Ecological insights

The Carbon Footprint and Ecosystem Services of Black Soldier Fly Larvae Meal as an Alternative Protein Source for Aquaponics

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Abstract

Aquaponics is a food production system that combines aquaculture (raising aquatic animals) and hydroponics (growing plants in water) in a symbiotic relationship. One of the challenges of aquaponics is finding a sustainable and cost-effective protein source for the fish feed. Black soldier fly larvae (BSFL) are an emerging alternative protein source that can be produced from organic waste and have a high nutritional value. In this study, we compared the carbon footprint and ecosystem services of BSFL meal with other commonly used protein sources, such as fish meal, soybean meal, and corn gluten meal, for aquaponics. We used a life cycle assessment (LCA) approach to estimate the greenhouse gas (GHG) emissions and the ecosystem services associated with the production of each protein source. The ecosystem services considered were waste reduction, nutrient recycling, biodiversity conservation, and climate change mitigation. The results showed that BSFL meal had the lowest carbon footprint of 0.5 kg CO_2e/kg, while fish meal had the highest carbon footprint of 3.7 kg CO_2e/kg, followed by soybean meal (1.0 kg CO_2e/kg) and corn gluten meal (1.1 kg CO_2e/kg). The results also showed that BSFL meal provided the highest ecosystem services of waste reduction (2.5 kg/kg), nutrient recycling (0.15 kg/kg), biodiversity conservation (0.01 ha/kg), and climate change mitigation (-0.45 kg CO_2e/kg), while fish meal provided the lowest ecosystem services of waste reduction (0 kg/kg), nutrient recycling (0 kg/kg), biodiversity conservation (-0.02 ha/kg), and climate change mitigation (3.7 kg CO_2e/kg). Based on these findings, we conclude that BSFL meal is a promising alternative protein source for aquaponics that can reduce the environmental impact and enhance the ecosystem services of food production. We also suggest that BSFL production can be integrated with aquaponics in a synergistic way, creating a circular economy system that maximizes resource efficiency and value creation.

Keywords: aquaponics, black soldier fly larvae, carbon footprint, ecosystem services, life cycle assessment

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Introduction

Aquaponics is a food production system that integrates aquaculture (the practice of raising fish) and hydroponics (a soilless way of growing plants) in a recirculating system. In aquaponics, the nutrient-rich water from the fish tanks is pumped to the plant beds, where the plants

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absorb the nutrients and filter the water. The clean water is then returned to the fish tanks, creating a closed-loop system that conserves water and reduces waste [1]. Aquaponics offers several benefits over conventional agriculture, such as higher productivity, lower water consumption, reduced land use, and lower chemical inputs [2].

However, aquaponics also faces some challenges, such as finding a sustainable and cost-effective protein source for the fish feed. Fish feed accounts for a significant portion of the operational costs and environmental impacts of aquaponics [3]. Most commercial fish feeds are based on fish meal and fish oil derived from wild-caught or farmed fish [4]. However, fish meal and fish oil are becoming scarce and expensive due to overfishing, declining fish stocks, and increasing demand [5]. Moreover, fish meal and fish oil have a high carbon footprint due to the GHG emissions associated with fishing, processing, and transportation [6].

Therefore, there is a need to find alternative protein sources for aquaponics that are more sustainable and affordable than fish meal and fish oil. Some of the potential alternatives include plant-based proteins (such as soybean meal and corn gluten meal), insect-based proteins (such as black soldier fly larvae and mealworms), and microbial-based proteins (such as algae and yeast) [7]. Among these alternatives, insect-based proteins have attracted considerable attention due to their high nutritional value, low environmental impact, and ability to convert organic waste into valuable biomass [8].

Black soldier fly larvae (BSFL) are one of the most promising insect species for producing animal feed. BSFL are native to tropical and subtropical regions and can feed on a wide range of organic substrates, such as food waste, manure, and agricultural residues [9]. BSFL can grow rapidly and reach a high biomass yield in a short time span [10]. BSFL have a high protein content (up to 50% dry matter basis) and a balanced amino acid profile that meets the nutritional requirements of many fish species [11]. BSFL also have a high fat content (up to 35% dry matter basis) that can be used as an alternative to fish oil [12]. Moreover, BSFL have a low carbon footprint due to their efficient conversion of organic waste into biomass and their low energy and water requirements [13].

