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Sustainability of pacific white shrimp culture strategies during a regional outbreak of white spot syndrome virus

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ABSTRACT

The present study evaluated economic, environmental, and social sustainability of three production strategies of Pacific white shrimp (*Litopenaeus vannamei*) during a regional outbreak of white spot syndrome virus. The strategies mainly differed by stocking densities (92, 14, 8 larvae·m^{-2}; D92, D14, and D8, respectively), fertilizer inputs, and other general management. Each dimension of sustainability was evaluated using sets of indicators. The D14 and D8 strategies showed greater economic feasibility than D92 because of the reduced operational costs and investments to buy post-larvae and feed. All strategies showed moderate environmental sustainability, but they had weakened economic and social sustainability due to the virus. The D14 (60) and D8 (62) strategies received the highest overall sustainability index. The D92 was the most environmentally favorable management strategy and social trend. In general, shrimp mariculture with a high initial stocking density cannot guarantee the return of the invested capital. The lower density strategies were economically viable due to the high prices paid per kilogram of shrimp due to the higher individual average weight and reduced apparent feed conversion ratio (D14 = 1.44 and D8 = 0.22). However, economic feasibility of these two strategies coincided with low creation of employment opportunities and income, decreased social sustainability, and increased environmental impact.

Keywords: Indicators of sustainability; Ponds; Shrimp aquaculture.

Estratégias de sustentabilidade no cultivo do camarão-branco-do-pacífico durante um surto regional do vírus da síndrome da mancha branca

RESUMO

O presente estudo avaliou a sustentabilidade econômica, ambiental e social de três estratégias de produção de camarão-branco-do-pacífico (*Litopenaeus vannamei*) durante um surto regional do vírus da síndrome da mancha branca. As estratégias diferiram principalmente pelas densidades de estocagem (92, 14, 8 larvas·m^{-2}; D92, D14 e D8, respectivamente), insumos de fertilizantes e outros manejos gerais. Cada dimensão da sustentabilidade foi avaliada por meio de conjuntos de indicadores. As estratégias D14 e D8 apresentaram maior viabilidade econômica do que a D92 por causa da redução dos custos operacionais e investimentos para compra de pós-larvas e ração. Todas as estratégias mostraram sustentabilidade ambiental moderada, mas enfraqueceram a sustentabilidade econômica e social em razão do vírus. As estratégias D14 (60) e D8 (62) receberam o maior índice geral de sustentabilidade. O D92 foi a estratégia de manejo e tendência social mais favorável ao meio ambiente. Em geral, a maricultura de camarão com alta densidade de estocagem inicial não pode garantir o retorno do capital investido. As estratégias de menor densidade foram economicamente viáveis pelos altos preços pagos por quilo de camarão por causa do maior peso médio individual e redução da taxa de conversão alimentar aparente (D14 = 1,44 e D8 = 0,22), no entanto a viabilidade econômica dessas duas estratégias coincidiu com a baixa criação de oportunidades de emprego e renda, a diminuição da sustentabilidade social e o aumento do impacto ambiental.

Palavras-chave: Aquicultura de camarão; Indicadores de sustentabilidade; Lagoas.

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INTRODUCTION

Shrimp farming represents the second largest group of exported species in terms of monetary value (FAO, 2020). The Pacific white shrimp (*Litopenaeus vannamei*) is the most farmed marine shrimp around the world. This species tolerates high stocking densities and shows high productivity. *Litopenaeus vannamei* culture has frequently suffered economic losses due to disease outbreaks, most notably the white spot syndrome virus (WSSV).

Outbreaks of WSSV have led to mass mortalities of entire shrimp stocks in several farms around the world and have been recorded in Brazil during the past decade (Tran et al., 2013; Nunan et al., 2014; Maia et al., 2016). Various management practices have been applied to mitigate the impacts of WSSV while maintaining adequate productivity. Other management practices aim to reduce pollution of the surrounding aquatic environment and atmosphere and improve the quality of life of stakeholders, thereby increasing environmental and social sustainability, and may have added value to the production (Boyd et al., 2010; Castillo-Soriano et al., 2013; Brito et al., 2014; Brito et al., 2016). Nevertheless, the efficacy of each management strategy to sustain *L. vannamei* farming under the threat of WSSV infection has not been assessed yet. However, the efficacy of each management strategy to sustain the cultivation of *L. vannamei* under the threat of WSSV infection may be associated with stress factors, especially those caused by high stocking densities (Trejo-Flores et al., 2016).

Since the use of antibiotics has been discouraged, probiotics are perceived as a sustainable alternative (Lazado and Caipang, 2014) as "substances produced by a protozoan that stimulated the growth of other beneficial cells." These cells can protect their host from pathogens by producing metabolites that inhibit the colonization or growth of other organisms, or by competing for resources such as nutrients or space (Vine et al., 2006; Srinivas et al., 2016).

A holistic approach to evaluate the overall sustainability of aquaculture should include the three dimensions of sustainability, i.e., economic, environmental, and social. The use of a set of quantitative indicators that reflect the key features of the dimensions of sustainability has facilitated the identification of strengths and weaknesses of different cultures or strategies for sustainable development (Valenti et al., 2011; Halle et al., 2017; Valenti et al., 2018). The determination of the indicators may be complemented by the application of the Drivers-Pressure-State-Impact-Response (DPSIR) model, which combines information from several indicators with management information (Moura et al., 2016).

This model carries out a systemic evaluation of data on economic, environmental, and social interactions in a single system to reveal the most sustainable management strategy of a resource and suggest the most important indicators (Nobre et al., 2010; Moura et al., 2016; Valenti et al., 2021). This approach has been applied to the management of natural resources in Europe using computer models such as the MULINO mDSS (Giupponi, 2007), which provides an interface between managers to assist in decision-making.

The objectives of this study were to evaluate and compare the economic, environmental, and social sustainability of three different management strategies of *L. vannamei* aquaculture when operating during a regional incidence of WSSV.

MATERIALS AND METHODS

Study Area

The present study was carried out at the commercial marine shrimp farm Aquarium Aquaculture, located in the municipality of Mossoró, Rio Grande do Norte, Brazil (05°05'56"S; 37°17'12"W). The farm is located near a hypersaline estuary of the Apodi river, in a region with many salt flats. The farm has an area of 800 ha, that consists of 80 ponds of 0.26 to 2.6 ha for the grow-out of *L. vannamei*. The water was sourced from both the Apodi river and from underground artisan wells. Twelve earthen ponds with areas ranging from 0.26 to 2.6 ha were used to evaluate the sustainability of the different shrimp farming management strategies.

Management strategies to mitigate losses from WSSV

Management strategy 1 (D92)

Four grow-out ponds with an area of 0.26 ha each were initially stocked at the density of 92 shrimps·m^{-2}. The production system was managed as a single grow-out phase in which the post-larvae were stocked directly in ponds immediately after the larviculture. The ponds were initially fertilized with a mixture of 100 kg·ha^{-1} of wheat bran, 30 kg·ha^{-1} of calcium nitrate, 20 kg·ha^{-1} of silicate and 20 kg·ha^{-1} of molasses, and were maintained with biweekly fertilizations of 30 kg·ha^{-1} calcium nitrate and weekly of 10 kg·ha^{-1} of molasses.

Management strategy 2 (D14)

Four grow-out ponds were initially stocked with the density of 14 shrimps·m^{-2}. The production system was managed as a single grow-out phase with an initial fertilization similar to the D92 management strategy, but with no maintenance fertilizations.

