

Eco-efficiency assessment of shrimp aquaculture production in Mexico

Antonio Cortés^{a,*}, Ramón Casillas-Hernández^{b,1}, Cristina Cambeses-Franco^a,
Rafael Bórquez-López^b, Francisco Magallón-Barajas^c, Walter Quadros-Seiffert^d,
Gumersindo Feijoo^a, Maria Teresa Moreira^a

^a CRETUS, Department of Chemical Engineering, Universidade de Santiago de Compostela, Santiago de Compostela, Spain

^b Department of Agricultural and Veterinary Sciences, Sonora Institute of Technology, Cd. Obregón, Mexico

^c Northwestern Center for Biological Research (CIBNOR), La Paz B.C.S., Mexico

^d Laboratory of Shrimp Marine, Department of Aquaculture, Federal University of Santa Catarina, Florianópolis, SC, Brazil

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ABSTRACT

Globally, human society faces the challenge of providing food to a growing population, at the same time that the effects of climate change and resource depletion must be addressed. Aquaculture allows to ensure a safe supply of different marine species and is a major technological and biological undertaking. Taking into account that in Sonora (Mexico), there are more than 200 aquaculture plants, the analysis of this sector implies a joint and harmonized assessment, considering not only life cycle assessment (LCA), but also data envelopment analysis (DEA). This study focuses on the application of LCA + DEA methodology to assess the ecoefficiency of 38 semi-intensive shrimp farms located in the state of Sonora. LCA results showed that feed management and electricity consumption are the main critical points in almost all the impact categories. Further improvement actions were evaluated, the replacement of wheat meal for Dried Distiller Grains with Solubles (DDGS) resulted in environmental impact reductions ranged from 2% to 57%, depending on the impact category. On the other hand, the installation of photovoltaic panels in the area was evaluated, looking for a shift towards a less carbon-intensive energy production. Overall, the implementation of these improvement measures will contribute to increased environmental protection and resource efficiency.

1. Introduction

Human society faces the enormous challenge of providing food for a continuously growing population while withstanding the effects of climate change and widespread degradation of natural resources. In particular, the fisheries sector plays an important role in social agendas, as evidenced by the strategies defined in the Sustainable Development Goals of Agenda 2030 (United Nations, 2015). In particular, the SDG 14 “Conserve and sustainably use the oceans, seas and marine resources for sustainable development” aims to prevent and reduce marine pollution, protect marine and coastal ecosystems, minimize the impacts of ocean acidification, and prohibit certain fisheries practices which contribute to overcapacity and overfishing.

In the seafood sector, fish consumption per capita increases by an average of about 1.5% per year (FAO, 2020). Considering this situation of increasing demand, aquaculture shows strong potential for food

security and can be used as a promising alternative to current intensive fishing (Little et al., 2016). In fact, in the latest statistics recorded by FAO, global fish consumption peaked at approximately 171 million tonnes, and aquaculture represented 47% of total production (FAO, 2018). Moreover, current aquaculture is very diverse, with the most produced species ranging from finfish such as carp, rainbow trout or salmon, to all kinds of molluscs and bivalves such as white shrimp, clams or oysters (OECD, 2017). Focusing on shellfish farming, the white shrimp (*Penaeus vannamei*) is the most produced, constituting 53% of the total crustaceans produced worldwide. Although Asian countries dominate the production, there is also a contribution from some American countries, with the outstanding share of Mexico (OECD, 2017).

Due to its physical, natural and social characteristics, Mexico has a real potential to be a leader in aquaculture. In 2017, Mexico had its highest historical record of 404,551 t of aquaculture production, with

* Corresponding author.

E-mail addresses: antoniojose.cortes.montoya@usc.es (A. Cortés), ramon.casillas@itson.edu.mx (R. Casillas-Hernández).

¹ Both authors have contributed equally.

shrimp being one of the main species cultivated with a production of 270,000 t. Most of the aquaculture production for this species is located in two states, Sonora and Sinaloa (Porchas-Cornejo et al., 2018). Shrimps are produced in three models of farming systems: extensive, semi-intensive and intensive. The differences lie in the level of technology applied, the control of physical-chemical and biometric variables, water consumption and the frequency of meal dosage. In recent years, the expansion of aquaculture systems has been accompanied by an intensification of the system and has generated social concerns on the associated sustainability issues. In this context, Life Cycle Assessment (LCA) is considered an appropriate methodology to evaluate the environmental impacts associated with shrimp farming. Among the different LCA studies of aquaculture production systems for marine products, some focus on the study of the environmental profile of shrimp farming (Henriksson et al., 2015; Järviö, 2018; Medeiros et al., 2017).

Data Envelopment Analysis (DEA) is a linear programming models-based methodology that aims to establish the efficiency of a set of multiple similar entities, called Decision-Making Units (DMU). DEA can identify those shrimp farms that are capable of producing more benefits and services by reducing resource use and waste generation. In this regard, several reports analysed the technical efficiency performance of aquaculture farms using DEA in Taiwan, Europe and Brazil (Chang et al., 2010; Gutiérrez et al., 2020; Santos et al., 2019). However, there are no previous studies in the literature that combine both methodologies, LCA and DEA, with the aim of evaluating this important sector of the Mexican economy and improving the environmental and operational performance of shrimp farms.

