Article

Environmental Assessment of Giant Freshwater Prawn, *Macrobrachium rosenbergii* Farming through Life Cycle Assessment

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Abstract: The giant freshwater prawn (GFP), *Macrobrachium rosenbergii* has emerged as a significant crustacean in global aquaculture. A cradle-to-farm Life Cycle Assessment (LCA) was used to assess the potential environmental impacts of GFP in Malaysia. The four main iterative farming phases involved were pond preparation, stocking, farming, and harvesting. The impact categories chosen were global warming, terrestrial ecotoxicity, terrestrial acidification, freshwater eutrophication, human non-carcinogenic toxicity, human carcinogenic activity, and water consumption. The software SimaPro 9.3.0.3 was used for impact analysis, with background data from the database Ecoinvent 3.0. and ReCiPe 2016 Midpoint (H) V1.06/World (2010). Among other environmental impact categories, stocking and harvesting phases contributed to human carcinogenic toxicity impact values of 33.33%, followed by farming (33.31%). Another impact category, freshwater ecotoxicity also produces the same pattern with the stocking and harvesting process, still generating the highest impact value of 33.34%, followed by farming (33.30%). Apart from the identified capital items that require consideration for future waste management in aquaculture, this LCA study found that *M. rosenbergii* farming generates a low impact to the environment, however, could inspire further research on other perspectives of sustainability.

Keywords: life cycle assessment; *Macrobrachium rosenbergii*; environmental impacts; Malaysia; aquaculture

1. Introduction

Aquaculture plays a significant role in providing the global protein supply as the utilization for human consumption increases every year. Out of the estimated global fish production of 179 million t, 156.4 million t were consumed in 2018, a rise of 2.3% compared to 152.9 million t in 2017 [1]. Asia remains a significant fish producer, with China dominating 35% of global fish production in 2018, and 76.5% of its production from aquaculture [1]. In 2018, inland aquaculture produced 51.3 million t of aquatic animals, accounting for 62.5 percent of the world's farmed food fish production, as compared with 57.9 percent in 2000. The dominant position of finfish was gradually reduced from 97.2 percent in 2000 to 91.5 percent (47 million t) in 2018, reflecting the strong growth of other species groups, particularly crustacean farming in freshwater in Asia.

As one of the developing countries in Asia, Malaysia is competing and aiming to boost its aquaculture production with various potential cultured species as one of the country's

economic contributors. Malaysia produced 400,017 metric t of aquaculture in 2020 to meet the demand of the fast-growing nation [2].

Among others, one of the aquaculture species of interest in Malaysia is the giant freshwater prawn, *Macrobrachium rosenbergii* de Man 1879. It is one of the significant crustaceans in the world aquaculture, and its culture has expanded rapidly on a global scale with a range of 217.7 to 238.4 thousand t of production from 2010 to 2018 [1]. *M. rosenbergii* is commonly found throughout tropical and sub-tropical countries and naturally distributed from northwest India to South-East Asian countries such as Vietnam, Philippines, Papua New Guinea and Northern Australia [3,4]. Hence its name, the Giant Freshwater Prawn (GFP) is the biggest species among other freshwater prawns, with a maximum reported total length of the male at 320 mm and weighing over 200 g, thus creating high demand in local and international markets [5,6].

Malaysia has been putting enormous efforts into developing local technical expertise, empowering breeding programs, developing hatcheries, and growing infrastructure in catering to the local and global demand for *M. rosenbergii* [7,8]. To date, the annual production of *M. rosenbergii* from 1500 grow-out pond areas in Malaysia ranges from 300–350 t, with the highest total production of adult giant freshwater prawn reaching 456.6 t in 2013, but decreasing to 213.4 t in 2018 due to the limited supply of wild brood stocks and low-quality fry for grow-out [8–10].

Even though there is no published article on the negative environmental impacts of *M. rosenbergii* farming, many previous studies have focused on the environmental threats as the catalyst of the production decline such as land factors, physico-chemical, topographic conditions, environmental factors related to soil, water, and climate, infrastructure, and the farmer's socio-economic characteristics [6,11,12]. Nevertheless, like other cultured species, the production of *M. rosenbergii* from the freshwater culture system has also been associated with possibilities of mismanagement of the culturing practice, including the limited supply of quality juveniles and the unavailability of suitable grow-out ponds, which are highly possible to impose environmental threats to the local ecosystem itself [13].

Across various intensities of farming systems and species cultured, sustainable aquaculture requires a holistic approach to strike a balance between the concern of consumers for the safe and quality protein resource while reducing environmental impacts derived from the farming system and providing a quality livelihood to the farmers [14,15]. The increasing consumption trend of Asian fisheries products has also raised environmental sustainability concerns, as aquaculture has always been associated with multiple potential environmental impacts as one of the environmental pollution sources [16,17]. These impacts include eutrophication, ecotoxicity, introductions of non-indigenous species, land use, excessive energy use, and freshwater use [18–24].

Henrikkson et al. [21] have drawn attention to the crucial need for Life Cycle Assessment (LCA) study for different aquaculture systems, particularly from the Asian region. LCA is commonly used to assess the environmental sustainability of a system, product, supply, or consumption chain and occupies a central role in policy-making decisions related to environmental footprints and eco-labelling, including those from agriculture [25,26]. This International Organization for Standardization (ISO)-standardized methodology evaluates the ecosystem impacts, human health, and natural resources throughout the entire process or product life cycle [27,28]. The application of LCA in aquaculture can assist in the decision-making process by identifying the hotspots of a system, points to reduce the environmental impacts, and considering several alternatives to choose which systems or processes contribute to the lowest environmental impacts.

Bohnes et al. [29] have depicted various levels of LCA in aquaculture, including microlevel (which focuses on a specific process, e.g., feed production), meso-level (e.g., assessing the entire farm) or macro-level (total country aquaculture assessment). However, specific to the development of the LCA study in the aquaculture sector in Malaysia, it is still limited in every aspect, as only a limited study has been conducted for cockle farming in the natural ecosystem [30], and for tilapia farming [31].

This study aims to assess the environmental impacts of the culture of the giant freshwater prawn in Malaysia using the cradle-to-farm gate LCA approach, and all types of major inputs will be considered, including infrastructure.

2. Materials and Methods

2.1. Production System

2.1.1. Farming Practice and Culture System

M. rosenbergii has several advantages in terms of breeding characteristics; it is a reasonable growth rate species, most prominent in size, has resistance to certain diseases, and convenient farming practices. Moreover, this species is in high demand for recreational fishing activity, especially in urban areas and creates high and stable market prices.