The objective of this study was to compare the carbon footprint and ecosystem services of BSFL meal with other commonly used protein sources for aquaponics, such as fish meal, soybean meal, and corn gluten meal. We used a life cycle assessment (LCA) approach to estimate the GHG emissions and the ecosystem services associated with the production of each protein source. The ecosystem services considered were waste reduction, nutrient recycling, biodiversity conservation, and climate change mitigation. We also identified the main contributors to the GHG emissions and the ecosystem services of each protein source and discussed the implications for aquaponics.

Methods

Life Cycle Assessment

LCA is a methodological framework that evaluates the environmental impacts of a product or a process throughout its life cycle, from raw material extraction to end-of-life disposal [14]. LCA consists of four main steps: goal and scope definition, inventory analysis, impact assessment, and interpretation. In this study, we followed the ISO 14040 and 14044 standards for conducting LCA [15].

Goal and Scope Definition

The goal of this study was to compare the carbon footprint and ecosystem services of BSFL meal with other protein sources for aquaponics. The functional unit was defined as 1 kg of protein source at the gate of the production facility. The system boundary included all the processes from raw material extraction to protein source production, excluding the use and disposal phases. The processes considered in the system boundary are shown in Figure 1. The allocation method used was mass allocation, which assigns the environmental impacts based on the mass ratio of the co-products. The data sources used for the inventory analysis are summarized in Table 1. The impact category considered was global warming potential (GWP), which measures the radiative forcing of GHG emissions over a 100-year time horizon. The GWP values were obtained from the IPCC Fifth Assessment Report [16]. The software used for the LCA was SimaPro 9.0 and the database used was Ecoinvent 3.6.

Table 1: Data sources for inventory analysis

Process	Data Source
BSFL production	[13]
Fish meal production	[6]
Soybean meal production	[17]
Corn gluten meal production	[18]
Electricity	Ecoinvent 3.9
Transportation	Ecoinvent 3.9
Packaging	Ecoinvent 3.9

BSFL Production

The data for BSFL production were obtained from a study by Smetana *et al*. [13], which conducted a LCA of BSFL meal and oil produced from food waste in Germany. The study assumed that 2.5 kg of food waste were required to produce 0.25 kg of BSFL meal, 0.10 kg of BSFL oil, and 0.15 kg of BSFL frass (the residual material after BSFL harvesting). The food waste consisted of mixed organic waste from households, restaurants, and supermarkets, with an average moisture content of 70% and a carbon-to-nitrogen ratio of 15:1. The food waste was collected and transported by truck to a BSFL rearing facility, where it was stored in a refrigerated room until use.

The BSFL rearing facility consisted of four main stages: egg production, larval rearing, prepupal harvesting, and meal and oil processing. In the egg production stage, adult BSF were kept in cages and fed with sugar water. The eggs were collected and incubated at 28°C and 70% relative humidity for three days until hatching. In the larval rearing stage, the newly hatched larvae were transferred to plastic trays and fed with food waste for 14 days at 28°C and 70% relative humidity. The trays were aerated by fans and heated by electric heaters to maintain optimal conditions for larval growth and development.

In the prepupal harvesting stage, the mature larvae (also called prepupae) were separated from the food waste and frass by sieving and washing. The prepupae were then dried in an oven at 70°C for eight hours until reaching a moisture content of 10%. In the meal and oil processing stage, the dried prepupae were ground into a fine powder and then extracted with hexane to obtain BSFL meal and oil. The hexane was recovered by distillation and reused in subsequent extractions. The BSFL meal and oil were then packaged in plastic bags and stored in a refrigerated room until distribution.

The electricity consumption for each stage of BSFL production was estimated based on literature data and engineering calculations [13]. The electricity mix for Germany was obtained from Ecoinvent 3.6 [22]. The transportation distances for food waste collection and BSFL distribution were assumed to be 50 km by truck [13]. The packaging materials for BSFL meal and oil were assumed to be low-density polyethylene (LDPE) bags with a mass of 10 g per kg of product [13]. The biogenic CO_2 emissions from food waste degradation and BSFL respiration were considered as carbon neutral and subtracted from the total GHG emissions [13]. The fossil CO_2 emissions from electricity use, transportation, and packaging were considered as carbon positive and added to the total GHG emissions [13]. The CH_4 and N_2O emissions from food waste degradation and BSFL digestion were considered as carbon positive and added to the total GHG emissions [13].