Within this framework, the goal of the current study was to apply the large amount of data available to carry out an environmental and eco-efficiency assessment of 38 semi-intensive farms located in Sonora using a combined LCA and DEA approach. In this manuscript, the environmental assessment is based on the principles established in ISO 14040 and 14,044 standards (ISO, 2006a, 2006b). Meanwhile, the concept of managed eco-efficiency is in accordance with the World Business Council for Sustainable Development (WBCSD): “The delivery of competitive priced goods that satisfy human needs while progressively reducing environmental impacts of goods and resource intensity throughout the entire life-cycle” (Schmidheiny, 1992). The environmental and eco-efficiency analyses were conducted in order to detect critical activities in the environmental profile of the process, identify operational inefficiencies, set input reduction objectives and compute the environmental impacts of inefficient practices in shrimp farming. The results of the eco-efficiency analysis will allow a realistic proposal of alternatives to improve environmental performance by identifying those facilities that under similar conditions may act as reference for their peers. This document also proposes the definition of a roadmap for more sustainable aquaculture production with a view to future environmental certification. In this regard, taking into account the data used in this study which represent a broad sample of the available data on shrimp production in Mexico, the analysis would not only focus on the assessment of similar facilities in a given geographical area, but also on a clear overview of the sector.

2. Materials and methods

2.1. System overview

In Mexico, most of the national shrimp production is concentrated in the northwest region, specifically in the states of Sonora and Sinaloa, where semi-intensive farms are the most abundant. Shrimp aquaculture in Mexico started in Sinaloa in the late 1960s in an artisanal way and carried out by fisherman and farmers. It gained momentum as a consequence of the economic stimulus caused by exports to the United States. From 1970 to 1988, shrimp aquaculture underwent technical, operational, administrative and organizational reforms. It was in 1980 when the first shrimp farm operating under the semi-intensive system

was built in Sinaloa. From 1988 to 2000, shrimp farming in Mexico grew significantly, driven by government policy. Above all, pronounced growth was observed in the states of Sinaloa and Sonora (Arreola-Lizárraga et al., 2019). The environmental impacts by aquaculture activities in Sonora are well documented, mainly pollution problems produced by the addition of feed and fertilizers to the ponds, triggering a phytoplankton bloom along the coastal areas of wastewater discharge (González et al., 2003). As detailed in Ponce-Palafox et al. (2011), the vegetation associated with shrimp farming in the state of Sonora is mostly semi-desertic, xeromorphic and succulents shrub-dominated, arranged in a matrix, so environmental impacts associated with land use change are not expected to be relevant. For this reason, in the present study, these impacts were excluded, attention was focused on impacts related to nutrient emissions to water.

These semi-intensive farms are characterized by their diversity in terms of land use and size, while maintaining traditional working conditions (Van et al., 2017). Generally, pond filling operations start in March and the shrimp fattening period lasts until October or November. Feed is applied in daily doses, in amounts that are adjusted according to pond biomass (Casillas-Hernández et al., 2006). The average stocking density is 20–30 individuals/m² and adult shrimps reach sizes around 30 g. The criteria for determining the ideal sales weight of shrimp are determined by the production margin, the market price and the production costs.

In general, the operation of these typical Mexican semi-intensive farms consists of the following phases:

- Pond preparation: Operations of ploughing and bottom levelling are carried out. In parallel, applications of quick lime and monitoring of the pond are performed, as well as the application of fertilizers to the soil. After these operations, seawater is pumped in for filling. Energy consumption are mainly attributed to pumping operations.
- Pond operation: The first stage carried out in the prepared ponds is larvae sowing. During this phase priority is given to feeding the post larvae and maintaining water quality. Therefore, maintenance operations such as water exchanges and operations to control environmental variables such as salinity, temperature and dissolved oxygen are carried out.
- Harvesting: This operation is performed by reducing the water level of the pond and using nets to collect the products. Generally, the time of collection is determined by several criteria, based on the shrimp size, market prices or when the water quality decreases, and a complete renewal is necessary.
- Ancillary operations: These actions complement the shrimp farms facilities, such as surveillance booths, warehouses and cellars, offices, and laboratories.

2.2. The LCA + DEA framework

The joint use of LCA and DEA methodologies dates from a 2009 study in which this method was applied to 62 mussel cultivation sites (Lozano et al., 2009). Since then, this methodology has been replicated and improved to determine the environmental impacts related to inefficient practices. In this case study, the five-step framework (Vázquez-Rowe et al., 2010) has been applied to analyse 38 Mexican shrimp farms. The methodology is structured in 5 steps: i) data collection and construction of life cycle inventory for each DMU; ii) determination of the life cycle environmental impacts of each DMU through the LCA methodology; iii) implementation of the DEA model to obtain the efficiency scores and operational objectives for each DMU. These operational objectives represent reductions in input consumption while maintaining output production; iv) impact assessment of LCI for new virtual DMUs based on the operational reductions established in step 3; v) interpretation of the results obtained, comparison among DMUs and verification of inefficient practices.

2.3. LCA methodology

The ISO 14040 and 14044 standards have been used as the basic methodology to carry out environmental assessment. These standards define the LCA phases as: goal and scope definition, inventory analysis, impact assessment and interpretation.

2.3.1. Goal and scope definition

The main objective of this case study is to analyse the significant environmental burdens of shrimp aquaculture and link them to operational inefficiencies. A secondary objective is to identify operational improvement actions to reach, totally or partially, the proposed theoretical goals.

The Functional Unit (FU) selected for the study was the production of one tonne of commercial size shrimp. This FU was the reference unit to which all inputs and outputs are referred. The aquaculture system evaluated was divided into three main subsystems. Fig. 1 represents the system boundaries considered for shrimp production by a semi-intensive aquaculture system.

SS1. Feed: This subsystem covers the processing and transport of raw materials to produce shrimp feed. This feed is formulated with 35% protein content and is mainly composed of fish meal, fish oil, soybean meal, wheat meal, maize-starch, and soybean oil.

SS2. Larvae includes the production of post-larvae in laboratories distributed throughout the state. This system includes chemicals for maintenance and cleaning operations of the ponds, energy consumption to achieve adequate aeration conditions and the feed used for larvae farming. Larvae feed is similar to that used for adult shrimp, and consists of fish meal, fish oil, soybean meal, wheat meal, maize-starch and soybean oil.