GFP commands the highest market value among other freshwater commodities, comparable to marine shrimp, which could potentially play a significant role in providing opportunities for farming a commodity with a high return. A kilogram of GFP commenced at the price of USD 14.50–17.85, as compared to USD 7.81–10.04 for Pacific white shrimp, *Litopenaeus vannamei*. GFP also has other advantages against marine shrimp due to its hardiness, which enables good survival after long transportation [32].

Pond preparation is crucial at the early stage of *M. rosenbergii* culture, as the size and depth of the ponds should be sufficient to cater for the best farm practices to avoid intense competition that may affect the size of the prawn. The farming of *M. rosenbergii* requires a suitable site for the construction of ponds where it needs sandy-clay soils with a clay content not exceeding 60%, as well as sufficient water resources [33]. A long square pond between 0.2 to 0.4 ha and a water depth between 0.75–1.2 m is recommended for *M. rosenbergii* farming. In this study, all farms are monoculture systems with pond sizes of approximately 1.5 ha/pond with 1.2 to 1.5-m depth. The recommended stocking rate is between 10 to 20 larvae/m^2. Paddle wheels or blowers are highly recommended during the stocking phase to ensure enough oxygen for the larvae's survival, especially during low oxygen supply at night time.

As the best practice at the earlier stage of pond preparation, ponds are usually sundried and treated with lime to re-fertilize the soil and restabilize the pH condition after each harvesting cycle. Exposure to the scorching sun will kill all types of pests and predators in the pond and stimulate the decomposition activity of organic matter such as feces and leaves. Farmers usually pumped water from the adjacent water resources supply. In this study, the water came from natural hill water resources, with a distance of approximately 500 m from the pond site.

All farmers in this study bought the larvae supply from other hatcheries with approximately 300,000 pcs per cycle. Therefore, hatchery activities are excluded from the system boundary, considering it is located in a different geographical location.

2.1.2. Water Quality

M. rosenbergii farming requires a clean water supply. All aquaculture farms in this study obtain natural water resources from nearby hill areas, pumped into the rearing pond area. Water pumped from hilly areas has a low risk of pollution. Basic biosecurity measures are in place to reduce risks of the disease attack and ensure proper environmental conditions for the whole farming phase, especially on the water quality aspect—the ideal water quality for giant freshwater prawn culture, as shown in Table 1.

Table 1. Water quality parameters for giant freshwater prawn culture [34].

Parameter	Range
Temperature	28 °C to 32 °C
pH	6.5–8.5
Dissolved oxygen	>4.0 mg/L
Alkalinity	40–100 ppm $CaCO_3$
Hardness	>50–100 ppm
Secchi disc	30–40 cm
Ammonia	<1.0 ppm
Nitrate	1–3 ppm
Copper	<0.1 ppm
Iron	<0.3 ppm

2.1.3. Feed Management

Formulated feeds are recommended to be given to the prawns, with a required protein content between 28 to 35%. The normal Feed Conversion Ratio (FCR) obtained is between 2 to 3 [33] using these feeds but reduced to a much lower FCR value of 1.8–3.0:1 [4] in the last decade. Farmers usually feed their prawns twice or thrice a day, morning and evening [35]. Starter feed is given for 1–2 months, followed by grower formula for 2–4 months, and the final two months with finisher feed until reaching harvest size [35]. The prawns are partially harvested by seining method, according to market size around 30 g/prawn, repeated until all prawns are harvested.

2.2. System Description

This study involves two aquaculture operators with a total of 15 aquaculture ponds in the Kuala Pilah and Jelebu districts. The farms are among Malaysia's primary producers, selected based on their annual production consistency, and have been operating for over 15 years. In the 2019, both farms produced 5215.5 kg of production, 5.2 t/year.

2.3. Goal and Scope Definition

Life Cycle Assessment (LCA) identifies the environmental impacts of the giant freshwater prawn culture activities. The defined functional unit was 1000 kg or one metric ton of the prawns' live weight.

2.4. Boundary System

This study conducted the cradle-to-farm gate approach, which involves four main iterative phases at the aquaculture farms: pond preparation, stocking, farming, and harvesting, as shown in Figure 1. This study does not include hatchery activity, as local farmers usually purchased post larvae from local hatcheries on different premises. Marketing is also excluded as this study focuses only on the farming process's activities. For impact analysis of farming activities, land use impact is excluded as the farming area has been gazetted as an agriculture area by the government. This study assumed there would be no further issue with land use.
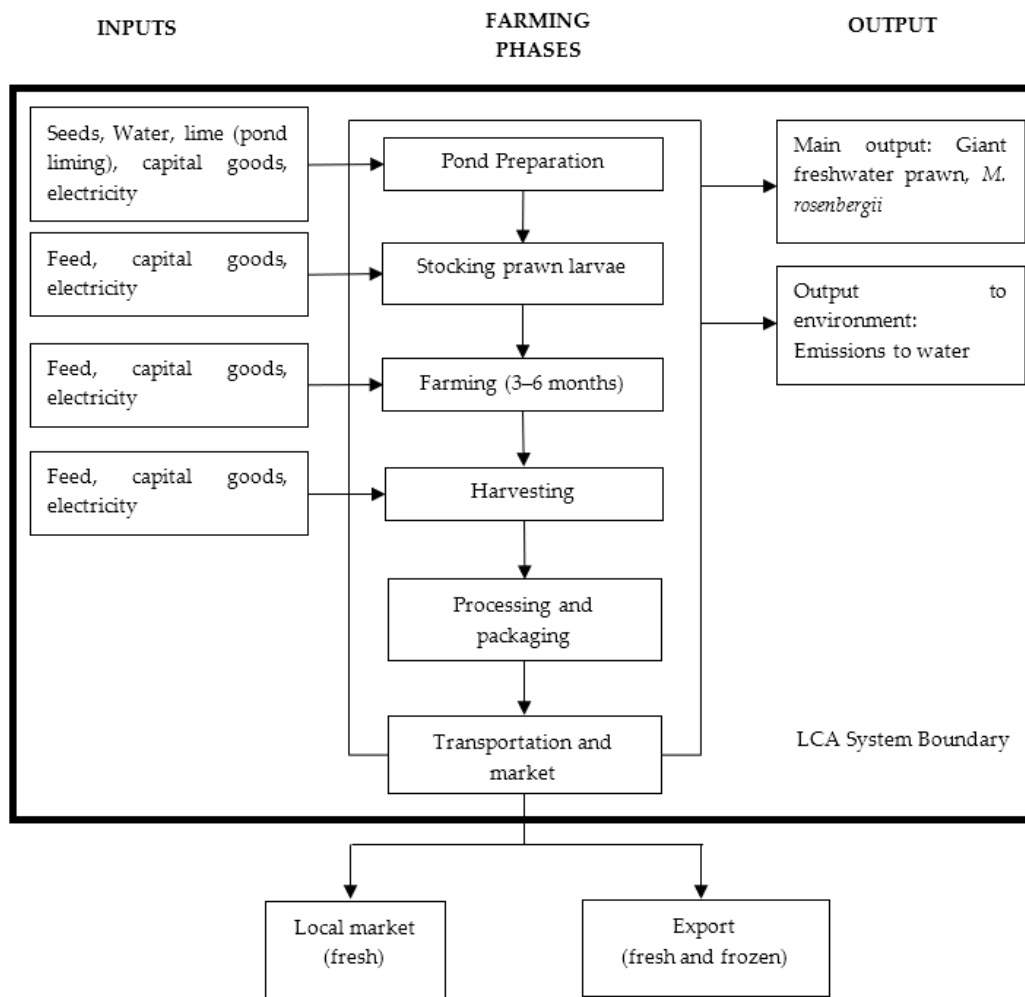
INPUTS   FARMING PHASES   OUTPUT

