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Measuring multidimensional sustainability in small-scale aquaculture: evidence from the Gulf of Nicoya, Costa Rica

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Introduction: The United Nations Development Programme has been instrumental in promoting the generation of productive activities that respond to a sustainable production model. In this regard, small-scale aquaculture merits particular attention for its demonstrated propensity towards sustainability. The present study analyses the levels of multidimensional sustainability through a case study of a small-scale aquaculture system, utilising a measurement system with indicators.

Materials and methods: Information was collected through the application of a measurement instrument during visits to oyster and shrimp farms. The evaluation process involved the analysis of 36 indicators, which were distributed across 12 sustainability variables. These variables addressed the technical, economic, social, environmental and governance dimensions. The results were analysed separately by species, and the sustainability trends presented were also evaluated.

Results: The findings indicate that both productive species demonstrate comparable levels of sustainability, exhibiting distinctions across the various dimensions. In terms of both social and economic dimensions, oyster production is the most significant. Conversely, in technical and governance dimensions, shrimp production is the most important. The study revealed discrepancies in the levels of sustainability, which varied according to geographic sector and the organisational structure of the farm. It has been demonstrated that larger farms tend to exhibit a greater degree of sustainability, characterised by extended production times and a family-oriented organisational structure.

Discussion: The analysis of the results addresses the contrasts in the levels of sustainability of shrimp and oyster production in the Gulf of Nicoya, and compares them with similar experiences in other latitudes. It delves into areas of opportunity in the region, such as technification, circular economy and good governance, through the presentation of success stories in other small-scale aquaculture systems around the world. It concludes that the priority areas for management in the region are strengthening the management and planning structure, cohesion and coordination of producer, circular economy model, and designing a specific sustainability index.

KEYWORDS

sustainable aquaculture, sustainability indicators, small scale, sustainable production, sustainability trends, sustainable management

1 Introduction

The term ‘sustainable development’ was coined by the United Nations (UN) to denote a development that “*makes it possible to meet present needs without compromising the ability of future generations to meet their own needs*” (World Commission of Environment and Development, 1987). Subsequently, this concept was delineated within 17 Sustainable Development Goals (SDGs), which call upon nations to adopt a transformative development style that responds to conditions of equity and equality, in conjunction with environmental respect (United Nations, 2016). To elaborate further, the United Nations (2016) propose that the objective of Sustainable Development Goal 12 (SDG 12) is to promote “Responsible Production and Consumption” with the aim of enhancing the efficiency of production in order to reduce consumption of resources and environmental degradation, thus improving the quality of life.

Aligned with this global framework, aquaculture is defined as an economic activity that is proposed by the Food and Agriculture Organization (FAO) as a sustainable productive alternative that reduces pressure on fishery resources, responds to food security needs and is a source of employment (Food and Agriculture Organization of the United Nations, 2024). As a result, the Blue Economy is a concept closely related to this vision. It is a sustainable model based on SDG 14: Underwater Life, which responds to fishing and aquaculture production systems. In this context, the objective is to enhance sources of income and food for coastal communities in a manner that is equitable and conducive to wellbeing (Bennett et al., 2019).

In terms of sustainability, small-scale aquaculture is of particular relevance, as it is an economic activity that represents a source of livelihood for economically vulnerable sectors (Syanya et al., 2024). The production model in question is distinguished by its household and community structures, characterised by low-density and low-cost production systems, and low levels of technification (Boyd et al., 2020; Haque et al., 2025; Subasinghe et al., 2009). These systems have been shown to have significant social relevance, insofar as they represent an alternative that contributes to poverty reduction through sources of direct and indirect employment (Ababouch et al., 2023; Padhy et al., 2022). Furthermore, it facilitates the integration of women in labour ecosystems, thereby fostering fairer and more equitable environments (Dompreeh et al., 2024). Additionally, low environmental impact associated to this type of production have been reported (Andrade Silva et al., 2025).

Consequently, small-scale aquaculture systems have the capacity to contribute directly or indirectly to Sustainable Development Goals 1, 2, 3, 4, 6, 5, 8, 10, 12, 13, 14, and 15 (Gallardo Lango et al., 2023). In the contemporary era, a plethora of successful sustainability projects have been documented on a global scale, including those in South America (Andrade Silva et al., 2025; Athanasiadis, 1999; Siar et al., 1995), Africa (Syanya et al., 2024) and South Asia (Haque et al., 2025). Conversely, within the Latin American context, this particular genre has witnessed a decline in its level of attention in recent decades (Athanasiadis, 1999).

The development of sustainable small-scale aquaculture projects is often linked to government management processes (Basnayake and De Silva, 2025), in which sustainability measurements are important (Valenti et al., 2018). Wohlenberg et al. (2022) posit that sustainability analysis through indicators constitutes a beneficial instrument in the decision-making process of management. Among the sustainability measurement schemes in aquaculture, the Aquaculture Performance Indicators (API) model stands out, where variables are analysed by economic, community and environmental dimensions using standardised indicators (Garlock et al., 2024; Chávez et al., 2023). Another approach to measuring sustainability establishes the relevance of measuring good governance through indicators that respond to variables in this dimension (Toonen et al., 2025). For its part, the FAO proposes a protocol organised by themes and sub-themes through which 118 indicators are defined for the dimensions of governance, environmental, economic and social wellbeing (Food and Agriculture Organization of the United Nations, 2012).

In this regard, multiple authors have referred to the issue of constructing sustainability measurement tools (Valenti et al., 2018; Chowdhury et al., 2006; Abidin et al., 2019; Ibrahim et al., 2023; Orou Sannou et al., 2023). These assessment systems are based on the use of standardised indices and indicators over time for measuring levels of sustainability (Samuel-Fitwi et al., 2012). However, it should be noted that these indicators are contingent upon specific organisational structure conditions, with defined measurement objectives. Consequently, there are no universally applicable lists of indicators (Kravchenko et al., 2019; Kim et al., 2022). In response to this, there is a necessity to develop context-specific indices and indicators (Wohlenberg et al., 2022). In the context of aquaculture, Valenti et al. (2018) underscore the significance of developing this type of tool to assess sustainability in aquaculture systems and to inform decision-making.

Along these lines, a previous study analysed sustainability indicators employed in economic activities comparable to aquaculture, with the objective of identifying those most suitable for the Gulf of Nicoya context. That study classifies 77 measurement indicators distributed across environmental, economic, legal-institutional, and socio-environmental dimensions. Using 10 selection criteria, it defines 25 indicators appropriate for analysing sustainability in the Gulf of Nicoya, Costa Rica (Robles-Herrera, 2025).

