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Quantifying sustainability: A sectoral and farm-level indicator system for sustainable aquaculture in Quang Ninh province (Vietnam)

An Thinh Nguyen[a] ✉ | Bao Ngoc Tran[a] | Huyen Trang Le[a] | Thuy Linh Pham[a] | Thuong T. Vu[a] | Huong T. Hoang[a] | Mai Huong T. Nguyen[a] | Tuyen T. Tran[b] | Sung Jae Lee[c] | Alyssa Dela Cruz[c]

[a]VNU University Economics and Business, Vietnam National University, Hanoi, Vietnam.
[b]Vinh University, Nghe An, Vietnam.
[c]Chiang Mai University, Chiang Mai, Thailand.

Abstract Aquaculture has recently experienced significant growth and has become a vital component of various economies worldwide; however, this expansion is currently being challenged by the simultaneous growth of other marine industries, raising concerns about the long-term sustainability of aquaculture operations. This study focuses on assessing the sustainability of aquaculture practices specifically in the coastal province of Quang Ninh, Vietnam. A total of 90 questionnaires are distributed to a diverse group of local stakeholders including aquaculture farmers, local residents, business professionals, and government officials. The indicator system including 10 economic sustainability indicators, 8 environmental sustainability indicators, and 11 social sustainability indicators are designed to capture a wide range of impacts and dependencies associated with aquaculture practices. A sensitivity analysis conducted as part of the study revealed that the revenue generated by aquaculture farms plays a crucial role in determining the overall success of these projects. Based on study findings, robust strategies are recommended to ensure the sustainability of aquaculture in Quang Ninh, including enhancing farming efficiency through the adoption of innovative and sustainable techniques. The Integrated Multi-Trophic Aquaculture (IMTA), which promotes a balanced ecosystem approach by allowing different species at various trophic levels to coexist synergistically, not only improves efficiency but also helps in reducing waste and minimizing environmental impacts. Advancements in aquaculture, particularly through the integration of modern, environmentally friendly techniques like IMTA, promise to enhance sustainability and boost Quang Ninh province's economy by creating jobs and conserving natural resources. To capitalize on these advancements, further research into innovative aquaculture methods is necessary, requiring collaboration among government bodies, educational institutions, and private investors to transform the aquaculture industry into a competitive and resilient sector.

Keywords: aquaculture, sustainability, indicator system, integrated multi-layer aquaculture, Quang Ninh Province, Vietnam

1. Introduction

Aquaculture is emerging as one of the most rapidly expanding sectors in global food production, addressing both the escalating demand for seafood and the critical issue of overfishing (FAO, 2020; Xuan et al., 2021). This growth is predominant in Asia, where approximately 95% of aquaculture workers are based, and approximately 80% of the world's shrimp production occurred in 2018 (FAO, 2020). However, the rapid expansion and intensification of this sector have brought significant environmental challenges, including water pollution, loss of biodiversity, disease outbreaks, and widespread habitat destruction (Klinger and Naylor, 2012; Ahmed and Thompson, 2019; Hai and Speelman, 2020). Additionally, issues such as labor standard violations and potential resource conflicts, often referred to as the tragedy of the commons, have been noted (Schlag, 2010). The negative impacts of aquaculture are profound, directly threatening the livelihoods of local communities and exacerbating poverty, thereby creating socioecological traps that reinforce vulnerability (Hanh et al., 2018). Despite these challenges, many practitioners lack the resources, knowledge, or governmental support necessary to transition to more sustainable practices (Hai and Speelman, 2020). Nevertheless, there is a demonstrated willingness among stakeholders to adopt sustainable methods, particularly when they perceive personal benefits such as increased yields or higher market prices (Xuan et al., 2021; Ngoc et al., 2021). In response to the need for more sustainable practices, some farmers have started combining fed aquaculture with extractive methods, utilizing the excess nutrients from fed species to support the growth of others and effectively absorbing and recycling waste within the ecosystem (Thierry et al., 2012). Furthermore, there is a growing shift toward multispecies approaches such as IMTA, which enhances sustainability by employing ecological principles and fostering beneficial interactions among diverse species (Chopin et al., 2012; Thierry et al., 2012). This system involves cultivating different species in close proximity, where the byproducts (organic and inorganic wastes) of one species serve as nutritional inputs for another, thus establishing a symbiotic relationship among the cultivated species and reducing environmental impact (Knowler et al., 2020). This approach not only mitigates the negative effects of traditional aquaculture practices but also contributes to a more ecologically balanced and sustainable aquaculture system.

The sustainability of aquaculture is comprehensively measured using an indicator system that spans three critical dimensions: economic, environmental, and social. Economic sustainability is centered on the efficient utilization of financial capital to cultivate profitable and resilient enterprises. It involves several key indicators: annual income (the sum of profit and opportunity costs) and the return on investment index, which gauges profitability relative to initial investments. Persistence analysis, which estimates the average lifespan of aquaculture businesses based on their operational years, and the risk rate, which considers factors that may escalate the risk of failure or reduce profitability, are also crucial. These metrics collectively assess the economic viability and resilience of aquaculture farms, allowing stakeholders to gauge the efficiency of financial management within operations (Valenti et al., 2018). However, poor economic sustainability, characterized by high costs, inefficient payback periods, and low rates of return, can lead to significant financial losses (Hai and Speelman, 2020). Social sustainability concerns the benefits that aquaculture brings to local economies, including boosting employment opportunities and fostering sustainable job creation. This dimension is evaluated through indicators such as turnover rates, equitable income distribution, community-shared benefits, enhanced food security, attention to future generations' needs, workplace safety, access to health programs, and ensuring that workers have sufficient free time for educational and community activities (Brears, 2021). Higher social sustainability reflects a direct positive impact on the local community and contributes to the overall well-being and development of the area. Environmental sustainability focuses on the efficient use of resources and minimizing environmental damage. This includes the management of nonrenewable resources such as space, water, and energy, as well as nitrogen and phosphorus. The sustainability of these practices is jeopardized by high rates of production waste, including excess feed, chemicals, and pathogens, which contribute to increased carbon emissions and pollution (Chopin et al., 2012; Brears, 2021). Poor management practices can lead to significant risks, such as water contamination, which can trigger severe disease outbreaks, adversely affecting both livestock and farmers' economic stability (Ngoc et al., 2021). IMTA is heralded for its ability to create sustainable waste management systems that enhance economic and environmental sustainability through increased production efficiency, potential price premiums, and product diversification (Brears, 2021). These three dimensions form a robust framework for assessing the sustainability of aquaculture practices, enabling stakeholders to identify strengths and areas for improvement. By focusing on these diverse yet interconnected aspects, the aquaculture industry can strive toward a more sustainable and prosperous future, benefiting not only the economic landscape but also enhancing environmental stewardship and social welfare.

Vietnam boasts a vast coastline spanning 3,260 kilometers, an extensive sea surface area exceeding 220,000 square kilometers, and approximately 400,000 hectares of mangrove forests, positioning it as a significant player in global aquaculture. It ranks as the fourth-largest producer of aquatic products worldwide and the third-largest shrimp producer, with the aquaculture industry experiencing an impressive average annual growth rate of 12.77% (Tri et al., 2022). Aquaculture in Vietnam not only is a critical source of employment and foreign exchange but also enhances food security and living standards in rural areas, contributing significantly to local and national economies (Hanh et al., 2017; Nguyen et al., 2018; Xuan et al., 2021). Despite these achievements, Vietnam faces substantial environmental challenges; over the last five decades, it has lost approximately 80% of its mangrove forests, a stark indicator of habitat destruction and biodiversity loss (Ngoc et al., 2021). Additionally, pollution and inadequate wastewater management continue to plague the aquaculture sector, leading to increased disease incidence and livestock mortality rates. This is particularly evident in the lobster aquaculture sector, where disease outbreaks have led to severe financial losses estimated at $US 30 million annually since 2007, alongside growing concerns about food safety due to the excessive use of antibiotics (Hai and Speelman, 2020; Ngoc et al., 2021). In response to these challenges, the national aquaculture strategy emphasizes the development of shrimp aquaculture as a key economic pillar, with the aim of bolstering investment and fostering growth (Xuan et al., 2021). The government is actively promoting sustainable practices within the industry, particularly in the Quang Ninh coastal province, where aquaculture is vital to local livelihoods but faces obstacles such as climate change, poor seed quality, and limited access to capital.

This study focused on providing a thorough analysis of the current state of aquaculture in Quang Ninh by developing comprehensive sustainability indicators. These indicators help assess the environmental, economic, and social impacts of aquaculture and will be instrumental in identifying the types and scales of aquaculture practices prevalent in the region. This study examines the role of government policies, technological advancements, and stakeholder engagement in enhancing the sustainability of aquaculture practices. By accomplishing these objectives, this research aims to offer insightful recommendations on how to advance a sustainable and economically prosperous aquaculture sector in Quang Ninh, thus supporting the broader goals of national aquaculture development in Vietnam.