Seeds, Water, lime (pond liming), capital goods, electricity → Pond Preparation

Feed, capital goods, electricity → Stocking prawn larvae

Feed, capital goods, electricity → Farming (3–6 months)

Feed, capital goods, electricity → Harvesting

Processing and packaging

Transportation and market

Main output: Giant freshwater prawn, *M. rosenbergii*

Output to environment: Emissions to water

LCA System Boundary

Local market (fresh)

Export (fresh and frozen)

Figure 1. *M. rosenbergii* production system in Malaysia and the LCA system boundary.

2.5. Data Inventory

Inventory data aims to develop the process flow and materials used in a product or the current system studied [36]. Data inventory was conducted through a questionnaire and interview with the respective farmers, and cross-checked with a professional contractor. In addition, water quality data was obtained from the relevant government agencies that periodically monitored water quality at the aquaculture farm. Identified inputs are feed ingredients, capital goods such as paddle wheels, blower, nets, piping system (inlet and outlet channel), electricity use, products, resources, and further relevant details.

Figure 1 shows the system boundaries based on the cradle-to-farm gate approach. Inventory data was collected for these culture facilities, starting from the pond preparation phase, which involves the post-larvae stocking until the final harvest of the giant freshwater prawn. Inputs were contributed from the technosphere, including electricity consumption, capital goods for farm operating systems and livestock feed. The only input from the environment is the water source, where the farms usually use upstream river water from the hill nearby or a stream.

Water quality data involved pollution measurement parameters: nitrate, nitrite, phosphate, total nitrogen, total phosphorus, and ammoniacal nitrogen. In addition, water quality data were collected from secondary information from the government agencies that conducted the annual water monitoring programs. The collection of inventories contributes to the detailed itemized culture system, and the process is shown in Table 2.

Table 2. Inputs and outputs for the cradle-to-farm gate LCA study for *M. rosenbergii* culture system and the related inventory based on Ecoinvent 3 database in the SimaPro Version 9.3 (PRé B.V Amersfoot, The Netherlands).

Input/Output	Unit	Amount	Inventory (Ecoinvent 3 Database, SimaPro Version 9.3)	Values (Based on 1-Tonne Live Weight of *M. rosenbergii*
Inputs from technosphere:				
i. Average aquaculture farm size	ha	1.5		
ii. Average size for each pond	ha	0.1–0.3		
iii. Average pond depth	feet	4		
iv. ostlarvae (bought from hatcheries)	pcs	300,000		
v. ransportation (4WD)—from hatcheries to the farm	km	389		
vi. Lime	25 kg/bag	15 bags	Lime, hydrated, lose weight {RoW} | market for lime, hydrated, lose weight | APOS, S	71.9 kg
vii. Feed:				
a. Starter (CP 5001)	25 kg/bag	10 bags	Fishmeal, 63–65% protein {GLO} | market for fishmeal, 63–65% protein | APOS, U	1.102 kg
			Soybean meal {RoW} | market for soybean meal | APOS, U	1.653 kg
			Wheat grain, feed {GLO} | market for | APOS, U	0.480 kg
b. Grower	25 kg/bag	8 bags	Fishmeal, 63–65% protein {GLO} | market for fishmeal, 63–65% protein | APOS, U	1.026 kg
			Soybean meal {RoW} | market for soybean meal | APOS, U	1.438 kg
			Wheat grain, feed {GLO} | market for | APOS, U	0.240 kg
c. Crushed corn	40 kg/bag	2 bags (final month before harvest)	Sweet corn {RoW} | sweet corn production | APOS, U	7.670 kg
viii. Capital goods:				
a. Blower	kg	17 kg/unit (9 units)	Iron-nickel-chromium alloy {GLO} | market for | APOS, U	3.451 kg
b. Paddlewheel	kg	1.5 kg/unit (9 units)	Polyethylene, high density, granulate {GLO} | market for | APOS, U	0.862 kg
			Steel, chromium steel 18/8 {G.L.O.} | market for | APOS, U	1.055 kg
c. Net	kg	15 kg/unit (4 units)	Nylon 6-6 {RoW} | market for nylon 6-6 | APOS, U	2.876 kg
d. Piping system (inlet and outlet)	kg	8001 kg/set (usage of 500 m from the river (water source/supply) to the farm area)	Polyethylene, high density, granulate {GLO} | market for | APOS, U	767.04 kg
e. Electricity	kWH	10,752 kWH/year	Electricity, high voltage {MY} | market for | APOS, S	227 kWh: pond preparation and harvesting 515 kWh: stocking and farming
Output to technosphere: Giant freshwater prawn	kg	1000		
Inputs from nature: Hill/stream water (outflow to river without any treatment)	m^3	Estimated: 2.830×10^{10}		
Output to nature: Untreated emissions to water	Nitrate Phosphate pH Temperature DO	0.015 ppm 0.21 ppm 7.92 26.98 °C 5.2		