Management strategy 3 (D8)

This management strategy consisted of two distinct growth phases after the larviculture. The first phase was an intermediate growth phase (nursery) carried out in raceways stocked with 1,000 shrimps·m^{-2} and lasted for 30 days. The raceways were initially fertilized using a mixture of 250 kg·ha^{-1} of wheat bran, 45 kg·ha^{-1} of calcium nitrate, and 40 kg·ha^{-1} of molasses. A probiotic mixture comprised of *Bacillus* spp. and *Lactobacillus* spp. was added at 0.2 kg·ha^{-1} to the production system as well. Probiotics were inoculated weekly at 0.1 kg·ha^{-1} and molasses at 20 kg·ha^{-1} to maintain a C/N ratio above 10, as suggested by Avnimelech (2009). In the second phase (grow-out), juveniles of *L. vannamei* were harvested from the raceways with a mean individual biomass of 0.98 ± 0.05 g and stocked in four grow-out ponds at the density of 8 shrimps·m^{-2}. The ponds were initially fertilized with 30 kg·ha^{-1} of calcium nitrate and 100 kg·ha^{-1} of dolomitic limestone. The ponds were fertilized weekly with 10 kg·ha^{-1} of calcium nitrate until the harvest. Feed in all management strategies had a crude protein content of 35 to 40% and was distributed by hand. The experimental cultures lasted ~79 days.

At the end of the cultures, pleopods of 50 shrimp from each management strategy were removed and stored in 95% ethanol for quantitative polymerase chain reaction (qPCR) to detect the presence of the WSSV. The virus was detected, identified and quantified using qPCR primers and TaqMan probes (Life Technologies), and an ABI 7300 real-time PCR system (Applied Biosystem).

Statistical analyses

The productive performance variables of survival, initial individual biomass, final individual biomass, apparent feed conversion, productivity, and the water quality variables of transparency, salinity, temperature, pH, and dissolved oxygen were tested for normality (D'Agostine's test) and homoscedasticity (Bartlett's test). When normality and homoscedasticity were met, means of the variables were compared using a one-way analysis of variance (ANOVA). When significant differences were detected among treatments, the means were compared post-hoc with the Tukey's test ($p < 0.05$).

Sustainability analyses

The three dimensions of sustainability (economic, environmental, and social) were assessed using 40 indicators proposed by Valenti et al. (2018) (Table 1). The formulas and methodologies used to calculate the indicators are described in Chowdhury et al. (2015); O'Ryan & Pereira (2015); Moura et al. (2016); and Valenti et al. (2018). All data to calculate the indicators were based on production per year.

Economic dimension

Economic sustainability consisted of 10 indicators, divided among the four categories: efficient use of financial resources,

Table 1. Indicators of economic, environmental and social sustainability.

Economic	Environmental	Social
Investment income ratio	Use of space	Salary equality
Internal rate of return	Water dependence	Proportional cost of work
Payback period	Proportion of renewable energy	Income distribution
Cost-benefit ratio	Eutrophication potencial	Remuneration per protuction
Net present value	General pollution	Race inclusion
Profit	Hormone pollution	Gender inclusion
Profitability index	Accumulation of phosphorus	Age inclusion
Product diversity	Accumulation of organic material	Work per area
Market diversity	Risk with cultivated species	Work per production
		Creation of direct occupations
		Creation of work positions
		Portion of self-employed
		Use of local laborers
		Fixation of income
		Local consumption
		Health benefits
		Education

Source: Valenti et al. (2018).

resilience capacity, capacity to absorb costs of negative externalities, and the capacity to generate capital for reinvestment. All the economic data were collected from the owners of the commercial farm Aquarium Aquaculture and individuals associated with the financial transactions of the shrimp market in the states of Rio Grande do Norte and Ceará, Brazil, in the year 2016.

All equipment, utensils, supplies, and management used in the production were recorded. The cost-return and cash-flow analyses were based on an initial investment that included pond construction, sheds, water supply, drainage system, kayaks, pumps, aerators, and other items of lower cost. The gross revenue was calculated based on the production, average selling price of shrimp in the year 2016, and the mean final individual biomass of the shrimps in the present study (Table 2). Profit was calculated by the difference between gross revenue and production costs, including taxes. The positive and negative externalities were evaluated and monetized considering the emissions and absorptions of nitrogen, carbon, and phosphorus using monetary values described in Chopin et al. (2010). The values for nitrogen, carbon, and phosphorus were USD $10 \cdot kg^{-1}$, USD $0.03 \cdot kg^{-1}$ and USD $4 \cdot kg^{-1}$, respectively. The price of carbon sequestration shows a market variation that ranges from USD 1 to USD $127 \cdot t^{-1}$. The opportunity cost includes farmer remuneration, interest over investment and operating capital, and land leasing. Annual production = production in kilograms per hectare for one year of cultivation; gross revenue (GR) = production·selling price of production; total operating costs (TOpC) = sum of fixed and variable costs spent during cultivation.

Table 2. Average selling prices of the shrimps praticed in the markets of Rio Grande do Norte and Ceará, Brazil, during the year 2016 (USD 1 = R$ 3,35).

Classification group	Weight* (g)	Price (USD)
1	6.5–8.5	6.46–7.69
2	8.6–10.5	7.84–9.23
3	10.6–12.5	9.38–10.46
4	12.6–14.5	10.61–11.07
5	14.6–16.5	11.23–11.69

*Individual average weight. Source: survey carried out with local producers.

Environmental dimension

Environmental sustainability was evaluated using a set of 10 indicators. The sediment generated in the production systems was quantified biweekly using sedimentation chambers placed in the grow-out ponds. The sedimentation chambers were placed directly in the grow-out ponds in duplicate for the three management strategies and remained submerged for 24 hours. Each sediment sample was weighed, and the particulate matter and organic material contents were calculated according to Buffon et al. (2009). Water samples were taken biweekly from the sedimentation chambers to determine particulate matter, total nitrogen (Koroleff, 1976), total phosphorus, and orthophosphate (Golterman et al., 1978). Ammonia, nitrite, and nitrate were determined according to Mackereth et al. (1978), and organic and inorganic carbon were determined using a VARIO-TOC carbon analyzer.

The mean individual mass of the shrimps was estimated weekly by weighing a sample of the population. The physical and chemical variables of the pond culture water–transparency, salinity, temperature, pH, and dissolved oxygen–were measured every two weeks. Measurements were taken at 7 a.m. and 6 p.m. A Secchi disc and a water quality parametermulti-sensor (HORIBA U-50) were used. After the harvest, survival was estimated by dividing the total biomass by the mean individual shrimp mass and the apparent feed conversion ratio (AFCR) was estimated by dividing the total mass of feed input by the total harvested shrimp biomass.

Emissions from diffusion and bubbles of CH_4, CO_2, N_2O, O_2 and N_2 gases were measured at the beginning, middle and end of the culture in each experimental pond. The gas emission through surface diffusion ($mg \cdot m^{-2} \cdot d^{-1}$) was estimated using a gas chamber (Soares & Henry-Silva, 2019). The gases were sampled by positioning the diffusion chamber facing downwards on the surface of the water. The gases emanating from the ponds tend to gradually accumulate in the air trapped inside the chamber. Gas samples were then taken from the diffusion chamber in a time series (0, 1, 2, and 4 minutes) using 30-mL syringes. Samples were subsequently stored in gasometric vials. The emission of gases through diffusion was measured for both the day and night periods.

The gases emitted through bubbles were estimated using inverted funnels with a diameter of 0.0707 m^2 and submerged just below the pond water surface (Soares & Henry-Silva, 2019). A graduated recipient filled with water was attached at the top of each funnel. The funnels remained in the ponds for 24 hours. The accumulated gas at the end of this period was withdrawn to record its volume and stored in gasometric vials. The vials were then transported to the laboratory to determine the compositions of methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), oxygen (O_2) and nitrogen (N_2) using gas chromatography. The gas compositions were given in % and then converted to $mg \cdot L^{-1}$. The mean daily emissions of all gases through diffusion and bubbling in each management strategy were combined to obtain the total flow of each gas ($mg \cdot m^{-2} \cdot d^{-1}$) over a 24-hour period and to observe if the shrimp production systems emit or absorb greenhouse gases.

The environmental sustainability indicators were defined to reflect the use of natural resources, the efficiency in the use of resources, the release of pollutants, and the risk of damage to genetic diversity and biodiversity. Indicators 1 to 6 mention the use of the main natural resources, such as space, water, energy, nitrogen and phosphorus.