In the case of Costa Rica, aquaculture is an economically, socially and environmentally relevant activity for rural communities (Instituto Costarricense de Pesca y Acuicultura, 2025), where aquaculture units typically respond to family systems with small-scale characteristics (Food and Agriculture Organization of the United Nations, 2022). The Gulf of Nicoya, in particular, is a coastal region characterised by low multidimensional development indices (UCR and PNUD, 2022) and historically hosts a large number of aquaculture farms with these characteristics (Ramírez et al., 2023). According to Ramírez et al. (2023), the area is highly relevant for the country’s aquaculture production, with an area of 1,435 hectares dedicated to shrimp production and 100% of the country’s oyster production. Fisheries and

aquaculture authorities have committed to sustainable aquaculture production that promotes economic development, improves the quality of life and protects the surrounding ecosystems (INCOPESCA and SEPSA, 2019). This highlights the strategic importance of developing sustainability indicators tailored to Costa Rica's aquaculture sector, particularly in the Gulf of Nicoya.

This study uses the aquaculture system of the Gulf of Nicoya as a case study to identify trends in multidimensional sustainability through measurement indicators that allow the definition of patterns and priorities for sustainability management. The objective of this study is to evaluate the level of sustainability of aquaculture units in the Gulf of Nicoya, using a system of multidimensional indicators that allow for the identification of areas of opportunity with a view to achieving sustainable production. Specifically, it answers the following questions: How do the levels of sustainability in the aquaculture system behave in its different dimensions? How do species differ in their sustainability behaviour per dimension? Are there patterns in sustainability behaviour that can be grouped by association variables? What are the priority areas for sustainability management according to the measurements?

2 Materials and methods

2.1 Study area

The Gulf of Nicoya is a coastal marine area in the Pacific Ocean off the coast of Costa Rica, located in the northern part of the country and bounded by the coordinates 10°00'00"N 85°25'00"W (Castro et al., 2021). The region is characterised by being a rural area with a high economic dependence on fishing (Juárez Matute et al., 2019). It has low socio-economic indicators, making it an area with significant social and economic challenges (UCR and PNUD, 2022). Aquaculture has been developing since 1975, with the first shrimp farm (Ramírez et al., 2023). Currently, the Gulf of Nicoya produces shrimp, oysters, snapper and mussels, with the first two being the most representative products (Robles-Herrera, 2025). In Figure 1 a site location of field research study area is presented.

2.2 Sampling design

The study was conducted between June 2023 and September 2024 in aquaculture farms located in the marine coastal regions of the inner Gulf of Nicoya, Costa Rica. Aquaculture units dedicated to the production of oysters and shrimp, the two most abundant products in the region, were included. A total of 49 aquaculture units were included in the study, distributed between five oyster farms (100% of the aquaculture units in the study area for this species) and 44 shrimp farms (42% of the aquaculture units in the study area for this species). A convenience sample was taken in order to gain an understanding of the farms. The following steps were taken: 1. A database of farms was created, integrating information from public entities (SENASA, MINAE, INCOPESCA) and the Costa Rican Chamber of Shrimp Farmers. 2. Producers were contacted by telephone and appointments were made to visit the farms. 3. Producers who could not be contacted by telephone were visited directly at their farms. Farms were excluded if the producer did not want to be part of the study or if the aquaculture

unit was inactive at the time of sampling. The sampling considered all farm grouping areas present in the Gulf of Nicoya. These include the sectors of Chomes, Colorado, Quebrada Grande, Morote, Cangelito, Jicaral, Lepanto, Isla Chira, and Isla Venado (Figure 1).

Sustainability information on aquaculture units was obtained from farm visits, using measurement instruments designed for this purpose. The instruments were developed based on instruments used by SENASA during field visits and fed with information from GlobalGAP checklist standards (GLOBALGAP, 2019). They were then reviewed by six experts in the field of aquaculture in Costa Rica. A field validation was carried out to verify producers' understanding of the instrument and the accuracy of the information obtained. An administrated structured questionnaire with open and closed questions was used, targeting farm owners and workers. The instrument included management, production, hiring, marketing, inputs used, and crop cycle practices aimed at responding to sustainability indicators. The questionnaire was administered by individuals from the field of industrial engineering who had been previously trained to collect the information. An observation instrument was also used to collect information on the state and characteristics of the infrastructure. The information obtained was systematised in a database with quantitative and qualitative variables. Sustainability rating.

The information obtained was systematised into a total of 36 sustainability indicators corresponding to 12 variables in the technical, economic, social, environmental and governance dimensions. These indicators were taken from various documents proposing indicators for measuring sustainability in the aquaculture and agriculture sectors. The selection process was based on the following criteria: availability of information, relevance, comprehensibility, scientific basis, validity of information, feasibility of measurement, relevance, targeting, simplicity and compatibility of indicators (Robles-Herrera, 2025). Details of the indicators used are presented in Table 1.

The qualitative data were transformed into 5-point scale indicators, with increasing values representing higher levels of sustainability. The quantitative information was normalised using Min-Max technique. In case it was required the indicator was inverted, follow the increasing levels of sustainability (Han et al., 2012). Furthermore, qualitative and quantitative association variables were taken into account, including geographical location, farm area, type of governance structure of the aquaculture unit, and species. The variables analysed were evaluated using a simple average of the available indicators for each farm. The calculation formula is presented in Equation 1.

$$V = \frac{i1 + i2 + i3 \dots}{ni} \quad (1)$$

- V=Variable level of sustainability by aquaculture unit
- i = Indicator score by aquaculture unit
- ni = Number of indicators

In cases where data for a specific indicator were unavailable for a given aquaculture unit, the indicator was omitted from the analysis. The corresponding variable was then reweighted proportionally using the remaining available indicators to ensure consistency in the overall assessment.

