	22.8	18	18	18	18
Supplements	60	6.6081	48.6	34.2	63.18[4]	63.18[4]	63.18[4]	63.18[4]
Phosphoric acid	0	25.424	0	0	0	0	0	0
Bentonite	0	11.2	0	0	0	0	0	0
Sodium phosphate	0	0	0	0	9	9	9	9
Ascorbic acid	0	0	0	0	1.8	1.8	1.8	1.8
Total	1500	1120	1620	1140	1800	1800	1800	1800

[1]Including mold inhibitor, vitamin premix, mineral premix, and Rovimix® Stay-C® 35.
[2]Including 64.8 kg of squid meal
[3]Including 34.2 kg of shrimp by-product meal and 11.4 kg of squid meal
[4]Including vitamin premix, mineral premix, choline chloride, butylated hydroxytoluene and sodium alginate

2.2.2 Shrimp larvae

The shrimp larvae used by the shrimp farms were purchased from larval suppliers. However, shrimp larvae rearing was not included in the system boundary of this study because the associated data was not available. According to Cao et al. (2011), larvae rearing only had an insignificant contribution to the life cycle environmental footprint of shrimp production. The larvae for the closed (Indiana) and semi-closed (Alabama) shrimp farms were supplied by a hatchery located in Florida. Sixty-eight kilograms of larvae were transported by air freight and diesel truck, and the transportation distances (2052 and 916 km from Florida to Indiana and Alabama, respectively) were estimated using Google Maps. The larvae (68 kg) for the open shrimp farm in Vietnam were purchased from local hatcheries and transported by diesel truck for 740 km then small motor riverboat (speed: 20 km/h; fuel consumption: 30 L diesel/100 km) for approximately 10 km to the farm (Jonell & Henriksson, 2015).

2.2.3 Shrimp farming

The operating data on the closed shrimp farm was provided by the farm manager. The shrimp farm has 12 tanks, each tank is 4.3 m in diameter. The postlarvae (10 days old) were raised using a biofloc system for 5 months until reaching the market size (20 g). During the cultivation, baking soda was used to keep the water pH at 7.8−8. The dissolved oxygen content and temperature of the water were regulated by aeration and electric heating. The data on the semi-closed farming was collected from Cao et al. (2011) in which shrimp was raised in earthen ponds, of 1.3 ha each. The main energy sources for farming operation including water pumping and aeration were electricity and diesel. Chemicals used to control the cultivation environment included chlorine to kill disease organisms before stocking the shrimp, $CaCO_3$ and CaO to increase the water pH, and triple superphosphate, urea, and poultry manure for fertilization. The data on the open shrimp farming was adapted from Jonell & Henriksson (2015). The postlarvae were produced locally (Cà Mau province) or in surrounding areas then transported to the open ponds in the mangrove area, where feed and fertilizer were not applied.

2.2.4 Processing and packaging

The shrimps produced from the three farms had different post-harvest treatments, as shown in Table 2.1. For the closed shrimp farm, the final product was whole shrimp, which was packed manually in plastic bags then paper boxes with ice for transportation. The final products of the semi-closed and open shrimp farms were headless and shell-on shrimps. Shrimp head was removed manually, which reduced the shrimp weight from 1000 to 833 kg. The following processes, including washing and packaging in plastic bags and paper boxes with ice, were done by machines. The data on all the related processes was collected from Cao et al. (2011).

2.2.5 Shrimp transportation

In this study, the destination of all the shrimp products was a local market in Chicago. The package (2646 kg, including shrimp, ice, packaging materials) from the closed shrimp farm in Indiana was transported by refrigerated diesel truck for 172.2 km. The semi-closed shrimp farm in Alabama shipped the package of 2199 kg by freezer diesel truck for 1508 km. For the open shrimp farm in Vietnam, the shipment of the package (2199 kg) started from Cà Mau by freezer diesel truck for 26.57 km to Năm Căn, then by ocean freighter for 19,053 km to Chicago Heights, IL, USA according to the information provided by an international freight shipping company (SeaRates, 2018). The package was finally delivered by a freezer diesel truck for 3 km to Chicago.

2.3 Impact assessment

The environmental performance of all the shrimp production scenarios analyzed in this study was determined by their associated midpoint environmental impacts, including terrestrial acidification potential (AP; kg SO2 eq.), freshwater eutrophication potential (EP; kg P eq.), and global warming potential (GWP; kg CO2 eq.). These three impact categories were selected because they have been found to be the most relevant to aquaculture production (Henriksson et al., 2011). The midpoint impacts were calculated using the ReCiPe 2016 Midpoint (E) v1.02 method. All the data was analyzed using SimaPro 8.0 software.

CHAPTER 3. RESULTS AND DISCUSSION

3.1 Environmental profile of intensive shrimp production

Table 3.1 summarizes the LCI data on 1000 kg of live shrimp from different production chains, this section focuses on the analysis of the intensive production system (IPS; employing closed shrimp farming) in Indiana. One thousand and five hundreds kilograms of shrimp feed was used to grow 1000 kg of live shrimp (i.e., FU) in the IPS, which was determined by the feed formula. As shown in Table 2.2, fishmeal (30%), wheat flour (30%), and soybean meal (20%) are the three major ingredients, as the protein sources, of the commercial feed used here (Feed C). In the shrimp farming stage, electricity was the main input. Since the farm is located in the temperate climate region featured by long winter with drastic temperature changes in a day, heating water to maintain its temperature favored by shrimp (> 20 ºC; FAO, 2009) is essential, however, electricity-consuming. Electricity is also used for aeration to increase the dissolved oxygen in water required for shrimp rearing in a closed system. Furthermore, the farm only uses baking soda to keep the water pH at 7.8−8. No water and electricity were used in the shrimp processing and packaging stage because shrimp is packed manually directly after harvest.