2. Methodology

2.1. Study area

Quang Ninh, a coastal province located in the Red River Delta of Vietnam, is well known for its extensive shrimp and fish farms. Its proximity to major cities such as the Hanoi capital city and Haiphong coastal city, along with its border with China, has facilitated the development of aquaculture trading and transportation (Hanh et al., 2017). The province features a diverse marine environment that extends more than 250 kilometers and includes important ecosystems such as mangroves, coral reefs, and seagrass beds. The numerous islands in the area create sheltered coves that protect aquaculture farms from strong winds and typhoons. Figure 1 shows that Quang Ninh Province includes 9 coastal and island districts (Mong Cai, Hai Ha, Dam Ha, Tien Yen, Van Don, Co To, Cam Pha, Ha Long, and Quang Yen) and houses more than 2,000 islands. It has an aquaculture land use area of 32,092 hectares, which encompasses 11,283 farms managed by 33 enterprises, 118 cooperatives, and 11,077 farmer households. The primary products are shrimp, mollusks, and marine fish. In 2023, aquaculture production in Quang Ninh was approximately 176 thousand tons, significantly boosting the provincial economy and enhancing international trade, particularly with China.

Quang Ninh Province is selected as a case study because of the multiple challenges its aquaculture sector currently faces. The province is emerging as a major contributor to Vietnam's seafood industry, showcasing potential not only to generate more jobs but also to widen the consumption of seafood products in markets, which in turn can enhance the overall socioeconomic development of the area. Additionally, economic progress in this sector has a positive effect on the country's national sovereignty and security. The fisheries sector in Quang Ninh is diverse, featuring a range of products, including whiteleg shrimp, sea cucumber, oyster, and various types of fish, such as shad, decapterus, grouper, and mackerel. This sector is vital for the local economy, as it significantly contributes to the livelihoods of people and to the growth of the provincial gross domestic product (GDP); notably, shrimp farming alone accounts for approximately 12% of the province's GDP (DAH, 2023). The strategic importance of Quang Ninh is underscored by its extensive borders, with approximately 120 kilometers of land and 191 kilometers of maritime boundary adjacent to China, making it a key gateway for the international trade of aquaculture products. However, the province is experiencing several adverse effects. Aquaculture production is characterized by low value added and fluctuations in the market, making it unstable. Additionally, the sector frequently clashes with other marine-utilizing industries, such as marine tourism and maritime transport. Environmental concerns also arise as aquaculture farms become sources of pollution that detrimentally affects the surrounding agricultural lands and households. Compounding these challenges is the issue of overfishing, which significantly reduces vital aquatic resources, thereby negatively impacting the sustainability and productivity of the aquaculture industry. Although Quang Ninh Province holds significant promise for boosting Vietnam's seafood output and improving socioeconomic conditions, it must navigate a complex array of challenges that threaten the sustainable development of aquaculture at both the sectoral and farm levels.

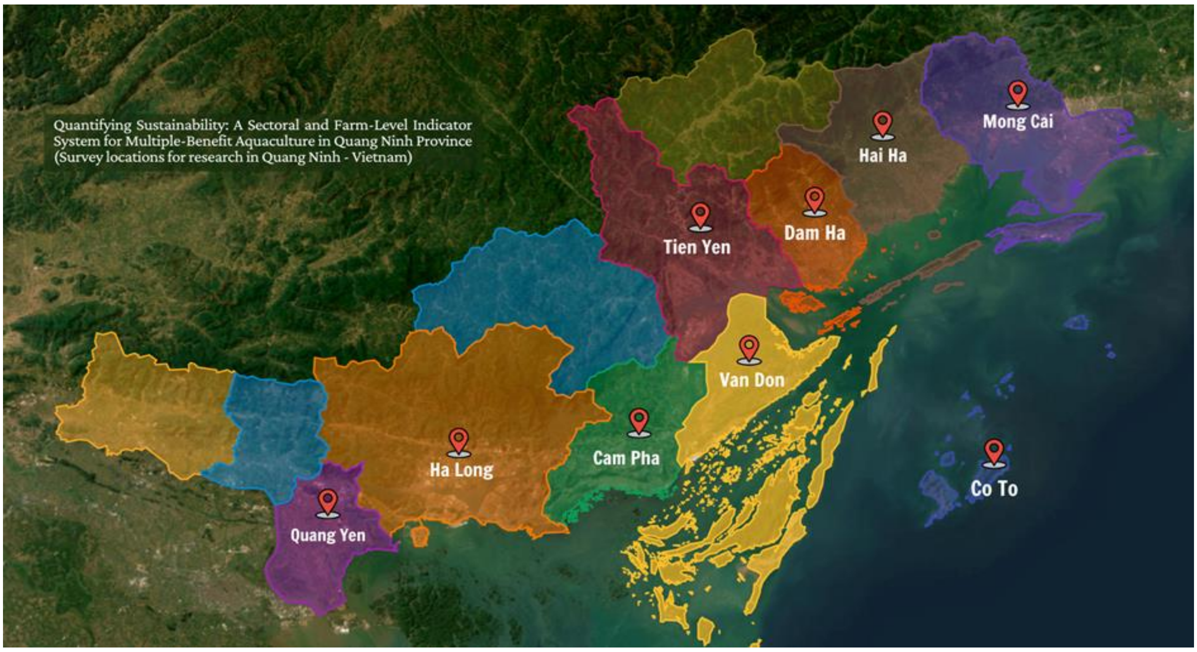

Figure 1 The location of 9 coastal and island districts in Quang Ninh Province, Vietnam.

2.2.1. Building the indicator system

The development of an indicator system for assessing the sustainability of aquaculture in Quang Ninh Province is thoughtfully designed to align with both local contexts and broader sustainability frameworks. The system's construction is influenced by established frameworks and recommendations from key studies, such as those by Rey-Valette et al. (2008, 2010) and Valenti et al. (2018), and it deeply integrates the principles of sustainable development as outlined in Agenda 21 (UN, 1992), which are specifically tailored to the needs and peculiarities of aquaculture. This comprehensive framework segregates sustainability into three principal dimensions: economic, social, and environmental. Each dimension is meticulously broken down into various indicators designed to measure and monitor sustainability effectively at both the individual farm and broader sector levels. For instance, farm-level indicators are directed at individual production units, which include diverse aquaculture practices such as oysters, shrimp, fish, Sipunculus nudus (peanut worm), and IMTA. Conversely, sector-level indicators aim to evaluate broader types of provincial aquaculture production, such as shrimp, mollusks, marine fish, and freshwater fish. This dual approach ensures a thorough analysis that captures both the microlevel operational details and macrolevel trends and impacts.

Figure 2 in the document illustrates a hierarchical tree of 29 sustainability indicators, which include 10 economic, 11 social, and 8 environmental indicators, each crafted to quantitatively assess the sustainability of aquaculture operations within Quang Ninh Province. Each indicator is clearly defined, and the levels of application (either sector-level 'S' or farm-level 'F') are specified to guide users on where and how each indicator should be applied. This hierarchical structure not only clarifies the applicability of each indicator but also facilitates an organized approach to sustainability assessment. Data collection for these indicators is meticulously planned: farm-level data are primarily gathered through questionnaires distributed to aquaculture farmers, providing insights directly from the ground. Meanwhile, data for sector-level indicators are derived from official documents and datasheets, which are supplied by both central and provincial governmental bodies. This methodological approach ensures that the sustainability assessments are both grounded in local realities and reflective of official statistics and records, thereby providing a robust and actionable dataset that can inform policy-making and strategic decisions aimed at enhancing the sustainability of the aquaculture sector in Quang Ninh.