SS3. Aquaculture: This subsystem includes both the transport of feed and the shrimp production operations themselves (filling and preparation of ponds, fattening and harvesting of shrimp). Maintenance operations, such water exchange and the monitoring of environmental parameters are carried out during this phase to maintain water quality. The transport of shrimps for processing, packaging and market operations associated were excluded from the study due to the lack of reliable data.

2.3.2. Data collection and life cycle inventory

A total of 38 Mexican shrimp farms were inventoried in this case study. All the facilities are grouped into nine local boards of aquatic health. The approximate location of the farms evaluated along the southern coast of Sonora is shown in Fig. 2.

In this study, the information to analyse the environmental burdens in shrimp production comes from primary sources. In particular, the data was provided by the State Committee on Aquatic Health of the State

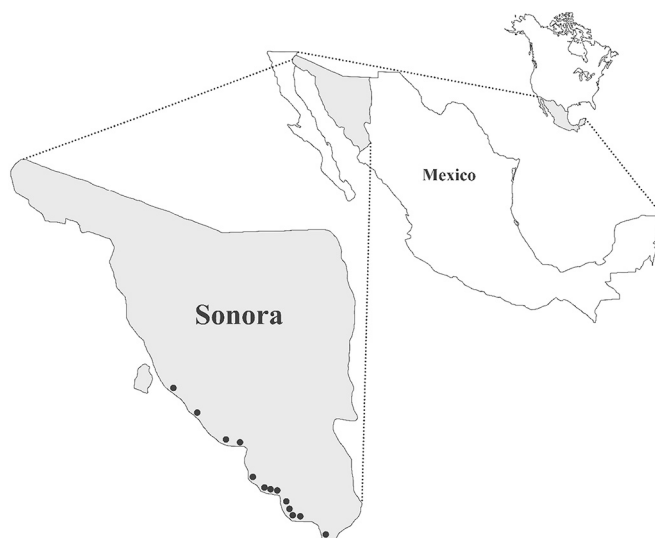


Fig. 2. Geographical coverage of the shrimp farms under assessment.

of Sonora (COESAES-Spanish acronym). In any LCA study, the data collection stage is a fundamental step to ensure the reliability and reproducibility of the environmental profile. Therefore, the use of primary sources ensures compliance with the requirements of ISO 14040 and 14,044 standards for data quality.

The information provided compiles relevant data to understand the operation of the different farms and comprises the following variables: Farming area (ha), stock density (organisms/m²), total shrimp production (t), survival rate (%) and Feed Conversion Ratio-FCR. FCR is a ratio that measures the efficiency with which the bodies of seafood convert feed into the desired output. Primary data were verified in order to calculate other determinant elements, these elements include production efficiency, amount of feed provided and electricity consumption, among others. Section S1 of the Supplementary material explains in more detail how these variables were calculated.

Water exchange in ponds was based on agricultural records of the region: evaporation was estimated from historical 10-year average monthly rates from 5.7 to 10.7 mm/day (Garatuza-Payan et al., 1998). Daily exchange rate was calculated at 11% according to a previous crop cycle analysis (Casillas-Hernández et al., 2006).

Direct emissions of suspended solids, nitrogen and phosphorus were obtained following the guidelines provided by farm managers. The nitrogen emitted to the environment has been determined as the difference between the nitrogen supplied to the system in the feed and the

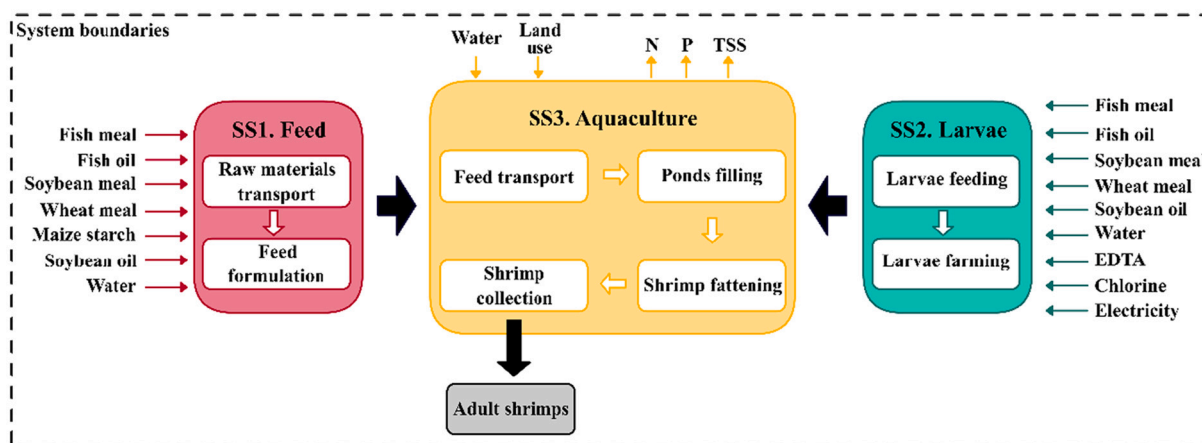


Fig. 1. Description of the shrimp aquaculture production system in Mexico.

nitrogen that is part of the composition of the adult shrimp. It has been taken into account that the protein content in the feed is 32% (Lee and Lee, 2018), while 16% of this protein is nitrogen (Pupim et al., 2013). Nitrogen in the adult shrimp body has been calculated considering a total protein content of 17.3%, a very similar value to that proposed by Dayal et al. (2013). Phosphorus emissions were obtained in the same way as nitrogen, considering that 1.7% of the feed supplied is phosphorus (Chatvijitkul et al., 2018). Similarly, a total phosphorus content of 0.3% was assumed for shrimp (Dayal et al., 2013). Finally, the total amount of suspended solids was estimated to be 5.3 times the total weight of produced shrimp. This emission factor was provided directly by the facility managers and it was calculated as the average of a series of estimates of six ponds over a year (Casillas-Hernández et al., 2006).