Table 3.1. Life cycle inventory of shrimp production chains employing different farming systems

Item	Unit	IPS (closed farming)	SPS (semi-closed farming)	EPS (open farming)
		Feed production[1]		
Total	kg	1500	1120	0
		Feed processing		
Steam	kg	480	358	0
Electricity	kWh	195	146	0
Fresh water	m^3	1.95	1.46	0
Land area	m^2	2.1	1.57	0

		Feed transportation		
Diesel truck	tkm	1509	1012	0
		Larvae transportation		
Airplane	tkm	140	62.3	0
Diesel truck	tkm	0	0	50.3
Boat (diesel)	L	0	0	3
		Farming		
Input				
Land use	m2	84	NA	28000
Water use	m3	75	NA	NA
Seawater	m3	0	13	0
Electricity	kWh	921	548	0
Diesel	L	0	24	0
Baking Soda	kg	110	0	0
Chlorine	kg	0	3.8	0
CaCO3	kg	0	909	0
CaO	kg	0	318	0
Triple superphosphate	kg	0	28	0
Urea	kg	0	21	0
Poultry manure	kg	0	283	0
Output				
Live shrimp	kg	1000	1000	1000
N emission	kg	0.0028	38	−70
P emission	kg	NA	3.5	−7
		Processing and packaging		
Input				
Live shrimp	kg	1000	1000	1000
Water	L	0	10413	10413
Plastic bag	kg	10.5	8.75	8.75

Paper box	kg	135	112	112
Ice	kg	1500	1250	1250
Electricity	kWh	0	458	458
Output				
Shrimp product	kg	1000; whole shrimp	833; headless shell-on shrimp	833; headless shell-on shrimp
		Transportation of final product to Chicago		
Refrigerator diesel truck	tkm	456	0	0
Freezer diesel truck	tkm	0	3316	64.6[1]
Ocean freight	tkm	0	0	41893

[1]The composition of each feed (i.e., Feed C and Feed S) is listed in Table 2.2.
[2]Including transportation from Cà Mau to Năm Căn (58.42 tkm), and from Chicago Heights to Chicago (6.596 tkm)
NA: not available

Figure 3.1 shows the contribution of each stage of the intensive production system (IPS; employing closed shrimp farming) in Indiana to its total environmental impacts. Feed production and farming stages were the major contributors to the AP (53% and 23%, respectively) and GWP (42% and 26%, respectively). The EP was dominated by farming, and processing and packaging stages, of 39% and 32%, respectively, while feed production accounted for 20%. The AP (13 kg SO2 eq) and GWP (1779 kg CO2 eq) produced by the shrimp feed were similar to those reported by Cao et al. (2011), of 15.8 kg SO2 eq and 2110 kg CO2 eq, respectively. Despite the small proportion, poultry by-product meal was the main ingredient of the shrimp feed causing AP and also produced the second-highest GWP after fishmeal. The high environmental impacts of poultry by-product meal (0.055 kg SO2 eq/kg, 5.7×10^{-4} kg P eq/kg, and 5.8 kg CO2 eq/kg) are mainly associated with agricultural production of poultry feed ingredients (Silva et al., 2017), and ammonia emission from poultry manure management (Henriksson et al., 2017). Electricity uses for water heating and aeration were the hotspot of the farming stage, regardless of the impact. Cao et al. (2011) cultivated shrimp using RAS which produced 2.5−4.5-fold higher AP and GWP than this study, because they used physical water filtration which consumed additional electricity than the biofloc system used here. Furthermore, since the beneficial bacteria in biofloc system can consume the excess feed in water, the EP of the farming stage was much lower than Cao et al.

(2011) by two orders of magnitude. For the impacts associated with the processing and packaging stage, paper boxes were responsible for 52% of the AP, 76% of the EP, and 54% of the GWP, and ice accounted for 44.5%, 23.5%, and 41%, respectively. Paper manufacturing generates large amounts of harmful environmental pollutants emitted to air and water, including nitrogen dioxide, sulfur dioxide for acid rain carbon dioxide for global warming, and nitrogen and phosphorus for eutrophication (Okoro, 2014). The high impacts produced by ice is because of the high energy intensity of ice making, ranging from 0.249 to 0.652 kWh per kg of ice (Yashar & Park, 2012).