Social dimension

The social dimension consisted of 20 indicators, divided among the four main categories: social equity, distribution of income, equal opportunities, and generation of jobs and benefits for local communities.

DPSIR/MULINO modeling

The concept model of the production systems was implemented using the software Multisectorial, Integrated and Operational Decision Support System for Sustainable Use of Water Resources at the Catchment Scale (MULINO mDSS), v5.12 (Giupponi, 2007). A subset of the original set of indicators was used as input data in this model, totaling 22 indicators distributed among the three dimensions of sustainability (economic, environmental, and social) and according to the DPSIR criteria (Table 3). The selected indicators served as input in the MULINO mDSS software and grouped according to the DPSIR criteria, namely:

- Driving force indicators, being considered here the aquaculture activity in cages;
- Indicators of pressure on the ecosystem;
- State indicators of the current conditions of the system studied;
- Indicators of the impacts caused by the activity;
- Responses in terms of management to mitigate the impacts generated.

Table 3. Indicators of sustainability used in the software MULINO mDSS according to the rules of the Drivers-Pressure-State-Impact-Response conceptual model.

Indicators	Weight	Criteria	Dimension
Annual profit	Motor force	0.249	Economic
Investment income ratio	Motor force	0.056	Economic
Work per production	Motor force	0.286	Social
Work per area	Motor force	0.006	Social
Accumulation of organic material	Pressure	0.055	Environmental
Accumulation of particulate matter	Pressure	0.006	Environmental
Accumulation of nitrogen	Pressure	0.011	Environmental
Accumulation of phosphorus	Pressure	0.022	Environmental
Gender inclusion	State	0.011	Social
Age inclusion	State	0.011	Social
Proportional cost of work	State	0.008	Social
Payback period	State	0.006	Environmental
Cost-benefit ratio	State	0.006	Economic
Remuneration per production	State	0.015	Social
Internal rate of return	State	0.007	Economic
Income distribution	State	0.006	Social
Eutrophication potential	Impact	0.008	Environmental
Water dependence Energy use	Pressure	0.007	Environmental
Energy use	Pressure	0.076	Environmental
Absorption and emission of CH_4	Pressure	0.051	Environmental
Absorption and emission of N_2O	Pressure	0.063	Environmental
Absorption and emission of CO_2	Pressure	0.075	Environmental
Changes in indicators	Response	0.007	All

The most important indicators are those that small changes in their values strongly influence the sustainability of the system.

The selected indicators served as inputs in the software MULINO mDSS and were grouped according to the DPSIR criteria:

- Indicators of motor forces, considering the activity of shrimp production in earthen ponds;
- Indicators of pressure on the ecosystem;
- Indicators of the state of current conditions of the studied system;
- Indicators of impacts caused by the activity;
- Responses in terms of management to mitigate the impacts generated.

An inadequate value would receive a value of 0, and an excellent and attainable value would receive a value of 100, then the scale was divided in equal or different portions according to the nature of the indicator.

The software MULINO was used to do a comparative analysis to calculate the performance of the indicators for each scenario. In this manner, the management strategies were evaluated in the software MULINO to simulate how the shrimp production systems would behave with different management strategies and stocking densities and, thus, evaluate which scenario presents greater sustainability. The decision algorithm used was simple additive weighting (SAW).

RESULTS

Production variables

Survival in D14 was significantly lower than that in other management strategies, with mean values of 12.2%. Management strategies D92, D14 and D8 presented average final individual biomass of 6.3 (65 days of cultivation), 9.4 (79 days of cultivation) and 6.9 g (51 days of cultivation), respectively. For the AFCR, significant differences were found between all management strategies, and the value in D92 (2.95/1) was significantly higher than the values observed in management strategies D14 (1.44/1) and D8 (0.22/1). At the end of the cultivations, the mean total biomass values were 2,972 kg·ha^{-1}·year^{-1} in D92, 1,427 kg·ha^{-1}·year^{-1} in D14 and 1,598 kg·ha^{-1}·year^{-1} in D8. There were no significant differences between the total biomass of shrimps in D14 and D8. However, the total biomass in D92 was significantly higher in relation to the other management strategies.

After harvest, survival and total biomass and AFCR were estimated (Table 4).

Table 4. Mean values and standard deviations of the productive performance characteristics for the different management strategies of the grow-out phase of *Litopenaeus vannamei*. Different letters in the same line indicate significant differences according to the analysis of variance followed by Tukey's test ($p < 0.05$).

Productive performance	Management strategies		
	D92	D14	D8
Survival (%)	42.9 ± 5.5^a	12.2 ± 3.5^b	39.3 ± 0.9^a
Initial individual mass (g)	0.004^a	0.004^a	0.98^b
Final individual mass (g)	6.3 ± 0.4^b	9.4 ± 1.8^a	6.9 ± 0.5^b
Apparent feed conversion ratio	2.95 ± 0.5^a	1.44 ± 0.41^b	0.22 ± 0.1^c
Cycles per year (number)	4.6	4.3	7.3
Yield (kg·ha^{-1}·year^{-1})	2,972 ± 45^a	1,427 ± 64^b	1,598 ± 41^b

Water quality

Mean salinity values were high in all management strategies (41.8 on D92; 46.0 on D14; and 61.1 on D8). The water temperature was according to the limits considered adequate for shrimp rearing (Pimentel et al., 2021), i.e., with mean values ranging from 28.5 to 29°C. There were no significant differences for the values of pH and dissolved oxygen. The physical and chemical variables of the pond culture water–transparency, salinity, temperature, pH, and dissolved oxygen–were measured every two weeks (Table 5).

Table 5. Mean values and standard deviations of limnological variable of *Litopenaeus vannamei* growing water with different management strategies. Ddistinct letters indicate significant differences by Tukey's test ($p \leq 0.05$).

	Management strategies		
Water quality variables	D92	D14	D8
Transparency (cm)	31.2 ± 8.6^a	33.7 ± 3.1^a	33.2 ± 1.1^a
Salinity (g·L^{-1})	41.8 ± 1.4^a	46.0 ± 1.6^a	61.1 ± 0.9^b
Temperature (°C)	28.9 ± 0.2^a	20.0 ± 0.6^a	28.5 ± 0.1^a
pH	8.4 ± 0.1^a	8.4 ± 0.1^a	7.8 ± 0.2^a
Dissolved oxygen (mg·L^{-1})	7.2 ± 0.7^a	5.6 ± 1.2^a	7.0 ± 0.8^a

White spot syndrome virus analysis

All shrimp specimens sampled and analyzed for WSSV were shown positive for the virus regardless the management strategy. The load for D92, D14 and D8 were 139, 84.3 and 45.9, respectively. The experimental cultures lasted 65, 79 and 51 days for treatments D92, D14 and D8, respectively.

Indicators of economic sustainability

Investments were calculated based on 1 hectare of cultivated area for a period of one year. Shrimp productivity ($kg \cdot ha^{-1} \cdot year^{-1}$) was 2,972 for D92, 1,427 for D14, and 1,598 for D8, which generated GR of USD 21,026.90 (D92), USD 12,179.45 (D14), and USD 11,305.85 (D8). Due to the high TOpC (Table 6), the D92 management strategy showed a negative profit of USD 42,348.03, while management strategies D14 and D8 showed positive profits of USD 4,325.04 and USD 1,878.49, respectively. Positive externalities of the *L. vannamei* cultivations were observed mainly as ecosystem services, which include the use of a recirculating aquaculture system, zero water exchange with the adjacent environment, and a sedimentation basin.

The diversity of production was low since the activity was carried out as shrimp monoculture and commercialized for human consumption in the major markets of São Paulo, Distrito Federal, Santa Catarina, Pernambuco, Ceará and Rio Grande do Norte, Brazil. These indicators are an average estimate of the production and selling prices of the product per kilogram (USD 8.27) (Table 6).