It is important to highlight the high volume of data handled in this case study, since life cycle inventory data has been collected from 38 shrimp farms. These inventories were classified according to farm size, so small farms with a total production of less than 150 t, medium farms between 150 and 500 t and large farms for shrimp production of more than 500 t were considered. Table 1 represents the life cycle inventory of an average medium-size farm, although the life cycle impact analysis was carried out for each of the 38 evaluated farms. It is also important to note that inventories of Subsystems 1 and 2 are similar for all farms while Subsystem 3 is specific for each facility.

2.3.3. Impact assessment

To convert the extensive list of life cycle inventory results into a useful list of environmental indicators, the ReCiPe 2016 v1.1 in a hierarchist perspective was used (Huijbregts et al., 2016). According to Henriksson et al. (2012), the following impact categories were selected: Global warming (GW), Stratospheric ozone depletion (SOD), Terrestrial acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Marine ecotoxicity (MET), Fossil resources scarcity (FRS) and Water consumption (WC). SimaPro 9.0 (PRé Consultants, 2017) was the software used for the computational implementation of the inventories.

2.4. DEA model selection

Based on different models described in the DEA methodology, three

Table 1
Life cycle inventory data for an average medium-size farm per FU.

Inputs					
SS1. Feed		SS2. Larvae		SS3. Aquaculture	
Materials	kg	Materials	kg	Materials	t
Fishmeal	495.1	Chloride	0.3	Feed from SS1	2
Fish oil	128.5	EDTA	0.1	Larvae from SS2	0.07
Soybean meal	495.1	Fishmeal	279.3	Transport	t·km
Wheat meal	368.9	Fish oil	55.1	Feed	140
Maize starch	337.9	Soybean meal	279.3	Energy	MJ
Soybean oil	66.8	Wheat meal	208.1	Electricity	13,333
Raw materials	L	Soybean meal	28.7	Raw materials	m ³
Water	240	Energy	kWh	Water	3,380.1
		Electricity	1,948.8	Land	ha
		Raw materials	m ³		0.3
		Water	19.3		
Outputs					
SS1. Feed		SS2. Larvae		SS3. Aquaculture	
Products	t	Products	t	Products	t
Feed to SS3	2	Larvae to SS3	0.07	Shrimp	1
				Emissions to water	t
				Suspended solids	5.3
				Nitrogen	0.076
				Phosphorus	0.03

of the most used ones were tested for the available dataset: Slacks-Based Measure (SBM), Charnes-Cooper-Rhodes (CCR) and Epsilon-Based Measure (EBM). These models were run with constant and variable return to scale conditions and the results were evaluated to determine the model that best fits the case study.

Finally, SBM model was selected as it follows a non-radial approach, which allows greater discrimination power to assess the efficiency of DMU than radial methods (Samuel-Fitwi et al., 2013). Another important attribute of this model is its advantages for matrix computation, since it allows to calculate the efficiency score regardless the units of measure used for the set of inputs and outputs (Thrall, 1996). The model estimates a production efficient frontier, which is the aggregation of the best performing DMUs (Lorenzo-Toja et al., 2015). DMUs that are fully efficient obtain an efficiency score of 1, the slacks with respect to this efficiency frontier for the inefficient DMUs determine the final efficiency score (Cooper et al., 2007).

Convexity, scalability and free arrangement of inputs and outputs are also assumed for the determination of the efficient production frontier. The applicability of this model is so high that many authors use it in very different fields, i.e. in the production of grapes for winemaking (Vázquez-Rowe et al., 2012), bioelectricity production from biomass gasification (Rajabi Hamedani et al., 2019), farm-scaled biogas plants (Lijó et al., 2017), grocery stores (Álvarez-Rodríguez et al., 2019) or wind farms (Iribarren et al., 2013). On the other hand, an input-oriented approach was chosen because the main objective of the case study is to minimize the use of resources (inputs) and possible environmental impacts without affecting the production of shrimp (outputs); but also because shrimp production is limited to the degree of technological development of each farm. Lastly, a constant return to scale (CRS) approach was chosen.

2.5. Input/output selection

The DEA matrix used in this study was composed of 7 inputs and 1 output (Table 2). These units were chosen for their operational importance and associated environmental impacts, according to the previous life cycle analysis.

It is important to emphasize that elements I-6 and I-7 are undesirable outputs, although they were considered as inputs for calculation purposes. The complete DEA matrix is shown in Section S2 of the Supplementary material. The computational implementation of the DEA matrix was carried out through the DEA-solver Pro software (Cooper et al., 2007).

2.6. Improvement actions

Once the critical stages in the environmental profile were determined, some improvement actions were determined to reduce the environmental impact of the system. Specifically, the variation of the life cycle impact was estimated with respect to two fundamental elements: the formulation of the feed and the energy requirements of the larvae tanks.

Feed management is a key factor that significantly affects water quality, final product quality and economic management of aquaculture

Table 2
Elements considered in the DEA matrix, codification, and measurement units.