2.6. Impact Analysis

This study uses the ReCiPe 2016 Midpoint (H) method available in the SimaPro software version 9.3 with the Ecoinvent 3 database. The selection of this method is based on the latest update on ReCiPe 2016 Midpoint (H), which provides characterization factors represented on the global scale instead of the European scale as most of the other methods provided in SimaPro [37]. Impacts measured in this study are as below:

i. global warming (kg CO_2 equivalent), which assemblage emissions of greenhouse gases

ii. terrestrial acidification (kg SO_2 equivalent to air), which assemblage proton increase in natural soils

iii. freshwater eutrophication (kg P equivalent), which assemblage phosphorus increase in freshwater

iv. terrestrial ecotoxicity (kg 1,4-DCB-equivalent to industrial soil), which assemblage hazard weighted increase in natural soil

v. freshwater ecotoxicity (kg 1,4-DCB-equivalent to freshwater), which assemblage hazard weighted increase in freshwater

vi. human carcinogenic activity (kg 1,4-DCB-equivalent to urban air) which assemblage risk increase of cancer disease incidence

vii. human non-carcinogenic activity (kg 1,4-DCB-equivalent to urban air) which assemblage risk increase of non-cancer disease incidence

viii. water consumption (m^3 water consumed) which assemblage increase in water consumption

3. Results

Environmental Impacts

Figure 2 presents selected environmental impacts from every phase of *M. rosenbergii* aquaculture. Human carcinogenic toxicity dominated the stocking, farming, and harvesting phases, followed by the freshwater ecotoxicity impact and freshwater eutrophication. Other environmental impacts, which were global warming, terrestrial acidification, terrestrial ecotoxicity, human non-carcinogenic toxicity, and water consumption, showed a lower impact. This study did not consider land-use change impact, as the dedicated culture area was specifically gazetted for agriculture/aquaculture purposes. Therefore, no land conflict will be predicted for this study. Water consumption was tapped via an inlet from the adjacent river, and this study shows no significant impact on water consumption.
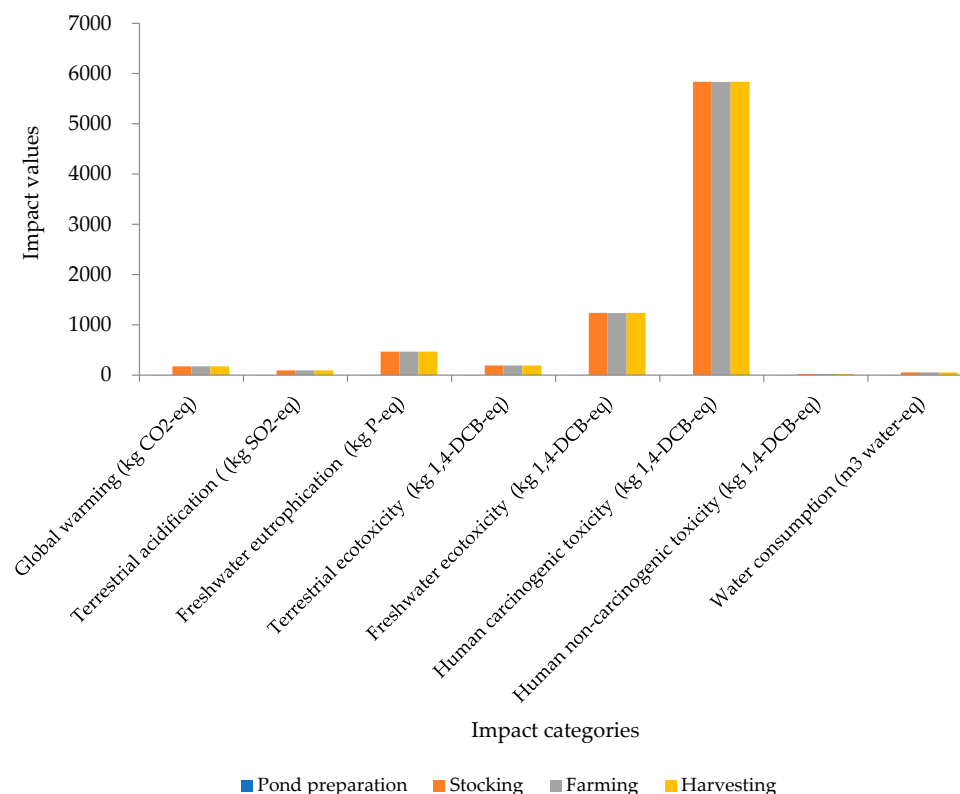

Figure 2. Environmental impact of *M. rosenbergii* farming activity based on the cradle-to-farm gate approach consisting of pond preparation, stocking, farming and harvesting.

Human carcinogenic toxicity for the midpoint impact category in ReCiPe 2016 refers to the emission of kg 1,4-DCB-eq [37], which in this study indicates the high usage of high-density polyethylene (HDPE) as the primary material for the piping system for water consumption from the adjacent river to the farming area. This study counted infrastructure among major inputs, as it is also crucial to consider all equipment as part of the physical waste that needs to be managed after a certain period. The previous LCA study for fish and prawn production has shown that infrastructure and equipment have contributed to a certain percentage of climate change, cumulative energy demand, and acidification [38].

Table 3 shows the quantitative values of all environmental impacts for four phases in *M. rosenbergii* farming practices. Stocking and harvesting phases contributed to human carcinogenic toxicity impact values of 33.33%, followed by farming (33.31%). Another impact category, freshwater ecotoxicity, also produces the same pattern with the stocking and harvesting process, still generating the highest impact value of 33.34%, followed by farming (33.30%). On the other hand, pond preparation shows a low environmental impact, as inputs considered at this phase only involve lime usage to re-fertilize the soil without feed inputs. At the same time, feed and capital goods are used in the stocking, farming, and harvesting phases. Therefore, the difference was predicted to be primarily caused by electricity for the paddle wheel and blower operation during the stocking, farming and harvesting phase.

Table 3. Environmental impact for *M. rosenbergii* farming practices with functional unit 1 tonne live weight.