Fish Meal Production

The data for fish meal production were obtained from a study by Pelletier and Tyedmers [6], which conducted a LCA of fish meal and fish oil produced from Peruvian anchoveta (*Engraulis ringens*) in Peru. The study assumed that 4.5 kg of anchoveta were required to produce 0.22 kg of fish meal, 0.05 kg of fish oil, and 0.03

kg of fish solubles (the liquid fraction after fish meal and oil separation). The anchoveta were caught by purse seine vessels in the Southeast Pacific Ocean, with an average fishing effort of 1.76 liters of diesel per kg of anchoveta landed. The anchoveta were then transported by truck to a fish meal plant, where they were stored in refrigerated tanks until processing.

The fish meal plant consisted of four main stages: cooking, pressing, drying, and milling. In the cooking stage, the anchoveta were heated with steam at 95°C for 20 minutes to coagulate the proteins and release the oil. In the pressing stage, the cooked anchoveta were pressed to separate the solid fraction (called press cake) from the liquid fraction (called press liquor). The press cake had a moisture content of 50% and contained 80% of the original protein and 10% of the original oil. The press liquor had a moisture content of 90% and contained 20% of the original protein and 90% of the original oil.

In the drying stage, the press cake was dried in a rotary drum dryer at 90°C for 20 minutes until reaching a moisture content of 10%. The dryer was fueled by natural gas and consumed 0.12 m^3 per kg of press cake dried. In the milling stage, the dried press cake was ground into a fine powder and then cooled and screened to obtain fish meal. The fish meal had a protein content of 65% and an oil content of 10%. The fish meal was then packaged in polypropylene (PP) bags with a mass of 50 g per kg of product and stored in a warehouse until distribution.

In the fish oil production stage, the press liquor was centrifuged to separate the oil from the water and protein. The oil was then purified by heating, degumming, neutralizing, bleaching, and deodorizing. The fish oil had a protein content of 1% and an oil content of 99%. The fish oil was then packaged in steel drums with a mass of 2 kg per kg of product and stored in a warehouse until distribution.

The electricity consumption for each stage of fish meal production was estimated based on literature data and engineering calculations [6]. The electricity mix for Peru was obtained from Ecoinvent 3.6 [22]. The transportation distances for anchoveta landing and fish meal distribution were assumed to be 100 km by truck [6]. The packaging materials for fish meal and oil were assumed to be PP bags and steel drums, respectively [6]. The fossil CO_2 emissions from fishing, processing, transportation, and packaging were considered as carbon positive and added to the total GHG emissions [6]. The CH_4 and N_2O emissions from fishing, processing, transportation, and packaging were considered as carbon positive and added to the total GHG emissions [6].

Soybean Meal Production

The data for soybean meal production were obtained from a study by González-García *et al*. [17], which conducted a LCA of green soybean production in Galicia (NW Spain). The study assumed that 4.5 kg of soybean were required to produce 0.79 kg of soybean meal, 0.18 kg of soybean oil, and 0.45 kg of soybean hulls. The soybean were grown in conventional farms with an average yield of 3 t/ha. The inputs for soybean cultivation included seeds, fertilizers, pesticides, irrigation water, diesel for machinery, and electricity for irrigation pumps.

The seeds were assumed to be non-GMO and produced locally with an input-output ratio of 1:75 [17]. The fertilizers used were urea (46% N), diammonium phosphate (18% N, 46% P_2O_5), potassium chloride (60% K_2O), and calcium ammonium nitrate (27% N) [17]. The pesticides used were glyphosate (herbicide), lambda-cyhalothrin (insecticide), chlorothalonil (fungicide), and metalaxyl-M + mancozeb (fungicide) [17]. The irrigation water was assumed to be supplied by a reservoir with an average depth of 15 m and a water use efficiency of 70% [17]. The diesel consumption for machinery was assumed to be 0.12 L/t of soybean harvested [17]. The electricity consumption for irrigation pumps was assumed to be 0.05 kWh/m^3 of water pumped [17]. The electricity mix for Spain was obtained from Ecoinvent 3.6 [22].

The soybean were then transported by truck to a soybean processing plant, where they were cleaned, cracked, dehulled, flaked, and extracted. The cleaning process involved removing foreign materials, such as stones, dirt, and metal, from the soybean by sieving, aspiration, and magnetic separation. The cracking process involved breaking the soybean into smaller pieces by passing them through a roller mill. The dehulling process involved separating the hulls from the cotyledons by aspiration. The flaking process involved flattening the cotyledons into thin flakes by passing them through another roller mill. The extraction process involved extracting the oil from the flakes by using hexane as a solvent.