	Label	Element	Unit
Inputs	I - 1	Seawater	m ³
	I - 2	Feed	t
	I - 3	Larvae	t
	I - 4	Electricity	MJ
	I - 5	Transport	t·km
	I - 6	Nitrogen	t
	I - 7	Phosphorus	t
Outputs	O - 1	Shrimps	t

facilities (Kong et al., 2020). In addition, it should be noted that environmental burdens from water discharge are derived from the portion of feed that is not consumed by the animals and remains in the pond water (Smáráson et al., 2017). All this leads to the proposal to replace some components of the feed with others of lesser environmental impact that result in similar levels of growth and survival. Oatmeal, barley meal, rye meal, rapeseed meal and Distillers Dried Grain with Solubles (DDGS) were chosen as possible options for the substitution of wheat meal. Wheat meal was proposed for replacement because it is the element with the greatest overall impact. In order to make a reliable substitution, the feed conversion factor and the nutritional composition of each alternative were analysed.

The shift from electricity production to photovoltaic panel generation was evaluated as another improvement action. This action follows the path set by the United Nations in the fight against climate change (United Nations, 2015). Even so, plant managers must adopt good practices to minimize energy use (Cao et al., 2011). Considering that Mexico is geographically located between 14° and 33° latitude and that the average daily irradiation is around 3.1 MJ m⁻² day⁻¹ (Lobit et al., 2018), photovoltaic energy seems to be a good option to reduce the environmental footprint of energy consumption. In order to consider the electricity generation through photovoltaic generators within the system boundaries, the Ecoinvent® process “Electricity, low voltage {MX}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted” was used.

3. Results

3.1. Environmental burdens of current DMUs

Section S3 of the Supplementary material presents the contribution of each of the elements of the inventory to the impact categories for average small, medium, and large farms. Fig. 3 breaks down the relative

contribution of the subsystems involved for the different farm sizes. There are no major differences between the distribution of impacts by subsystems for the different sizes assessed. SS1. Feed and SS2. Larvae are primarily responsible for environmental burdens in most impact categories, except for freshwater eutrophication and water consumption. In these two categories, subsystem SS3. Aquaculture is the most relevant with 95–96% in FE and 92–97% in WC.

The environmental burdens in the GW category come mainly from the electricity requirements of SS1 and SS2. These electrical consumptions are related to the milling of wheat and soybean grains to obtain meals and the need for aeration in the larvae tanks to maintain optimal growth conditions (Tien et al., 2019), respectively. The contribution of these two sub-systems is equally relevant in the SOD category, coming from the emissions of dinitrogen monoxide (N₂O) from agricultural production of maize, wheat, and soybean.

Regarding the eutrophication categories, some differences can be found in the behaviour of the FE and ME categories. With respect to FE, SS3. Aquaculture is the main contributor due to direct phosphorus emissions (95%). This phosphorus, although an essential nutrient in aquaculture ecosystems, can play a central role in environmental pollution (Luo et al., 2018). Direct nitrogen emissions are also emitted from this subsystem, although they are not very relevant. In ME category, this subsystem has little influence, highlighting the contributions related to agricultural activities related to feed production. Finally, the impact on the WC category is also important, in which SS3. Aquaculture stands out with percentages from 92% to 97%, due to the large amount of water pumped to fill the ponds.

3.2. DEA calculation and efficiency scores

The DEA matrix presented in Section S2 of the Supplementary material was implemented into the DEA-solver Pro software (Cooper et al., 2007). The results that can be extracted from the model are the

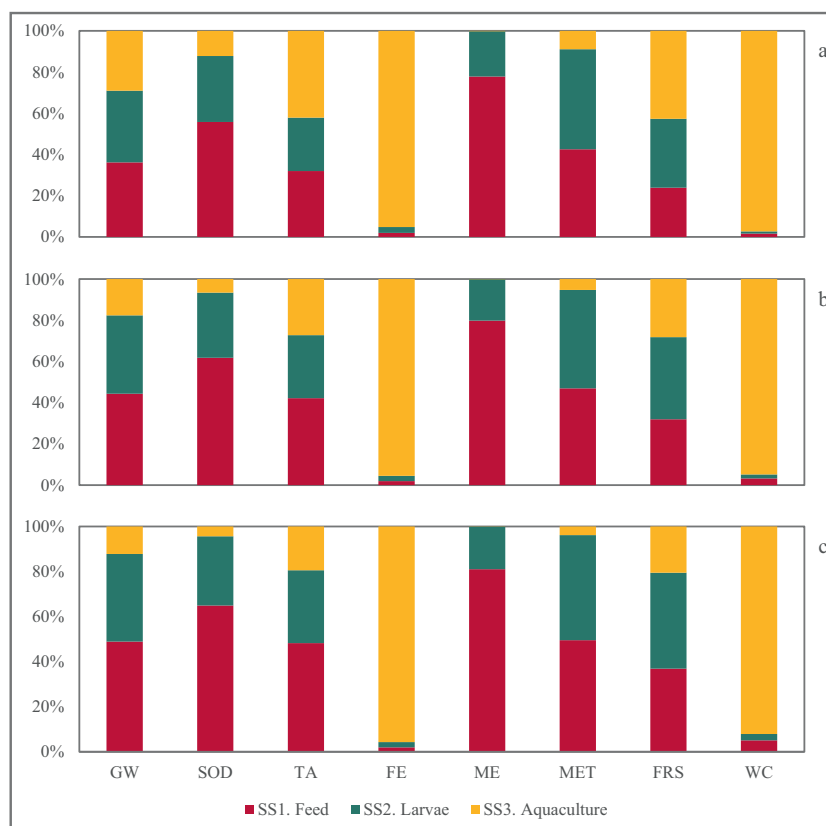


Fig. 3. Relative contribution of the different subsystems in shrimp production for average small (a), medium (b) and large (c) farms.

efficiency scores for each of the DMUs under assessment. The obtained DEA efficiency scores can be found in Table 3. Of all the shrimp farms evaluated, just over 13% (5 of 38 farms) were found fully efficient ($\Phi = 1$). However, although only 5 farms were considered fully efficient, the efficiency index can be considered high in general, as only four farms have efficiency values below 0.6 and an average efficiency of 0.79 is achieved. This average efficiency of the sample is relatively high compared to a previous study applied to similar systems. Chang et al. (2010) performed a DEA analysis to 70 seafood aquaculture facilities with an average efficiency of 0.55. It is also important to note that the farms with high efficiency index correspond to those of larger size, while small and medium farms obtained worse results.