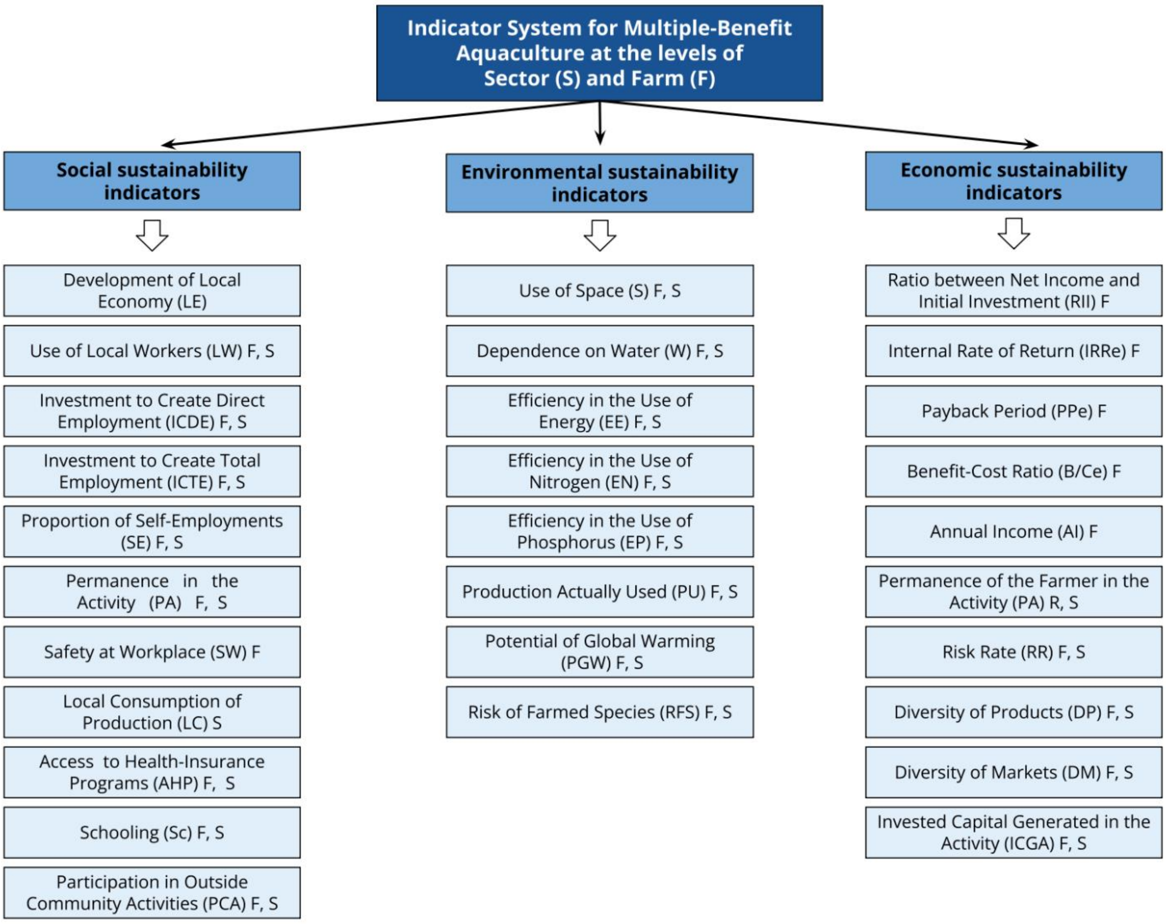

Figure 2 Hierarchical tree of indicators for aquaculture sustainability. (where S = sector-level indicators; F = farm-level indicators).

a) Economic sustainability indicators

1. Ratio between Net Income and Initial Investment (RII) F

This indicator measures the efficiency of the investment to an aquaculture project by showing how much profit is generated for each dollar invested initially:

RII = Net income/initial investment.

2. Internal Rate of Return (IRRe) F

This indicator indicates the annualized growth rate of an investment to an aquaculture project over its lifetime. A higher IRR suggests a more attractive investment:

$$\sum_{i=0}^{n} \frac{Bi - Ci + Epi - Eni}{(1 + IRR)^{i}} = 0$$

where B_i is the total benefit (or revenue) of year i; C_i is the total cost of year i (capital + operating costs); Ep_i is the total positive externalities; En_i is the total negative externalities; n is the number of years in operation, n ≥ 20; and i is the i^{th} year.

3. Payback Period (PPe) F

This indicator shows how long it takes to recover the initial investment from the project's cash flow. A shorter payback period implies quicker financial recovery from considered aquaculture project:

$$\sum_{i=o}^{j} NCF_{i} = 0$$

in which j is PP in years; NCF_i is the annual net cash flow of year i; i = 0, 1, 2... j... n, with n ≥ 20.

4. Benefit–Cost Ratio (B/Ce) F

This indicator compares the total benefits of an aquaculture project to its total costs. A B/C ratio greater than 1 indicates that the benefits outweigh the costs.

$$B/C = \frac{\sum_{i=o}^{n} \frac{Yi}{(1+r)^{i}}}{\sum_{i=o}^{n} \frac{K_i}{(1+r)^{i}}}$$

where Y_i is the net annual benefit of year; I = B_i − O_i + Ep_i – En_i; B_i is the total benefit (or revenue) of year i; O_i is the operating cost of year i; Ep_i is the total positive externalities; En_i is the total negative externalities; K_i is the capital outlay for assets of year i (initial investments + reinvestments); r is the discount rate; and n is the number of years in operation, with n ≥ 20.

5. Annual Income (AI) F

This indicator is a straightforward measure of the ongoing revenue generated by the aquaculture activity.
AI = GR – OC – D – T – F
where GR is gross revenue, OC is operating costs, D is depreciation, T is taxes, and F is fees.

6. Permanence of the Farmer in the Activity (PA) R, S

This indicator focuses on the long-term involvement of the person managing the aquaculture project. A longer permanence of the farmer in the activity suggests a sustainable activity that provides a livelihood.

$$PA = \sum_{i=o}^{n} \frac{Fi}{n}$$

where F_i is the number of years in operation of farm i, i = the i^{th} farm, and n is the total number of farms.

7. Risk Rate (RR) F, S

This indicator assesses the vulnerability of the aquaculture project to various economic risks. A lower economic risk rate indicates a more stable and sustainable activity.
RR = number of risk factors observed/number of risk factors analyzed
The economic risk rate includes 11 specific criteria that increase the economic risk of negative impacts on aquaculture: (a) lack of a business plan during the planning stage; (b) the owner/manager lacks technical or administrative capacity, or there is no trained staff; (c) administrative deficiencies in logistics and troubleshooting, such as neglecting emergency systems to prevent disruption of the electrical supply on farms that depend on electricity to operate equipment; (d) lack of a well-established market for the product, i.e., the producer needs to develop the market; (d) the farmer is installed at an inappropriate site, such as subject to flooding, drought or other climate constraints; urban, rural and industrial pollution; legal restrictions (e.g., environmentally protected area); (f) lack of technical support and/or extension services to improve

management and to solve problems, such as diseases, sanitary, economic and market issues; (g) lack of nocturnal and weekend supervision and/or surveillance and security systems against theft; (h) practice of intensive system, adding much material and energy and operating close to the carrying capacity of the system; (i) institutional instability: continual changes in laws and regulations by funding, regulatory and enforcement agencies; and

8. Diversity of products (DP) F, S

The number of products and services traded, such as the number of fish species, other agricultural products and/or services. An aquaculture project with a wider variety of products and services reduces reliance on a single source of income, making it more adaptable and resilient.

DP = {1, 2, 3, 4, 5, 6... n}

Where: n is the total number of aquaculture products and services traded.

9. Diversity of Markets (DM) F, S

The number of markets exploited by the aquaculture household or enterprise to trade the products and services, such as foreign markets (exportation), whole-sales, retailers, hotels, restaurants, farmers' markets, farm-gates (farm stands), and others. Selling aquaculture products across different markets reduces dependence on any single customer, contributing to long-term sustainability.

DM = {1, 2, 3, 4, 5, 6...n}

Where: n is the total number of aquaculture products and services traded.

10. Invested Capital Generated in the Activity (ICGA) F, S

This indicator refers to the reinvestment of profits back into the activity, which can be a sign of a sustainable aquaculture project growing organically.*ICGA = part of the investment generated in the activity/total investment.*

b) Social sustainability indicators

1. Development of Local Economy (LE) S

This indicator measures the positive influence of the aquaculture sector on the local economy:
LE = use of products and services from local markets ($)/total products and services used ($)

2. Use of Local Workers (LWs) F, S

This indicator reflects the aquaculture project's contribution to local employment opportunities.
LW = number of jobs generated that permit recruitment among the local population/total number of jobs generated

3. Investment to Create Direct Employment (ICDE) F, S

This indicator focuses on the financial resources dedicated to creating jobs directly within the aquaculture activity itself.
ICDE = investment/number of jobs generated

4. Investment to Create total employment (ICTE) F, S

This indicator expands the scope beyond direct employment to consider the indirect jobs created throughout the aquaculture supply chain.
ICTE = investment/number of jobs and self-employed jobs generated (direct + indirect)

5. Proportion of Self-Employments (SE) F, S

This indicator reflects the empowerment of individuals within the community to establish their own aquaculture-related businesses.
SE = number of self-employed jobs generated/total number of jobs generated

6. Permanence in the Activity (PA) F, S

This indicator is viewed from a social perspective, indicating job security and satisfaction for workers in aquaculture industry.
PA = average time spent by each worker in the aquaculture industry (in years)

7. Safety at work (SW) F

This indicator is crucial for ensuring the physical and mental well-being of employees in aquaculture farms.