Table 6. Values obtained for the indicators of economic sustainability for the different management strategies of the grow-out of *Litopenaeus vannamei* (USD 1 = R$ 3,25).

Indicators	Management strategies		
	D92	D14	D8
Annual production (kg)	2,972	1,427	1,598
Gross revenue (USD)	21,026.90	12,179.45	11,305.85
Total operating cost (USD)	63,374.93	7,854.41	9,427.36
Investment income ratio (USD)	-0.42	0.16	0.13
Internal rate of return (%)	-	33.7	28.9
Payback period (yr)	- 0.8	8.6	6.3
Benefit-cost ratio (USD)	-3.93	1.05	0.68
Net present value (USD)	-394,860.87	37,256.76	11,775.45
Profit (USD)	-42,348.03	4,325.04	1,878.49
Negative externalities (USD)	0	0	0
Positive externalities (USD)	20.74	41.35	128.77
Rentability index	0.33	1.55	1.20
Profitability index	-2.01	0.35	0.16
Diversity of product	1	1	1
Diversity of market	6	6	6

Indicators of environmental sustainability

Significant differences were observed between management strategies for some of the sedimentation rates of the nutrients, showing a trend of reduction towards the end of the culture for the generation of particulate material (D92 and D8), particulate material, ammonia, nitrite, total inorganic carbon and total organic carbon, whereas nitrite became stabilized (Table 7).

The indicators of environmental sustainability showed water dependencies of 39.55, 89.61, and 103.88 m^3 per ton of shrimp and space requirements of 15.3, 30.1, and 45.7 $m^2 \cdot kg^{-1}$ of shrimp for the D92, D14, and D8 management strategies, respectively. The nitrogen accumulation was 1.7, 3.9, and 11.7, and phosphorus was 0.5, 0.7, and 3.3 kg per ton of harvested product for the D92, D14, and D8 management strategies, respectively. Renewable energy, general pollution, and hormone pollution received a value of 0 since none of these were used in the production systems (Table 8).

The production systems accumulated particulate matter at rates of 141.11, 146.77, and 513.10 kg per ton of shrimp produced in management strategies D92, D14, and D8, respectively. The particulate matter consisted of 0.24, 0.52, and 0.05% of organic matter, which generated a discharge of 0.34, 0.77, and 0.27 kg of organic matter per kilogram of shrimp produced for the D92, D14, and D8 management strategies, respectively. The eutrophication potential showed that the systems released 43.6, 52.4, and 7.1 for nitrogen and 9.2, 11.1, and 1.5 kg of phosphorus per ton per production cycle for the management strategies D92, D14, and D8, respectively.

For the gases, methane (CH_4) emission was 19.7 kg per ton of shrimp produced in the D14 management strategy, and absorption was -4.8 and -4 kg per ton of shrimp produced in the D92 and D8 management strategies, respectively. Carbon dioxide (CO_2) emissions were 15 and 47.8 kg per ton of shrimp produced in the D14 and D8 management strategies, respectively, and absorption of CO_2 was -57.9 kg per ton of shrimp produced in D92. Nitrous oxide (N_2O) emissions were 0.04 and 0.77 kg per kilogram of shrimp produced for the management strategies D92 and D14, respectively. N_2O was absorbed at a rate of -0.02 kg per ton of shrimp produced in D8.

Indicators of social sustainability

The labor required to carry out the cultivations was 1.17 (D92), 1.46 (D14), and 2.04 (D8) man-hour-year per square meter ($mhy \cdot m^{-2}$). The work required per unit of production was 0.01 man-hour per kg of shrimp produced ($mh \cdot kg^{-1}$) for the D92 management strategy and 0.03 for the D14 and

Table 7. Means ± standard deviation for the sedimentation of particulate material, ammonia, nitrite, nitrate, total phosphorus, total nitrogen, total organic carbon, and total inorganic carbon for the D92, D14 and D8 management strategies.

Indicators	Management strategies		
	D92	D14	D8
Particulate material ($mg \cdot cm^{-2} \cdot day^{-1}$)	14.6 ± 1.5[a]	6.1 ± 0.9[a]	22.0 ± 3.8[b]
Ammonia ($ug \cdot cm^{-2} \cdot day^{-1}$)	5.0 ± 1.9[a]	5.3 ± 1.3[a]	8.2 ± 3.8[b]
Nitrite ($ug \cdot cm^{-2} \cdot day^{-1}$)	0.12 ± 0.07[a]	0.07 ± 0.03[a]	3.73 ±1.0[b]
Nitrate ($ug \cdot cm^{-2} \cdot day^{-1}$)	20.7 ± 1.45	20.0 ± 1.0	23.4 ± 10.0
Total phosphorus ($ug \cdot cm^{-2} \cdot day^{-1}$)	35.2 ± 10.4[a]	14.6 ± 2.6[b]	64.8 ± 6.4[c]
Total nitrogen ($mg \cdot cm^{-2} \cdot day^{-1}$)	0.02 ± 0.001	0.02 ± 0.002	0.03 ± 0.002
Total organic carbon ($mg \cdot cm^{-2} \cdot day^{-1}$)	0.57 ± 0.10	0.60 ± 0.07	0.69 ± 0.02
Total inorganic carbon ($mg \cdot cm^{-2} \cdot day^{-1}$)	0.80 ± 0.12	0.71 ± 0.14	0.80 ± 0.05

Table 8. Values obtained for the indicators of environmental sustainability for the different management strategies of the grow-out of *Litopenaeus vannamei* in earthen ponds for the management strategies D92, D14, and D8.

Indicators	Management strategies		
	D92	D14	D8
Use of space ($m^2 \cdot kg^{-1}$)	15.3	30.1	45.7
Water dependence ($m^3 \cdot t^{-1}$)	39.55	89.61	103.88
Use of energy ($MJ \cdot kg^{-1}$)	22.40	43.90	66.50
Proportion of renewable energy (%)	0	0	0
Use of nitrogen ($kgN \cdot t^{-1}$)	153	74.9	11.4
Use of phosphorus ($kgP \cdot t^{-1}$)	32.4	15.8	2.4
Accumulated of nitrogen ($kgN \cdot t^{-1}$)	1.7	3.9	11.7
Accumulated of phosphorus ($kgP \cdot t^{-1}$)	0.5	0.7	3.3
Production actually used (%)	60	60	60
Potential of eutrophication ($kgN \cdot t^{-1}$)	43.6	52.4	7.1
Potential of eutrophication ($kgP \cdot t^{-1}$)	9.2	11.1	1.5
Pollution general (herbicide e pesticide $kg \cdot kg^{-1}$)	0	0	0
Pollution by hormones ($kg \cdot kg^{-1}$)	0	0	0
Accumulation of organic matter ($kgOM \cdot t^{-1}$)	340	770	270
Accumulation of particulate material ($kgPM \cdot t^{-1}$)	141.11	146.77	513.10
Risk of farmed species	4	4	4
Emission and absorption of CH_4 ($kgCH_4 \cdot t^{-1}$)	-4.8	19.7	-4.0
Emission and absorption of CO_2 ($kgCO_2 \cdot t^{-1}$)	-57.9	15.0	47.8
Emission and absorption of N_2O ($kg\ N_2O \cdot t$)	0.04	0.77	-0.02

D8 management strategies. The wage equity was 73% for D92, 70% for D14, and 69% for D8. Values of racial inclusion (100%), inclusion of gender (61%), and age inclusion (50%) were the same for all three management strategies since no changes in the workforce occurred between the management strategies.

The company did not offer health benefits, the employees were assisted by the Unified Health System (SUS), and the education levels of the employees indicated that only 15% were currently involved in scholarly activities (Table 9). The permanence of each employee in the company was of three years. Regarding the participation of employees in external community activities, 50% of the employees had ties with the rural union or fishermen colony (agriculture workers unions).

Among the work safety items, the company provided 67% of the equipment and actions necessary to carry out activities with relative safety. Among the 15 items verified for the work safety indicator, five were considered irrelevant since they were considered of little or no use in shrimp farms. These items were the use of life jackets, safety glasses, equipment that alleviates physical exertion, use of machines and equipment by a qualified professional, and posted signs to warn of possible danger areas.