For the inefficient farms ($\Phi < 1$), the software also suggests important operational reduction targets to make them efficient, these operational reductions are shown in Section S4 of the Supplementary material. An average operational reduction of 24.4% is proposed for the complete set of DMUs and inputs analysed. The reductions in I-1 (seawater) and I-2 (electricity) stand out, with 36.7% in both. It is important to note that these reductions are based on the theoretical efficient frontier and their achievement may be limited for technical or operational reasons (Lijó et al., 2017), such as providing sufficient nutrients to shrimps or the impossibility of purchasing new and more efficient equipment. Therefore, these operational reductions should be considered as the maximum potential for input reduction that can be achieved in shrimp aquaculture production and hence the sample of farms evaluated has a greater margin for improvement in the future. If the proposed reductions are analysed in detail, the DMUs with low efficiency values are identified. For example, the high reduction rates present in all inputs of DMUs 7, 23, 31 and 34 should be highlighted.

3.3. Environmental burdens of virtual DMUs

This section contains the results obtained after the last stage of the methodology. The last stage of the LCA/DEA methodology consists of the estimation of the life cycle impacts for “virtual” operations resulting from the application of the theoretical operational reductions proposed in Section 3.2. In this way, the environmental savings due to efficient operation can be estimated by comparing the environmental profile before and after the operational reductions proposed by the DEA methodology. It is important to note that, due to the high variability of results between impact categories, the ReCiPe normalization factors were applied to achieve an overview of the environmental performance of each DMU. As shown in Fig. 4, the reduction targets applied to DMUs significantly affected the environmental performance.

Some percentages of reduction in environmental impact from 3.6% to 69.9% are achieved. As expected, the greatest reductions occurred on the farms with the lowest efficiencies, such as DMU 23 (69.9%) and DMU 31 (50.7%). While the smallest reductions were found on farms that were already close to full efficiency (DMU 6 and 30). The results show that this methodology can be considered adequate to identify the link between operational and environmental performance of multiple, as all virtual farms have a similar environmental profile, corresponding to

Table 3
Efficiency scores (Φ) of the complete sample of shrimp farms.

DMU	Φ	DMU	Φ	DMU	Φ	DMU	Φ
1	0.78	11	0.71	21	0.58	31	0.44
2	0.77	12	0.83	22	0.87	32	0.76
3	0.81	13	1	23	0.38	33	1
4	0.79	14	0.81	24	0.68	34	0.57
5	0.77	15	0.88	25	0.76	35	0.89
6	0.94	16	0.75	26	0.83	36	0.84
7	0.55	17	0.84	27	0.74	37	0.80
8	0.76	18	0.85	28	0.87	38	1
9	1	12	0.77	29	0.64		
10	0.76	20	1	30	0.89		

the optimal level of operation.

3.4. Improvement actions

The proposed improvement measures were evaluated independently, comparing the environmental profile with that of the base scenario. Fig. 5 plots the environmental results related to feed production when wheat meal is substituted by any of the proposed alternatives.

In the view of the results, only the replacement of wheat meal by barley meal or by DDGS seems to be environmentally friendly. Analysing barley meal in detail, the reductions in environmental impacts are limited, although a 14% decrease in the SOD category stands out. Regarding DDGS, environmental improvements are more notable, such as 56.7% in SOD, 39.2% in MET or 30.2% in TA categories. DDGS therefore would be a viable substitute of wheat meal for feed production due to the following factors: (i) acceptable nutritional value, with a high protein content (Rhodes et al., 2015); (ii) relatively low market cost; (iii) no competition with the food industry and (iv) budding production linked to the growing importance of bioethanol industry.

Regarding electricity consumption, Fig. 6 shows the variation in environmental impact with regards to the operation of a farm if, instead of considering the average Mexican profile for electricity supply, all energy is considered as solar photovoltaic energy.

The installation and use of photovoltaic panels would result in a 15% reduction in carbon footprint, in addition to a 10% reduction in TA and 23.2% in FRS. Only in MET category the impact would increase slightly by 12.3%. This category would increase due firstly to the mounting structure and secondly to the manufacture of the photovoltaic panel (Ling-Chin et al., 2016). Bearing in mind that the high impact in this category is derived from a structure whose useful lifetime is quite long, it can be concluded that the implementation of these photovoltaic panels in the facilities will have a positive effect on the environmental impact (Corcelli et al., 2019).

4. Discussion

In this study, a wide range of impact categories were used in order to obtain an overview of the environmental performance of the process. The impact categories analysed have made it possible to cover a wide spectrum of environmental impacts related to global warming, the ozone layer, acidification, eutrophication, ecotoxicity and natural resources scarcity. Thus, this paper includes, among others, the GW, TA, FE and ME categories which, according to Henriksson et al. (2012), cover the most commonly used in LCA applied to aquaculture systems.