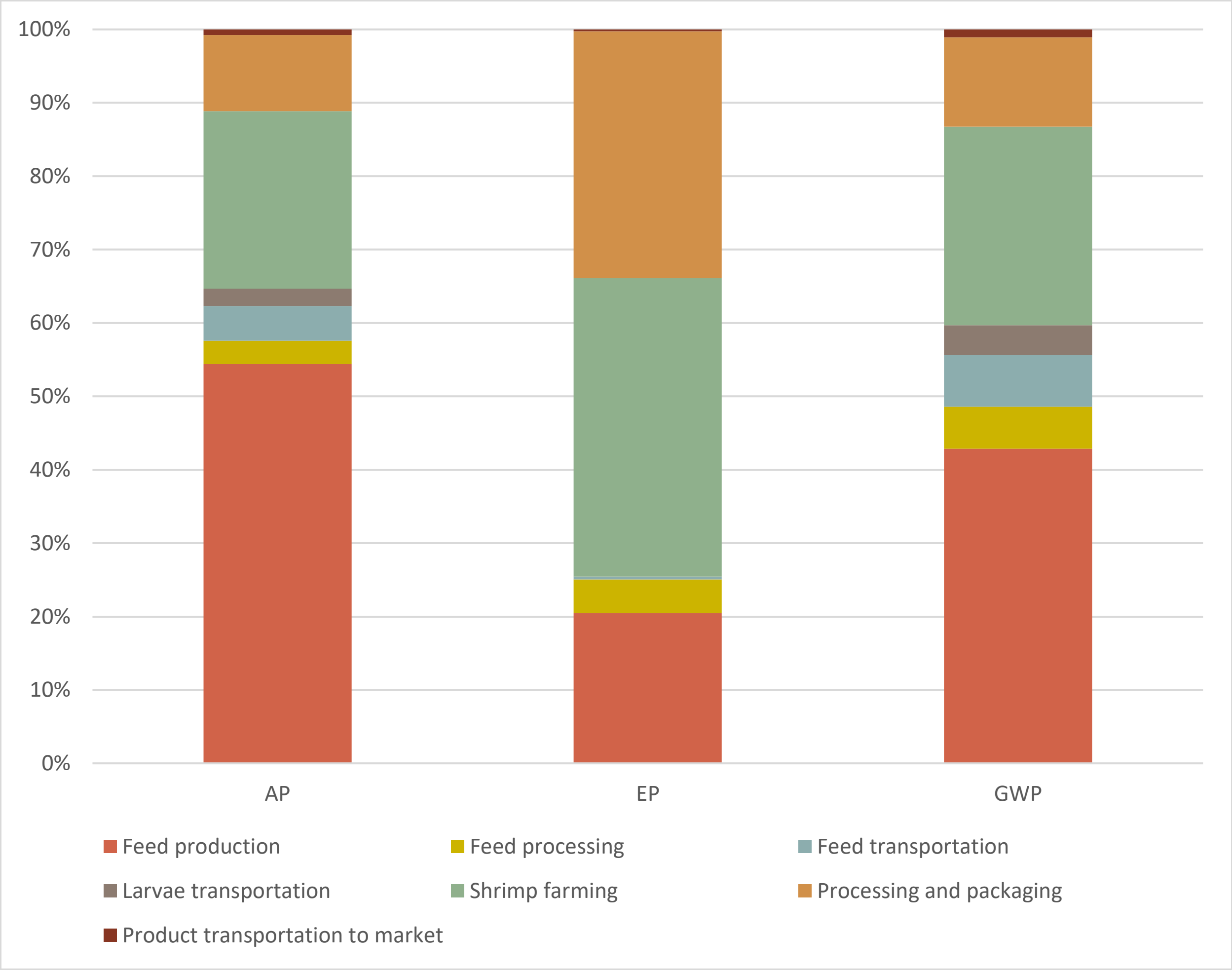


Figure 3.1. Environmental profile of IPS.

3.2 Effect of diet composition on the environmental performance of shrimp production

As shown in Figure 3.1 that feed production was the environmental hotspot of the IPS, particularly in terms of AP and GWP. To improve the sustainability of the IPS, the environmental consequences of six alternative shrimp feeds (Feed 1-6; Table 2.2) with different compositions were analyzed and compared to the feed currently used by the farm studied (Feed C; Table 2) as the baseline scenario. In this study, using different shrimp diets was assumed to only affect the feed production, processing and transportation stages of the IPS, but not the following stages, so the same LCI data on these stages (Table 3.1) was applied.

Fishmeal is the best source of protein because it is rich in essential amino acids, essential fatty acids, minerals, and vitamins (Suárez et al., 2009). With all of the essential amino acids, soybean is a great protein source to replace fishmeal in animal feeds (Alam et al., 2005; Jatobá et al., 2017). As shown in Table 2.2, compared to Feed C, Feed 1 has a lower poultry by-product meal content which is replaced by soybean meal, corn grains and broken rice. Furthermore, palm oil takes the place of fish oil to provide essential fatty acids. Feed 2 is the only alternative feed tested here has a lower FCR than Feed C, in which several plant proteins sources have higher contents to partly substitute for animal proteins. For Feeds 3-6, fishmeal is replaced by soybean meal, corn gluten meal and wheat meal at different levels, and fish oil content is increased. It is important to note that despite different protein sources, Feeds 3-6 have the same FCR (1.8). The FCR of a feed highly depends on its formula, alternative feeds may have different FCR but they should be digestible and have equal contents of amino acids and fatty acids to prevent influences on shrimp growth (Moreno-Arias et al., 2018).

Table 3.2 summarizes the environmental impacts of each stage in the shrimp production systems applying different shrimp feeds. For the feeds analyzed here, altering the composition did not change the environmental impact pattern of the IPS from the baseline scenario (Figure 3.1) that,feed production was still the major contributor to the AP and GWP, regardless of the feed, and farming produced the highest EP followed by processing and packaging. The differences among the environmental impacts of the shrimp feeds mainly resulted from two sources: FCR and feed ingredients (Roy et al., 2009). Cultivating shrimp using the feed of higher FCR requires a larger amount of feed to fulfill the FU (i.e., 1000 kg shrimp), and thus can cause higher environmental impacts associated with feed production, processing and transportation.