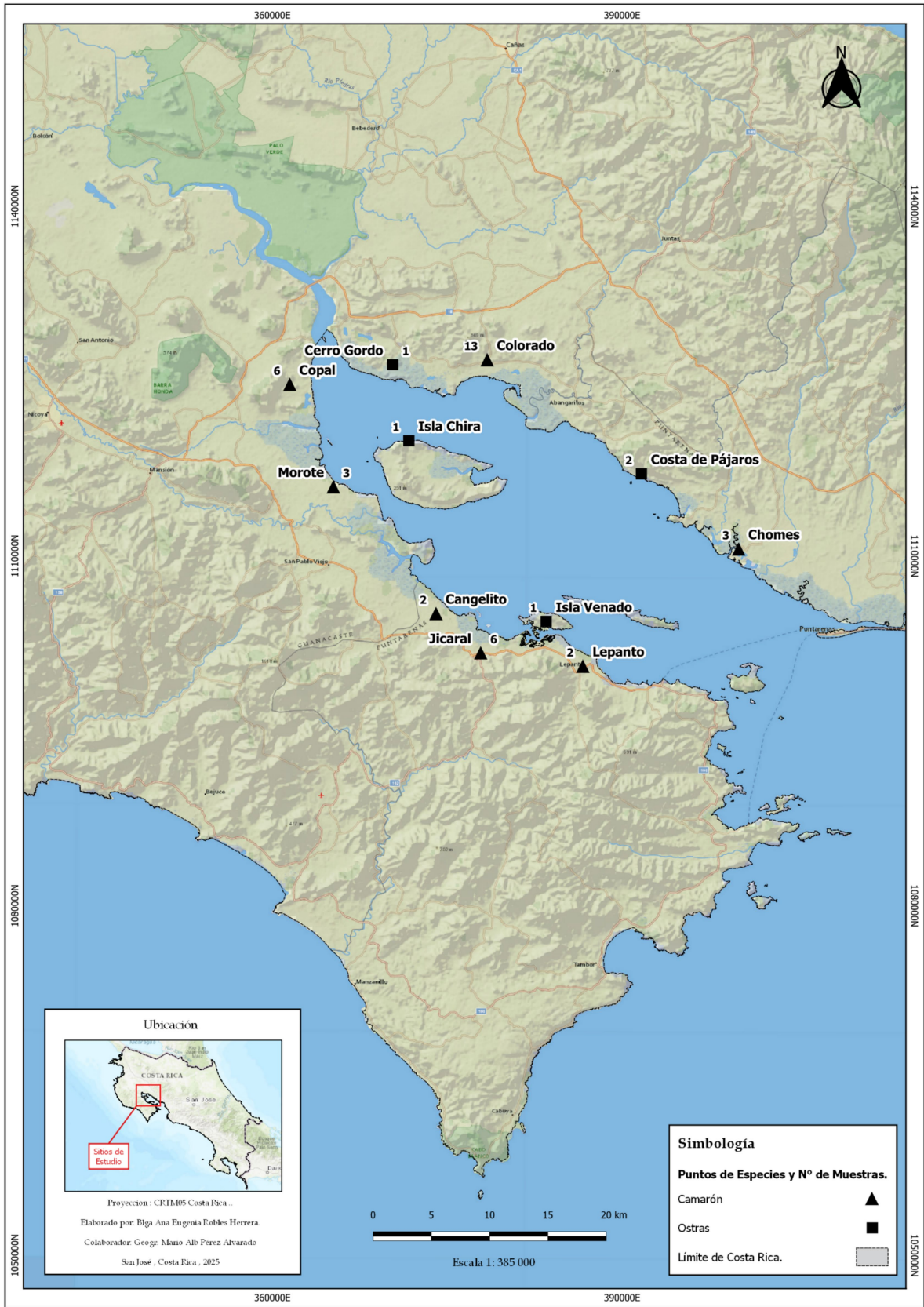


FIGURE 1
Distribution of aquaculture units assessed along the Gulf of Nicoya by species and number of farms sampled. Source: Map created by Mario Perez Alvarado, using information from the study.

TABLE 1 Sustainability indicators according to the measurement variables of the technical, economic, social, environmental and governance dimensions.

Technical dimension		Economical dimension	
Variable ecoefficiency	Production stability Production History of production Period in production	Variable circular economy	Raw material recirculation Waste valorization Local trade
Variable technological advance	Technical advice Cultural techniques using Level of planning and records using	Variable finance structure	Linkage with other economic activities Gross income Level of indebtedness
		Variable richness distribution	Employability Partial jobs Number of owners Rate of self-employment Family members
Social dimension		Environmental dimension	
Variable social responsibility	Community outreach Hiring gender equity Female participation Community access	Variable environmental responsibility	Emissions Waste management Energy saving
Variable workplace health	Workday Access to potable water Child labour Legality of the contracting	Variable agroecological management	Integrated pest management Integrated soil management Biohazard prevention Use of natural products Use of biological promoters
Variable knowledge capital	Generational change in education Producer's educational level Training		
Governance dimension			
Variable regulatory compliance	Permit compliance Land tenure	Variable guild integration	Associativeness

Details of the definitions and sources of the indicators are provided in [Supplementary material](#).

The calculation of the sustainability level for each dimension was achieved by applying the methodology proposed by [Abreu et al. \(2019\)](#) to construct an index to measure rural development. The author posits that the geometric mean enables the mitigation of the impact of extreme values in the calculation of indicators that are weighted ([Abreu et al., 2019](#)). In consideration of the aforementioned factors, the geometric mean of the variables constituting the index was utilised to determine the sustainability level of each dimension on an individual farm. The formula under consideration is presented in [Equation 2](#).

$$D = \sqrt[n]{v_1 * v_2 * \dots} \quad (2)$$

- D = Dimension level of sustainability by aquaculture unit
- v = Variable level of sustainability by aquaculture unit
- n = number of variables involved

Consequently, the overall sustainability level was calculated, taking into account all the dimensions per aquaculture unit. The geometric mean formula advocated by [Abreu et al. \(2019\)](#) was utilised, as demonstrated in the [Equation 3](#).

$$S = \sqrt[5]{T * E * S * A * G} \quad (3)$$

- S = Global sustainability level by aquaculture unit
- T = Technique dimension level by aquaculture unit
- E = Economic dimension level by aquaculture unit
- S = Social dimension level by aquaculture unit
- A = Environmental dimension level by aquaculture unit
- G = Governance dimension level by aquaculture unit

2.3 Analysis of results

The results obtained were then used to construct a matrix integrating the values of indicators, variables and dimensions for each farm, for the purpose of statistical analysis. The R Studio software was employed in conjunction with the basic, dplyr, reshape2, factoExtra, ggplot2, cluster and gridExtra libraries. A normality analysis was performed for each variable and dimension using the Shapiro Wilk test. Once the normality assumptions were verified, an ANOVA test was used to determine whether there were significant differences between dimensions and variables. If the variable did not follow the normality assumptions, a Friedmann test was used. In consideration of the cultural and managerial distinctions between the two species, a distinct analysis was conducted for each. In the context of shrimp production, a statistical analysis was conducted to ascertain the impact of various factors on the dimensions, variables and association variables of the shrimp. Concurrently, a correlational analysis by indicators was employed to identify trends in sustainability behaviour in terms of indicators. Finally, a cluster analysis by farm was applied, including all aquaculture units in the study. This enabled the aquaculture units to be divided into subgroups, thus facilitating the consideration of sustainability trends in management proposals.