The results obtained in this study are comparable with previous results reported in LCA studies on shrimp aquaculture performance. Jonell and Henriksson (2015) applied the life cycle assessment to mangrove-shrimp farms. Their study, similarly to what has been done for Mexican farms, considered a “cradle to farm-gate” approach, although with some difference. Both studies included energy supply, raw material extraction, agriculture, shrimp larval production, and shrimp cultivation and harvesting. In addition, infrastructure was not included in either study because of its negligible influence. It is important to note the operational differences between them, as Mexican farms continue to use traditional techniques and the use of chemicals is not reported. Chemicals are responsible for improving productivity in aquaculture systems by improving larval survival rates, feeding efficiency, and pathogen control, but they also have a negative impact on the environment due to their ecotoxicity. Jonell and Henriksson (2015), who considered the same FU (1 t of shrimp), only evaluated the most common impact categories (eutrophication, acidification and global warming). The carbon footprint obtained in this study is 7.6 kg CO₂ eq per kg live shrimp at the farm gate, while Jonell and Henriksson (2015) reported 27.4 kg CO₂ eq per kg for conventional aquaculture shrimp production. They also carried out the same evaluation to organic production, obtaining better results, around 13.3 kg CO₂ eq per kg. This same trend can be found in

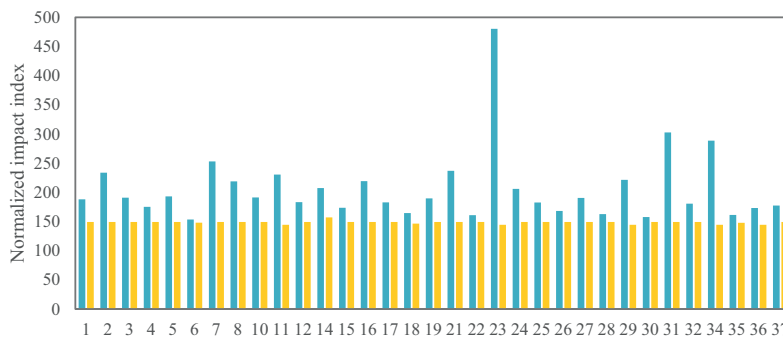


Fig. 4. Normalization results for original (blue) and virtual (yellow) DMUs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

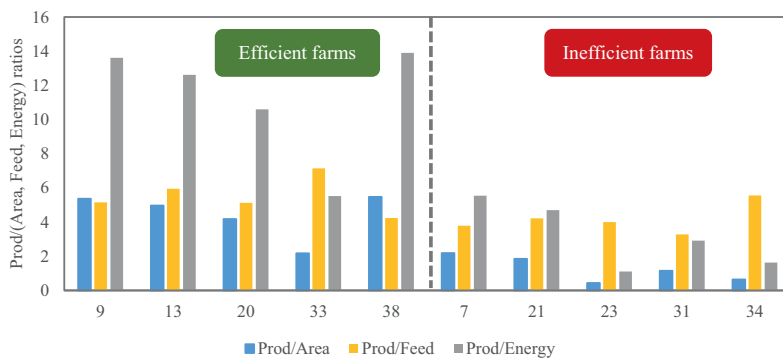


Fig. 5. Production/area, production/feed and production/energy ratios for efficient farms (left of the dotted line) and inefficient farms (right of the dotted line).

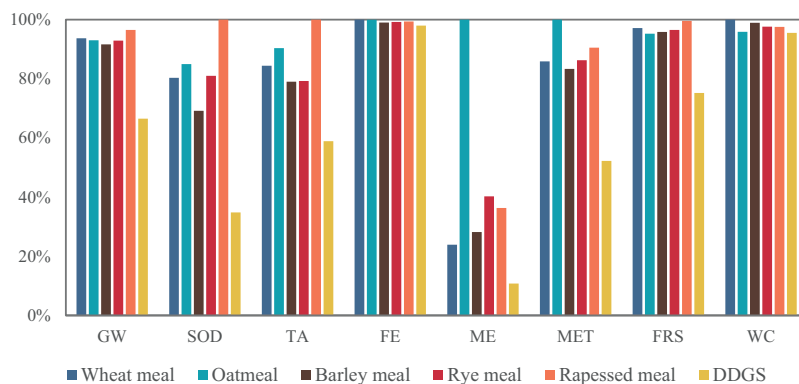


Fig. 6. Environmental impact related to feed formulation with the different alternatives proposed.

acidification category, worse results in traditional than organic production (10.1 and 8.1 kg SO₂ eq, respectively), but much higher than the value of 37 g SO₂ per kg reported in this study. The use of diesel for removing pond sediments, zeolites used in the shrimp grow-out phase and the applications of NPK and P₂O₅ to increase productivity could explain the differences between both studies.

Medeiros et al. (2017) analysed the production of *Macrobrachium amazonicum* in Brazil. Although it is not the same species as that produced in Mexico, the operating conditions are similar. In addition, it should be noted that the components of the feed used are also similar, with vegetable components such as soybean meal and wheat flour and other animal elements such as fish oil. However, the life cycle of the two species is different, which is reflected in the results obtained, since in the

present study 2 kg of feed per kg live shrimp at farm gate are needed, while in Medeiros et al. (2017) 2.7 kg per kg are required. In conclusion, almost identical results of 38 g SO₂ eq per kg are reported for the acidification category, while the carbon footprint results are 11.1 kg CO₂ eq per kg shrimp.

In contrast, the carbon footprint values reported in this study are slightly higher than those obtained in a previous study that evaluated organic shrimp production in Taiwan (Chang et al., 2017). Although the authors considered the distribution and use stage within the system boundaries, these life cycle stages were omitted for the comparison of results. Thus, the cradle-to-gate carbon footprint of organic shrimp production in Taiwan was 5.7 kg CO₂ eq per kg shrimp, a significantly lower value than the obtained in this study (7.6 kg CO₂ eq per kg

shrimp). Furthermore, the author concludes that both electricity consumption and feed formulation are determining elements in the final environmental burdens. Therefore, it can be considered that the farms evaluated in this study have, in general, a good environmental performance, at least in terms of carbon footprint and terrestrial acidification, at similar levels to organic and certified production. It is important to note that results in terms of eutrophication have not been compared due to methodological differences between the CML (Guinée et al., 2002) and ReCiPe methodologies. Moreover, the high reduction of the environmental impacts in terms of eutrophication (freshwater and marine) should be highlighted. Both categories were reduced by almost 18% and 19% respectively.

