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Sustainability Assessment of White Shrimp (*Penaeus vannamei*) Production in Super-Intensive System in the Municipality of San Blas, Nayarit, Mexico

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Abstract: The super-intensive white shrimp system is more productive (t ha^{-1}) than traditional systems. However, it implies greater investment in infrastructure and machinery, a continuous supply of electricity, and a specialized workforce. Therefore, the sustainability of a shrimp farm model operating in a super-intensive system in Nayarit (Mexico) was evaluated using financial analysis and life cycle assessment. The investment is important, but the fixed costs (16%) are much lower than variable costs (84%). The super-intensive farm is economically viable, with an overall profitability (29%) that is higher than that of other agri-food activities in Mexico. It is also an activity that generates a lot of employment, in relative terms, as well as economic movement in the area. The potential environmental impacts are higher than those registered in semi-intensive shrimp systems but slightly lower than those registered in intensive systems. The estimated global warming value per kg of shrimp is 5.08 kg CO_2-eq, an intermediate value. Also, as the shrimp production is much higher than in traditional systems, it could have a great and positive impact on the maintenance and regeneration of the mangrove ecosystem.

Keywords: *Penaeus vannamei*; super-intensive; sustainability; economics; costs; LCA

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1. Introduction

The production of aquatic organisms peaked in 2018 at approximately 179 million tonnes. Aquaculture represented 46% of the total production for human consumption, and 52% of the products used to make fishmeal and fish oils are included. The countries that led this list in terms of production volumes were China, Indonesia, India, Vietnam, the Philippines, and Bangladesh [1]. The per capita consumption of aquaculture products has grown significantly, from 9.9 kg in the 1960s to 20.5 kg in 2018. The increase in demand has been due to population growth, the increase in economic income in households, and the trend toward healthy eating. The supply has increased because of the development of technologies for aquaculture, since the contribution of fishing has remained around 90 million tonnes since the 1990s [1].

According to FAO [1], for the year 2018, crustaceans represented 11.4% of the total production in aquaculture (82 million tons), to which the white shrimp, *Penaeus vannamei* made the greatest contribution (52.9%), followed by the red swamp crayfish, *Procambarus clarkii* (18.2%), the Chinese river crab, *Eriocheir sinensis* (8.1%), and the giant tiger prawn, *Penaeus monodon* (8.0%). The main countries for shrimp production are: China, Indonesia, and Viet Nam. Mexico ranks seventh in the world and contributes 3% of the total world shrimp production. In general, this industry has undergone enormous growth because of the growing demand from the northern countries (Western Europe and North America), which currently import 80% of the shrimp produced worldwide [1].

Unfortunately, the development of shrimp farming on the coasts of tropical regions around the world has been primarily at the cost of deforestation of extensive mangrove areas [2,3]. The mangrove is not only one of the most productive tropical ecosystems, with great biodiversity, but also plays an important role in the provision of valuable ecosystem services, such as protection of the coast against storms and erosion, maintenance of water quality [3–5], and the capture and sequestration of CO_2 from the atmosphere [5,6]. Although various activities are responsible for deforestation, aquaculture has been the main one [3]. Fortunately, extensive systems with low productivity (0.15–0.5 t ha^{-1}) have given way to semi-intensive systems (0.5–2 t ha^{-1}) and more productive, intensive systems (7–20 t ha^{-1}) [7], which has helped to reduce the pressure on the mangrove ecosystems [8].

A specific case that could reflect this situation is found in Nayarit (Mexico). Fresh shrimp production in 2019 in Nayarit was 11,740 t, which represents 8% of the total production of this species in Mexico [9]. This output was obtained in a cultivated area of 14,428 ha, which means an average yield of 0.88 t ha^{-1} year^{-1}, although the yield varies between 0.58 and 1.16 t ha^{-1} year^{-1}. Most of the production is carried out in semi-intensive systems (95.5%) and only 4.5% by intensive means [10]. Shrimp farming in Nayarit has developed within the complex of coastal lagoons known as the Marismas Nacionales. Its extension includes a coastline of 289 km, and more than 150,000 hectares of tidal channels, flood plains, and lagoons, which represents 4.0% of the total coastline of the Mexican Pacific [11]. Until now, the introduction of super-intensive systems has been due exclusively to private initiative. The aim has been to increase the productivity and increase profits. It is, therefore, a potential territory for the development of aquaculture, especially shrimp farming. However, these areas coincide with mangrove ecosystems rich in biological diversity. The increased production of farmed shrimp in the area can be seen as a positive sign of economic development, but is also traumatic for coastal ecosystems. The felling of mangroves for the establishment of shrimp companies represents the greatest danger of deterioration [11].

One solution to maintain a balance between economic development and mangrove conservation is the establishment of systems that are much more productive than those currently in place, and that consequently require much less land area. In this sense, the super-intensive systems, technically known as heterotrophic and biofloc systems, provide very high yields, of up to 68–80 t ha^{-1} [7,12], with a minimum renewal of water to eliminate waste [12–17]. To achieve these favorable conditions, it is necessary to simulate a trophic chain on a microscopic scale in order to eliminate waste from the system, mainly nitrogenous and phosphorus compounds; for this, autotrophic organisms (microalgae) and heterotrophic organisms (bacteria and protozoa) are added.