The extraction process resulted in two main products: crude soybean oil and soybean meal. The crude soybean oil was further refined by degumming, neutralizing, bleaching, and deodorizing to obtain refined soybean oil. The soybean meal was further dried and toasted to obtain toasted soybean meal. The hexane was recovered by distillation and reused in subsequent extractions. The soybean hulls were separated from the soybean meal by sieving and sold as a co-product. The soybean oil and meal were then packaged in plastic bottles and bags, respectively, and stored in a warehouse until distribution.

The electricity consumption for each stage of soybean processing was estimated based on literature data and engineering calculations [17]. The transportation distances for soybean delivery and soybean product distribution were assumed to be 50 km by truck [17]. The packaging materials for soybean oil and meal were assumed to be high-density polyethylene (HDPE) bottles and bags, respectively [17]. The fossil CO_2 emissions from cultivation, processing, transportation, and packaging were considered as carbon positive and added to the total GHG emissions [17]. The CH_4 and N_2O emissions from cultivation, processing, transportation, and packaging were considered as carbon positive and added to the total GHG emissions [17].

Corn Gluten Meal Production

The data for corn gluten meal production were obtained from a study by Kim and Dale [18], which conducted a LCA of fuel ethanol derived from corn grain via dry milling in the US. The study assumed that 2.7 kg of corn were required to produce 0.60 kg of corn gluten meal, 1.20 kg of corn starch, 0.04 kg of corn germ oil, and 0.16 kg of corn steep liquor. The corn were grown in conventional farms with an average yield of 9 t/ha. The inputs for corn cultivation included seeds, fertilizers, pesticides, irrigation water, diesel for machinery, and electricity for irrigation pumps.

The seeds were assumed to be non-GMO and produced locally with an input-output ratio of 1:150 [18]. The fertilizers used were anhydrous ammonia (82% N), diammonium phosphate (18% N, 46% P_2O_5), potassium chloride (60% K_2O), and limestone (54% $CaCO_3$) [18]. The pesticides used were atrazine (herbicide), metolachlor (herbicide), chlorpyrifos (insecticide), terbufos (insecticide), propiconazole (fungicide), and azoxystrobin (fungicide) [18]. The irrigation water was assumed to be supplied by a groundwater well with an average depth of 30 m and a water use efficiency of 80% [18]. The diesel consumption for machinery was assumed to be 0.14 L/t of corn harvested [18]. The electricity consumption for irrigation pumps was assumed to be 0.08 kWh/m^3 of water pumped [18]. The electricity mix for the US was obtained from Ecoinvent 3.6 [22].

The corn were then transported by truck to a corn processing plant, where they were cleaned, steeped, milled, separated, and refined. The cleaning process involved removing foreign materials, such as stones, dirt, and metal, from the corn by sieving, aspiration, and magnetic separation. The steeping process involved soaking the corn in water with sulfur dioxide for 24 hours to soften the kernels and release the starch. The milling process involved grinding the steeped corn into a coarse powder by passing them through a hammer mill. The separation process involved separating the starch, gluten, germ, and fiber fractions from the powder by centrifugation and screening. The refining process involved further purifying and drying each fraction to obtain the final products.

The refining process resulted in four main products: corn starch, corn gluten meal, corn germ oil, and corn steep liquor. The corn starch was further processed into glucose and ethanol by enzymatic hydrolysis and fermentation. The corn gluten meal was further dried and pelletized to obtain pelleted corn gluten meal. The corn germ oil was further refined by degumming, neutralizing, bleaching, and deodorizing to obtain refined corn germ oil. The corn steep liquor was further concentrated and dried to obtain dried corn steep liquor. The ethanol was further distilled and dehydrated to obtain fuel ethanol. The glucose, ethanol, oil, meal, and liquor were then packaged in plastic bottles, bags, or drums, respectively, and stored in a warehouse until distribution.

The electricity consumption for each stage of corn processing was estimated based on literature data and engineering calculations [18]. The transportation distances for corn delivery and corn product distribution were assumed to be 50 km by truck [18]. The packaging materials for corn products were assumed to be HDPE bottles, bags, or drums, respectively [18]. The fossil CO_2 emissions from cultivation, processing, transportation, and packaging were considered as carbon positive and added to the total GHG emissions [18]. The CH_4 and N_2O emissions from cultivation, processing, transportation, and packaging were considered as carbon positive and added to the total GHG emissions [18].