SW = number of equipment pieces, actions, and practices that provide safety for workers available on the farm/number of analyzed equipment pieces, actions and practices that provide safety for workers

The following items should be analyzed when relevant: (a) use of life vests; (b) use of sunglasses; (c) use of protective goggles against mud, scale, and other uses; (d) use of pigmented gloves; (e) use of waterproof and antiskid boots; (f) use of protective clothing against sun or rain; (g) use of equipment to relieve physical stress; (h) use of proper lighting in the work area; (i) use of proper electrical and plumbing installations; (j) use of machines, equipment, implements, furniture, and tools that provide the employee with good posture, visualization, movement, and operation; (k) use of machines and equipment by a qualified professional; (l) use of protective lab coats (or common aprons) when indicated; (m) guarantee of rest breaks for activities that require standing; (n) first-aid kit, well equipped and easy to access; (o) signs indicating possible danger areas; (p) availability of fire extinguishers and other emergency equipment; and (q) training programs for workers to operate equipment properly.

8. Local Consumption of Production (LC) S

This indicator reflects how the aquaculture activity contributes to local food security and dietary needs.

LC = mass of product sold in the local market/total production

9. Access to Health-Insurance Programs (AHP) F, S

This indicator shows the aquaculture project's contribution to the healthcare of the workers and their families.

AHP = number of employees and owners with health insurance/total number of employees and owners

10. Schooling (Sc) F, S

This indicator reflects the aquaculture project's support for educational opportunities within the community.

Sc = number of employees that study/total number of employees

11. Participation in Outside Community Activities (PCA) F, S

This indicator measures the integration of the aquaculture project with the broader social fabric of the community.

PCA = number of workers participating in community activities/number of total workers

c) Environmental sustainability indicators

1. Use of Space (S) F, S

This indicator deals with the sea water area required to produce a specific amount of seafood. Lower space usage suggests a more efficient use of resources. This indicator measures the sea water area used (ha, sq. m) per unit of production (kg, t, units)

S = area used/production

2. Dependence on Water (W) F, S

This indicator quantifies the amount of water utilized per unit of production. Only water that is actually consumed should be taken into account. Water that is returned to the environment in a condition similar to when it was withdrawn is not considered consumed; however, if it is discharged from pollution, it should be regarded as consumed.

W = consumed volume/production

3. Efficiency in the Use of Energy (EE) F, S

This indicator reflects the amount of energy required to produce a unit of seafood. It considers energy used for operations, feed production, and transportation.

EE = energy recovered in production/energy applied

4. Efficiency in the Use of Nitrogen (EN) F, S

These indicators measure how efficiently these essential nitrogen nutrients are used in aquaculture. Excessive nitrogen release can contribute to water pollution.

EN = mass of nitrogen recovered in production/mass applied of nitrogen

5. Efficiency in the Use of Phosphorus (EP) F, S

These indicators measure how efficiently these essential phosphorus nutrients are used in aquaculture. Excessive phosphorus release can contribute to water pollution.

EP = mass of phosphorus recovered in production/mass applied phosphorus

6. *Production Actually Used (PU) F, S*

This indicator refers to the amount of produced seafood that is actually consumed. Higher PU indicates efficient utilization of resources.

PU = mass of unused portions of the farmed organism/total mass produced

7. *Potential of Global Warming (PGW) F, S*

This indicator assesses the contribution of aquaculture to greenhouse gas emissions (GHGs), particularly GHGs from some types of aquaculture.

PGW = Load of greenhouse-effect gases released to the atmosphere/mass or units produced

Greenhouse gases = mass of CO_2 + CH_4 + N_2O, measured in CO_2 equivalents

8. *Risk of Farmed Species (RFS) F, S*

This indicator addresses the potential environmental risks associated with the farmed species itself.

RFS = {1, 2, 3, 4, 5, 6 or 7}

The risk of farmed species consist of 7 specific criteria that increase the risk of negative impacts on aquaculture: 1 = Local strain farmed in an open or closed system; 2 = Species within the same basin (but not local strain) farmed in a closed system; 3 = Species within the same basin farmed in an open system; 4 = Allochthonous species, native species with reduced genetic variability, or hybrid (native or allochthonous species) farmed in a closed system; 5 = Allochthonous species, native species with reduced genetic variability, or hybrid (native or allochthonous species) farmed in an open system; 6 = Transgenic variety of any species farmed in a closed system; 7 = Transgenic variety of any species farmed in an open system.

2.2.2. Data collection

The questionnaire for this study is meticulously designed with 90 detailed questions aimed at assessing key sustainability indicators across economic, social, and environmental aspects. These indicators apply to various aquaculture practices, including the farming of oysters, shrimp, fish, and Sipunculus nudus and within Integrated Multi-Trophic Aquaculture (IMTA) systems. Before deployment, the questionnaire underwent a thorough validation process with the help of experienced aquaculture experts. Their feedback ensured that the questions were both relevant and precise and crucial for gathering data that accurately reflected the current sustainable practices and challenges in aquaculture in Quang Ninh Province.

The data are collected through face-to-face interviews, chosen for their ability to foster detailed, personal interactions with the respondents. Conducted by a research team from VNU University of Economics and Business, Vietnam, with the support of a provincial project in Quang Ninh Province, these interviews targeted aquaculture farmers across nine coastal and island districts. The interview schedule is strategically divided into two phases, in November 2023 and January 2024, to accommodate the seasonal activities and availability of the farmers.

The effectiveness of the interviews is greatly enhanced by the participants' readiness to share their experiences and insights. This openness allows researchers to gain a deeper understanding of participants' practices. Typically, each interview lasted between 30 and 45 minutes, giving researchers sufficient time to explore the qualitative aspects of aquaculture practices.

The outcome of these interviews is a comprehensive dataset consisting of 189 satisfactory responses. These responses are carefully organized by region and species, facilitating an analysis that highlights regional differences and trends in aquaculture practices. Additionally, the data collected included visual and audio recordings, expanding beyond traditional questionnaire responses. These multimedia elements are systematically sorted by region and species, enhancing both the depth and scope of the analysis.

This rich and varied dataset provides both a quantitative and qualitative overview of current practices and forms a crucial basis for further academic research and the development of policies aimed at enhancing sustainability in aquaculture. Such detailed information is essential for stakeholders who are interested in understanding the nuances of sustainable practices and who are committed to supporting the long-term health of the aquaculture industry.

3. Results

3.1. Building indicators

3.1.1. Sustainability of aquaculture at the sector level

Table 1 shows that total aquaculture production in Quang Ninh will increase from 124,000 tons in 2018 to 175,324 tons in 2023, representing an average annual growth rate of 7.2%. This growth comprises a 2.7% annual increase in capture fisheries and a more substantial 9.5% annual increase in aquaculture production. The aquaculture zones expanded both in scale and output, with the total farming area growing by 11,347 hectares to reach 32,092 hectares in 2023.

The province supports 16 breeding and supply facilities that contribute approximately 3 billion seeds annually to both local and external markets. There has been a strategic shift in the fishing fleet, which now totals 5,556 vessels, moving away from nearshore fishing practices to optimize operations. By 2023, the aquaculture landscapes in Quang Ninh featured 11,283 farming facilities, including a mix of enterprises, cooperatives, and individual households. The aquaculture sector now meets 37.4% of the local demand for on-site breeding stocks. Significant investments have been made in the infrastructure for breeding and concentrated aquaculture, aiming to strengthen key development areas.

Table 1 Assessment of the sustainability of the aquaculture sector in Quang Ninh Province in 2023.

Indicators (unit)	2018	2023	Average Annual Growth (%/year)
Total Production (tons)	124,000	175,324	7.2
Capture Production (tons)	80,000	81,609	2.7
Aquaculture Production (tons)	44,000	93,716	9.5
Aquaculture Area (hectares)	20,745	32,092	6.3
Number of Aquaculture Facilities	8,101	11,283	4.0
Aquaculture Yield (tons/hectare)	2.1	2.9	4.3

During this period, the aquaculture sector in Quang Ninh Province adopted numerous advanced farming technologies and environmentally friendly materials conducive to sustainable growth. The introduction of high economic value species such as cold-resistant shrimp, pomfret, and seaweed leads to increased productivity, volume, and product value. By 2023, aquaculture production will account for 53.5% of the total, achieving an average yield of 2.9 tons per hectare, marking a 9.7% average growth rate from 2018 to 2023. Despite a reduction in the labor force, the transition toward semi-intensive and intensive farming methods covered 21.5% of the farming area, highlighting a significant shift in production methods, although traditional farming practices remained predominant, covering 78.5% of the area. The aquaculture sector not only experiences growth in production and area but also makes commendable strides toward integrating sustainable practices and technologies, setting a benchmark for responsible aquaculture development.

Aquaculture in Quang Ninh Province shows a dynamic trajectory of growth and diversification, marking a significant footprint in Vietnam's aquaculture industry. As of 2023, advancements in technology, sustainable practices, and strategic species selection have positioned the province at the forefront of the aquaculture sector. Table 2 details the contributions of subsectors such as shrimp, mollusk, marine fish, and freshwater aquaculture to both the local economy and the broader national aquaculture landscape in 2023.