As the baseline scenario, Feed C had the second highest AP and GWP among all the feeds compared, which were mainly contributed by fishmeal (15% and 32%, respectively) and poultry by-product meal (31% and 24%). Wheat flour and soybean meal were the hotspot ingredients of the EP of Feed C, accounting for 32.2% and 20%, respectively. For the six alternative shrimp feeds analyzed, only Feeds 1 and 2 can improve the environmental performance of the IPS in terms of all impacts. Feed 2 was found to be the most environment-friendly option, which reduced the life cycle AP, EP and GWP, by 18%, 8% and 19% because it has the lowest FCR, of 1.14. Despite a high FCR (1.62), Feed 1 generated the second-lowest impacts due to its low content of poultry by-product meal (2%). However, replacing wheat flour in Feed C (baseline) by corn gluten meal (Feed 6; Table 2.2) increased the AP, EP and GWP of feed production by 21%, 11%, and 24%, respectively. While Feeds 3-6 have the highest FCR (1.8), Feed 6 contains a high proportion of corn gluten meal (37%), resulting in the highest AP and GWP and the third highest EP because corn gluten meal has the second-highest environmental impacts (0.015 kg SO2 eq/kg, 2.3×10^{-4} kg P eq/kg, and 1.6 kg CO2 eq/kg) among the protein sources analyzed here. The high fertilizer use for corn cultivation causes nitrogen leakage and nitrous oxide emission from fields (Roy et al., 2009; Samuel-Fitwi et al., 2013), which are responsible for the high EP and GWP of corn gluten meal. Moreover, in addition to the fuel use for tractors on fields, corn dry milling is an energy-intensive process, which are both the hotspots of GWP in corn gluten meal production. Fishmeal, accounting for 30% of Feed 6, was the second-largest contributor to the AP (14.7%) and GWP (30.5%) of its production. Feeds 3 and 5 have the same FCR and corn gluten meal content, but Feed 5 produced a higher GWP because it has higher fishmeal content (20%). The GWP of fishmeal (1.2 kg CO2 eq) is more than double that of soybean meal due to the high energy consumption for fish by-product dehydration (Henriksson et al., 2017). However, replacing all the fishmeal by soybean meal (72%), as shown in Feed 3, produced the highest EP among all the feeds mainly because of the high fertilizer use for soybean production (Samuel-Fitwi et al., 2013).

Although fishmeal sourced from wild-captured forage fish is the primary protein source in aquafeed, the reliance of aquaculture on marine ingredients is unsustainable (Hua et al., 2019). However, the results of this LCA study showed that compared to the baseline scenario, shrimp feeds with reduced or no fishmeal (i.e., Feeds 3-5) do not necessarily improve the environmental performance of the IPS. Instead, some alternative protein sources, e.g., corn gluten meal, could result in increased environmental impacts. The effect of feed replacement on the sustainability of other aquaculture species has also been studied through LCA approach. Similar to the findings of the current study, Samuel-Fitwi et al. (2013) identified sustainable sourcing as the main priority to improve the environmental performance of aquafeed industry. Substituting soybean meal and rapeseed meal for 50% of fishmeal in trout feed reduced the environmental impacts (AP, EP and GWP) by 14−43%.

Table 3.2. Environmental impacts of IPS employing different shrimp feeds.

Feed	Feed production	Feed processing	Feed transportation	Larvae transportation	Shitmp farming	Processing and packaging	Product transport to market	Total
	AP (kg SO_2 eq)							
C	13.4	1.57	1.16					25.4
1	11.3	1.69	1.25					23.6
2	9.4	1.19	0.88					20.8
3	12.4	1.88	1.39	0.59	5.96	2.56	0.19	25.0
4	12.1	1.88	1.39					24.7
5	12.8	1.88	1.39					25.3
6	16.2	1.88	1.39					28.8
	EP (kg P eq)							
C	0.27	0.124	0.0052					1.38
1	0.22	0.135	0.0056					1.34
2	0.19	0.095	0.0039					1.27
3	0.37	0.15	0.006	0	0.535	0.443	0.0036	1.51
4	0.32	0.15	0.006					1.46
5	0.29	0.15	0.006					1.43
6	0.3	0.15	0.006					1.44
	GWP (kg CO_2 eq)							
C	1779	357	293					4270
1	1328	386	317					3871
2	1132	271	223					3468
3	1405	428	352	167	1123	505	45.4	4027
4	1535	428	352					4156
5	1762	428	352					4384
6	2205	428	352					4827

3.3 Comparison of shrimp production chains employing different farming systems

In addition to feed production, farming was another priority to reduce the environmental impacts of shrimp production (Figure 3.1). In this section, the environmental performance of two shrimp production chains using semi-intensive and extensive farming systems were analyzed and compared with the IPS.