Obviously, the first point is to determine the viability and economic profitability of the super-intensive system in the territory of Nayarit. This production system is more efficient, but it also requires more infrastructure and machinery, a continuous supply of energy, and a specialized labor force. It is also important to assess the environmental impact from a life cycle assessment (LCA) perspective. An integrative approach is necessary, considering the impacts at both the local and global scale, to better understand the consequences of aquaculture for the natural environment [18]; this has been applied previously for fish farming [18–23] and for the cultivation of shrimp [4,5,24–27]. However, the super-intensive system has not been evaluated environmentally and economically. Therefore, the question is: is the super-intensive shrimp system sustainable from the economic, social, and environmental perspectives?

The objective is the evaluation of the super-intensive heterotrophic white shrimp (*Penaeus vannamei*) aquaculture system in Nayarit (Mexico) from the economic, social, and environmental perspectives, through economic and financial analysis and life cycle assessment.

2. Materials and Methods

To evaluate the sustainability of the white shrimp aquaculture in a super-intensive heterotrophic system, first a shrimp farm model was defined based on the information provided by a company located on the coast of the municipality of San Blas, Nayarit, Mexico. Second: (i) A financial economic analysis was carried out for the cost accounting analysis aspect; (ii) indicators of the social impact of the activity were evaluated; and (iii) a life cycle assessment was applied.

2.1. Shrimp Farm Model

A super-intensive shrimp farm model was designed based on the biological, technical, and engineering requirements necessary for this purpose. For this, the biological, health, and financial information for two years (second half of 2017, 2018, first half of 2019) of the company "Acuícola y comercializadora orgánico de Matanchén S.P.R. DE R.L." was taken as a reference. This company is located at kilometer 12 of Matanchén Bay, San Blas, Nayarit, Mexico. Consequently there is no number of data for each of the variables involved and therefore, obviously, there is no statistical analysis of the data, as in other published works that use a similar methodology [18–21,28,29]. There are also studies that evaluate a model based on information from different sources, but they cannot apply statistics to all variable [22,23,30].

Super-intensive shrimp ongrowing involves biofloc and heterotrophic systems [15,16]. These are based on the creation of a trophic chain on a microscopic scale where waste products (nitrogenous and phosphorus compounds), through biochemical processes, become a source of nutrients for the feeding and proliferation of beneficial bacteria, microalgae, and zooplankton, which at the same time are used as a complementary food for shrimp. In this way, in addition to the high productivity per unit of volume, the renewal of water is very low (less than 10% daily), compared to conventional systems, since the biological waste generated in the production processes is recycled.

This shrimp farm model occupies a plot of 0.75 ha and has an annual production of 57,904 kg year^{-1}. The cultivation begins with paralarvae acquired from a commercial hatchery, which are sown at a density of 500 specimens m^{-3} in circular tanks and grown to the commercial size of 12 g. The survival rate is 80%, and the feeding is with commercial feed; the FCR (feed conversion rate) is 1.4. The ongrowing period lasts from 90 to 120 days, and so 3 cycles are completed per year.

2.1.1. Facilities and Investments

The shrimp farm model comprises one building and auxiliary facilities, auxiliary systems, and the cultivation facility. The latter has 20 high-density polyethylene (HDPE) flat-bottom circular tanks with a diameter of 16 m and a useful height of 1 m, with a capacity for 201 m^3 of water. These are located on a concrete slab, under a greenhouse structure and roof. The facility has a hydraulic system for the supply and distribution of water, as well as its drainage; an aeration system for the culture tanks; and an electrical network system for the water pump, electric blowers, and lighting. The entire system was sized for maximum operational capacity in order to guarantee the maintenance of the species-specific biological and technical requirements.

The initial investment is considered to comprise the expenses associated with the infrastructure (exterior cover, equipment, auxiliary systems) and the means amortizable in several annuities. It also includes government procedures, permits, concessions, and biological and technical feasibility studies. The budget chapters include: land development; infrastructures (buildings and auxiliary facilities); auxiliary hydraulic, aeration, and electrical systems, laboratory equipment, furniture, and transportation; aeration and water-pumping equipment; and culture tanks.

2.1.2. Means of Production

The means of production involved in the ongrowing process (Table 1) in the farm are:

- Pre-cultivation activities. These consist of washing and disinfection of tanks, the entire hydraulic and aeration system, and utensils. A sodium hypochlorite solution is applied. Afterwards, the water in the tanks is matured by applying a commercial probiotic and molasses.
- Sowing of paralarvae. The paralarvae are purchased from a specialized hatchery. Their average weight can vary from 10 to 70 mg. An established shrimp industry protocol is followed that includes stress testing, larval counting, acclimatization, and stocking in the culture tanks.
- Pharmaceuticals and other products. Vitamins and antibiotics in the food for preventive (3 g kg^{-1}) and curative (6 g kg^{-1}) treatments, for about 6 days; and the replacement of zeolites and gravel in the filtration units.
- Feeding. The first food ingested by the paralarvae in the culture tanks is the mesocosm plankton that grows during the maturation of the water. The feeding with a commercial feed having a protein content of 45%—at a rate of 16% of the biomass, distributed in 12 daily rations, every 2 h—is also started. The feed ration is adjusted according to the weekly weight increase. The crude protein (CP) content in the feed is decreased as the weight of the shrimp increases. Four types of feed are used in each fattening cycle: raceway (45% CP) from arrival to 0.5 g; crumb (40% CP) from 0.5 g to 2 g; 35% CP micropellet from 2 g to 6 g: and 30% CP pellets from 6 g onwards.
- Staff. Two field assistants, two guards, a technician, and a head of production (engineer).
- Electricity. The energy consumption is due to the use of 5 electro blowers (10 HP and 7457 kW h, working for 2520 h in one production cycle); 2 centrifugal pumps (5 HP and 3728 kW h, working for 525 h in one production cycle) for water renewal; lighting (0.5 HP and 0.372 kWh, working for 525 h in one production cycle) of the production unit; and domestic use related to socket outlets and other uses. It is important to note that, when evaluating the economic cost, it has been taken into account that there is a subsidy in Mexico for the agricultural sector that reduces the price of each kWh by 50% [31].
- Rent. The rental expenses comprise the annual rental of the land (0.75 ha) where the farm is located.
- Miscellaneous expenses. These include the purchase of fuel and lubricants for the diesel generator, automobiles, and the maintenance of machinery and equipment.

Table 1. Annual inputs.

Description	Amount Per Year	Amount Per kg of Shrimp
	Pre-cultivation activities	
Sodium hypochlorite (g)	15,000	0.2590
Probiotic (kg)	43,428	0.7500
Molasses (kg)	8448	0.1459
Paralarvae (number of shrimp)	6,031,711	104.0000
	Drugs and others	
Vitamins (kg)	41	0.0007
Antibiotics (kg)	41	0.0007
Filter material (kg)	500	0.0086
	Feed	
Raceway 45% (kg)	4222	0.0729
Crumb 40% (kg)	12,667	0.2188
Micropellet 30% (kg)	33,778	0.5833
Pellet 30% (kg)	30,400	0.5250
	Electricity	
Electro blowers (kWh)	281,875	4.8680
Centrifugal pumps (kWh)	11,745	0.2028
Illumination (kWh)	587	0.0101

2.2. Economic Evaluation

The economic evaluation was carried out by means of a financial economic analysis, involving a cost/benefit analysis [32–36]. It is a microeconomic analysis in a free market for shrimp. In any economic viability analysis, the period of time is determined by the useful life of the fixed assets (Tables 2 and 3); in our case, the useful lives used to calculate depreciation are shown in Table 4. Both the costs and the incomes are those of one year of production. To carry out this analysis, the operating costs were identified, subsequently grouped by chapters, and classified into fixed costs and variable costs.

- Fixed assets or fixed costs. The calculation of the expenses generated by the shrimp farm investment (K_0) was carried out with the help of the price generator for the construction of Mexico [37]. For those work units which, due to their detail, were not in this database, we used data from professional work—endorsed by the Official College of Agronomists of Murcia—carried out by García García [38] regarding the facilities of land-based marine aquaculture. To determine the annual fixed assets the amortization linked to the investment was taken into account using the linear or constant quotas method.
- Variable costs. The variable costs or operating costs (VC) were determined by the expenditure of inputs, services, and activities used in the course of an accounting year. They were calculated taking as a reference the cost of the inputs used and the activities carried out in the production process (Table 1).
- Opportunity costs. For each of the costs, both fixed and variable, their opportunity cost (OC) was calculated. In other words, the alternative use of money in risk-free savings bank accounts was taken into account. To calculate this OC, an interest rate of 2.61% was used, which was established taking into account the average interest rate of the Mexican government bonds, calculated with data from the last 10 years, minus the average inflation in the same period.
- Incomes. Once all the costs had been obtained and classified, the total income (I) was calculated from the sale of the shrimp biomass at source at an average price of 4.4 USD kg^{-1}. This value was established as a reference based on the company's records during the last three years.

2.2.1. Economic Indexes

To analyze the economic feasibility of the super-intensive system, first, the net margin (NM) was calculated as the difference between the income and total costs (TC) [35,39], using the following equation: NM = Income − (Fixed Costs + Variable Costs + Opportunity costs)

From the NM the following economic indexes were calculated:

- NM/VC: this indicates the return on invested capital in the short term.
- NM/K_0: this is an indicator of the long-term return on invested capital (Investment = K_0).
- NM/TC: this shows the overall profitability of the activity.
- VT (viability threshold): is the same as the average total cost of production. So, this indicates the minimum sale price of the product at its origin for the activity to be viable. Its calculation is VT = TC/Production (USD kg^{-1}).
- BEP (break-even point): this indicates the minimum production, for the average market sale price, for the activity to be viable. It was calculated from the same equation as the VT [34,35,40]. The BEP was also expressed in relation to the annual production (t $year^{-1}$), number of culture tanks (n), and culture density (shrimp m^{-3}).

2.2.2. Elasticity

The elasticities of certain relevant variables with respect to the overall profitability of the activity (NM/TC) were also calculated. In general, elasticity is the sensitivity of variation that one variable exhibits when another variable experiences change. Specifically, it shows the percentage increase or decrease that one variable suffers due to an upward variation of another. Its calculation has been described by several authors [41,42]. Those variables that have a greater impact, are susceptible to change, and are included in the most important accounting chapters: investment (K_0) shrimp sale price (SP), paralarvae price (PL), electricity price (EP), feed price (FP), feed conversion rate (FCR), stocking density (SD), and survival (S). The sign (–) in the elasticity indicates that the dependent and independent variables are inversely proportional. The sign (+) indicates direct proportionality.