Shrimp Farming: The area dedicated to shrimp farming, which encompasses the cultivation of both white-leg shrimp and black tiger shrimp, totals 7,500 hectares. This expanse represents 10% of the national shrimp farming area, which itself covers 747,761 hectares across the country. Within these 7,500 hectares, a significant portion, 4,700 hectares, is utilized for industrial shrimp farming. This type of farming is quite productive, yielding a total of 24,876 tons of shrimp. This production accounts for 14.2% of the total aquaculture output within the province and contributes 2.3% to the national shrimp production, which is 1,014,877 tons. Furthermore, the average yield of shrimp farming in this region is calculated at 3.3 tons per hectare, indicating a robust level of productivity in the utilized farming practices.

Mollusk Farming: The total area dedicated to mollusk farming in coastal river mouths and sea surfaces has reached 9,500 hectares, marking a significant expansion of 6,222 hectares since 2013. This considerable growth highlights increasing interest and investment in mollusk cultivation in these areas. Similarly, the production of mollusks has substantially increased, with current values reaching 42,465.5 tons, an impressive increase of 27,143.5 tons from the 2013 production levels. The average yield from these farming efforts now exceeds 4.47 tons per hectare, demonstrating the efficiency and productivity of the farming techniques employed. The primary species cultivated in these regions include clams, mussels, river oysters, and Pacific oysters. The methods used for farming these species are diverse, encompassing rafts, hanging cages, and tidal flat farming techniques, each chosen based on environmental suitability and species requirements. These techniques are well suited to coastal and river mouth habitats, leveraging natural aquatic conditions to foster mollusk growth. This type of aquaculture is predominantly focused in specific regions, notably in the island district of Van Don and the four coastal districts of Dam Ha, Hai Ha, Quang Yen, and Mong Cai. These areas are key centers for mollusk farming and contribute significantly to overall production. The strategic focus on these districts highlights their optimal conditions for mollusk farming and their importance to the regional aquaculture industry. This targeted development in these areas not only boosts local economies but also plays a crucial role in meeting both domestic and international demand for various mollusk species.

Marine Fish Farming: The area allocated for marine fish farming currently spans 2,208 hectares, containing a substantial total of 15,000 cages. This represents significant growth in infrastructure, with an increase of 6,687 cages since 2018. This expansion highlights the growing investment and development in the aquaculture sector, specifically in marine fish cultivation, reflecting both increased capacity and enhanced farming techniques over the last few years. This specific type of aquaculture is concentrated in the regions of Van Don, Dam Ha, Hai Ha, and Cam Pha. These areas are strategically chosen for their suitable marine environments that support the optimal growth and health of marine fish species. Geographical selection is crucial because it ensures that the conditions—ranging from water quality to habitat complexity—are ideal for the species being farmed. The primary species cultivated on these marine farms include snappers, groupers, and pompanos. These species are particularly valued for their commercial and culinary demand, both locally and internationally. The total production from these efforts reached 12,980.7 tons, indicating a robust yield and successful cultivation practices. This level of production not only meets significant portions of local and national seafood demand but also supports the livelihoods of many people involved in the aquaculture industry within these districts. The focus on these specific species and regions demonstrates a targeted approach to aquaculture that aligns with market demands and environmental capabilities, ensuring sustainable growth and productivity in the sector. This strategic development is instrumental in bolstering the aquaculture industry, enhancing food security, and providing economic benefits through the export and local sale of high-value fish species.

Freshwater Aquaculture: The area designated for freshwater aquaculture now extends to 2,501 hectares, demonstrating a consistent focus on expanding and enhancing this sector within the aquaculture industry. This expansion facilitated a production output of 9,000 tons, marking an increase of 394 tons since 2018. Such growth is indicative of both improved farming techniques and increased capacity across the sector. The average yield from these freshwater farms is now over 3.6 tons per hectare, reflecting a significant productivity rate that underscores the efficiency of current aquaculture practices. Within this sector, the primary species being farmed include mono-sex tilapia and a variety of traditional freshwater species, such as carps, mullets, and catfish. These species have long been common in freshwater aquaculture due to their resilience, adaptability to different farming environments, and strong market demand. The cultivation of these plants continues to form the backbone of freshwater aquaculture production. In addition to these traditional species, there has been a strategic shift toward the cultivation of high economic value species that offer greater profitability margins. This includes the farming of soft-shell turtles, frogs, wild roaches, and notably, cold-water fishes such as salmon and sturgeon. The inclusion of these species is a response to evolving market demands and an attempt to diversify aquaculture production toward more niche and luxury seafood products. The development of aquaculture for such high-value species not only taps into premium market segments but also encourages the adoption of advanced farming technologies and methods. These methods are essential for meeting the specific environmental needs of sensitive species such as salmon and sturgeon, which require colder water temperatures and specific water quality parameters to thrive. This strategic diversification and expansion in freshwater aquaculture underscore the industry's adaptability and responsiveness to both market trends and environmentally sustainable practices. By broadening the range of species farmed and improving yields, the sector is well positioned to continue its growth trajectory, contributing significantly to food security, economic development, and the livelihoods of those dependent on aquaculture.

Table 2 Assessment of the sustainability of aquaculture farming types in Quang Ninh Province in 2023.

Category	Area(ha)	Production (tons)	Yield (tons/ha)	Notes
Shrimp Farming	7,500	24,876	3.3	Accounts for 2.3% of the country's total shrimp production
Mollusk Farming	9,500	42,465.5	>4.47	Increased by 6,222 ha compared to 2013
Marine Fish Farming	2,208	12,980.7	5.89	Increased by 6,687 cages compared to 2018
Freshwater Farming	2,501	9,000	>3.6	Increased by 394 tons compared to 2018

3.2. Sustainability of aquaculture at the farm level

3.2.1. Economic sustainability

The assessment of economic sustainability for various types of aquaculture in Quang Ninh covers four distinct categories: shrimp, fish, Sipunculus nudus, and IMTA. According to the data presented in Table 3, IMTA exhibited the most favorable economic indicators. It boasts the highest ratio of net income to initial investment at 2.59, suggesting that it yields significant returns for every unit of money invested. This is complemented by a high internal rate of return (IRR) of 62.74%, which underscores the profitability of IMTA over time. Furthermore, the benefit–cost ratio (BCR) of 1.505 confirms the economic benefits of this type of aquaculture. Despite these robust economic figures, the annual income for IMTA stands at a moderate figure of 21.04, indicating that while investment returns are high, the absolute annual income is less impressive compared to other types.

Shrimp farming, on the other hand, is associated with greater economic risk, reflected by a 50% risk rate, which points to a volatile market environment. An IRR of 48.11% was recorded, indicating that when successful, shrimp farming cycles can be extremely profitable. However, its benefit–cost ratio is relatively low at 0.204, and it also has the lowest annual income at

8.00. This makes shrimp farming an appealing yet risky choice for investors who are prepared to deal with significant market fluctuations for the chance of substantial profitability.

Fish farming is characterized by a strong economic profile, with a high net income to initial investment ratio of 1.74 and the highest IRR among the non-IMTA sectors at 56.47%. It also boasts the highest annual income at 207.14 and maintains a healthy benefit–cost ratio of 0.603, suggesting that fish farming is both lucrative and sustainable. The moderate risk rate of 30% highlights the importance of diligent market analysis and risk management in maximizing profitability.

Although less common, Sipunculus nudus farming has a promising economic perspective, with a net income to initial investment ratio of 1.93 and an IRR of 44.98%. Its benefit–cost ratio is 1.108, indicating favorable returns, although the annual income is somewhat lower at 9.12 due to its limited market scope. A moderate risk rate of 20% implies that while price stability is generally better than that in shrimp farming, vigilance is still necessary.

Overall, the results suggest that aquaculture in Quang Ninh Province presents a diverse array of economically sustainable options, with particularly high returns from IMTA and fish farming. Shrimp farming, despite its inherent market volatility, offers a 'high risk, high reward' scenario that could result in significant profits under optimal conditions. Sipunculus nudus represents a stable, if moderate, investment opportunity, potentially broadening the scope of the province's aquaculture portfolio. This diversity underscores the region's ability to leverage aquaculture as a key component of its economic development strategy.

Table 3 Indicators of economic sustainability for aquaculture in Quang Ninh Province (unit: tons/hectare/VND, with 25,000 VND = 1$).