With regard to efficiency scores, the results obtained from the DEA study showed that only 5 of the 38 farms evaluated were considered efficient, which represents a low value compared to previous LCA/DEA studies applied to the agri-food sector (Iribarren et al., 2011; Laso et al., 2018; Lozano et al., 2010; Vázquez-Rowe et al., 2010). It should be noted that these previous studies did not analyse aquaculture production but focused on other agro-industrial production systems such as fishing, mussel rafts or wine production. Although it was found that few DMUs were fully efficient, it is important to note that most DMUs achieved efficiency values above 0.5. In fact, only 5 were found to be below 0.6. Therefore, the average efficiency value of the sample evaluated is a reasonably high value of 0.79 (see Section 3.2). The robustness of this instrument in handling these heterogeneous and different datasets should be highlighted, allowing to go one step further than the computation of an average inventory (Lorenzo-Toja et al., 2015). The results obtained seems consistent when checking the behaviour of some key factors for the farm operation (Section 3.1), which showed that electricity and feed consumption are the main hot spots of the process. In addition, the study area was also considered as a key and limiting point in different types of aquaculture (Theodoridis et al., 2017). Thus, Fig. 7 shows the performance of production/area, production/feed and production/energy ratios for efficient and inefficient farms.

As shown in Fig. 7, the production/area and production/energy ratios are very high for the most efficient farms. However, the case of DMU 33 should be noted, as neither of these ratios is high, but the farm presents an efficient operation. This can be explained by the fact that it has a very high production/feed ratio, which highlights the importance of feed in the environmental and operational performance of the process. While it is true that inefficient farms (to the right of the dotted line) do not have significantly lower production/feed values than efficient ones, the combination of the three ratios clearly gives the worst results. This makes it clear that, in order to seek operational and environmental efficiency, action must be taken on all possible lines of action, prioritising a balanced improvement of all variables.

These measures can be expected to have a positive long-term impact on the receiving water body (Gulf of California). Since, as determined above (Ahrens et al., 2008) the reduction of N losses to surface waters

will buffer denitrification events and N₂O emissions to Valley drains, and N export events to estuaries and the Gulf of California.

5. Conclusions

The path towards a real Circular Economy in the seafood sector requires the proposal of sustainable alternatives that address wild fisheries and improve food security. Life Cycle Assessment was used to evaluate the environmental aspects associated with shrimp production farms in the state of Sonora (Mexico). The results showed that feed formulation and electricity consumption in larval tanks are the main “hot-spots” of the process.

The joint application of Life Cycle Assessment and Data Envelopment Analysis provided a comprehensive approach for the verification of ecoefficiency, as it quantifies the environmental burdens related to operational inefficiencies. It was possible to distinguish operationally inefficient farms and, although only 5 out of 38 were considered fully efficient, the average efficiency of the sample was 0.79. The expected reductions in input consumption were significant, resulting in estimated reductions from 3.6% to 69.9% in the normalized impact index depending on the DMU. The farms with the largest reductions were generally small and medium-sized, while the larger farms were the most efficient.

As a result of the eco-efficiency analysis, several improvement actions were proposed that resulted in the convenience of installing photovoltaic panels and decreasing the food conversion ratio by substituting wheat meal in the feed. Substitution by DDGS proved to be the most promising option, ensuring reductions of between 2% and 57% depending on the impact categories.

In conclusion, the potential of aquaculture to meet the demand for seafood is shown as an excellent opportunity to contribute to the healthy nutrition of the population, while paying attention to the conservation of marine resources. Since the main priority is the use of environmentally sustainable alternatives, this study emerges as a useful guide for shrimp farm managers, particularly in Mexico.

Author statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in *Aquaculture*.

Authorship contributions

Conception and design of study: R. Casillas-Hernández; R.Bórquez-

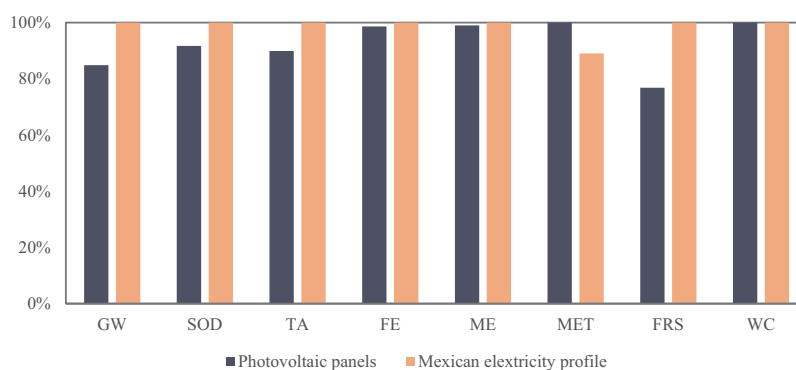


Fig. 7. Environmental results regarding farm operations considering the use of photovoltaic energy or the Mexican electricity profile.

López, M. T. Moreira; G. Feijoo.

Acquisition of data: R. Casillas-Hernández; R. Bórquez-López; F. Magallón-Barajas; W. Quadros-Seiffert.

Analysis and/or interpretation of data: A. Cortés; C. Cambeses-Franco; M. T. Moreira; G. Feijoo.

Drafting the manuscript: A. Cortés; C. Cambeses-Franco; M. T. Moreira, G. Feijoo.

Revising the manuscript critically for important intellectual content: M. T. Moreira; G. Feijoo, R. Casillas-Hernández.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.aquaculture.2021.737145>.

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