2.3. Social and Territorial Evaluation

The evaluation of the social impact of the system was carried out using three indicators:

- AWU/ha (agricultural work unit per ha): this is an indicator of the generation of employment linked directly to rural areas. To establish the employment generated, the labor required to carry out the tasks of the aquaculture activity already described was calculated. An Agricultural Work Unit (AWU) corresponds to the work performed by one person employed full-time in a rural farm [35,43].
- CRE (contribution to regional economy): this is an indicator of the economic impact of shrimp farming on the rural population. It was calculated as the unit income (USD ha^{-1}); it has social relevance since it measures the gross economic productivity and the impact on the environment and the rural population.
- ST (surface threshold): like the previous one, this is an indicator linked to the territory [35,44]. It is calculated from the BEP, and establishes the minimum area (ha) necessary for the exploitation to be viable; that is, the farm size at which the income equals the total costs.

2.4. Environmental Evaluation

Life cycle assessment (LCA) is a standardized method [45,46] that estimates the potential environmental impacts throughout the entire life cycle of a product, from the extraction of raw materials to the final disposal. LCA consists of four stages: (1) the definition of the objective and scope; (2) inventory; (3) impact analysis; and (4) interpretation.

The purpose of this LCA is to contribute to the sustainability evaluation in the case study, but also to provide data to enhance our scientific knowledge of the potential impacts due to the cultivation of white shrimp in a super-intensive system.

The functional unit was established as 1 kg live-weight of white shrimp. This LCA was based on a methodological attributional approach and can be regarded as a "cradle to shrimp farm-gate" assessment. As the production of shrimp was treated as a mono-functional system, no allocation procedure was applied. However, in the elaboration of the feed, co-products (meals and oils) are used for which a mass allocation was used. The system boundaries include inputs and outputs that were grouped into the following system components:

- Electricity. The electric energy consumed by electro blowers, centrifugal pumps, and lighting (Table 1).
- Feed. As the supplying companies do not provide the composition of the feed raw materials, that described by Cao et al. [26], which also includes data in relation to manufacturing (energy and materials), was used. Therefore, the assumption was made that only one type of feed is used throughout the cycle (Table 1). It has been considered that the feed factory is located in Ecuador and that the raw materials come from the US (soybean meal, soybean oil, and wheat meal) and Peru (fish meal).
- Product. This corresponds to products for disinfection, molasses, pharmaceuticals, and filter material (Table 1).
- Fuel. Diesel and gasoline consumed by vehicles operating at the shrimp farm (Table 1).

The production of paralarvae was not taken into account in this LCA, because the necessary information was not available. However, this component should not have a significant effect on the impacts: in the intensive cultivation of this species, a contribution to the associated global warming, acidification, and eutrophication of 3.56%, 2.62%, and 0.37%, respectively, has been registered [26]. The facilities and infrastructure were not taken into account either. In general, their contribution in the different aquaculture systems is not significant [20,29], except in the offshore fish farming, where it has been suggested that it has some relevance [22,23]. In the case of the white shrimp, contributions of the infrastructures in intensive systems of 0.12%, 0.57%, and 0.03%, respectively, to global warming, acidification, and eutrophication have been registered [26].

The LCA was performed with SimaPro 9.1 [47], which integrates background databases and different environmental assessment methodologies; it is the most widely used software in agri-food production, including fishing and aquaculture [23,26,48–52].

The foreground data for the life cycle inventory are shown in Table 1. For the background data, the Ecoinvent 3.6 and Agri-footprint 4.0 databases were used. For the processes related to electrical energy, fuels, products, and transport, the Ecoinvent database was used. Agri-footprint (mass allocation) was used for the feed raw materials (fish meal, soybean meal, wheat meal, fish oil, and soybean oil).

The inventory data were classified in order to characterize the potential environmental impacts, using the software SimaPro 9.1. The methodology used was the CML-IA baseline [53], and the impact categories used in this study were: abiotic depletion (AD), abiotic depletion fossil fuels (ADFF), global warming (GW), ozone layer depletion (OLD), human toxicity (HT), fresh water aquatic ecotoxicity (FWAE), marine aquatic ecotoxicity (MAE), terrestrial ecotoxicity (TE), photochemical oxidation (PO), acidification (A), and eutrophication (E).

For the interpretation of the results, a contribution analysis was carried out to calculate the percentage contributions of the different components of the system to each category of impact. The global contribution was also used; this indicates how each component contributes globally to all impact categories [22,23].

3. Results and Discussion

3.1. Economic Analysis

3.1.1. Investment

As shown in Table 2, the system requires a significant initial investment of 430,522 USD. The land conditioning chapter is the highest, representing 34.8%. The infrastructure (24.2%) and auxiliary systems (23.6%) chapters are also relevant. However, the equipment only accounts for 3.1%. This value is lower than that described in the ongrowing of sole (*Solea senegalensis*), between 10.2% and 12.9% [30], and of octopus (*Octopus vulgaris*), 13.0% [54]. In these systems, the water flow requirements to maintain the optimal quality of the water in the tanks are very high, while in the heterotrophic and biofloc systems [13,16] the water renewal rate is very low.