Indicators	Value				
	Oyster	Shrimp	Fish	Sipunculus nudus	IMTA
Ratio between Net Income and Initial Investment	1.20	1.02	1.74	1.93	2.59
Internal Rate of Return	38.12%	48.11%	56.47%	44.98%	62.74%
Payback Period	5.00	5.00	5.00	5.00	5.00
Benefit–Cost Ratio	0.181	0.204	0.603	1.108	1.505
Annual Income	43.91	8.00	207.14	9.12	21.04
Diversity of Markets	3.00	3.00	3.00	3.00	3.00
Diversity of Products	2.00	2.00	2.00	2.00	2.00
Permanence of the Farmer in the Activity	10.00	15.00	15.00	20.00	20.00
Risk Rate (Price)	20%	50%	30%	20%	10%
Invested Capital Generated in the Activity	90.00	90.00	90.00	90.00	90.00

3.2.2. Environmental sustainability

The assessment of environmental sustainability across various aquaculture practices, including those involving oysters, shrimp, fish, Sipunculus nudus, and IMTA, incorporates multiple indicators, as outlined in Table 4. One critical indicator, the "use of space," shows significant variation among the farming methods. IMTA systems are noted for their comparatively lower space usage, scoring 30, in contrast to oyster farming, which scores significantly higher at 166.6. This disparity indicates that IMTA, through its integrative approach of cocultivating multiple species, may more efficiently utilize the available aquaculture space, potentially reducing the ecological footprint of such operations.

Another key indicator, "Efficiency in the Use of Nitrogen and Phosphorus," remained consistent at 15% across all species. This uniformity suggests a standard practice of nutrient management within the region's aquaculture practices. However, this also points to an opportunity for improvement—tailoring nutrient management strategies specifically for each species could increase efficiency and reduce the environmental impact of these nutrients.

The "Potential of Global Warming" impact is another crucial environmental indicator that varies significantly among the species analyzed. Fish aquaculture has a lower potential impact, with a value of 3.75, indicating a lesser contribution to global warming. In contrast, Sipunculus nudus exhibited the highest value at 7.75, suggesting a greater environmental impact. This variance highlights the importance of considering global warming potential when evaluating the sustainability of different aquaculture practices.

Regarding the "Risk of Farmed Species," shrimp aquaculture is identified as carrying the highest risk, rated at 2.00. This elevated risk level is likely due to the high sensitivity of shrimp to changes in environmental parameters and their susceptibility to diseases. Conversely, IMTA systems are associated with a moderate risk level of 0.50. The diversified nature of IMTA, which involves incorporating multiple species into a single farming operation, likely contributes to a more resilient system that can buffer against the impacts of disease and environmental fluctuations.

Overall, there is scope for enhancement, particularly in terms of optimizing space utilization and reducing the risks associated with monoculture farming. IMTA systems have emerged as a particularly promising model, offering notable advantages in terms of environmental impact reduction and risk mitigation. Such systems could serve as a model for future aquaculture practices, aiming for a balance between productivity and environmental responsibility.

Table 4 Indicators of environmental sustainability for aquaculture in Quang Ninh Province (Unit: tons/hectare/VND, with 25,000 VND = 1$).

Indicators	Value				
	Oyster	Shrimp	Fish	Sipunculus nudus	IMTA
Use of Space	166.60	156.7	50.00	10.00	30.00
Dependence on Water	0.00	0.00	0.00	0.00	0.00
Efficiency in the Use of Energy	0.00	0.00	0.00	0.00	0.00
Efficiency in the Use of Nitrogen (%)	15	15	15	15	15
Efficiency in the Use of Phosphorus (%)	15	15	15	15	15
Production Actually Used	0.00	0.00	0.00	0.00	0.00
Potential of Global Warming	6.25	5.75	3.75	7.75	3.25
Risk of Farmed Species	1.00	2.00	0.28	0.28	0.50

3.2.3. Social sustainability

The assessment of social sustainability indicators across various aquaculture practices, including oysters, shrimp, fish, Sipunculus nudus, and IMTA, reveals the consistent application of local economic development strategies. Each species scored a value of 1.00, indicating a uniform approach to strengthening local economies across different aquaculture forms.

Labor utilization remains consistent, underscoring the sector's commitment to engaging and employing the local community. However, the level of investment in creating direct employment varies greatly among the different species. Oyster farming, for instance, demands the most investment, with a value of 1019.52, reflecting its labor-intensive nature. On the other hand, Sipunculus nudus cultivation requires the least investment, at 147, indicating less labor-intensive operations or smaller-scale practices.

The range of self-employed individuals in these sectors varies from 0.09 to 0.19, with IMTA and fish farming showing the highest figures. This suggests more opportunities for entrepreneurship within these systems, potentially leading to greater individual economic stability and innovation in aquaculture practices. Additionally, the permanence of activity also shows variability, with fish farming exhibiting the longest duration at 10:00, which could imply a more stable and sustainable livelihood for those involved in this sector.

Workplace safety varies, with shrimp farming achieving the highest value of 0.68. This could either reflect more robust safety protocols or inherently less hazardous conditions compared to other forms of aquaculture. Furthermore, the local consumption of production received full scores for Sipunculus nudus and IMTA, demonstrating a strong connection between local production and consumption. This not only supports local food systems but also plays a crucial role in minimizing supply chain emissions.

All forms of aquaculture reported full access to health insurance programs, showcasing the industry's commitment to worker welfare. Nevertheless, the uniform lack of schooling opportunities, scored at 0.00 across all species, represents a significant deficiency. Addressing this gap is essential for improving the educational prospects of those involved in the sector.

Community engagement levels, as measured by participation in outside community activities, were found to be moderately low, ranging from 0.05 to 0.07. While this shows some level of involvement, there is room for improvement in fostering stronger community ties and resilience.

Overall, the results illuminate the complex social dynamics within aquaculture practices and underscore significant areas for enhancing social sustainability. While there are notable successes in economic contributions and healthcare provisions, opportunities exist to bolster education and community involvement, which are vital for a more sustainable and integrated approach to aquaculture.

3.3. Sensitivity Analysis

In every scenario within the aquaculture sector, revenue and costs are pinpointed as fundamental elements that significantly influence the economic sustainability of projects. These financial factors are crucial because they directly affect profitability, the ability to reinvest, and the overall financial health of aquaculture operations. Therefore, operators must prioritize meticulous management of these factors. This involves not only monitoring but also strategically manipulating both revenue and costs to ensure the optimal performance and sustainability of their ventures. Enhancing revenue might include diversifying product lines, improving product quality to attract premium prices, expanding into new markets, or leveraging marketing techniques to increase sales volume. Additionally, operators can explore partnerships or certifications that can add value to their offerings and attract a broader customer base.

On the cost side, minimizing expenses without compromising quality is essential. This could involve adopting more efficient technologies, optimizing feed conversion ratios, reducing energy usage, and streamlining operations to reduce waste. Effective cost management also involves regular reviews of supply chain logistics and negotiations with suppliers to secure better prices or terms. Operators should be prepared to adapt their strategies in response to changes in the market environment or regulatory landscape. This proactive approach involves continuous learning and adaptation to new techniques and technologies that can drive both cost efficiency and revenue growth. For aquaculture ventures to thrive and sustain in the long term, a balanced approach to managing both revenue enhancement and cost reduction is needed. By focusing strategically on these areas, operators can build robust businesses that not only survive but also prosper in the competitive aquaculture industry.

Table 5 Indicators of social sustainability for aquaculture in Quang Ninh Province (unit: tons/hectare/VND with 25,000 VND = 1$).

Indicators	Value				
	Oyster	Shrimp	Fish	Sipunculus nudus	IMTA
Development of Local Economy	1.00	1.00	1.00	1.00	1.00
Use of Local Workers	1.00	100	1.00	1.00	1.00
Investment to Create Direct Employment	1019.52	769.34	493.17	147.00	162.78
Investment to Create Total Employment	637.20	572.13	269.86	111.8	184.45
Proportion of Self-Employments	0.13	0.15	0.18	0.09	0.19
Permanence in the Activity	6.00	8.00	8.00	10.00	7.00
Safety at Workplace	0.47	0.68	0.66	0.35	0.74
Local Consumption of Production	0.08	0.09	1.00	1.00	1.00
Access to Health-Insurance Programs	1.00	1.00	1.00	1.00	1.00
Schooling	0.00	0.00	0.00	0.00	0.00
Participation in Outside Community Activities	0.07	0.06	0.06	0.05	0.05

Table 6 presents the results of a sensitivity analysis for aquaculture farms in Quang Ninh Province.

**** Sensitivity of Oyster Farming***

Considering the financial stability of oyster farming, it becomes evident that revenue is a crucial factor that has a significant impact on the NPV of the project. Specifically, a 10% reduction in revenue can lead to a sharp decline in NPV, which can even become negative under certain circumstances. This situation becomes more pronounced if, alongside the decrease in revenue, there is also a 10% increase in operating costs. Under such dual pressure, the profitability of oyster farming is severely compromised, potentially rendering the operation economically unviable.

This financial dynamic underscores the high sensitivity of oyster farming projects to fluctuations in revenue. Given this sensitivity, revenue is identified as the most critical factor affecting the overall effectiveness and sustainability of such ventures. Therefore, a meticulous analysis of this factor is essential when assessing the viability of oyster farming operations. Understanding the potential impact of revenue changes helps in identifying risk factors that could threaten the financial health of the project.