Environmental Impact (Method: ReCiPe 2016/Midpoint)	Pond Preparation	Stocking	Farming	Harvesting
Global warming (kg CO_2-eq to air)	0.619 (0.12%)	175.427 (33.93%)	175.446 (33.30%)	175.432 (33.29%)
Terrestrial acidification (kg SO_2-eq to air)	0.125 (0.04%)	92.986 (33.33%)	92.860 (33.29%)	92.988 (33.33%)
Freshwater eutrophication (kg P-eq to freshwater)	0.573 (0.04%)	465.93 (33.32%)	465.974 (33.23%)	465.922 (32.32%)
Terrestrial ecotoxicity (kg 1,4-DCB-eq to industrial soil)	0.614 (0.11%)	192.226 (33.33%)	191.626 (33.23%)	192.222 (33.33%)
Freshwater ecotoxicity (kg 1,4-DCB-eq to freshwater)	0.547 (0.01%)	1236.683 (33.34%)	1235.309 (33.30%)	1236.674 (33.34%)
Human carcinogenic toxicity (kg 1,4-DCB-eq to urban air)	3.439 (0.02%)	5835.63 (33.33%)	5831.60 (33.31%)	5835.632 (33.33%)
Human non-carcinogenic toxicity (kg 1,4-DCB-eq to urban air)	0.0179 (0.03%)	22.33 (33.33%)	22.314 (33.31%)	22.331 (33.33%)
Water use (m^3 water-eq consumed)	0.0167 (0.01%)	53.160 (33.33%)	53.14 (33.32%)	53.165 (33.33%)

Capital goods that have been used in farm operations are known to have become a major contributor to previous LCA studies [39]. Capital goods in this study counted major farming equipment used in the operation cycle. Figures 3–6 show the environmental impacts derived from the related capital goods and energy use from electricity for all phases in the *M. rosenbergii* culture activities. The pond preparation phase did not count the use of capital goods, as it focuses more on re-stabilizing the structure of the pond using lime. Therefore, only lime use and electricity were major inputs, showing that lime use dominated the environmental impact of this phase. However, overall, pond preparation has the lowest environmental impact among all phases. Results showed that the piping system dominated human carcinogenic, terrestrial and freshwater ecotoxicity. This finding is in line with the physical appearance that the piping system is dominant as its main

function is to tap natural water from the adjacent hilly area approximately 500 m from the farming area.
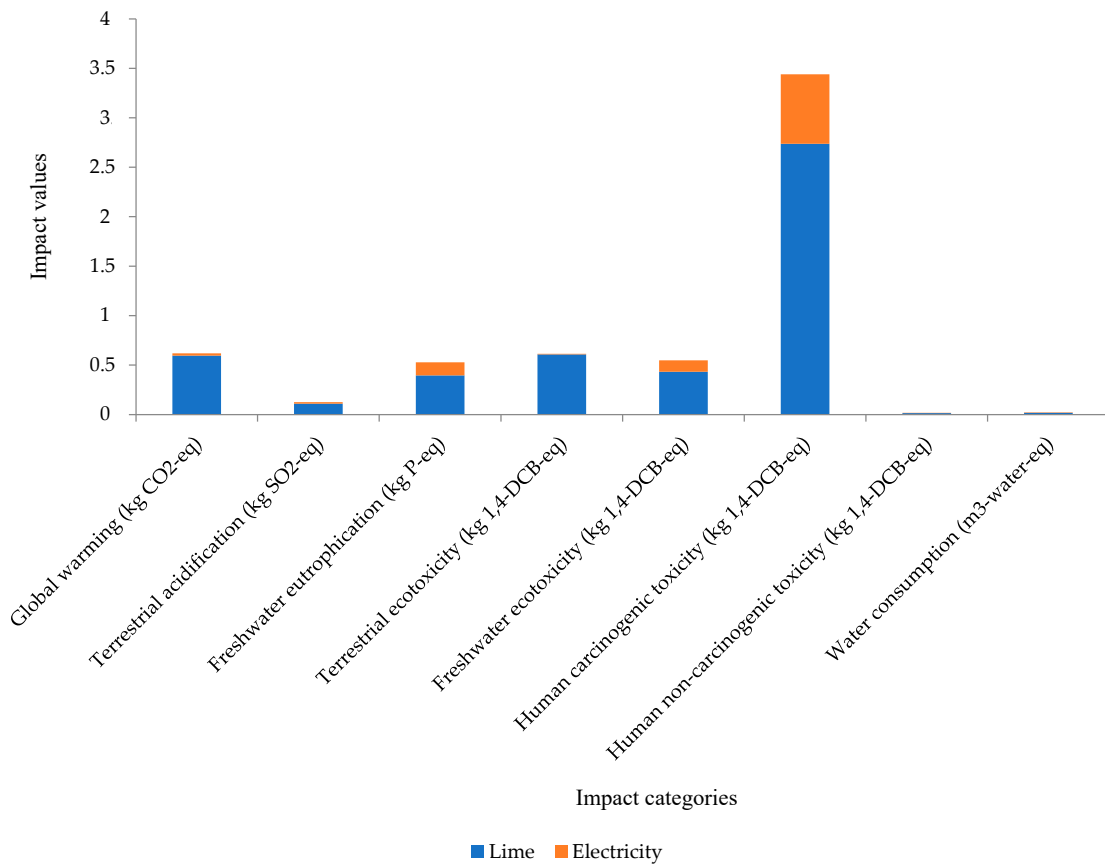