3 Results

3.1 Comparative sustainability analysis between species

A comparative analysis of species in terms of sustainability, considering all dimensions, shows that there are no significant differences in the sustainability of oyster and shrimp production

($X = 0.9318$; d.f. = 4; $p = 0.92$). The average value for the overall sustainability level of shrimp production was 2.51 ± 0.45 , and the average value for oyster production was 2.46 ± 0.20 . However, as demonstrated in Figure 2, disparities can be identified across the dimensions. Specifically, shrimp production exhibits higher values in comparison to oyster production, particularly in the technical and governance dimensions. By contrast, oyster production has been demonstrated to demonstrate superior social and economic sustainability, as evidenced by increased wealth distribution and employment equity.

3.2 Sustainability in oyster production

In relation to oyster production, a range of sustainability values from 1.00 to 3.80 were identified. As illustrated in Table 2, the mean values for the level of sustainability are displayed according to each dimension and variable. The highest values were observed in the economic and social dimensions, where all variables demonstrated sustainability levels above 3.00. The variables of Richness distribution, Social responsibility and Workplace health are those which are most conducive to sustainability. This phenomenon is exemplified by the farm management characteristics observed, wherein aquaculture units are situated in public areas accessible to community members. In certain

instances, producers have devised strategies to incorporate community members into aquaculture units through complementary businesses such as tourism, trade, and mechanical services. The management of these production units is characterised by their governance through producer associations, which include women within their membership. The working hours observed in these units are equitable, and access to drinking water is guaranteed. Nevertheless, the indicator of the Legality of contracting demonstrated low values. This is due to the fact that producers are unable to meet the insurance requirements demanded by law, as they are incapable of bearing the associated economic burden.

On the other hand, the variables with the lowest sustainability values are present in the technical and governance dimensions. In terms of the technical dimension, the variable Technology application has the lowest values. It can be observed that production is carried out with basic levels of technology, without permanent technical advice or production planning for decision-making. They have the support of the National University, which monitors production on a regular basis and provides management recommendations. On the other hand, in terms of governance, Guild association variable had the lowest values, where it can be seen that all oyster producers maintain communication, cohesion and collaboration among themselves; however, there is no formal group that integrates them and allows them to work as a bloc that represents them.

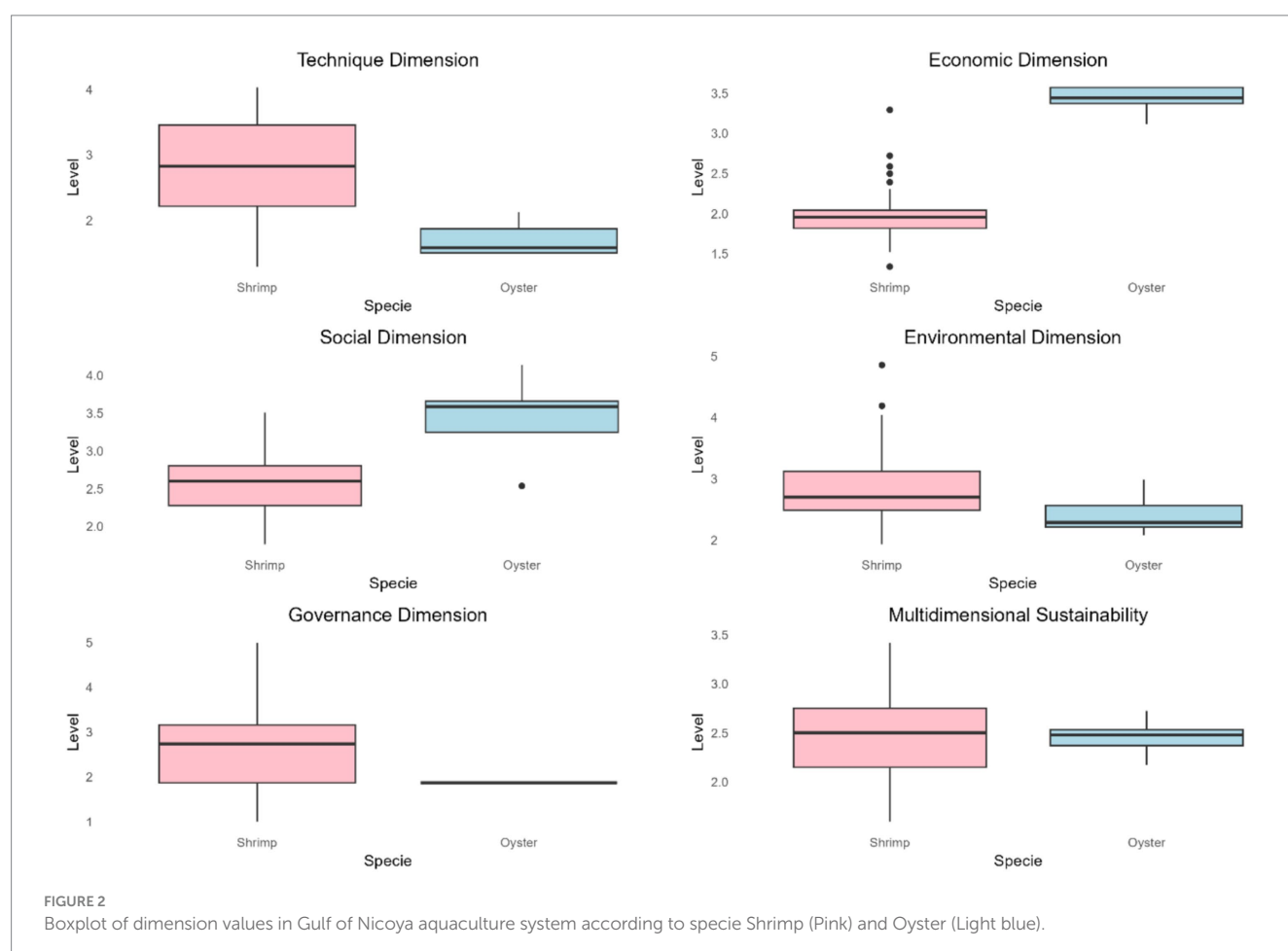


TABLE 2 Sustainability indicators for oyster production in Gulf of Nicoya, Costa Rica.