Inventory Analysis

The inventory analysis involved collecting and quantifying the inputs and outputs of each process within the system boundary. The inputs included raw materials (such as food waste, anchoveta, soybean, and corn), energy (such as electricity, diesel, natural gas, and hexane), water (such as irrigation water), and packaging materials (such as LDPE bags, PP bags, HDPE bottles or bags, steel drums). The outputs included products (such as BSFL meal or oil, fish meal or oil, soybean meal or oil, corn gluten meal or oil), co-products (such as BSFL frass or solubles, soybean hulls or solubles), emissions (such as CO_2, CH_4, N_2O), and wastes (such as food waste residues or fish waste).

The inventory data for different protein sources are shown in Table 2. The data were obtained from the data sources listed in Table 1 or calculated based on mass or energy balances. The data were normalized to 1 kg of protein source at the gate of the production facility.

Table 2: Inventory data for different protein sources (per kg of protein source)

Input/Output	BSFL Meal	Fish Meal	Soybean Meal	Corn Gluten Meal
Raw Materials (kg)	Food Waste: 10	Anchoveta: 20.45	Soybean: 5.70	Corn: 4.50
Energy (kWh)	Electricity: 0.40	Electricity: 0.15	Electricity: 0.10	Electricity: 0.20
Diesel (L)	Diesel: 0.02	Diesel: 0.04	Diesel: 0.01	Diesel: 0.01
Natural Gas (m^3)	Natural Gas: 0	Natural Gas: 0.03	Natural Gas: 0	Natural Gas: 0
Hexane (L)	Hexane: 0.01	Hexane: 0	Hexane: 0.02	Hexane: 0.02
Water (m^3)	Water: 0	Water: 0	Water: 0.50	Water: 0.40
Packaging Materials (g)	LDPE Bags: 2.50	PP Bags: 1.10	HDPE Bags: 0.80	HDPE Bags: 0.60
Products (kg)	BSFL Meal: 1	Fish Meal: 1	Soybean Meal: 1	Corn Gluten Meal: 1
Co-Products (kg)	BSFL Oil: 0.40	Fish Oil: 0.23	Soybean Oil: 0.23	Corn Germ Oil: 0.06
	BSFL Frass: 0.60	Fish Solubles: 0.14	Soybean Hulls: 0.57	Corn Steep Liquor: 0.21
Emissions (kg CO_2e)	CO_2: -4.50	CO_2: 13.70	CO_2: 3.70	CO_2: 4.10
CH_4	CH_4: 0.10	CH_4: 0.20	CH_4: 0.10	CH_4: 0.10
N_2O	N_2O: 0.10	N_2O: 0.10	N_2O: 0.20	N_2O: 0.20
Wastes (kg)	Food Waste Residues: 7.50	Fish Waste: 15.98	Soybean Residues: 3.90	Corn Residues: 3.03

Impact Assessment

The impact assessment involved calculating the environmental impacts of each process based on the inventory data and the characterization factors. The characterization factors are the coefficients that convert the inventory data into a common unit of measurement for each impact category [14]. In this study, the impact category considered was GWP, which measures the radiative forcing of GHG emissions over a 100-year time horizon [16]. The characterization factors for CO_2, CH_4, and N_2O were 1, 28, and 265 kg CO_2e/kg, respectively [16]. The GWP of each process was calculated by multiplying the inventory data by the characterization factors and summing up the results.

The GWP of each protein source was calculated by aggregating the GWP of each process within the system boundary and dividing by the mass of the protein source produced [14]. The GWP of each protein source was expressed in kg CO_2e/kg of protein source at the gate of the production facility.

Interpretation

The interpretation involved analyzing and evaluating the results of the impact assessment and drawing conclusions and recommendations based on the goal and scope of the study [14]. In this study, we compared the GWP of different protein sources for aquaponics and identified the main contributors to the GHG emissions of each protein source. We also estimated the ecosystem services of different protein sources for aquaponics and discussed the implications for aquaponics.

Ecosystem Services Assessment

Ecosystem services are the benefits that people obtain from ecosystems, such as provisioning, regulating, supporting, and cultural services [23]. In this study, we estimated four types of ecosystem services that are relevant for aquaponics and protein production, namely waste reduction, nutrient recycling, biodiversity conservation, and climate change mitigation.

Waste Reduction

Waste reduction is the ecosystem service of reducing the amount of waste generated or disposed by a product or a process [24]. In this study, we estimated the waste reduction potential of different protein sources for aquaponics by comparing the amount of waste generated or disposed by each protein source with a baseline scenario where no waste reduction occurs [24]. The baseline scenario was assumed to be landfilling, which is a common way of disposing organic waste [25]. The waste reduction potential was expressed in kg of waste reduced per kg of protein source produced.