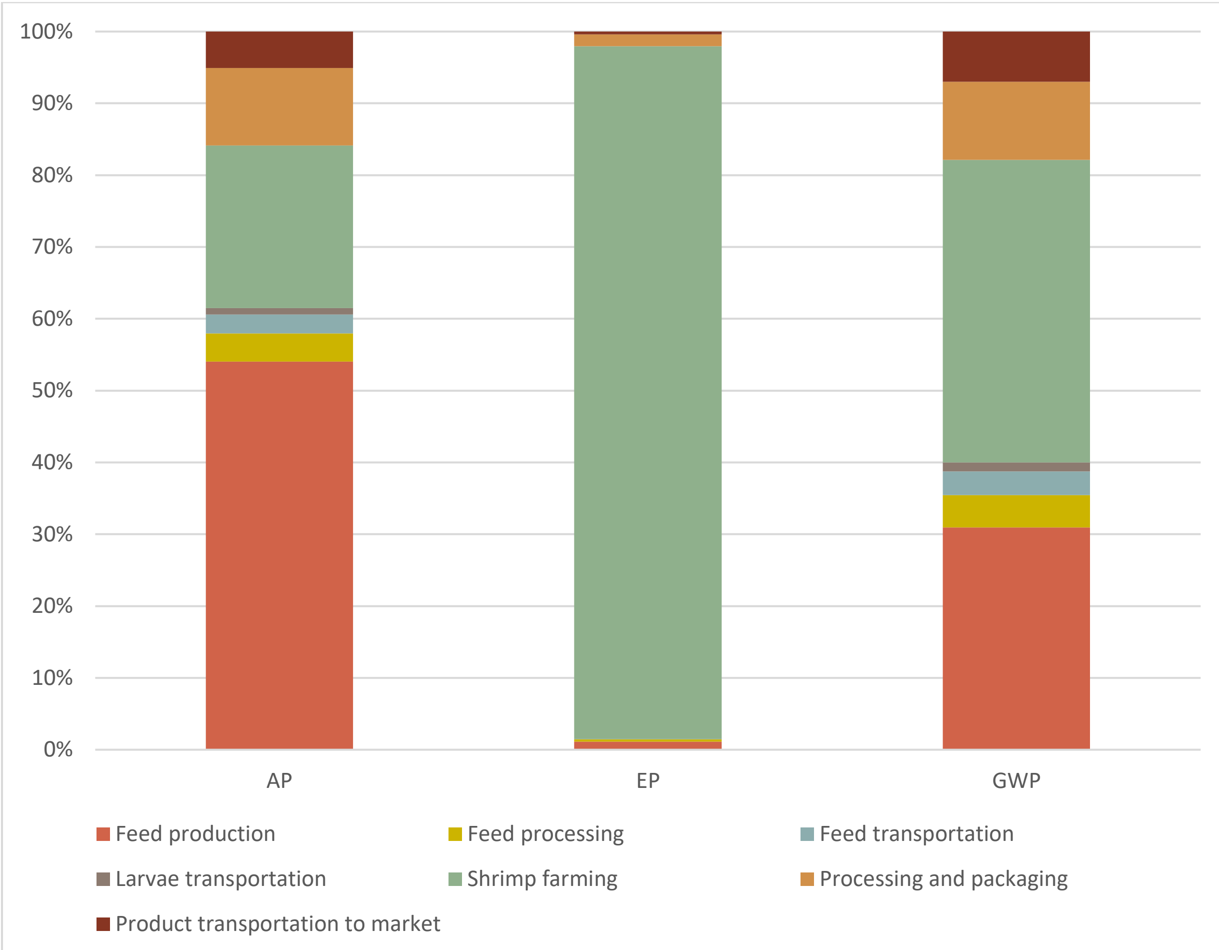
Table 3.1 compares the LCI of different production chains. The semi-intensive production system (SPS; employing semi-closed shrimp farming) in Alabama had a 34% lower feed consumption (FCR) than the IPS, because it relies on natural feed like phytoplankton in the pond in addition to the commercial feed (Feed S). Furthermore, with a similar content of soybean meal to Feed C, Feed S consists of one-third sorghum and one-sixth poultry by-product meal but only 3% fishmeal. The lower amount of feed used by the SPS resulted in lower material and energy inputs required for feed processing and transportation stages, including steam, electricity, freshwater, land and diesel. The extensive production system (EPS; employing open shrimp farming) in Cà Mau, Vietnam depends completely on natural feed hence no inputs are required for feed-related stages. In the shrimp farming stage, the electricity use of the SPS was lower by 68% than that of the IPS because of the lower demand for warm water in the Southern US than the Midwestern US (Indiana). Moreover, the SPS applies chlorine to kill disease organisms before stocking shrimp, and CaCO3 and CaO to increase the water pH, as well as triple superphosphate, urea, and poultry manure as fertilizers to augment natural feed such as phytoplankton (Green, 2015), which result in high nitrogen and phosphorous emissions. In the processing and packaging stage, the SPS and EPS used more water for washing the harvested shrimps and more electricity due to the deheading process. However, the uses of plastic bag, paper box and ice were lower in the SPS and EPS by 20% compared to the IPS because the final products of the SPS and EPS are headless shrimp which has a 16.7% lower weight than the whole shrimp produced by the IPS.

Figure 3.2a shows the life cycle environmental profile of the SPS. Similar to the IPS, shrimp feed accounted for the highest AP (54%) and second-highest GWP (30.9%) because Feed S contains a significant proportion of poultry by-product meal (Table 2.2). Shrimp farming is another hotspot responsible for 22.6% and 42% of the total AP and GWP, respectively, mainly due to the uses of electricity and calcium carbonate. Calcium carbonate is used to increase the water pH of aquaculture systems (Boyd, 2017), its production is highly energy-demanding, leading to a high GWP (Gloria, 2016). Farming is predominant stage with 96.5% of the total EP because of the high emissions of nitrogen and phosphorus generated by the fertilizers (triple superphosphate, urea and poultry manure).