Table 2. Investment summary (K_0).

Chapter	Concept	Budget UDS	Budget/ Chapter UDS	% on K_0
Land development	Preliminary studies and licenses Earthworks Floors and drainage	19,550 32,080 98,301	149,931	34.8%
Infrastructure	Building and auxiliary facilities	104,155	104,155	24.2%
Auxiliary systems	Hydraulic system Blowers system Electrical installation Laboratory, furniture and transportation	19,759 14,910 36,426 30,370	101,465	23.6%
Equipment	Blower and pumping equipment	13,235	13,235	3.1%
Cultivation units	Culture tanks	61,736	61,736	14.3%
	Investment		430,522	100.0%

The relationship between the investment and the annual production is 7435 USD t^{-1} (Table 3), higher than that reported in the semi-intensive system: 828 USD t^{-1} [55]. This is due to the fact that the latter is a low-tech system with little investment in infrastructure. However, while the investment is nine-times higher in this super-intensive system, shrimp production is twenty times higher. By contrast, the investment/production ratio is lower than that reported for the intensive ongrowing of octopus (€ 10,188 t^{-1} [54]) and sole, € 12,967 t^{-1} [30]. However, these species have a higher commercial value, which can offset high investments, leading to subsequent recovery of capital.

Table 3. Cost and net income structure from a super-intensive shrimp farm. Annual output of 58 tonnes.

Economic Parameters	UDS	UDS tn^{-1} of Shrimp
Initial investment K_0	430,522	7435
Fixed assets	31,444 (16%)	543
Variable costs	164,740 (84%)	2845
Total cost	196,184	3398
Total incomes	253,213	4373
Net margin	57,029	985

(% of the total cost).

3.1.2. Cost Structure

The general accounting structure (Table 3) resulting from the costs and income shows that the annual fixed costs amount to 31,444 USD (Tables 3 and 4) and the VC to 164,740 USD. In other words, the activity requires a significant investment but when we treat it as an annual fixed cost, it represents only 16% of the total cost of production, the VC being much more important (84%). The total cost of 3398 USD t^{-1} is somewhat higher than the reference values for this species, 2500–3000 USD t^{-1} [7], but the production is higher. In fact, the income is high (253,213 USD), although the price of shrimp is moderate (4.4 USD kg^{-1}), due to the high productivity of the system (57,904 kg). As a consequence, the NM is 57,029 USD $year^{-1}$, equivalent to 985 USD t^{-1} (Table 3).

Table 4. Annual fixed costs.

Chapter	Investment (UDS)	UL (Years)	RV (UDS)	Amortization (UDS)	FC (UDS)	%/TC *
Land development	149,931	30	0	4998	5128	2.60%
Infrastructure	104,155	15	0	6944	7125	3.60%
Auxiliary systems	101,465	10	0	10,147	10,411	5.30%
Equipment	13,235	5	1324	2382	2445	1.20%
Cultivation units	61,736	10	0	6174	6335	3.20%
Investment	430,522	–	–	–	31,444	16.00%

UL: useful life; RV: residual value; FC: fixed costs. The fixed cost (FC) includes corresponding opportunity cost. * %/TC: percentage of each cost on total cost (TC).

Of the fixed costs (Table 4), those due to the auxiliary systems (5.3%), infrastructures (3.6%), and culture tanks (3.2%) stand out. The preparation of the land, which represented the highest investment, has a very low impact on the fixed costs because the depreciation period is 30 years.

The VC for one year of production amounts to 164,740 USD (Table 5) and represents 84.0% of the total cost, with feed being the most expensive input (37.4% of the production costs). These results agree with those of Fraga-Castro and Jaime-Ceballos [56], who found that the cost of artificial feed represents between 30 and 40% of the total costs of shrimp farms with intensive systems, and that its variation depends on a number of factors—the quality of the paralarvae and culture management, and the feed quality and feed distribution being among the most relevant.

Table 5. Variable costs.

Chapter	Variable Costs (VC) (UDS)	%/TC *
Preliminary activities	1305	0.70%
Paralarvae	33,309	17.00%
Drugs and chemicals reagents	5291	2.70%
Feed	73,432	37.40%
Personal	31,452	16.00%
Electricity	12,316	6.30%
Land rent	3854	2.00%
Various	3782	1.90%
Subtotal	164,740	84.00%

The variable cost (VC) includes corresponding opportunity cost. * %/TC: percentage of each cost on total cost (TC).

The energy expenditure represents 6.3%, a relatively low value if we consider that the aeration systems are operating continuously. This low value is due to the policies implemented in Mexico, since for the agricultural sector there is a subsidy that reduces the price of each kWh by 50%, which significantly lowers the energy costs [31].

3.1.3. Evaluation Using Economic Indicators

The economic indicators (Table 6) show that shrimp ongrowing in the super-intensive system is economically viable. The long-term profitability, measured as NM/K_0, is 13.2%, which is higher than the fixed income of the Mexican public debt expressed as a 10-year State Bond for the period 2010–2019 (6.60%), which can be used as a reference. The short-term profitability, evaluated as NM/VC, indicates a higher profitability in the short term (34.6%) than in the long term.