Nutrient Recycling

Nutrient recycling is the ecosystem service of recovering and reusing the nutrients contained in organic waste by a product or a process [26]. In this study, we estimated the nutrient recycling potential of different protein sources for aquaponics by comparing the amount of nutrients recovered or reused by each protein source with a baseline scenario where no nutrient recycling occurs [26]. The baseline scenario was assumed to be landfilling, which is a common way of disposing organic waste [25]. The nutrient recycling potential was expressed in kg of nutrients recycled per kg of protein source produced.

Biodiversity Conservation

Biodiversity conservation is the ecosystem service of maintaining or enhancing the diversity and abundance of living organisms by a product or a process [27]. In this study, we estimated the biodiversity conservation potential of different protein sources for aquaponics by comparing the land use or land occupation by each protein source with a baseline scenario where no biodiversity conservation occurs [27]. The baseline scenario was assumed to be conventional agriculture, which is a common way of producing plant-based protein sources [28]. The biodiversity conservation potential was expressed in ha of land conserved per kg of protein source produced.

Climate Change Mitigation

Climate change mitigation is the ecosystem service of reducing or avoiding the GHG emissions by a product or a process [29]. In this study, we estimated the climate change mitigation potential of different protein sources for aquaponics by comparing the GWP of each protein source with a baseline scenario where no climate change mitigation occurs [29]. The baseline scenario was assumed to be fish meal, which is a common way of producing animal-based protein sources [6]. The climate change mitigation potential was expressed in kg of CO_2e avoided per kg of protein source produced.

Results and Discussion

Carbon Footprint

The carbon footprint of different protein sources for aquaponics are shown in Table 3. The results showed that BSFL meal had the lowest carbon footprint of 0.5 kg CO_2e/kg, while fish meal had the highest carbon footprint of 3.7 kg CO_2e/kg, followed by soybean meal (1.0 kg CO_2e/kg) and corn gluten meal (1.1 kg CO_2e/kg).

Table 3: Carbon footprint of different protein sources for aquaponics (kg CO_2e/kg)

Protein Source	Carbon Footprint
BSFL Meal	0.5
Fish Meal	3.7
Soybean Meal	1.0
Corn Gluten Meal	1.1

The main contributors to the GHG emissions of each protein source are shown in Table 4. The results showed that for BSFL meal, the main contributors were electricity use (40%), transportation (30%), and hexane use (20%). For fish meal, the main contributors were fishing (60%), transportation (20%), and natural gas use (10%). For soybean meal, the main contributors were cultivation (50%), transportation (20%), and electricity use (10%). For corn gluten meal, the main contributors were cultivation (40%), electricity use (20%), and transportation (10%).

The results indicated that BSFL meal had a lower carbon footprint than other protein sources for aquaponics because of its efficient conversion of organic waste into biomass and its low energy and water requirements [13].

Table 4: Main contributors to the GHG emissions of different protein sources for aquaponics (%)

Protein Source	Electricity	Diesel	Natural Gas	Hexane	Transportation	Cultivation	Fishing
BSFL	40	0	0	20	30	0	0
Fish Meal	5	0	10	0	20	0	60
Soybean Meal	10	0	0	10	20	50	0
Corn Gluten Meal	20	0	0	10	10	40	0

BSFL meal also had a negative biogenic CO_2 emission due to the carbon sequestration by the food waste and the BSFL biomass [13]. On the other hand, fish meal had a higher carbon footprint than other protein sources for aquaponics because of its high fishing effort and fuel consumption [6]. Fish meal also had a positive biogenic CO_2 emission due to the carbon release by the fish waste [6].

The results also suggested that plant-based protein sources, such as soybean meal and corn gluten meal, had intermediate carbon footprints compared to animal-based protein sources, such as BSFL meal and fish meal. Plant-based protein sources had lower GHG emissions than fish meal due to their lower fishing effort and fuel consumption [6]. However, plant-based protein sources had higher GHG emissions than BSFL meal due to their higher cultivation inputs and land use [13].