In light of this, oyster farm operators are advised to prioritize strategies that focus on both increasing revenue and reducing costs. Increasing revenue could involve diversifying the product range, enhancing product quality to cater to premium markets, or implementing more effective marketing strategies to expand the customer base. On the other hand, reducing costs might involve optimizing feed efficiency, improving operational efficiencies, or adopting new technologies that decrease labor and maintenance costs.

By taking a proactive approach in managing these key areas, operators can better cushion their ventures against financial instabilities and ensure a more robust economic outlook for their oyster farming operations. This dual strategy not only helps in mitigating risks due to revenue fluctuations but also enhances overall project sustainability and profitability.

When there is a decrease of 10% in revenue or when both revenue decreases and operating costs increase by 10%, the NPV experiences a significant decline, potentially transitioning into negative territory. This suggests that oyster farming may become economically unviable under such circumstances. Revenue emerges as the most sensitive factor influencing project effectiveness. Hence, thorough scrutiny of this factor is imperative when evaluating the feasibility of oyster farming. Operators need to prioritize implementing strategies aimed at boosting revenue while simultaneously curbing costs to ensure the sustainability and profitability of oyster farming endeavors.

**** Shrimp Farming***

Like in oyster farming, shrimp farming projects also face significant financial vulnerability under certain economic conditions. A 10% decrease in revenue alone, or combined with a 10% increase in operating costs, leads to a sharp decline in NPV. This downturn can even result in a negative NPV, thereby making the shrimp farming project economically unfeasible. This pattern highlights the critical importance of revenue as a key sensitivity factor in the economic viability of shrimp farming. Given this dynamic, it is essential for shrimp farming operations to undertake meticulous analysis of revenue streams and to pay close attention to operational strategies. By doing so, they can work toward improving financial outcomes, ensuring that the project remains viable and can withstand fluctuations in cost and income. Implementing effective measures to either enhance revenue or efficiently manage and possibly reduce operating costs can significantly mitigate the risks associated with these economic pressures.

**** Fish Farming***

In the case of fish farming, encountering a 10% decrease in revenue, a 10% increase in costs, or both scenarios occurring concurrently leads to a significant reduction in the NPV. However, the impact, while notable, does not render the NPV negative. This distinction is crucial because unlike oyster and shrimp farming, fish farming maintains economic viability even under these stressful financial conditions. The NPV remaining positive under such scenarios suggests that fish farming has a resilient economic structure that can absorb financial shocks better than some other types of aquaculture.

Given this resilience, both revenue and costs emerge as critical sensitivity factors in the economic analysis of fish farming. These factors demand detailed scrutiny and strategic management to ensure that the operation remains profitable despite potential financial adversities. It is essential for operators not only to understand these economic levers but also to actively engage in practices that optimize these elements.

Strategic management might involve enhancing operational efficiency, innovating in fish farming techniques, exploring premium markets for higher revenue streams, or managing input costs more effectively. By focusing on these areas, operators can safeguard their operations against downturns in revenue or spikes in costs, thereby sustaining profitability even when economic conditions are less than ideal.

**** Sipunculus Nudus Farming***

Similar to fish farming, Sipunculus nudus farming demonstrates a degree of economic resilience when faced with financial pressures. A 10% reduction in revenue, a 10% increase in costs, or the occurrence of both of these events concurrently can have a substantial impact on the NPV of such farming projects. However, even with these financial strains, the NPV does not dip into negative territory. This resilience indicates that Sipunculus nudus cultivation maintains its economic viability even under challenging conditions.

Given this context, it becomes critical for operators to pay close attention to both revenue generation and cost management. Effective revenue management might involve strategies such as exploring new markets, improving product quality to command higher prices, or enhancing marketing efforts to increase sales. On the cost management side, operators could look at optimizing feed efficiency, reducing energy consumption, or negotiating better terms with suppliers.

By focusing on these areas, operators can help ensure the continued effectiveness and profitability of their Sipunculus nudus farming projects. The dual focus on maintaining or increasing revenue while carefully controlling expenses is essential for sustaining operation through economic fluctuations and for capitalizing on the inherent economic robustness of this type of aquaculture.

**** IMTA Farming***

In the case of the IMTA system, experiencing a 10% decrease in revenue or a 10% increase in operating costs—especially when both occur simultaneously—leads to a noticeable reduction in the NPV. However, despite this decrease, the NPV remains positive, which signifies that IMTA farming is still economically viable and potentially profitable under such stressed financial conditions.

The resilience of IMTA's NPV under these circumstances highlights the intrinsic economic strengths of this farming approach. IMTA involves the simultaneous cultivation of multiple interdependent species from different trophic levels of the ecosystem, which can optimize resource efficiency and reduce waste. This complexity, however, also makes IMTA more sensitive to fluctuations in revenue and costs than single-species farming systems.

Given this sensitivity, it is crucial for operators to undertake thorough financial planning and management. This should include detailed analysis of both revenue streams and cost structures. Understanding the specific factors that influence revenue, such as market demand for the various species grown, pricing strategies, and effective marketing techniques, is essential. Similarly, a careful review of the main cost drivers, including feed costs, labor, and system maintenance, is necessary to identify areas where efficiencies can be improved.

Effective management in IMTA also involves being proactive about market conditions and potential environmental impacts that could affect productivity and costs. Operators should consider strategies such as diversifying species to hedge against the failure of any single crop, enhancing system designs for energy efficiency, and investing in technology that can improve yield and quality across different species.

Therefore, to ensure the sustainability and profitability of IMTA farming, operators must focus on both meticulous financial analysis and strategic operational management. This dual approach will enable them to navigate the complexities of IMTA farming and capitalize on its unique benefits while mitigating the risks associated with its sensitivities to market and operational variables.

Table 6 Sensitivity analysis for aquaculture farms in Quang Ninh Province, Vietnam. (unit: 25,000 VND = 1$).

Farms	Oyster		Shrimp		Fish		Sipunculus nudus		IMTA	
	NPV (VND)	Switching % NPV	NPV (VND)	Switching % NPV	NPV (VND)	Switching % NPV	NPV (VND)	Switching % NPV	NPV (VND)	Switching % NPV
(o) Original value	5102.97	100%	6780.81	100%	17882.96	100%	1086.62	100%	2687.13	100%
(i) Decrease in gross benefits by 10%	1511.79	70,38%	2629.48	61.22%	12869.91	28.03%	865.64	20.34%	2220.32	17.37%
(ii) Increase in total cost by 10%	2022.09	60,38%	3307.56	51,22%	14658.20	18,03%	974.30	10.34%	2489.03	7.37%
(iii) Decrease in gross benefits 10%and increase in total cost 10%	-1713.52	100,34%	-972.96	100,14%	8018.41	55.16%	631.83	41.85%	1755.26	34.68%

4. Discussions

The study's findings delve into the sustainability of aquaculture at both the sectoral and farm levels along the Quang Ninh coast of Vietnam, particularly examining the dynamics between IMTA and traditional mono-aquaculture practices. Specifically, it looks at their respective impacts and outcomes. Shrimp farming, a major activity spanning from Tien Yen to Mong Cai, covers approximately 4,480 hectares, which constitutes approximately 56.2% of the area designated for shrimp cultivation. Although this segment of aquaculture has proven to be highly profitable, it is not without its significant challenges; notably, the risks associated with disease outbreaks that manifest as sudden death and body discoloration among shrimp. Compounding the issues within the sector is the practice of using untreated wastewater. This not only contributes to environmental pollution but also complicates disease management, as the same contaminated water becomes a vector for recurring outbreaks across multiple farming cycles. In attempts to control losses, especially during peak seasons, there has been a marked increase in the use of pesticides and antibiotics among shrimp farmers. This practice underscores a critical knowledge gap, as many operators in Quang Ninh are potentially unaware of the specific regulations governing the use of permissible antibiotics in aquaculture, as noted by Chi et al. (2017). Consistent with this observation, Xuan and Sandorf (2020) suggested that when selecting advanced farming methods, farmers tend to prioritize factors that yield immediate success, often at the expense of long-term sustainability and compliance. Disease management remains a dominant concern for 65% of shrimp farmers, with other significant issues such as water pollution and seed quality being major concerns for 13% and 9% of farmers, respectively. Data from 2015-2016 highlight that diseases and climate change affect 8% and 10% of the total shrimp farming area, respectively, underscoring the vulnerability of this sector to environmental factors (DAH, 2017). Given these challenges, it is crucial to prioritize the selection of high-quality seeds and to integrate scientific and technological advancements into production processes to enhance both yield and disease resistance. Moreover, providing support to shrimp farmers—through access to capital, skill acquisition in modern aquaculture techniques, and assistance in implementing these advancements—is essential for nurturing a resilient and sustainable shrimp farming industry in Quang Ninh. This comprehensive approach not only aims to mitigate immediate issues but also fosters long-term sustainability and profitability within the aquaculture sector.