Modeling of sustainability

The overall sustainability showed different behaviors between management strategies in relation to the three dimensions of sustainability in the DPSIR/MULINO model. The systems were considered sustainable when the distribution of the indicator set was towards the center of the triangle, while a distribution towards the edge of the triangle indicated sustainability in one or two of the dimensions (Fig. 1). The D92 management strategy showed a sustainability distributed toward the environmental dimension with a tendency towards the social dimension and was considered economically unviable. The D14 and D8 management strategies showed distributions towards the economic dimension and were less distributed towards the environmental and social dimensions, indicating that these management strategies are more economically sustainable. The D8 scenario had the highest overall sustainability index with a value of 62, followed by the D14 (60) and D92 (45) management strategies (Table 10).

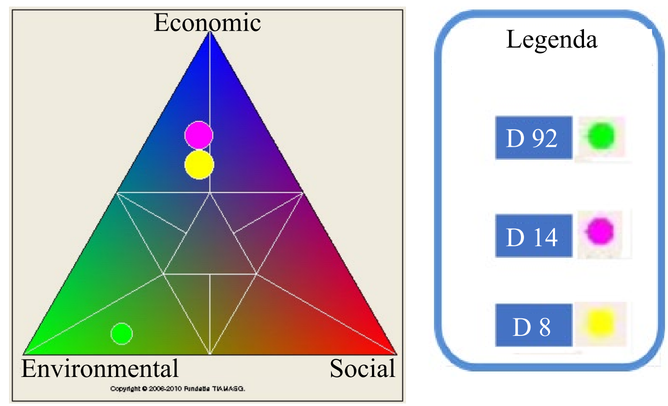

Figure 1. Triangle of sustainability.

Table 9. Mean values obtained for indicators of social sustainability for the different management strategies of the *Litopenaeus vannamei* grow-out production.

Indicators	Management strategies		
	D92	D14	D8
Salary equality (%)	73	70	69
Proportional cost of labor (%)	50	47	56
Income distribution (USD)	-0.24	0.21	0.32
Remuneration of work per unit of production (USD·kg^{-1})	9.08	2.60	3.31
Racial inclusion (%)	100	100	100
Gender inclusion (%)	61	61	61
Age inclusion (%)	50	50	50
Required work per unit of occupied area (MHY·M^{-2})	1.17	1.46	2.04
Required work per unit of work per production (MH·kg^{-1})	0.01	0.03	0.03
Investment to create direct employment(USD·jobs^{-1})	1,846	1,318	1,318
Investment to create total employment (USD·jobs^{-1})	861	615	615
Proportion of self-employments (%)	25	20	14
Use of local workers (%)	50	60	50
Fixation of income (%)	85	85	85
Local consumption of production (%)	0	0	0
Access to health-insurance programs	100	100	100
Schooling (%)	15	15	15
Permanence in the activity (year)	3	3	3
Participation in outside community activities	50	50	50
Work safety (%)	67	67	67

Table 10. Scores of sustainability generated by the software MULINO mDSS in the economic, environmental, and social dimensions for each management strategies and general index of sustainability.

Scenario	Scores			Index
	Economic	Environmental	Social	
D92	7	70	23	45
D14	68	19	13	60
D8	58	24	18	62

DISCUSSION

Production variables

The presence of the WSSV in 100% of the sampled specimens may have been a determining factor for the low survival observed in all management strategies. Trejo-Flores et al. (2016) obtained similar survival rates (50%) upon identifying contamination of *L. vannamei* by this pathogen. Low survival associated with excess feed input in the 92 shrimps·m^{-2} treatment may have contributed to higher apparent feed conversion values. Sookying & Davis (2011) and Brito et al. (2016) obtained feed conversion values of 1.31 and survival of 94% with different feed management strategies in the cultivation of *L. vannamei* with high initial stocks, corroborating that higher survival and total biomass coincides with the reduced AFCR. The lower apparent feed conversion in the 8 shrimps·m^{-2} is perhaps related to the management strategy, which favors the compensatory growth of shrimps.

Limnological variables

The ideal salinity for cultivation of the *L. vannamei* is between 15 and 25, and the osmotic equilibrium point for this species is 24.7 (Boyd, 1999). The high salinity values recorded in the present study are due to the location of the ponds, which are near the estuarine region of the Apodi/Mossoró River and receive water from salt flats. The capacity of the *L. vannamei* to osmoregulate and, thus, survive significantly decreased following infection with the WSSV. The present study suggests that extreme salinities (5 or 54) are more harmful than seawater (Ramos-Carreño et al., 2014). Moreno-Figueroa et al. (2017) cultivated *L. vannamei* in salinity of 45 ± 2 and recorded survival of 84.2%, hence the low survival in the present study was likely due to the presence of the virus, in addition to the high salinity.

The mean values of dissolved oxygen were similar to those described in Krishna et al. (2015), which used initial stocking densities of 40 to 80 shrimps·m^{-2} and obtained dissolved oxygen values of 4.6 to 6.2 mg·L^{-1}.

Analysis of white spot syndrome virus

The presence of white spot virus in all management strategies is reflected in the low survival. Guertler et al. (2013) recorded a higher viral load of 5.6 × 10^{6}, which resulted in 100% mortality of the shrimp population within the first five days of cultivation. The water temperature of the earthen ponds may have facilitated contamination, as several authors cite that temperatures ranging between 22 and 30°C, and the proliferation of white spot virus (Fegan & Clifford III, 2001; Sonnenholzner et al., 2002; Centro de Investigaciones Biológicas del Nordeste, 2008; Costa et al., 2010; Rubio-Castro et al., 2016; Trejo-Flores et al., 2016).

Economic sustainability

The management strategy of 92 shrimps·m^{-2} showed no economic feasibility, whereas the 14 and 8 shrimps·m^{-2} management strategies showed economic feasibility. These results are probably due to the reduced operational costs for managing a low shrimp density, of which include lower investments in the acquisition of post-larvae, feed, fertilizers, and labor. The low economic sustainability of the high-density strategy was related to high values of TOpC. These high production costs were related to feed expenses, acquisition of post-larvae, cultivation time, and high apparent feed conversion. The commercialization of any production system must attract revenues that exceed the operational costs. Hence, high operating costs make the maximum net revenue of the production systems unfeasible (Valderrama & Engle, 2002).

The total operating cost of the 8 shrimp·m^{-2} strategy was higher than that of the 14 shrimp·m^{-2}, probably due to the initial use of greenhouses to produce large post-larvae, which increases production costs and reduces revenues and cost-effectiveness. The use of these alternatives decreased the economic sustainability for this treatment. The two low density strategies showed positive internal rate of return values that were higher than the basic interest rate (Brazilian interest rate = 13.6% per year), suggesting that this activity is economically feasible when practiced with less intensive productions.

The internal rate of return observed in the present study may be associated with the high values atypical of commercializing the shrimp production due to the low supply of the product as influenced by white spot virus and mortality of the production.

The positive net presents values of the two low-density strategies suggest economic feasibility. The investment is considered economically feasible if the difference between the current value of benefits and the present value of costs or disbursements was positive (Sanches et al., 2013). Profit in the 8 shrimps·m^{-2} management strategy was approximately 55% lower than in the 14 shrimps·m^{-2}, perhaps due to the high costs of rearing juvenile shrimp in an intermediate nursery phase in raceways. The diversity of products was low in the three management strategies due to the cultivation systems being carried out as monocultures.

On the other hand, the diversity of markets was high when considering that the productions were commercialized in several Brazilian states and in the state where the shrimp was produced (Rio Grande do Norte), which is the second largest shrimp producer in the country. The payback period in the 8 shrimps·m^{-2} strategy was lower than that in the 14 shrimps·m^{-2} perhaps due to a reduced cultivation time that permits a greater number of production cycles per year. The high payback period values of the two low-density strategies were probably associated with reduced values of the final shrimp biomass. The reduced harvested biomass showed lower GR, which led to a reduction in profits and consequently a higher payback period.