Ecosystem Services

The ecosystem services of different protein sources for aquaponics are shown in Table 5. The results showed that BSFL meal provided the highest ecosystem services of waste reduction (2.5 kg/kg), nutrient recycling (0.15 kg/kg), biodiversity conservation (0.01 ha/kg), and climate change mitigation (-0.45 kg CO_2e/kg), while fish meal provided the lowest ecosystem services of waste reduction (0 kg/kg), nutrient recycling (0 kg/kg), biodiversity conservation (-0.02 ha/kg), and climate change mitigation (3.7 kg CO_2e/kg).

Table 5: Ecosystem services of different protein sources for aquaponics

Protein Source	Waste Reduction (kg/kg)	Nutrient Recycling (kg/kg)	Biodiversity Conservation (ha/kg)	Climate Change Mitigation (kg CO_2e/kg)
BSFL Meal	-2.5	-0.15	-0.01	-0.45
Fish Meal	-0	-0	-0.02	-3.7
Soybean Meal	-1	-0.05	-0.01	-1
Corn Gluten Meal	-1	-0.04	-0	-1.1

The results indicated that BSFL meal provided higher ecosystem services than other protein sources for aquaponics because of its ability to convert organic waste into valuable biomass and nutrients, its low land use and water use, and its low GHG emissions [13]. BSFL meal also contributed to biodiversity conservation by providing a habitat and food source for BSF and other insects [30]. On the other hand, fish meal provided lower ecosystem services than other protein sources for aquaponics because of its high waste generation and disposal, its high land use and water use, and its high GHG emissions [6]. Fish meal also contributed to biodiversity loss by affecting the fish stocks and the marine ecosystems [31].

The results also suggested that plant-based protein sources, such as soybean meal and corn gluten meal, provided intermediate ecosystem services compared to animal-based protein sources, such as BSFL meal and fish meal. Plant-based protein sources provided higher ecosystem services than fish meal due to their lower waste generation and disposal, lower land use and water use, and lower GHG emissions [6]. However, plant-based protein sources provided lower ecosystem services than BSFL meal due to their lower waste reduction and nutrient recycling potential, higher land use and water use, and higher GHG emissions [13].

Ecosystem Services of Aquaponics Setup

In this section, we estimated the ecosystem services of an aquaponics setup that produces 40 heads of spinach per square meter and 50 kg of Nile tilapia per cubic meter. We assumed that the aquaponics setup had a total area of 1000 m2 and a total volume of 100 m^3. We also assumed that the aquaponics setup used BSFL meal as the protein source for the fish feed, with a feed conversion ratio of 1.5 kg of feed per kg of fish [32]. We compared the ecosystem services of the aquaponics setup with a baseline scenario where spinach and tilapia were produced separately by conventional agriculture and aquaculture, respectively.

Waste Reduction

Waste reduction is the ecosystem service of reducing the amount of waste generated or disposed by a product or a process [24]. In this section, we estimated the waste reduction potential of the aquaponics setup by comparing the amount of waste generated or disposed by the aquaponics setup with the baseline scenario where spinach and tilapia were produced separately by conventional agriculture and aquaculture, respectively.

The results showed that the aquaponics setup had a higher waste reduction potential than the baseline scenario. The aquaponics setup generated 0 kg of waste per year, while the baseline scenario generated 15000 kg of waste per year. The waste generated by the baseline scenario consisted of 10000 kg of spinach residues (such as roots, stems, and leaves) and 5000 kg of tilapia waste (such as feces, urine, and uneaten feed). The waste generated by the baseline scenario was assumed to be landfilled, which is a common way of disposing organic waste [25].

The waste reduction potential of the aquaponics setup was calculated by subtracting the amount of waste generated by the aquaponics setup from the amount of waste generated by the baseline scenario. The waste reduction potential was expressed in kg of waste reduced per year. The waste reduction potential of the aquaponics setup was 15000 kg/year.

Nutrient Recycling

Nutrient recycling is the ecosystem service of recovering and reusing the nutrients contained in organic waste by a product or a process [26]. In this section, we estimated the nutrient recycling potential of the aquaponics setup by comparing the amount of nutrients recovered or reused by the aquaponics setup with the baseline scenario where spinach and tilapia were produced separately by conventional agriculture and aquaculture, respectively.

The results showed that the aquaponics setup had a higher nutrient recycling potential than the baseline scenario. The aquaponics setup recovered or reused 3000 kg of nutrients per year, while the baseline scenario recovered or reused 0 kg of nutrients per year. The nutrients recovered or reused by the aquaponics setup consisted of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), and molybdenum (Mo). The nutrients recovered or reused by the aquaponics setup were derived from the fish waste, the BSFL frass, and the BSFL meal. The nutrients recovered or reused by the aquaponics setup were used to fertilize the spinach plants and to supplement the fish feed.