Table 6. Economic assessment indicators.

Description	Value
NM/K_0 (%)	13.2
NM/VC (%)	34.6
NM/TC (%)	29.1
VT (cost UDS per kg)	3.4
BEP (minimum tn year^{-1})	44,863
BEP (minimum number of tanks)	15
BEP (minimum survival %)	55
BEP (minimum density shrimp/m^3)	309

NM: net margin. K_0: investment. VC: variable costs. TC: total costs. VT: viability threshold. BEP: break-even point.

The global profitability (NM/TC) is 29.1%, a relatively high figure if we compare it with other activities in the Mexican agri-food sector. In corn production the profitability is only 14.6% [57], while for the production of cattle in farms the profitability fluctuates between 4% and 16% [58]. Also, the profitability is superior to that of other aquacultural activities. In the intensive tilapia (*Oreochromis niloticus*) system the profitability is 22% [59]; although the productivity of tilapia is higher than that of shrimp (up to 150 t ha^{-1}), the sale price is lower (1.57 USD kg^{-1} [60]) and, therefore, the margin with respect to production costs is lower.

The UR in relation to the average cost of production is 3.4 USD kg^{-1} (Table 6), a higher value than that reported in semi-intensive systems, which are around 1.5 USD kg^{-1} [55]. However, the producers consulted in the study area place it at a higher value, around 2.3 USD kg^{-1}. The average sale price for the super-intensive system is 4.4 USD kg^{-1}, so the profit margin per kg produced is 1 USD kg^{-1}. To be economically viable, the shrimp farm has to produce at least (BEP) 44.86 t year^{-1} (Table 6). Also, the facility must have at least 15 culture tanks, a stoking density of 309 shrimp m^{-3}, and a survival rate of 55%.

3.1.4. Analysis of the Elasticity

The results of the elasticity calculations (Table 7) show how the percentage variation of some system variables can affect the profitability of the project. As was stated earlier, the sign (–) indicates that the dependent and independent variables are inversely proportional, while the sign (+) indicates direct proportionality.

Table 7. Elasticities of different variables in relation to profitability (NM/TC).

Variables	Profitability	Elasticity Value	Relationship
Selling price	(SP/profitability)	+4.44%	Very elastic
Survival	(S/profitability)	+2.82%	Very elastic
Stocking density	(SD/profitability)	+2.06%	Elastic
FCR	(FCR/profitability)	–1.69%	Elastic
Feed price	(FP/profitability)	–1.65%	Elastic
Investment	(K_0/profitability)	–0.72%	Inelastic
Paralarvae price	(PL/profitability)	–0.65%	Inelastic
Energy price	(EP/profitability)	–0.28%	Inelastic

NM: net margin. TC: total costs. FCR: feed conversion rate.

The following stands out for their impact on profitability: the shrimp sales price (for every 1% increase in this price, profitability would increase by 4.44%), survival, cultivation load, conversion factor, and the price of the feed. However, the price of the larvae, the electricity price (in the present case, with a 50% subsidy), and the investment are of little relevance.

Some variables have market values that the producer cannot influence. However, the incorporation of technology and good management practices can improve the FCR, survival, stoking density, or electricity consumption of the system in such a way that profitability is optimized. For example, the FCR could be reduced through improvements in feeding management and planning and/or the incorporation of automatic feed distribution and control systems [22]. Likewise, economies of scale linked to larger farms could have positive effects on profitability. For example, normally, an increase in the acquisition of feed or larvae allows somewhat lower prices to be paid [61,62]. Also, the more qualified personnel, such as the chief production engineer, would be able to run a larger operation, without an impact on the labor costs.

3.2. Evaluation Using Social and Territorial Indicators

This activity is characterized by a much higher job creation (up to 8 direct jobs per ha, Table 8) than semi-intensive cultivation (employment in the study area is 0.30 employees per ha). In addition, although indirect jobs were not evaluated, these may amount to about six for temporary complementary tasks (harvesting and fitting-out of facilities), transport of inputs, and the sale of the shrimp.

Table 8. Social and territorial assessment indicators for super intensive systems.

Indicator	Value
Direct employment (AWU ha^{-1})	8
CRE (UDS ha^{-1})	337,617
Territorial productivity (t ha^{-1})	77.2
Surface threshold (ha)	0.6

CRE: contribution to regional economy. AWU: agricultural work unit.

The contribution to regional economy (CRE) indicates that this productive system has a high socioeconomic impact on the rural population, since the annual gross economic productivity amounts to 337,617 USD ha^{-1}. These revenues are due to the market price of the product and the high biomass harvested. This value is much higher than that obtained in other agri-food activity in the area of Nayarit: 13,119 USD ha^{-1} in semi-intensive shrimp farming, and 10,461 USD ha^{-1} in the avocado crop, which is the most productive system (values calculated from data from SIAP [60]).

Furthermore, it is important to point out that for a system to be viable under super-intensive conditions, it only requires 0.60 ha for the activity to be economically profitable (Table 8). This fact is very important for territories with limited suitable land. Also, it allows high demand to be satisfied with low land use—a positive outcome for mangrove ecosystems, which would no longer need to be converted into culture ponds. In the same way, this type of activity, by incorporating new technologies for production, intensifies productivity due to economies of scale, unlike traditional agriculture that has constant yields [63].