Shrimp mariculture is a resilient activity and generates positive externalities. The present study quantified the nitrogen, carbon and phosphorus credits that can generate a monetary return due to positive externalities, which can result in increased revenues. Externalities are an essential value in neoclassical economics (Gómez-Baggethun et al., 2010). Aquaculture farmers may receive economic incentives to implement sustainable practices by providing environmental and social services (Chopin et al., 2010). The monetary values identified as carbon (absorption of nutrients) credits were lower than those found by Pereira et al. (2020), which evaluated the cultivation of algae in the southwest tropical Atlantic and showed the value of USD 262·t^{-1}. The higher value of carbon credits indicated in Pereira et al. (2020) was due to the algae cultivation requiring no commercial feed, which is a major source for the release of nutrients into the environment.

The rentability and profitability indices were lower in the 92 shrimps·m^{-2} strategy than in the two lower density strategies, given the high total operating costs driven by the higher average apparent feed conversion values. Profitability is related to the revenues and costs generated from the cultivation. Therefore, economic sustainability depends on the productivity of the cultivation and the sales price per unit of production. The gains observed in the two low-density strategies were due to the high prices paid per kilogram of shrimp harvested during the survey period, of which the prices were related to the low availability of shrimp due to the outbreak of the WSSV.

Environmental sustainability

The environmental sustainability of the production systems was influenced by the generation of solid wastes, since much of the particulate matter produced in shrimp ponds is an aggregation of chemical products, fertilizers, shrimp feces, undigested feed, undesired organisms, and detritus (Flaherty et al., 2000; Hall, 2004; Paul & Vogl, 2011). The high sedimentation rates were probably related to the inputs needed to increase the shrimp biomass and due to the eutrophication of the water, which is typical of marine shrimp production systems.

The dependence of the activity on both water and area combined with the organic matter and potential accumulation of particulate matter were factors that reduced the environmental sustainability for all management strategies. These values were higher than those found for the culture of tilapia in net tanks in a reservoir in a semi-arid region of Brazil, which registered a water dependence of 4.69 m^3·t^{-1} (Moura et al., 2016; Valenti et al., 2018). Pereira et al. (2020) cultivated *Hypnea pseudomusciformis* algae in long-line structures in the southwest tropical Atlantic, recorded 0.00 m^3·t^{-1} for water dependence.

The high values found are due to the cultivation system in which the structures used are dug earthen ponds and directly depend on the mechanical pumping water for shrimp farming. This prevented the pollution of effluents in adjacent environments of a riparian forest and a permanent preservation area. Eutrophication was mitigated when considering the retention of sediments with high contents of nitrogen, carbon, and phosphorus. The other positive externality was that the activity is the production of a high-quality food. Phosphorus was higher in the 8 shrimps·m^{-2} strategy when compared to the other two strategies.

This may be related to the use of an intermediate nursery phase to rear high stocking densities of shrimp, which require an intensive use of feed inputs and fertilizers. Commercial feeds are likely the primary source for the accumulation of phosphorus in the environment (Fourooghifard et al., 2018). The values assigned to herbicide, pesticide (pollution general), and hormone pollution were zero since none of these products were used in the systems analyzed in the present study. Thus, these systems were considered as relatively sustainable in the environmental point of view.

Variations were observed for the emission and absorption of greenhouse gases in all management strategies. Nitrous oxide (N_2O) was emitted in the 92 and 14 shrimps·m^{-2} management strategies and absorbed in the 8 shrimps·m^{-2} management strategy. Methane (CH_4) was emitted from the 14 shrimps·m^{-2} strategy and was absorbed in the other two treatments. Carbon dioxide (CO_2)

was absorbed only in the high-density strategy and emitted from the two low-density strategies. Thus, the present study presents no clear pattern for the emission and absorption of greenhouse gases for these shrimp production systems. Yang et al. (2015) reported that the cultivation of *L. vannamei* in earthen ponds in China was a source of greenhouse gases, emitting large amounts of CH_4 and CO_2 and a reduced amount of N_2O.

Social sustainability

Shrimp production showed little social sustainability for most indicators, employing 50% of the workforce with little work per unit area and unit of production. The low social sustainability may be related to the feed management, which requires little labor to distribute the feed, and the reduced production of biomass resulting from high mortality rates. Low production leads to a reduction of labor as a strategy to reduce costs. Wage equality was ~70% for all management strategies. The salaries shown for the shrimp productions vary according to the level of the position, with the highest salaries being earned by those in charge, followed by the vigilantes and feeders. No local consumption of the shrimp was observed because the productions were sold in other Brazilian states.

The value of 100 was attributed to health benefits, since all company employees are served by a federal public health system, called SUS, which provides services from primary care to complex procedures and offers emergency care for people who suffer accidents. This health service is free and maintained with the collection of taxes from citizens and companies. Considering the dynamics of production and the applied management, only 15% of the employees were receiving education. The permanence of employees in the activity was relatively high despite the productions being reduced to mitigate outbreaks of the WSSV. Permanence in the activity was perhaps due to the working conditions offered by the company, which provided work stability to those involved in the production process.

The negative distribution of income observed for the 92 shrimps·m^{-2} management strategy was due to the high costs of production and the inability to generate profits. The compensation of the labor observed for the two low-density strategies represented 32 to 48% of the production costs. This distribution of income was similar to that observed in Moura et al. (2016), which identified the compensation of labor to be 42% of production costs for net-cage tilapia farming as managed by a cooperative. However, the relationship of direct and indirect income and the creation of jobs as a function of the investment by the company was low for all management strategies due to a decrease in the number of employees as caused by outbreaks of the white spot virus. The virus also led to a lower number of stocked ponds and changes in the management of production to reduce costs. The reduction of employees reduced the social sustainability.

The reduced production of shrimp biomass led to a relatively high compensation for the labor in all management strategies due to the high labor costs per kilogram of harvested shrimp. The indicators that increased social sustainability for the 92 shrimps·m^{-2} management strategy were the compensation of the labor per production, gender inclusion, and the proportion of self-employed workers, perhaps due to the generation of more labor to manage the shrimp ponds with high initial populations.

Modeling of the sustainability

The 14 and 8 shrimps·m^{-2} management strategies presented the most balanced position among the three dimensions of sustainability, but with a tendency towards the economic dimension, and received the highest index of general sustainability. It is noteworthy that sustainability must be evaluated from a multi-criteria point of view rather than by a singular vision in a multidimensional space, and should be balanced through a system according to the economic, environmental, and social dimensions of modern aquaculture.

The shift of sustainability towards one of the dimensions is always considered as detrimental to the other two. Therefore, the best sustainability is with an index that best overlaps the three dimensions. Thus, all management strategies in the present study showed low overall sustainability by having an index far from the center of the triangle, as generated by the MULINO Mdss. The 14 and 8 shrimps·m^{-2} management strategies were the most economically sustainable perhaps due to the lower operating costs that would lead to greater profits. These management strategies showed internal rates of return greater than the interest rates observed in the market, resulting in higher indices of profitability. The high-density strategy was the most favorable to the environment and showed a tendency towards the social dimension, having the highest values of sustainability scores generated by the software MULINO for these dimensions. The greater displacement of the high-density strategy from economic sustainability was associated with higher total operating costs, which led to losses for most of the economic indicators in this management strategy.

The methodology that combines matrices or sets of indicators is the most efficient and most used measurement of sustainability in aquaculture and its processes. These indicators allow independent criticisms and evaluation of each aspect of the activity, revealing the limitations and the elements that should be improved to obtain a more sustainable system. One of the indicators that may have contributed to a lower balance of absolute sustainability in marine shrimp farming in earthen ponds for all management strategies of the present study may be associated with the low productivity, which led to increased operational costs per production and caused reduction of employed labor.