Dimension	Variable	Average	Standard Deviation	Dimension Friedman probability	Statistic probe	Dimension Friedman D.F.
Technique		1.71	0.27	0.025*	5 ⁱ	1
	Ecoefficiency	2.55	0.54			
	Technology Application	1.20	0.44			
Economic		3.41	0.19	0.041*	6.4 ⁱ	2
	Circular Economy	3.00	0.00			
	Financial Structure	3.56	0.48			
	Richness distribution	3.76	0.36			
Social		3.43	0.59	0.82	0.4 ⁱ	2
	Social Responsibility	3.80	0.76			
	Workplace Health	3.68	0.95			
	Knowledge Capital	3.07	1.06			
Environmental		2.43	0.36	0.18	1.8 ⁱ	1
	Environmental Responsibility	2.00	0.58			
	Agro ecological Management	2.99	0.26			
Governance		1.87	0.00	0.025*	5 ⁱ	1
	Regulatory Compliance	3.5	0.00			
	Guild Association	1	0.00			
Sustainability		2.46	0.20	0.0035**	13.56 ⁱ	3

*Significant probability.

**Highly significant probability.

ⁱFriedman Chi Square.

3.3 Sustainability in shrimp production

The analysis of shrimp production shows that there are significant differences between the dimensions ($F = 7.551$; d.f. = 4; $p = 1.27e-05^{***}$). Table 3 shows the average sustainability level values for each variable by dimension for shrimp production. Sustainability values range from 1.14 to 3.17, with the highest values for Financial structure, Workplace health, Agro ecological management, and Guild association. In contrast, the variable with the lowest values was Circular economy.

Getting deeper on sustainability tendencies, the economic dimension stands out as the dimension with the lowest values and significant differences between the variables that comprise it, with an antagonism between the Circular economy and Financial structure variables. In terms of Circular economy, aquaculture units show an absence of both Raw material recirculation and Waste valorization, with a lack of options available in the vicinity of the farms to implement such practices. In contrast, the Financial structure has very high values for the Level of indebtedness indicator, where all producers have opted to finance their production with their own income, and where producers have opted for partial harvest strategies and short cycles to refinance their operating costs. Likewise, it presents high values for the Local Trade indicator, where all producers opt for national trade and, in many cases, have implemented partial marketing strategies in the locality. However, the Gross Income and Linkage with other economic activities show high variability between farms, with a marked tendency towards low values.

The Governance dimension is characterised by being the second dimension with the highest levels of sustainability; however, it shows the greatest disparity between farms. Significant differences were also found between variables. The Regulatory compliance variable presents extreme values in terms of Land tenure and Permits compliance indicators, where many farms operate illegally without permits and on rented land, while others are in the process of obtaining permits and a few have all the necessary permits. In contrast, in terms of the Guild Association variable, it has the highest average value per variable for shrimp production. It has the Costa Rican Chamber of Shrimp Producers (CAPROCAM) representing the sector; however, the levels of association of aquaculture units vary significantly between extreme values, with a large number of aquaculture units not affiliated with CAPROCAM.

The Technical, Social and Environmental dimensions present average sustainability values with no significant differences between variables. The Technology application variable stands out for its high levels of disparity between farms, where some farms have high levels of planning and technical advice, in contrast to farms that do not have these elements at all.

3.4 Sustainability trends

The analysis of association variables shows that shrimp production differs significantly between the sectors studied ($F = 6.123$; D.F. = 3; $p = 0.00215^{**}$), with the Quebrada Grande sector showing the highest sustainability values and the greatest disparity in results. This result

TABLE 3 Sustainability values by dimension for shrimp production in Gulf of Nicoya, Costa Rica.

Dimension	Variable	Average	Standard Deviation	Dimension ANOVA probability	Statistic probe	Dimension ANOVA D. F.
Technique		2.74	0.76	0.99	0 ⁱⁱ	1
	Ecoefficiency	2.80	0.69			
	Technology Application	2.8	1.06			
Economic		1.99	0.37	8.1e-14***	60.19 ⁱ	2
	Circular Economy	1.14	0.33			
	Financial Structure	3.00	0.42			
	Richness distribution	2.39	0.70			
Social		2.58	0.46	0.064	2.817 ⁱⁱ	2
	Social Responsibility	2.56	0.79			
	Workplace Health	3.00	0.67			
	Knowledge Capital	2.57	0.13			
Environmental		2.81	0.64	0.064	1.73 ⁱⁱ	2
	Environmental Responsibility	2.72	0.76			
	Agro ecological Management	2.95	0.69			
Governance		2.76	1.15	0.024*	5.30 ⁱⁱ	1
	Regulatory Compliance	2.45	1.13			
	Guild Association	3.17	1.40			
Sustainability		2.50	0.45	1.6e-06***	29.6 ⁱ	4

*Significant probability.

***Very highly significant probability.

ⁱFriedman Chi Square.ⁱⁱANOVA.

was consistent across all dimensions. This sector is characterised by farms that follow a large-scale production model, as well as small-scale farms. On the other hand, no significant differences were found between aquaculture units based on the type of organisation of the farm owners ($F = 3.09$; D.F. = 2; $p = 0.0593$). However, it was found that in terms of the technical dimension, family and single-owner aquaculture units had higher values than companies ($F = 3.60$; D.F. = 2; $p = 0.0387$). These trends can be seen in Figure 3.

Correlational analysis reveals a series of trends among indicators that explain the sustainability performance of farms (Figure 4). On the one hand, small and old farms tend to have a family structure that is not very dependent on trade union organisation and have low levels of education, a tendency towards greater recirculation of raw materials and closer ties with the community. In contrast, large farms are characterised by higher levels of education and more planned use of technology. They tend to have more legally compliant contracts and are more isolated from the community, although they have stronger guild links.

On the other hand, there is a positive correlation between productivity, gross income, integrated pest management and the number of farm owners. Another marked trend was that the more generations of producers on the farm, the lower the tendency to take on debt.

The cluster analysis carried out shows that, in terms of sustainability, aquaculture farms can be grouped into four main groups, as shown in Figure 5. The first group corresponds to oyster

production, which has sustainability characteristics specific to this type of production, as detailed in section 3.2. Shrimp production is subdivided into three groups: Group 2, which was previously identified within the Quebrada Grande sector, corresponds to larger-scale farms. It has higher levels of sustainability in the technical, economic and governance dimensions, while intermediate values are identified in the social and environmental dimensions; Group 3 is characterised by farms with low levels of governance in all sectors studied and low levels of sustainability in all dimensions; Group 4 includes the remaining shrimp farms, with representatives from all sectors and intermediate sustainability values in all dimensions and medium to high values for the Associativeness indicator.