3.3. Environmental Evaluation

Table 9 shows the different environmental impacts for the system components. In comparison with other LCAs of shrimp ongrowing in intensive systems, the values of the impact categories that can be compared (GW, A, and E) are close to those observed here (Table 10), although they are higher than those of semi-intensive cultivation.

Table 9. Potential environmental impacts (PEIs) of the production of 1 kg live-weight of white shrimp.

PEI	Total	Electricity	Feed	Product	Fuel
AD (kg Sb-eq)	3.01×10^{-5}	1.23×10^{-5}	1.55×10^{-5}	2.19×10^{-6}	1.07×10^{-7}
ADFF (MJ)	$6.48 \times 10^{+1}$	$4.29 \times 10^{+1}$	$1.96 \times 10^{+1}$	6.63×10^{-1}	1.74×10^{0}
GW (kg CO_2-eq)	5.08×10^{0}	3.33×10^{0}	1.67×10^{0}	5.83×10^{-2}	2.05×10^{-2}
OLD (kg CFC−11-eq)	3.87×10^{-7}	2.49×10^{-7}	1.02×10^{-7}	1.26×10^{-8}	2.23×10^{-8}
HT (kg 1,4-DB-eq)	2.25×10^{0}	1.72×10^{0}	4.40×10^{-1}	7.88×10^{-2}	1.07×10^{-2}
FWAE (kg 1,4-DB-eq)	2.67×10^{0}	2.24×10^{0}	3.48×10^{-1}	7.48×10^{-2}	3.67×10^{-3}
MAE (kg 1,4-DB-eq)	$4.01 \times 10^{+3}$	$3.47 \times 10^{+3}$	$4.20 \times 10^{+2}$	$1.18 \times 10^{+2}$	$1.04 \times 10^{+1}$
TE (kg 1,4-DB-eq)	5.21×10^{-2}	1.82×10^{-2}	3.37×10^{-2}	1.82×10^{-4}	4.11×10^{-5}
PO (kg C_2H_4-eq)	9.57×10^{-4}	5.66×10^{-4}	3.67×10^{-4}	1.38×10^{-5}	9.37×10^{-6}
A (kg SO_2-eq)	2.62×10^{-2}	1.41×10^{-2}	1.15×10^{-2}	4.45×10^{-4}	2.13×10^{-4}
E (kg PO_4-eq)	1.07×10^{-2}	5.85×10^{-3}	4.65×10^{-3}	1.76×10^{-4}	2.43×10^{-5}

AD: abiotic depletion. ADFF: abiotic depletion fossil fuels. GW: global warming. OLD: ozone layer depletion. HT: human toxicity. FWAE: fresh water aquatic ecotoxicity. MAE: marine aquatic ecotoxicity. TE: terrestrial ecotoxicity. PO: photochemical oxidation. A: acidification. E: eutrophication.

Table 10. Potential environmental impacts in different aquaculture systems for 1 kg live-weight of white shrimp.

Aquaculture System	Country	GW	A	E	Ref.
		kg CO_2-eq	kg SO_2-eq	kg PO_4-eq	
Super-intensive	Mexico	5.0788	0.0262	0.0107	This study
Intensive	China	5.2800	0.0439	0.0630	[26]
Intensive	USA	5.9100	0.0506	0.0015	[25]
Intensive	Thailand	5.2100	0.0185	0.0106	[24]
Semi-intensive	China	2.7500	0.1940	0.0323	[26]
Semi-intensive	Colombia	3.6000	0.0240	0.0047	[27]

GW: global warming. A: acidification. E: eutrophication.

The components of the system that contribute the most, globally, to the environmental impacts are electricity (62.41%) and feed (34.02%) (Figure 1). In intensive land-based fish farming systems [18,20,64], as well as in intensive shrimp systems [24–26], these two components are also the ones that have the greatest impacts. The contribution of products (2.46%) and fuel (1.11%) is very low.

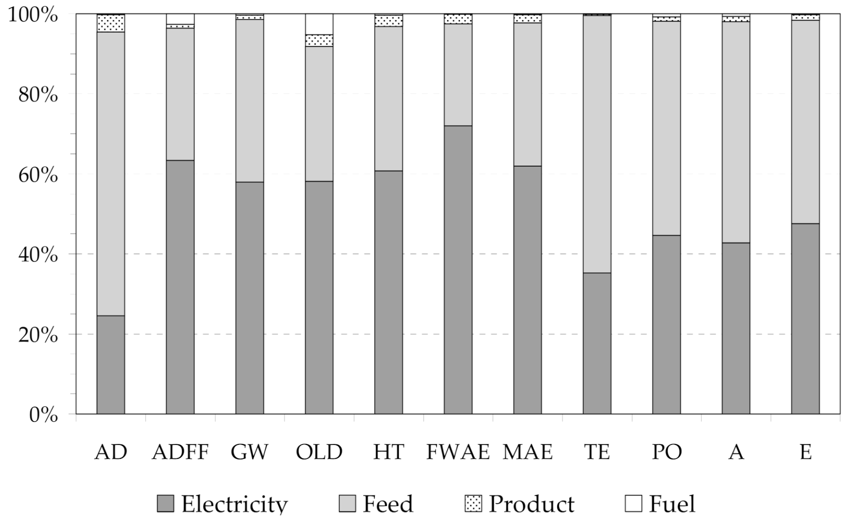

Figure 1. Contribution of the components of the system to potential environmental impacts. AD: abiotic depletion. ADFF: abiotic depletion fossil fuels. GW: global warming. OLD: ozone layer depletion. HT: human toxicity. FWAE: fresh water aquatic ecotoxicity. MAE: marine aquatic ecotoxicity. TE: terrestrial ecotoxicity. PO: photochemical oxidation. A: acidification. E: eutrophication.