The EPS had a very different environmental impact pattern (Figure 3.2b) from the IPS and SPS because the EPS studied here is based on mangrove-shrimp farming, in which feeding and cultivating conditions are fully controlled by natural environment and requires no additional material and energy inputs for its operation, hence no associated impacts are generated. Furthermore, the farming stage showed a negative EP (−52.8 kg P eq), indicating that it mitigated local freshwater eutrophication because mangrove forests can absorb the nitrogen and phosphorous in the effluents from surrounding ponds (Robertson & Phillips, 1995). Transportation of final product to market contributed the highest AP (75%) and GWP (55%), which was followed by shrimp processing and packaging, of 24% and 44%, respectively.

Table 3.3 compares the environmental impact of each stage of the IPS, SPS and EPS. The EPS was the most environment-friendly production chain, regardless of the impact category, at all the stages except larvae transportation due to the EP caused by riverboat, and product transportation to the market in Chicago because of a much longer distance from Vietnam. The total AP and GWP of the EPS were 48−55% and 66−75% lower than those of the IPS ad SPS. The SPS was least sustainable in terms of all the environmental impacts, which generated moderately higher total AP and GWP, by 17% and 39%, respectively, and produced a 21-fold total EP compared to the IPS. Although the SPS used the feed of lower FCR (1.12) than the IPS (1.5), its feed production generated higher AP, EP and GWP, by 17%, 16% and 2.9%, respectively, because the poultry by-product meal content of Feeds S is more than three times of that of Feed C (Table 2.2). The SPS had a 40%-lower electricity use for farming than the IPS, but it used larger amounts of chemicals and fertilizers, which resulted in higher environmental impacts at the farming stage for all categories. The AP and GWP of larvae transportation of the IPS were 2 and 15 times as high as those of the SPS and EPS, respectively, due to the longer distance from larvae farm to shrimp farm (Table 2.1).

(a)


100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
AP
EP
GWP
Feed production
Feed processing
Feed transportation
Larvae transportation
Shrimp farming
Processing and packaging
Product transportation to market

(b)

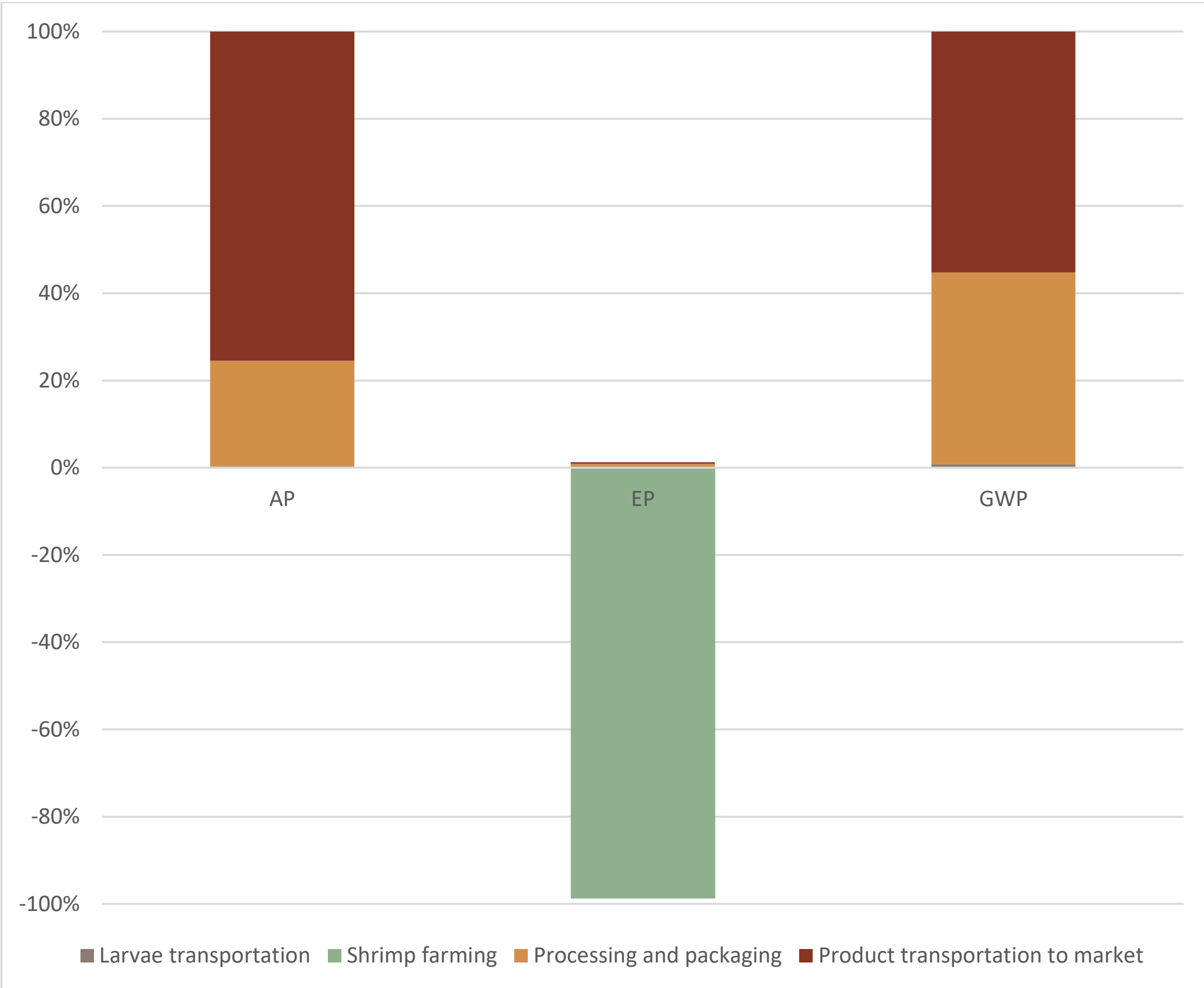


Figure 3.2. Environmental profiles of (a) SPS and (b) EPS.