The study presented as a limitation the availability of information on farms, as some producers do not keep records of this data or choose not to share it. The indicators with the highest number of missing values were: Relationship with the community (18), Productivity (9), Gross income (9), Emissions (5), Environmental responsibility (4), Valuation (4), and Production stability (2). Given that each of these indicators contributes to different variables, the contribution of these missing values was diluted in the rest of the indicators of the variables to which they contribute.

4 Discussion

The study shows that although shrimp and oyster production have similar levels of sustainability, there is a difference in terms of scale.

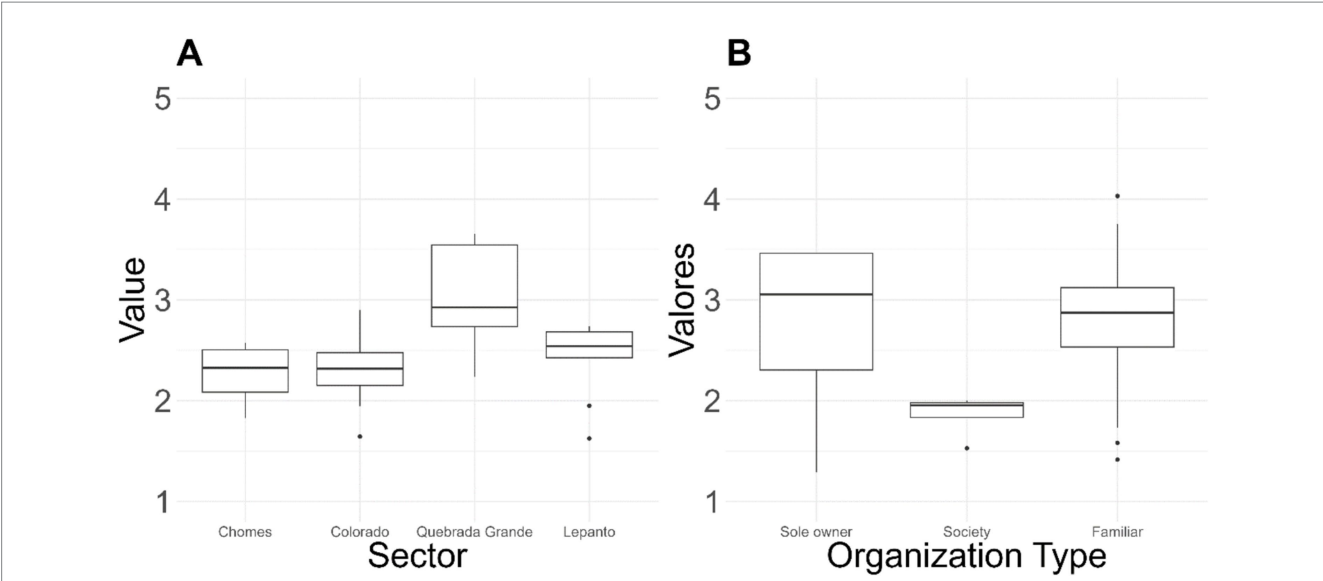


FIGURE 3 Boxplot of sustainability value in Gulf of Nicoya shrimp aquaculture system by association variables. (A) Global Sustainability by Sector and (B) Technique Sustainability by type of owner organization.