Electricity contributes significantly to all impact categories, varying from 41% (AD) to 86% (MAE). In most impacts it contributes more than 50%, except in AD (41%) and TE (35%). A solution to reduce the potential impacts due to this component of the system would be to implement renewable energy systems such as photovoltaics and wind turbines [26] in the shrimp farm.

Feed also makes a significant contribution to all impact categories, varying from 10% (MAE) to 65% (TE), although only for TE and AD (52%) does it contribute more than 50%. Raw materials for feed make a greater contribution to the impacts than manufacturing. In terms of GW, for example, the former accounts for 29% and the latter 2%, fishmeal making the greatest contribution (17%). These results coincide with what has been described for fish culture, so the composition of raw materials should be considered in order to reduce their potential environmental impacts, as suggested by various authors [22,28,29,65]. This aspect can be addressed by the feed manufacturer but not by the shrimp producer, although the producer can optimize the FCR by increasing the feeding efficiency [22].

In terms of GW, the contribution of electricity is 66% and that of feed is 33%. In intensive shrimp aquaculture in China these values differ, being 46% and 41%, respectively [26]. These differences are the result of a higher FCR (1.6), but also lower electricity consumption (2.55 kWh kg^{-1} of shrimp). However, in the culture of *Oncorhynchus mykiss* in the RAS system, where the FCR is 0.86, the energy contribution reaches values as high as 88% [64]. The electricity consumption registered in the present work is double that of the intensive systems [26], but the production is three-times higher and the CO_2 emissions are similar.

The super-intensive system is very efficient in terms of the biomass production/land area ratio, which is 77.20 t ha^{-1} $year^{-1}$. However, in the Nayarit area, in traditional cultivation, it is only 0.88 t ha^{-1} $year^{-1}$ [9]. This means that the current occupied area of 14,428 ha, with a production of 11,740 t, could hypothetically be reduced to only about 152 ha. This is even more relevant considering that the establishment of shrimp farming has led to the replacement, primarily, of coastal ecosystems of great environmental interest, especially the mangrove swamps [3–5]. These swamps have been replaced by various human activities, particularly aquaculture [3]. The estimates of the greenhouse gas emissions as a result of the replacement of mangroves by aquaculture ponds show figures much higher than those due to the aquaculture itself. Thus, the production of 1 kg of shrimp in extensive systems supposes 184 kg CO_2-eq [5] or 1603 kg CO_2-eq [4], with a shrimp production of only 0.130 and 0.275 t ha^{-1} $year^{-1}$, respectively. The difference between these two estimates is due to the criteria that were taken into account in each of the studies [5]. In any case, the emissions are much higher than those that can be attributed only to the shrimp aquaculture (Table 10). Obviously, for the same global production in a given territory, the higher the shrimp production per unit area, the lower the CO_2 emissions. Thus, the super-intensive system should be considered as a viable alternative to increase shrimp production, through the conversion of extensive and semi-extensive systems. In this way, the destruction of the mangrove ecosystem would be stopped and large extensions of this emblematic ecosystem, of capital importance worldwide for the sustainability of biodiversity, would be recovered.

4. Conclusions

The super-intensive white shrimp farming system is an economically profitable activity in the territory of Nayarit. The overall profitability (29%) is relatively high, especially in comparison with other activities in the Mexican agri-food sector. The investment is important but its impact on profitability is not, the fixed costs (16%) being much lower than the VC (84%); of the latter, those referring to feed and staff stand out. Socially, it is an activity that generates a lot of quality employment as well as economic movement over the territory.

Environmentally, and from a life cycle perspective, the potential impacts are higher than those recorded in semi-intensive shrimp systems but slightly lower than those in intensive systems. The estimated value of GW is 5.08 kg CO_2-eq, an intermediate value. Among the components of the system, electricity and feed stand out for their contribution to the environmental impacts. The great environmental virtue of this system lies in its high efficiency as measured by the biomass production/land surface ratio, which is about 88 times higher than that of the traditional systems that mostly exist in Nayarit; in their establishment, these have replaced ecosystems of great environmental interest, especially that of the mangrove. Implementation of this system means not only minimization of the pressure on the mangrove, but also its recovery if there is a reconversion of the current production system.

The shrimp farm can optimize the economic profitability and the environmental footprint through investments in technological improvements and good management practices, in order to improve the variables such as survival, conversion factor, or stoking density. It can also reduce the environmental costs of its electricity consumption with the use of clean energy.

To sum up, the production of white shrimp with super-intensive technology is viable from the economic, social, and environmental points of view, thus guaranteeing sustainable development of this activity in the Nayarit area and, presumably, in other areas.

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