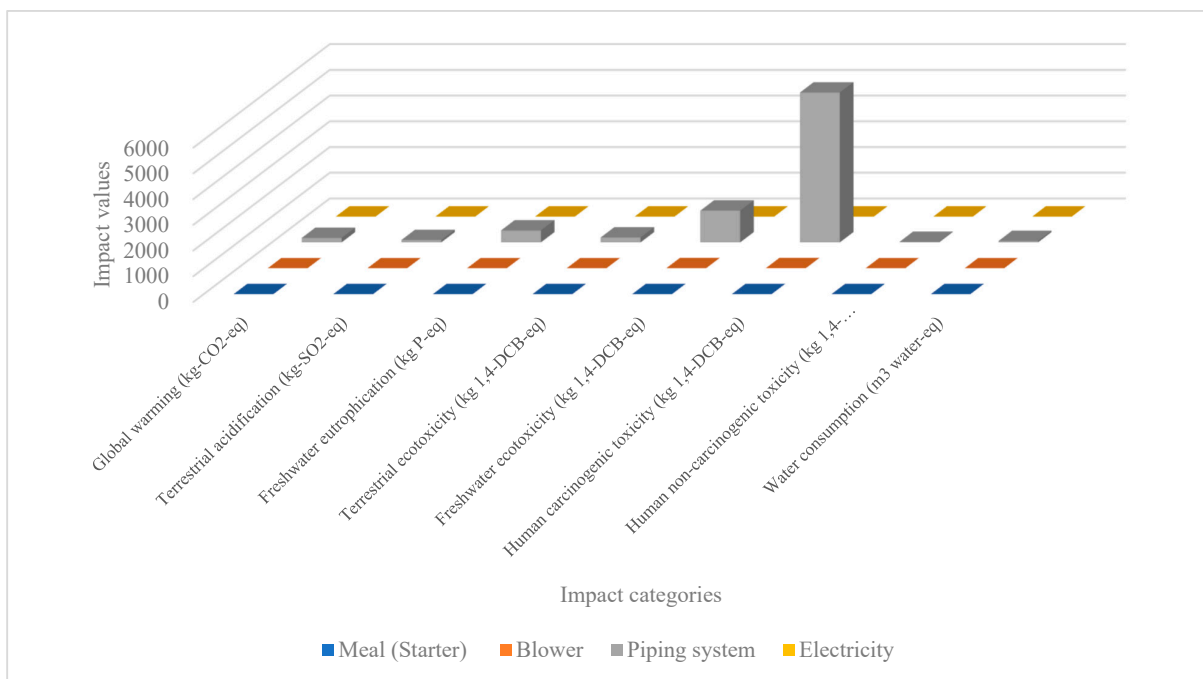**Figure 3.** Environmental impacts caused by the capital goods for the pond preparation phase.

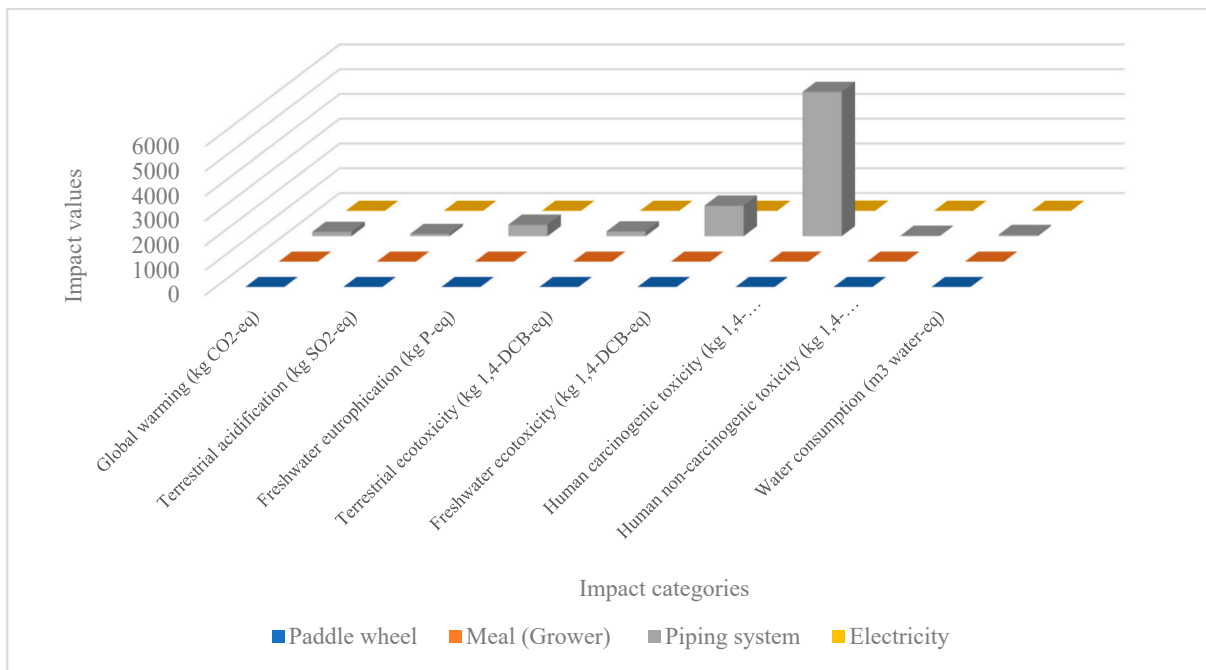**Figure 4.** Environmental impacts caused by the capital goods for the stocking phase.

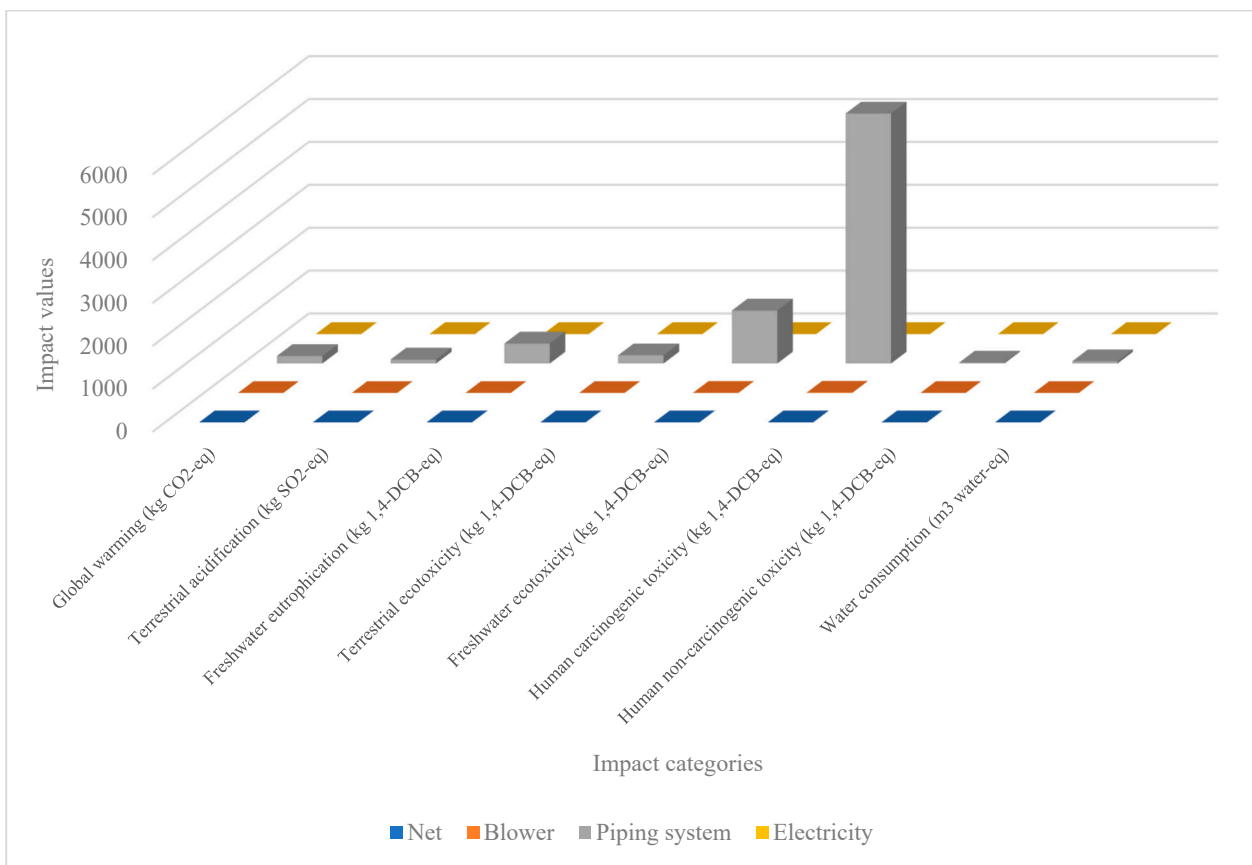**Figure 5.** Environmental impacts caused by the capital goods for the farming phase.