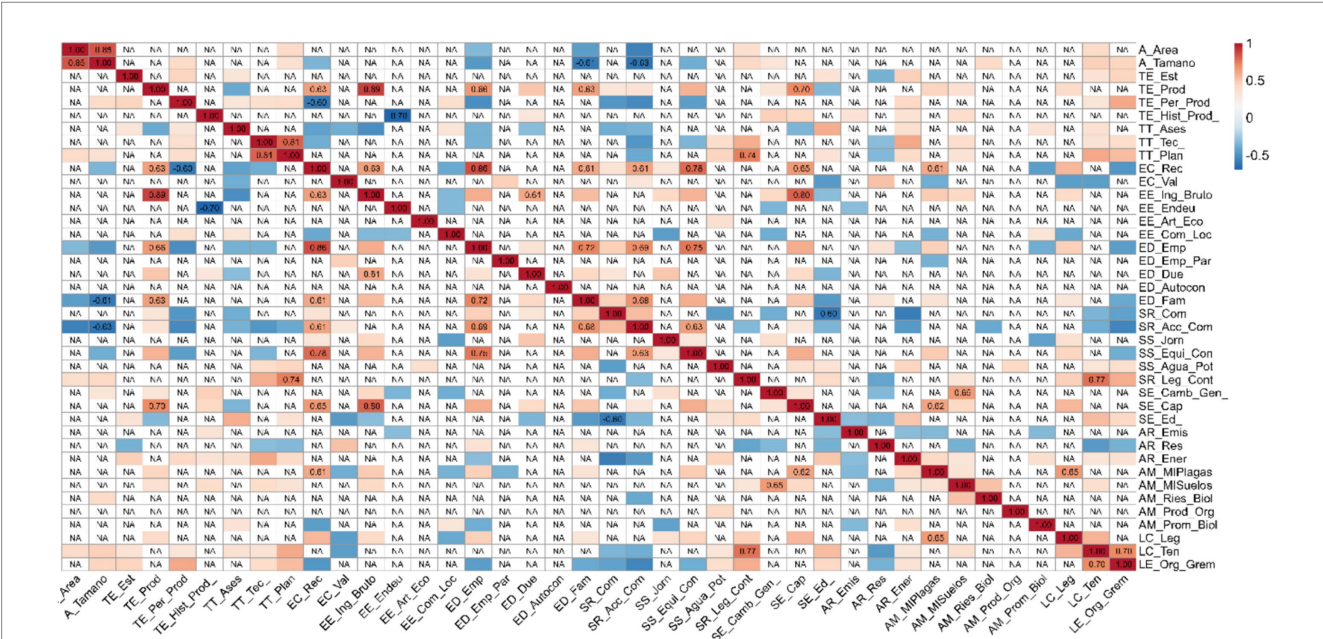
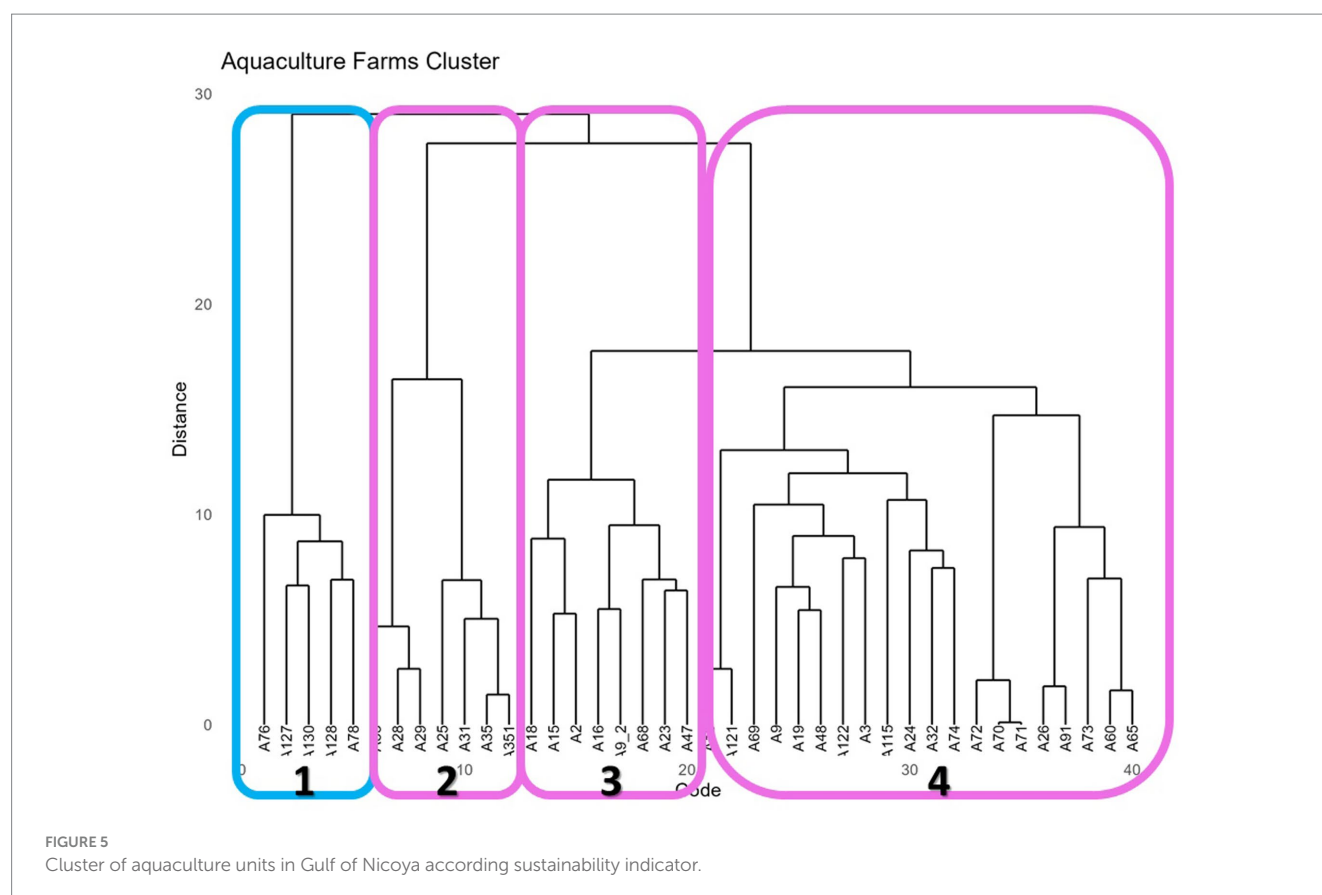


FIGURE 4 Multiple correlation analysis between sustainability indicators applied to farms in the aquaculture system of the Gulf of Nicoya, Costa Rica.

This coincides with the findings of Garlock et al. (2024), who reported that aquaculture indicators for mollusc production have higher environmental and social sustainability values than crustacean production. This pattern is due to the fact that mollusc farming does not require the use of feed and instead reduces sediments and assimilates nutrients such as phosphorus available in the environment, which reduces its environmental impact and confers lower economic risk properties (Garlock et al., 2024). These properties were considered in Costa Rica to develop oyster production as a social development alternative for impoverished communities (Rojas-Alfaro et al., 2017).

In contrast, shrimp production is highly dependent on the addition of feed and inputs, which entails significantly higher investment costs (Valverde and Varela, 2020). The results of the study show that oyster production has high social and economic values linked to the number of owners per aquaculture unit, gender equality, and fair working conditions. These results are particularly relevant, considering that one of the main socio-environmental risks of small-scale aquaculture in Central America lies in gender equality and working conditions (Food and Agriculture Organization of the United Nations, 2019). This reflects the potential of oyster production as an economically



accessible productive alternative for low-income sectors that responds to the needs for gender equality and social equity faced by aquaculture.

On the other hand, according to Joffre et al. (2017), technological innovation in aquaculture is necessary to achieve ecological and social sustainability. Along these lines, the aquaculture industry reports significant development in technologies at all levels of complexity that improve production efficiency, reduce production costs, and improve its ecological footprint (Joffre et al., 2017). However, producers' adoption of new technologies is influenced by multiple economic, social, technological resource access, farm type and institutional factors (Kumar et al., 2018). This study shows that family-type units tend to have better technical management values. However, both oyster and shrimp production face significant challenges in terms of technical dimension. Aspects such as planning, record keeping and technical advice show low values among a large number of producers. These are determining factors for the application of new technologies, which allow for the establishment of implementation and monitoring phases for the technologies applied (Kumar et al., 2018). Considering the above, it is important for small-scale aquaculture production to develop good planning and record-keeping practices as a first step towards the implementation of technologies.

Another factor limiting the implementation of new technologies is the lack of financial resources for their implementation (Kumar et al., 2018). The Gulf of Nicoya case study highlights a clear trend towards self-financing in aquaculture production. This is related to the lack of credit lines available to this sector, which has been identified by INCOPECSA as an area of opportunity at the institutional level in Costa Rica (INCOPECSA and SEPSA, 2019). This constraint has been

identified in other small-scale aquaculture productions around the world. Such is the case in Africa, where this situation is attributed to the absence of institutions with credit lines for this sector, reputational constraints of the aquaculture sector as credit subjects, and deficient financial plans (Gallardo Lango et al., 2023). From this perspective, institutional strengthening efforts towards the sustainability of small-scale aquaculture should consider comprehensive economic strengthening plans, coordinated with local and international financial institutions that promote specific credit lines for the sector with support and financial training programmes.