Table 3.3. Environmental impacts of shrimp production chains employing different farming systems

System	Feed production	Feed processing	Feed transportation	Larvae transportation	Shrimp farming	Processing and packaging	Product transportation to market	Total
AP (kg SO_2 eq)								
IPS	13.4	1.57	1.16	0.59	5.96	2.56	0.19	25.4
SPS	16.1	1.17	0.777	0.26	6.75	3.23	1.51	29.8
EPS	0	0	0	0.04	0	3.23	10.05	13.3
EP (kg P eq)								
IPS	0.27	0.124	0.0052	0	0.535	0.443	0.0036	1.38
SPS	0.32	0.093	0.0035	0	27.5	0.47	0.11	28.5
EPS	0	0	0	0.00024	−52.8	0.47	0.202	-52.1
GWP (kg CO_2 eq)								
IPS	1779	357	293	167	1124	505	45.4	4270
SPS	1832	267	197	74.5	2495	642	415	5922
EPS	0	0	0	11.1	0	642	807	1461

CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

4.1 Conclusions

This study performed a LCA from cradle to the market in the Midwestern US on 1000 kg of live shrimp grown by three aquaculture systems, covering eight feed formulas. Shrimp feed showed the highest contributions to the total AP and GWP of the IPS owing to the poultry by-product meal and fishmeal contained as the protein sources. However, replacing fishmeal by plant proteins did not necessarily improve the environmental performance of the IPS because corn gluten meal produces higher environmental impacts, and soybean meal has a higher EP. Furthermore, the FCR of the alternative feeds played a key role in determining their environmental consequences. The EP of the IPS was dominated by shrimp farming, in which electricity use was the hotspot. Compared to the IPS, the EPS was more environment-friendly because it relies on natural feed and does not need additional material and energy inputs for its operation. In contrast, due to the large amounts of chemicals and fertilizers required, the SPS was the least sustainable option in this study. This LCA study can provide US farmers with the groundwork to design and operate shrimp production at reduced environmental cost. As sustainable consumption is one of the United Nation's sustainable development goals, the results of this study are expected to guide Midwestern consumers to make more informed decisions on the purchase of imported or domestically produced shrimp at markets.

4.2 Recommendations for future work

Further investigations to improve and extend the current study include:

(i) LCA model improvements. Larvae hatching and rearing were not included the system boundary of this study due to limited data availability, further collection of data on these stages can improve the accuracy of the LCA model. Furthermore, primary data on the farming practices and feeds applied by shrimp farms across this country is needed to provide more insights into the regional effect on the environmental sustainability of US shrimp production.

(ii) Sustainability from nutrition and dietary perspectives. Since shrimp is a great source of protein for human consumption, in addition to mass-based FU used in this study, nutritionally based FU should be incorporated into the LCA model to better evaluate the environmental performance of shrimp (e.g., environmental impacts per gram of protein provided), considering that nutrient delivery is its primary function. Moreover, while it is generally recommended to reduce meat consumption for preventing diet-related health risks, further LCA studies are needed to comprehensively examine the environmental consequences of diets with increased shrimp intake. The results can help develop more sustainable dietary patterns, in terms of minimizing global environmental burdens while maximizing human health.

(III) Life cycle costing. Economy is one of the three pillars of sustainability where most businesses are on firm ground. To be a sustainable shrimp production, a farm must be profitable. Life cycle costing is an important economic analysis used to select the most cost-effective option among different alternatives to purchase, own, operate, maintain and, finally, dispose of a product or process, when each is equally appropriate to be implemented on technical grounds. Combining with the current LCA study, the costs and resulting revenue of different options for shrimp farming operation, including cultivation unit design, feed, filtration system (mechanical, biofloc, etc.), energy source (fossil fuel, renewable energy), wastewater treatment, etc., need to be further analyzed to promote a more sustainable shrimp production in terms of high profit margin and low environmental footprint.

4.3 Practical implications for stakeholders

Our planet needs great efforts from both farmers and consumers to mitigate the environmental burdens associated with food supply chains. The results of this study confirm that feed production has a significant effect on the environmental performance of aquaculture production, its negative impacts could be minimized by choosing a diet formula with low FCR and avoiding poultry by-products ingredients. Also, this study indiacates that energy consumption is the environmental hotspot in closed shrimp farming, hence using renewable energy, for example wind energy in the Midwestern US, is expected to improve the sustainability of their products. For the semi-closed shrimp farms, wastewater generated from ponds contains a large quantity of harmful chemicals that must be properly treated before discharge to the environment. Consumers also play a critical role in the development of sustainable aquaculture. This study can serve as educational materials to increase social awareness of environmental issues of aquaculture production, and attract people to tour local farms and learn about sustainable farming, which can increase the profits of farmers and local communities. For the long term, the results of this study offer first-hand information for the development of eco-labeling for shrimp, which can promote its market value.