Figure 6. Environmental impacts caused by the capital goods for the harvesting phase.

Concern should be given to the disposal management of this material by the respective authority in the future. While for energy use, the total electricity consumption during stocking and harvesting phases was higher than in pond preparation and farming phases

due to the frequent use of paddle wheels and blowers for better ventilation to the livestock, feed imposed a low environmental impact in all phases, and it is predicted that all farms are implementing good pond circulation and management practices and being particular about the water quality level at the input and output channels.

4. Discussion

4.1. Environmental Impact

Asia has dominated 89% of the world's aquaculture production of farmed aquatic animals [1]. Nevertheless, a detailed review of the LCA study revealed that more LCA studies are needed from Asia as it only encountered 24% of the reviewed 65 LCA studies [29]. A similar scenario calls for the need to explore additional LCA studies for freshwater fish, which dominate 60% of global farmed fish production. The review found that 42% of LCA studies were dominated by diadromous fish [29]. A few LCA studies have been selected and summarized for shrimp and prawn farming in Table 4 below.

Table 4. Summary of selected LCA studies related to freshwater prawn farming.

Country	System and Species	Source of Data	Software/Method	Environmental Impacts	Allocation	References
Brazil	Monoculture & Polyculture: Amazon river prawn *(Macrobrachium amazonicum)*	Primary data (Experimental) Secondary data	SimaPro v8.0.5/CML-IA version 3.02 method	Climate change Eutrophication Cumulative Energy Demand Land Occupation Acidification Net Primary Production Use (NPPU) Water dependence	System expansion Mass allocation Energy allocation Economic allocation	[38]
Philippines	Polyculture (Tilapia, Milkfish, Mud crabs, tiger prawn, wild species	Primary data	SimaPro v.7.0/ Ecoinvent v2.2 database.	Eutrophication Acidification Climate change Land occupation Net primary production use (NPPU) Total cumulative energy demand (TECD) Total human labour	Energy-based allocation Economic allocation	[39]
Brazil	Comparison of two monoculture systems *(M. rosenbergii* and *M. amazonicum)*	Secondary data from previous studies	SimaPro v.7.3/CML 2001 method	Climate change Eutrophication Acidification Energy use Net primary production use (NPPU) Surface use Water dependence	No allocation	[16]
Malaysia	Monoculture *(M. rosenbergii)*	Primary data (at farm level) Secondary data	SimaPro v.9.3 Method: ReCiPe 2016	Global warming Terrestrial acidification Freshwater eutrophication Terrestrial ecotoxicity Freshwater ecotoxicity Human carcinogenic Human non-carcinogenic Water consumption	No allocation (monoculture system)	This study

Table 4 shows the comparisons from previous LCA studies in terms of (i) types of system; (ii) data collection; (iii) region; and (iv) LCA method, which leads to the difference in environmental impacts. Most LCA studies focused on the polyculture system [16,39], except for [38], whose system was conducted at the experimental stage to better understand the interactions of controlled factors on system performance. In addition, data sources for most studies were obtained based on actual data collection at the premise or farm and secondary data from the previous studies, except for [16] which largely depends on secondary data.

Environmental impacts derived from polyculture systems were evaluated based on the allocations, since it involves many species as shown in Table 4, but most of the studies produced a low environmental impact for *M. rosenbergii* compared to other species [16,38,39].

A study on the experimental condition found that the rearing stage of *M. rosenbergii* contributes to eutrophication, land occupation, and water dependence [38]. Another study by Aubin et al. [39] found that 67% of acidification impact was dominated by farm operations, caused by the energy used from daily operations and the estimated ammonia emission from the water. Santos et al. [16] focused on the best management effluent practices among two *Macrobrachium* species; *M. rosenbergii* vs *M. amazonicum* and proved that the former had a lower environmental impact than the latter.

However, Medeiros et al. [40] suggested that farm productivity did not influence system efficiency from an environmental perspective. The study by Aubin et al. [39] found that productive sites showed a lower eutrophication level, indicating the efficient water-cleaning role of ponds that recirculate nutrients from the inlet water. On the other hand, a comparison between the same species reared in monoculture and polyculture suggested that the degree of intensification is not a relevant concept for distinguishing the impacts of aquaculture systems [39].

While some LCA studies choose not to include the influence of infrastructure on environmental impact [40–42], our study found that the influence of physical infrastructure could not easily be excluded. Previous LCA studies counted infrastructures such as anti-bird nets, platforms, aerators, inlets, and outlet pipes. These were predicted to change the magnitudes of specific impacts by contributing 7.12% to climate change, 9–15% to cumulative energy demand and 7–18% to acidification [14,38].

This study reveals the high impact of human carcinogenic impact and freshwater ecotoxicity, and is thus similar to the review by Ghamkar et al. [43]. They discovered that most of the impacts from infrastructure could be seen in the marine ecotoxicity potential. In aquaculture, microplastics are usually derived from the damaging and aging of commercial fishing gear [44]. Recently, microplastic has become an emerging environmental threat and is proven to contaminate seafood, transfer toxic pollutants to human beings, and possibly impose a high risk of cancer [45]. While from the seafood safety context, microplastic bioaccumulation triggers various adverse effects on aquatic organisms and impacts human health via consuming contaminated seafood [46,47]. The aquaculture industry may suffer from plastic pollution, mainly when plastic products are widely used for aquaculture [48]. However, the risks of microplastics in real-world environments and their impacts on humans are yet unknown, and additional research is needed to thoroughly address this issue [49–51]. In a nutshell, respective stakeholders can propose a proper management plan for physical waste, especially to evaluate the use of plastic products in the aquaculture farming system.