On the other hand, at the farm management level, producers have opted for debt reduction strategies to improve their financial status. In terms of financial structure, poorly managed leverage can reduce the liquidity and income of the production unit; however, if managed efficiently, it can increase investment capital and income (Gil Leon et al., 2018). This implies that the implementation of financing sources at the farm level for the implementation of new technologies should not lose sight of the break-even point in leverage levels, so that they are sustainable over time (Mauricio et al., 2018). In contrast, economies of scale strategies have been shown to reduce production costs and increase income in agricultural systems (Gil Leon et al., 2018). In the case of the Gulf of Nicoya, this trend is present in partial harvest strategies and short production cycles (Valverde and Varela, 2020).

From an environmental sustainability perspective, indicators show high variability in management practices, with areas of opportunity for agroecological management on a large number of farms. In contrast, some management techniques using probiotics have been

recommended as environmentally friendly sustainable practices for aquaculture systems (Amenyogbe, 2023). Along these lines, the use of probiotics, prebiotics and synbiotics as feed additives has been shown to have favourable results in terms of feed conversion, immune response, mortality and morbidity from bacterial infections, faecal excretion and improved water quality (Hosseini et al., 2024). Likewise, the use of probiotics to stimulate the production of heterotrophic bacteria has been documented, impacting phytoplankton and sediment communities and improving the production system (Paiva-Maia et al., 2013). Another sustainable management technique involves the addition of organic substrates to promote the development of periphyton, resulting in higher primary productivity and improved water quality (Santhiya and Athithan, 2024). Considering the trend towards the use of biological promoters in aquaculture units in the Gulf of Nicoya, these are practices that require less financial investment and are environmentally sustainable, and could be considered in small-scale aquaculture systems such as the case study.

On the other hand, the study reflects a marked area of opportunity for sustainability in the implementation of practices aimed at the circular economy in both productions. Along these lines, multiple authors document the implementation of multitrophic systems (IMTA) as sustainable techniques that respond to circular economy models (Azhar and Memiş, 2023; Ahmed and Glaser, 2016; Fang et al., 2016; Marques et al., 2022). One example is the application of aquaponic techniques, which has been reported with successful experiences in small-scale aquaculture systems, with strategies for female inclusion in India (Tanuja et al., 2023). Another case is the implementation of silvopastoral systems in mangrove systems associated with marine shrimp production (Ahmed et al., 2018). These systems are significantly more complex (Chary et al., 2022), so GN farms should consider greater economic investment and technical support for their implementation. However, they have been recommended for small-scale aquaculture systems in Latin America because they offer economic advantages such as increased system productivity and economic gains (Rodríguez Vázquez et al., 2011), as well as improved system health (Price et al., 2014).

In terms of governance, the study highlights an area of opportunity in the Gulf of Nicoya. Although sectoral association structures exist, there are differences with marked geographical segmentation in the level of involvement and commitment of producers to the organisation. This level of engagement shows a clear correlation with the level of sustainability on farms. Therefore, it is necessary to work on strengthening the governance model for the aquaculture system in the Gulf of Nicoya. The Blue Economy Model promotes inclusive governance in coastal and aquaculture systems, in order to enhance food security, wellbeing and economic growth (Bennett et al., 2019). From this perspective, He et al. (2022) propose a meta-governance model that establishes ethical principles for decision-making involving all actors involved in the process. This model establishes coordination between the government sector, the productive sector and the commercial sector in the implementation of practices that empower and guide producers and promote a values-based decision-making model (He et al., 2022). In this sense, producer organisations could play a key role in coordinating this meta-governance system, leading to more sustainable production.

Finally, several authors highlight the importance of monitoring sustainability in aquaculture systems through context-specific indices

and indicators (Valenti et al., 2018; Chowdhury et al., 2006; Abidin et al., 2019; Orou Sannou et al., 2023). However, analysis of the case of the Gulf of Nicoya, Costa Rica, revealed a significant limitation in the availability of information. This is a criterion that should be considered when selecting sustainability indicators (Li et al., 2023). Furthermore, sustainability indices must be validated in the context to which they are applied, so that the viability and reliability of the results can be guaranteed in practical terms.

Considering the results of the study and the Blue Economy model, the aquaculture system in the Gulf of Nicoya presents significant opportunities for development. From this perspective, a sustainable development plan should be proposed that integrates all productive actors in the value chain, civil society, academia, and the public sector. This plan should consider key elements for productive development, including: 1. An implementation plan for good aquaculture practices that includes components for registration and production monitoring. 2. A system to strengthen aquaculture investment through training in financial management and financing structures. 3. A circular economy strategy that connects local actors through linkages that promote the economy at scale. 4. An environmental management plan that incorporates proper waste management and promotes agroecological management of aquaculture units and fosters resilience to climate change; and 5. A participatory governance system that strengthens coordination within the productive sector and incorporates all actors in the system into decision-making.

5 Conclusion

The study revealed that, in the case of aquaculture in the Gulf of Nicoya, there are intermediate levels of sustainability for both types of production, where the main areas of opportunity are the application of technology, the circular economy, trade associations and regulatory compliance. Oyster farming dominates in the economic and social dimensions, while shrimp farming dominates in the technical and governance dimensions.

The study also revealed some relevant trends, such as that larger units with longer production times tend to be more sustainable. Likewise, aquaculture units with an organisational structure have higher values in the technical dimension.

Taking these findings into account, it is recommended that the priority areas for management in relation to farm sustainability are: Strengthening the management and planning structure on farms, Cohesion and coordination of producer associations, Promotion of a circular economy model that enhances economic, social and environmental sustainability, and Design of a specific sustainability index, with relevant and few indicators, to monitor the evolution of the sector and support decision-making.

Data availability statement

The datasets presented in this article are not readily available because the datasets include sensible private information, which cannot be shared. The information is protected by Costa Rican law. Requests to access the datasets should be directed to ana.robles@ulatina.cr.

Ethics statement

Ethical approval was not required for the studies involving human participants, as Costa Rican law does not require committee approval for this type of information. The research was conducted in accordance with relevant local legislation and institutional requirements. All participants provided their written informed consent to participate in the study. Moreover, the research is grounded in a doctoral pre-project approved by the DOCINADE program, which underwent institutional review at the planning stage to ensure compliance with ethical standards.

Author contributions

AR-H: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. TG: Conceptualization, Methodology, Supervision, Writing – review & editing. AH-U: Conceptualization, Supervision, Writing – review & editing. RR: Writing – review & editing. MB: Conceptualization, Methodology, Validation, Formal analysis, Writing – review & editing, Supervision.

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Conflict of interest

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2025.1656410/full#supplementary-material>

SUPPLEMENTARY TABLE 1

Definition of indicators used and reference sources by variables and dimensions.

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