CONCLUSIONS

All management strategies of the present study were considered unsustainable when analyzed according to the framework of the economic, environmental, and social dimensions of sustainability. In general, the sets of indicators used in the present study were adequate to assess the sustainability of shrimp mariculture in earthen ponds and were able to reflect the main strengths and weaknesses of the different management strategies and densities. The DPSIR model evaluated the sustainability of production, demonstrating an imbalance of this activity in the three dimensions analyzed when practiced during a regional outbreak of WSSV.

CONFLICT OF INTEREST

Nothing to declare.

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Conceptualization: Bessa Junior AP; **Data curation:** Junior AP; **Writing – original draft:** Junior AP; **Writing – review and editing:** Junior AP, Valenti WC, Flickinger DL, Henry-Silva G G; **Final approval:** Valenti WC.

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REFERENCES

Avnimelech, Y. (2009). *Biofloc technology. A practical guide book*. Baton Rouge: World Aquaculture Society, 2009.

Boyd, C.E. (1999). *Codes of practice for responsible shrimp farming*. St. Louis: Global Aquaculture Aliance.

Boyd, C.E.; Wood, C.W.; Chaney, P.L. & Queiroz, J.F. (2010). Role of aquaculture pond sediments in sequestration of annual global carbon emissions. *Environmental Pollution*, 158(8): 2537-2540. https://doi.org/10.1016/j.envpol.2010.04.025

Brito, L.O.; Arana, L.A.V.; Soares, R.B.; Severi, W.; Mirandar, H.; Silva, S.M.B.C.; Coimbra, M.R.M. & Galvez, A.O. (2014). Water quality, phytoplankton composition and growth of *Litopenaeus vannamei* (Boone) in an integrated biofloc system with *Gracilaria birdiae* (Greville) and *Gracilaria domingensis* (Kutzing). *Aquaculture International*, 22: 1649-1664. https://doi.org/10.1007/s10499-014-9771-9

Brito, L.O.; Chagas, A.M.; Silva, E.P.; Soares, R.B.; Severi, W. & Galvez, A.O. (2016). Water quality, Vibrio density and growth of Pacific white shrimp *Litopenaeus vannamei* (Boone) in an integrated biofloc system with red seaweed *Gracilaria birdiae* (Greville). *Aquaculture Research*, 47: 940-950. https://doi.org/10.1111/are.12552

Buffon, A.G.M.; Tauk-Tornisielo, S.M. & Pião, A.C.S. (2009). Tempo de vida útil da represa velha da microbacia do córrego da barrinha, Pirassununga, SP, Brasil. *Arquivos do Instituto Biológico*, 76(4): 673-679. https://doi.org/10.1590/1808-1657v76p6732009

Castillo-Soriano, F.A.; Ibarra-Junquera, V.; Escalante-Minakata, P.; Mendoza-Cano, O.; Ornelas- Paz, J.J.; Almanzaramírez, J.C. & Meyer-Willerer, A.O. (2013). Nitrogen dynamics model in zero water exchange, low salinity intensive ponds of white shrimp, *Litopenaeus vannamei*, at Colima, México. *Latin American Journal Aquatic Research*, 41(1): 68-79. https://doi.org/10.3856/vol41-issue1-fulltext-5

Centro de Investigaciones Biológicas del Nordeste. 2008. *Resumen ejecutivo del informe final del proyecto programa integral de sanidad acuícola en camarón*. La Paz: CIBNOR.

Chopin, T.M.; Troell, G.K.; Reid, D.; Knowler, S.M.C.; Robinson, A.; Neori, A.H.; Buschmann, S.J.; Pang & Fang, J. (2010). Integrated multi-trophic aquaculture (IMTA)—A responsible practice providing diversified seafood products while rendering biomitigating services through its extractive components. In: Franz, N.; Schmidt, C.C. (Eds.). *Proceedings of the Organisation for economic co-operation and development (OECD) workshop "Advancing the Aquaculture Agenda: Policies to Ensure a Sustainable Aquaculture Sector"*, 2010. Paris: Organization for Economic Co-operation and Development. p. 195-217.

Chowdhury, A.; Kahirun, Y. & Shivaoti, G.P. (2015). Indicator-based sustainability assessment of shrimp farming: a case for extensive culture methods in South-western coastal Bangladesh. *Ecological Indicators*, 18(4): 261-281. https://doi.org/10.1504/IJSD.2015.072646

Costa, S.W.; Vicente, L.R.M.; Souza, T.M.; Andreatta, E.R. & Marques, M.R.F. (2010). Parâmetros de cultivo e a enfermidade da mancha-branca em fazendas de camarões de Santa Catarina. *Pesquisa Agropecuária Brasileira*, 45(12): 1521-1530.

Fegan, D.F. & Clifford III, H.C. (2001). Health management for viral diseases in shrimp farms. In: *Special session on sustainable shrimp culture, aquaculture*. Baton Rouge: The World Aquaculture Society. p. 168-198.

Flaherty, M.; Szuster, B. & Miller, P. (2000). Low salinity inland shrimp farming in Thailand. *Ambio*, 29(3): 174-179. https://doi.org/10.1579/0044-7447-29.3.174

Food and Agriculture Organization (FAO). (2020). *The State of World Fisheries and aquaculture (SOFIA)*. Rome: Fisheries and Aquaculture Department.

Fourooghifard, H.; Matinfar, A.; Mortazavi, M.S.; Roohani, G.K. & Mirbakhsh, M. (2018). Nitrogen and phosphorous budgets for integrated culture of *Litopenaeus vannamei* with red seaweed Gracilaria corticata in zero water exchange system. *Iranian Journal of Fisheries Sciences*, 17(3): 471-486. https://doi.org/10.22092/IJFS.2018.116382

Giupponi, C. (2007). Decision Support Systems for Implementing the European Water Framework Directive: the MULINO approach. *Environmental Modeling and Software*, 22(2): 248-258. https://doi.org/10.1016/j.envsoft.2005.07.024

Golterman, H.L.; Climo, R.S. & Ohnstad, M.A.M. (1978). *Methods for physical and chemical analysis of fresh waters*. 2.ed. Oxford: IBP.

Gómez-Baggethun, E.; Groot, R.; Lomas, P.L. & Montes, C. (2010). The history of ecosystem services in economic theory and practice: From early notions to markets and payment schemes. *Ecological Economics*, 69: 1209-1218.

Guertler, C.; Rieg, T.; Mejia-Ruiz, C.H.; Lehmann, M.; Barracco, M.A. & Perazzolo, L.M. (2013). Hemograma e sobrevivência de camarões marinhos após silenciamento do WSSV por RNA de interferência. *Pesquisa Agropecuária Brasileira*, 48(8): 983-990.

Hall, D. (2004). Explaining the diversity of Southeast Asian shrimp aquaculture. *Journal of Agrarian Change*, 4(3): 315-335. https://doi.org/10.1111/j.1471-0366.2004.00081.x

Halle, M.; Bizikova, L.; Wolfe, R.; Crawford, A.; Casier, L.; Sharma, S. & Potts, J. (2017). *Sustainable development goals: IISD perspectives on the 2030 – Agenda for sustainable development*. IISD. Available at: http://www.iisd.org/library/iisd-perspectives-2030-agenda-sustainable-development. Accessed on: Mar. 19, 2017.

Koroleff, F. (1976). Determination of nutrients. In: Grasshoff, K. (Ed.). *Methods of Seawater Analysis*. New York: Verlag Chemie Weinhein. p. 117-181.

Krishna, P.V.; Prakash, B.K.; Kumar, V.H. & Prabhavathi, K. (2015). Growth, survival and production of pacific white shrimp *Litopenaeus vannamei* at different stocking densities under semi intensive culture systems in andhra pradesh. *International Journal of Advanced Research*, 3: 446-452.

Lazado, C.C. & Caipang, C.M.A. (2014). Atlantic cod in the dynamic probiotics research in aquaculture. *Aquaculture*, 424-425: 53-62. https://doi.org/10.1016/j.aquaculture.2013.12.040

Mackereth, F.J.H.; Heron, J. & Talling, J.F. (1978). *Water analysis:* some revised methods for linologists. London: Freshwater Biological Association.