4.2. Feed Management

Eutrophication is the most frequent environmental impact connected to feed usage [52]. In this study, the farmers used alternative feeds other than commercial feeds to reduce the FCR closer to the harvest stage. This also was reported by New and Kutty [4] with a FCR value of 1.8–3.0:1 achieved using these farm-made feeds. This practice of lowering FCR is better for the environment [23].

Reusing pond effluents and sediments as fertilizers, as practiced in China, would reduce the impact of eutrophication compared to those nutrients from modern aquaculture systems [23]. Bohnes et al. [29] have found that FCR is the crucial driver of cumulative energy demand, net primary production use, acidification, and climate change. Low FCR will result in low environmental impacts [53], as it decreases the amount of feed and reduces the nutrient losses released to the pond bottom and into the water [38], hence also contributing to low productivity.

4.3. Effluent Management

Effluent management is another major contributor to environmental impact, particularly eutrophication, as it can modify aquatic ecosystem communities and causes environmental pollution [14,38,54]. To reduce operating costs and possible effects of suboptimal

water quality for farming, most farmers locate their farms in near-pristine areas to get enough clean water from the stream and hill water resources. They benefit from a clean site with lower temperatures and a less polluted environment. Moreover, these farms could reduce the construction of a waste management facility, and all the wastewater will be discharged directly to the nearest river without any prior treatment.

Since this study was conducted at the actual farms, we propose that the management of waste/effluent dispersal and treatment facilities are crucial and should be included in the planning stage for *M. rosenbergii* farming in Malaysia. None of the farms had a water treatment system, and effluent was released directly into the nearby river. Comparatively, a previous LCA study of another freshwater prawn species, the Amazon River prawns by Medeiros et al. [38] was conducted in an experimental system, therefore their system was probably equipped with a proper treatment system.

Zainoddin [34] has proposed a systematic flowchart in waste treatment facilities for giant freshwater prawn farming in Malaysia, which covers a water inlet, water outlet, flow out system, pond construction, buildings, and other related facilities as shown in Figure 7. The treatment pond system should comprise at least 5–10% of the operational culture area. In addition, the facility must have an effluent pond and a wastewater collection pond (1% of the pond area).
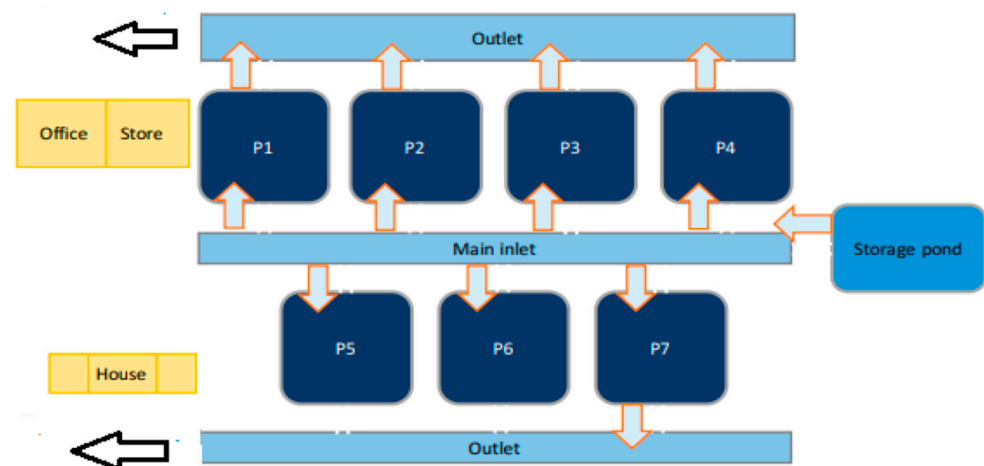

Figure 7. Schematic diagram of *M. rosenbergii* culture system, modified from [34]. P1–P7 refers to the number of culture ponds.

4.4. Allocations

Other studies for LCA in aquaculture were on polyculture systems that applied allocation in its impact analysis, since it involved the production of many products [38,39]. Therefore, it is necessary to divide the environmental impacts of the process between the products based on a few choices such as economy allocation, or mass and energy-based allocations. The International Oganization for Standardization [27] has outlined a few approaches to handling allocation: expanding the product system, allocation by physical relationship, or allocation by other relationship. However, this study did not apply allocations as giant freshwater prawn is a monoculture system culture and does not associate with any by-products.

4.5. Uncertainty Analysis

Uncertainty analysis is usually conducted to check the effect of inaccurate data due to the difference in environmental performances of varied suppliers, or whether the production process can still operate under different conditions [36]. However, this study did not perform uncertainty analysis, since the data collected from fifteen ponds are considered too minimal to be compared with the range of data variety we received. This situation was similar to the study by Aubin et al. [39], which excluded uncertainty analysis as it was

challenging to minimize variability around estimated means. The situation is predicted as we were collecting data from traditional farmers who may not be able to provide accurate information, and most of the data is based solely on the farmer's knowledge and experience. Nevertheless, we referred to an expert supplier for the nearest characterization of the equipment for capital goods.

5. Conclusions

Apart from the identified capital items that require consideration for future waste management, this LCA study found that *M. rosenbergii* farming generates a low impact on the environment. Nevertheless, the LCA study is very much dependent on the species reared, types of farming systems, and types of inputs considered in the studied system boundary. Developing countries play a significant role in providing fish resources, and LCA's potential to address sustainability issues should be given to this region. LCA should be introduced and widened among key aquaculture players, especially in Asia. For high-value species such as giant freshwater prawns, a low environmental impact study from the LCA methodology could be potentially valuable for further promotion exclusively via ecolabelling marketing. A larger system boundary considering hatchery inputs and the marketing phase should be the focus of future LCA studies for GFP farming. A future study could broaden viewpoints by focusing on the impacts of various feed meals for cultured species, the usage of plastic items along the production chain, effluent and waste management, and other elements that contribute to sustainable aquaculture practice.

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