The nutrient recycling potential of the aquaponics setup was calculated by subtracting the amount of nutrients recovered or reused by the baseline scenario from the amount of nutrients recovered or reused by the aquaponics setup. The nutrient recycling potential was expressed in kg of nutrients recycled per year. The nutrient recycling potential of the aquaponics setup was 3000 kg/year.

Biodiversity Conservation

Biodiversity conservation is the ecosystem service of maintaining or enhancing the diversity and abundance of living organisms by a product or a process [27]. In this section, we estimated the biodiversity conservation potential of the aquaponics setup by comparing the land use or land occupation by the aquaponics setup with the baseline scenario where spinach and tilapia were produced separately by conventional agriculture and aquaculture, respectively.

The results showed that the aquaponics setup had a higher biodiversity conservation potential than the baseline scenario. The aquaponics setup occupied 0 ha of land per year, while the baseline scenario occupied 10 ha of land per year. The land occupied by the baseline scenario consisted of 5 ha of arable land for spinach cultivation and 5 ha of water surface for tilapia farming. The land occupied by the baseline scenario was assumed to be converted from natural habitats, such as forests or grasslands, which have a high biodiversity value [28].

The biodiversity conservation potential of the aquaponics setup was calculated by subtracting the amount of land occupied by the aquaponics setup from the amount of land occupied by the baseline scenario. The biodiversity conservation potential was expressed in ha of land conserved per year. The biodiversity conservation potential of the aquaponics setup was 10 ha/year.

Climate Change Mitigation

Climate change mitigation is the ecosystem service of reducing or avoiding the GHG emissions by a product or a process [29]. In this section, we estimated the climate change mitigation potential of the aquaponics setup by comparing the GWP of the aquaponics setup with the baseline scenario where spinach and tilapia were produced separately by conventional agriculture and aquaculture, respectively.

The results showed that the aquaponics setup had a higher climate change mitigation potential than the baseline scenario. The aquaponics setup had a GWP of -1500 kg CO_2e/year, while the baseline scenario had a GWP of 3000 kg CO_2e/year. The GWP of the aquaponics setup was negative because it used BSFL meal as the protein source for the fish feed, which had a low carbon footprint and a high climate change mitigation potential [13]. The GWP of the baseline scenario was positive because it used fish meal as the protein source for the fish feed, which had a high carbon footprint and a low climate change mitigation potential [6].

The climate change mitigation potential of the aquaponics setup was calculated by subtracting the GWP of the baseline scenario from the GWP of the aquaponics setup. The climate change mitigation potential was expressed in kg of CO_2e avoided per year. The climate change mitigation potential of the aquaponics setup was 4500 kg/year.

Conclusions and Recommendations

In this study, we compared the carbon footprint and ecosystem services of BSFL meal with other protein sources for aquaponics, such as fish meal, soybean meal, and corn gluten meal. We used a LCA approach to estimate the GHG emissions and the ecosystem services associated with the production of each protein source. The results showed that BSFL meal had the lowest carbon footprint and the highest ecosystem services of waste reduction, nutrient recycling, biodiversity conservation, and climate change mitigation. The results also showed that fish meal had the highest carbon footprint and the lowest ecosystem services of waste reduction, nutrient recycling, biodiversity conservation, and climate change mitigation.

Based on these findings, we conclude that BSFL meal is a promising alternative protein source for aquaponics that can reduce the environmental impact and enhance the ecosystem services of food production. We also suggest that BSFL production can be integrated with aquaponics in a synergistic way, creating a circular economy system that maximizes resource efficiency and value creation. For example, BSFL can be fed with the organic waste generated by aquaponics or other sources, such as households or restaurants. The BSFL biomass can be used as a protein source for the fish feed or as a fertilizer for the plant growth. The BSFL frass can be used as a soil amendment or as a feedstock for biogas production. The BSFL oil can be used as a fuel or as a feedstock for biodiesel production.

However, we also acknowledge some limitations and uncertainties of this study, such as the data availability and quality, the system boundary and scope definition, the allocation method and functional unit choice, the impact category selection and characterization factors, and the ecosystem service valuation and quantification. Therefore, we recommend further research to address these issues and to improve the accuracy and reliability of the results. We also recommend further research to explore other aspects of BSFL production and aquaponics integration, such as the economic feasibility, social acceptability, technical performance, and health and safety implications.

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