Maia, E.P.; Modesto, G.A.; Brito, L.O. & Galvez, A.O. (2016). Intensive culture system of *Litopenaeus vannamei* in commercial ponds with zero water exchange and addition of molasses and probiotics. *Revista de Biologia Marina y Oceanografia*, 51(1): 61-67. https://doi.org/10.4067/S0718-19572016000100006

Moreno-Figueroa, L.D.; Naranjo-Páramo, J.; Alfredo Hernández-Llamas, A.; Vargas-Mendieta, M.; Hernández-Gurrola, J.A. & Villarreal-Colmenares, H. (2017). Performance of a photo-heterotrophic, hypersaline system for intensive cultivation of white leg shrimp (*Litopenaeus vannamei*) with minimal water replacement in lined ponds using a stochastic approach. *Aquaculture Research*, 49: 57-67. https://doi.org/10.1111/are.13432

Moura, R.S.T.; Valenti, W.C. & Henry-Silva, G.G. (2016). Sustainability of Nile tilapia net-cage culture in a reservoir in a semi-arid region. *Ecological Indicators*, 66: 574-582. https://doi.org/10.1016/j.ecolind.2016.01.052

Nobre, A.M.; Robertson-Andersson, D.; Neori, A. & Sankar, K. (2010). Ecological–economic assessment of aquaculture options: comparison between abalone monoculture and integrated multi-trophic aquaculture of abalone and seaweeds. *Aquaculture*, 306(1-4): 116-126. https://doi.org/10.1016/j.aquaculture.2010.06.002

Nunan, L.; Lightner, D.; Pantoja, C. & Gómez-Jiménez, S. (2014). Detection of acute hepatopancreatic necrosis disease (AHPND) in Mexico. *Diseases of Aquatic Organisms*, 111(1): 81-86. https://doi.org/10.3354/dao02776

O'Ryan, R. & Pereira, M. (2015). Participatory indicators of sustainability for the salmon industry: the case of Chile. *Marine Policy*, 51: 322-330. https://doi.org/10.1016/j.marpol.2014.09.010

Paul, B.G. & Vogl, C.R. (2011). Impacts of shrimp farming in Bangladesh: Challenges and alternatives. *Ocean & Coastal Management*, 54(3): 201-211. https://doi.org/10.1016/j.ocecoaman.2010.12.001

Pereira, S.A.; Kimpara, J.M. & Valenti, W.C. (2020). Sustainability of the seaweed *Hypnea pseudomusciformis* farming in the tropical Southwestern Atlantic. *Ecological Indicators*, 121: 107101. https://doi.org/10.1016/j.ecolind.2020.107101

Pimentel, O.A.L.F.; Oliveira, V.Q.; Oliveira, C.R.R.; Severi, W.; Gálvez, A.O.; Amado, A.M. & Brito, L.O. (2021). Assessment of different ionic adjustment strategies in low-salinity water on the growth of Litopenaeus vannamei and microbial community stoichiometry in a synbiotic nursery system. *Aquaculture Research*, 53: 50-62. https://doi.org/10.1111/are.15552

Ramos-Carreño, S.; Valencia- Yáñez, R.; Correa-Sandoval, F.; Ruíz-García, N.; Díaz-Herrera, F. & Giffard-Mena, I. (2014). White spot syndrome virus (WSSV) infection in shrimp (*Litopenaeus vannamei*) exposed to low and high salinity. *Archives of Virology*, 159(9): 2213-2222. https://doi.org/10.1007/s00705-014-2052-0

Rubio-Castro, A.; Luna-González, A.; Álvarez-Ruíz, P.; Escamilla-Montes, R.; Fierro-Coronado, J.A.; López-León, P.; Flores-Miranda, M.C. & Diarte-Plata, G. (2016). Survival and immune-related gene expression in *Litopenaeus vannamei* co-infected with WSSV and *Vibrio parahaemolyticus*. *Aquaculture*, 464: 692-698. https://doi.org/10.1016/j.aquaculture.2016.08.024

Sanches, E.G.; Tosta, G.A.M. & Souza-Filho, J.J. (2013). Viabilidade econômica da produção de formas jovens de bijupirá (*Rachycentron canadum*). *Boletim do Instituto de Pesca*, 39: 15-23.

Soares, D.C.E. & Henry-Silva, G.G. (2019). Emission and absorption of greenhouse gases generated from marine shrimp production (*Litopeneaus vannamei*) in high salinity. *Journal of Cleaner Production*, 218: 367-376. https://doi.org/10.1016/j.jclepro.2019.02.002

Sonnenholzner, S.; Rodríguez, J. & Calderon, J. (2002). Temperature and WSSV: CENAIM studies promising shrimp culture technique. *Global Aquaculture Advocate*, 5: 55-57.

Sookying, D. & Davis, D.A. (2011). Pond production of Pacific white shrimp (*Litopenaeus vannamei*) fed high levels of soybean meal in various combinations. *Aquaculture*, 319(1-2): 141-149. https://doi.org/10.1016/j.aquaculture.2011.06.049

Srinivas, D.; Venkatrayulu, Ch. & Swapna, B. (2016). Sustainability of exotic shrimp *Litopenaeus vannamei* (Boone, 1931) farming in coastal Andhra Pradesh, India: Problems and Issues. *European Journal of Experimental Biology*, 6(3): 80-85.

Tran, L.; Nunan, L.; Redman, R.M.; Mohney, L.L.; Pantoja, C.R.; Fitzsimmons, K. & Lightner, D.V. (2013). Determination of the infectious nature of the agent of acute hepatopancreatic necrosis syndrome affecting penaeid shrimp. *Diseases of Aquatic Organisms*, 105(1): 45-55. https://doi.org/10.3354/dao02621

Trejo-Flores, J.V.; Luna-González, A.; Álvarez-Ruíz, P.; Escamilla-Montes, R.; Peraza-Gómez, V.; Diarte-Plata, G.; Esparza-Leal, H.M.; Campa-Córdova, A.I.; Gámez-Jiménez, C. & Rubio-Castro, A. (2016). Protective effect of Aloe vera in *Litopenaeus vannamei* challenged with *Vibrio parahaemolyticus* and white spot syndrome vírus. *Aquaculture*, 465: 60-64. https://doi.org/10.1016/j.aquaculture.2016.08.033

Valderrama, D. & Engle, C.R. (2002). Economic optimization of shrimp farming in Honduras. *Journal of the World Aquaculture Society*, 33(4): 398-404. https://doi.org/10.1111/j.1749-7345.2002.tb00019.x

Valenti, W.C.; Barros, H.P.; Moraes-Valenti, P.; Bueno, G.W. & Cavalli, R.O. (2021). Aquaculture in Brazil: past, present and future. *Aquaculture Reports*, 19: 100611. https://doi.org/10.1016/j.aqrep.2021.100611

Valenti, W.C.; Kimpara, J.M. & Preto, B.L. (2011). Measuring aquaculture sustainability. *World Aquaculture Society Magazine*, 42(3): 26-30.

Valenti, W.C.; Kimpara, J.M.; Preto, B.L. & Moraes-Valenti, P. (2018). Indicators of sustainability to assess aquaculture systems. *Ecological Indicators*, 88: 402-413. https://doi.org/10.1016/j.ecolind.2017.12.068

Vine, N.G.; Leukes, W.D. & Kaiser, H. (2006). Probiotics in marine larviculture. *FEMS Microbiology Reviews*, 30(3): 404-427. https://doi.org/10.1111/j.1574-6976.2006.00017.x

Yang, P.; He, Q.; Huang, J. & Tong, C. (2015). Fluxes of greenhouse gases at two different aquaculture ponds in the coastal zone of southeastern China. *Atmospheric Environment*, 115: 269-277. https://doi.org/10.1016/j.atmosenv.2015.05.067