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SUPPLEMENTARY MATERIALS

Table S1. Environmental impacts of different life cycle stages of the IPS

	Amount	AP ($kg\ SO_2$ eq)	EP (kg P eq)	GWP ($kg\ CO_2$ eq)
Feed production				
Ingredient (kg)				
Fishmeal	450	1.98	0.00035	561
Soybean meal	300	1.51	0.0536	159
Wheat flour	450	3.13	0.0865	200
Rice bran	75	1.52	0.0192	95.4
Soybean lecithin	45	0.34	0.0304	230
Fish oil	45	0.136	0.00002	38.4
Poultry by-product	75	4.12	0.0425	433
Supplement	60	0.684	0.0419	61.7
Total	1500	13.4	0.27	1779
Feed processing				
Steam (kg)	480	0.397	0.017	145
Electricity (kWh)	195	1.17	0.11	213
Freshwater (m^3)	2.0	0	0	0
Land (m^2)	2.1	0	0	0
Total		1.57	0.124	357
Feed transportation from processing facility to farm				
Diesel truck (tkm)	1509	1.16	0.0052	293
Larvae transportation				
Airplane (tkm)	140	0.59	0	167
Shrimp farming				
Baking soda (kg)	110	0.44	0.0298	117

Electricity (kWh)	921	5.52	0.505	1006
Water use (m^3)	74.7	0	0	0
Land use (m^2)	83.8	0	0	0
N emission (kg)	0.0028	0	0.00028	0
Total		5.96	0.535	1123
Processing and packaging				
Ice (kg)	1500	1.14	0.1	208
Plastic bag (kg)	10.5	0.09	0.002	25.5
Paper box (kg)	135	1.33	0.337	272
Total		2.56	0.443	505
Product transportation to market				
Diesel truck (tkm)	456	0.19	0.0036	45.4

Table S2. Environmental impacts of different life cycle stages of the SPS

	Amount	AP (kg SO2 eq)	EP (kg P eq)	GWP (kg CO2 eq)
Feed production				
Ingredient (kg)				
Soybean meal	416	2.15	0.075	221
Fishmeal	33.6	0.148	0.00003	41.9
Poultry by-product meal	179	9.84	0.102	1034
Sorghum	362	2.58	0.074	358
Corn gluten meal	35.5	0.533	0.0078	55.4
Fish oil	50.1	0.249	0.00004	70.2
Phosphoric acid	25.4	0.508	0.057	39.6
Bentonite	11.2	0.045	0.0026	5.53
Supplements	6.61	0.072	0.0044	6.46
Total	1120	16.1	0.322	1832

Feed processing				
Steam (kg)	358	0.297	0.013	108
Electricity (kWh)	145.6	0.874	0.08	159
Freshwater (m3)	1.46	0	0	0
Land (m2)	1.57	0	0	0
Total		1.17	0.093	267
Feed transportation from processing facility to farm				
Diesel truck (tkm)	1012	0.777	0.00348	197
Larvae transportation				
By airplane (tkm)	62.3	0.263	0	74.5
Shrimp farming				
Diesel (L)	23.9	0.0327	0.00056	10.2
Electricity (kWh)	548	3.29	0.301	597
Sea water (m^3)	13	---	---	---
Chlorine (kg)	3.8	0.0196	0.00182	4.67
$CaCO_3$ (kg)	909	1.97	0.414	1432
CaO (kg)	318	0.274	0.0061	320
Triple superphosphate (kg)	28.3	0.88	0.0571	60.9
Urea (kg)	21.2	0.289	0.0077	69.8
Poultry manure (kg)	283	NA	NA	NA
N emission (kg)	38	0	3.8	0
P emission (kg)	3.5	0	22.9	0
Total		6.75	27.49	2495
Processing and packaging				
Ice (kg)	1250	0.948	0.087	173

Plastic bag (kg)	8.75	0.076	0.0017	21.2
Paper box (kg)	112	1.12	0.279	226
Water (L)	10413	0	0	0
Electricity (kWh)	458	1.08	0.102	219
Total		3.23	0.47	643
Product transportation to market				
Freezer truck (tkm)	3316	1.51	0.11	415

Table S3. Environmental impacts of different life cycle stages of the EPS

	Amount	AP (kg SO2 eq)	EP (kg P eq)	GWP (kg CO2 eq)
Larvae transportation				
Diesel truck (tkm)	50.3	0.0386	0.00017	9.78
Boat (diesel) (L)	3	0.0041	0.00007	1.28
Total		0.0427	0.00024	11.1
Shrimp farming				
N emission (kg)	−70	0	−7	0
P emission (kg)	−7	0	−45.8	0
Total		0	−52.8	0
Processing and packaging				
Ice (kg)	1250	0.948	0.087	173
Plastic bag (kg)	8.75	0.076	0.0017	21.2
Paper box (kg)	112	1.11	0.279	226
Water (L)	10413	0	0	0
Electricity (kWh)	459	1.08	0.102	219
Total		3.23	0.47	643

Product transportation to market				
Freezer truck (tkm)	65	0.015	0.00111	4.14
Ocean freight (tkm)	41893	10.03	0.2005	803
Total		10.05	0.202	807