Although oyster farming in Quang Ninh does not yield profits as high as those of other aquatic species, it provides a steady and reliable source of income for local farmers. This form of aquaculture is characterized by a low-risk model that primarily necessitates investment in cages and capitalizes on the natural breeds available in the surrounding environment, which helps reduce the overhead costs associated with breeding. However, there have been increases in investment costs associated with oyster farming, particularly due to new requirements for using high-density polyethylene (HDPE) floats. This shift from traditional foam floats to HDPE is driven by a need to enhance both environmental protection and the quality of the product. HDPE floats are recognized for their durability and reduced environmental impact, as they do not degrade into harmful microplastics as traditional foam does. Quang Ninh has been at the forefront of this significant transition. According to a recent study by Trang et al. (2023), 88% of the buoys used in oyster farming in the province have been replaced with HDPE alternatives. While these new buoys are more expensive—they cost 3 to 4 times more than their foam counterparts—the provincial government is actively supporting this change. The commitment to deploying HDPE buoys in oyster farming underscores the need for a broader strategy to ensure the sustainable development of the local aquaculture industry. This initiative not only reflects an adherence to more environmentally friendly practices but also represents a long-term investment in enhancing the quality of the aquaculture products. When the initial costs are higher, the benefits of switching to HDPE include greater buoyancy, reduced maintenance costs, and a lower environmental footprint, which contribute to the sustainability and eventual profitability of aquaculture operations in Quang Ninh. This proactive approach by the provincial government demonstrates a commitment to supporting local farmers and promoting sustainable industry practices that align with global environmental standards.

Sipunculus nudus holds significant economic value due to its rarity and demand, particularly in markets where it is prized as a delicacy. The farming of Sipunculus nudus primarily depends on natural seed sources, with extensive farming methods being the most prevalent. These methods typically involve low-intensity, low-input techniques that utilize the natural environment to raise worms. While some attempts have been made to introduce more intensive farming models for Sipunculus nudus, these practices are not yet widespread. The shift toward intensive models, which involve higher density and controlled environment farming, has been slow due to various challenges, including the need for more precise management and greater initial investments. Given the economic importance and ecological sensitivity of Sipunculus nudus, there is a real threat of resource depletion through overexploitation. Recognizing this risk, local authorities have taken proactive steps to ensure sustainable management and conservation of this valuable resource. In particular, two comanagement models have been implemented in the communities of Minh Chau and Quan Lan within the Van Don Island district and in the sandstorm bed of the Dai Binh commune in the Dam Ha coastal district. These models are designed to balance the needs of local communities with conservation efforts, fostering cooperative resource management among stakeholders. To further protect the Sipunculus nudus population, the local government has instituted regulatory measures, including a seasonal ban on the natural exploitation of these worms. This ban, which is effective annually from June 1 to July 30, is intended to allow for the reproductive cycle of the species, ensuring that their numbers can be replenished. Additionally, conservation efforts include the release of at least 5 million Sipunculus nudus seeds back into the natural environment each year to boost native populations and help sustain the ecological balance. These initiatives reflect a comprehensive approach to managing Sipunculus nudus resources, blending regulatory measures with proactive conservation efforts. By establishing controlled exploitation periods and enhancing the natural population through seed releases, the authorities aim to secure the long-term viability of Sipunculus nudus farming while preventing overexploitation, which could lead to the decline of this species.

Marine fish farming along the coast of Quang Ninh Province occupies a substantial area of 1,036 hectares and produces a notable output of 8,150 tons in the year 2022. This activity is primarily focused in strategic locations such as Cam Pha, Van Don, and Dam Ha, with Van Don and Cam Pha emerging as central hubs for marine aquaculture. These areas are critical due to their conducive marine conditions and accessibility, which facilitate efficient aquaculture operations. The increasing market demand for fresh seafood, especially for natural and locally sourced specialties, is putting considerable pressure on fishery resources. This demand is not only local but also international, with countries such as Japan, which is the world's largest seafood-consuming nation, heavily relying on Vietnam for its supply of marine fish such as squid, mackerel, tuna, and grouper. As Vietnam's primary seafood export market, Japan's consumption patterns significantly influence the production strategies and export priorities of Vietnamese marine aquaculture. However, the expansion of marine fish farming to meet this rising demand has created complex challenges. One of the most pressing issues is the increased demand for feed, which often leads to the overexploitation of small marine fish used as feedstock. This overexploitation can disrupt marine ecosystems and lead to the depletion of essential fish stocks, posing long-term sustainability issues. Additionally, marine fish farming in Quang Ninh is beset by several other challenges, including disease, environmental pollution, and market instability. Disease outbreaks can decrease fish populations and severely impact profitability, while environmental pollution affects the health of both the marine environment and the fish farmed within it. Market instability, influenced by international trade dynamics, consumer preferences, and economic conditions, can also create unpredictable operating conditions for fish farmers. To address these challenges, it is crucial for stakeholders in Quang Ninh's marine fish farming industry to adopt sustainable farming practices. This includes implementing improved disease management protocols, adopting environmentally friendly farming technologies, and engaging in responsible feed sourcing to reduce ecological impacts. Furthermore, diversifying markets and enhancing the value chain of marine fish products can help stabilize the industry and reduce dependency on a single export market. Efforts in these areas can help ensure the long-term viability of marine fish farming in Quang Ninh, contributing to the economic stability of the region while safeguarding its marine ecosystems.

To ensure the sustainable development of aquaculture, it is essential to embrace a multifaceted approach that includes conducting research on new species varieties, protecting the environment, enhancing the synergy between production and consumption, and diversifying export markets. In particular, a thorough comparison between the efficacy of IMTA systems and traditional mono-cultural farms, which focus on single species such as oysters, shrimp, fish, or Sipunculus nudus, is vital. Such comparative analyses can illuminate the strengths and weaknesses of each system and provide valuable insights that could inform policy adjustments aimed at facilitating the broader adoption of IMTA practices. IMTA systems, which involve the concurrent cultivation of multiple species from different trophic levels within the same system, have been proposed as a more sustainable form of aquaculture that can potentially address economic, environmental, and social challenges more effectively than mono-culture practices. To evaluate this, it is crucial to quantitatively compare these systems across the three pillars of sustainability: social, economic, and environmental. This comprehensive approach not only assesses direct outputs and profitability but also considers the broader impacts on community welfare and ecological health. Economically, IMTA may offer enhanced productivity and stability of income due to diversified crops that can buffer against the market or biological shocks affecting any single species. Environmentally, IMTA could lead to better resource efficiency and lower environmental impacts per unit of seafood produced, as waste products from one species can be recycled as inputs (such as fertilizer or food) for another. Socially, IMTA systems might support more robust community relations and local economies by providing a variety of employment opportunities and increasing resistance to economic downturns related to specific aquaculture species. To translate these potential benefits into practice, it is imperative to develop and implement suitable policies that promote the adoption of IMTA. These policies should aim to overcome barriers such as high initial investment costs, lack of technical knowledge, and regulatory constraints that currently hinder wider adoption. Support mechanisms might include funding for research and development, training programs for farmers, incentives for sustainable practices, and the development of standards and certifications that encourage market acceptance and consumer trust. Achieving sustainability in aquaculture through IMTA requires not only the recognition of its potential benefits but also a concerted effort to integrate these systems into existing aquaculture policies and practices. By doing so, it is possible to enhance the sustainability of the industry, promoting a healthier environment, a more stable economy, and improved social outcomes.

From an environmental standpoint, the formulation of appropriate policy is crucial for ensuring sustainability, as it plays a pivotal role in shaping interactions between wildlife and humans. As noted by Rupprecht et al. (2020), these policies can either lead to conflict or promote mutual flourishing, depending on how they are crafted and implemented. Policies that carefully consider and plan for the coexistence of human activities and wildlife are essential for fostering an environment where both can thrive. Economically, supportive government policies are vital for encouraging the adoption of IMTA. By providing aquaculture farms with necessary land use licenses, investments, and subsidies, the government can facilitate the quicker and more widespread adoption of IMTA practices. Such measures can significantly lower the barriers to entry for new participants and enhance the scalability of existing operations, thereby boosting the economic viability of the aquaculture sector. However, if these policies neglect environmental consequences, such as the unchecked use of chemicals, improper land use, and inadequate waste disposal, they can lead to what Rupprecht et al. (2020) describe as "overprovision" and "overinvestment." This situation results in a misalignment among the three pillars of sustainability: economic, social, and environmental. For example, the overuse of chemicals can lead to ecological damage that compromises the long-term viability of aquatic and surrounding terrestrial ecosystems, which in turn can affect social attitudes toward aquaculture and economically impact those reliant on these ecosystems for their livelihoods. This highlights the critical importance of well-considered, holistic policies that integrate environmental stewardship with economic incentives to ensure the successful expansion of IMTA. Effective policies must address not only the economic and operational aspects of aquaculture but also incorporate stringent environmental regulations to prevent degradation and promote sustainability. Moreover, as Valenti et al. (2018) suggested, the absence of practical and supportive policies can leave aquaculture farmers without the essential resources needed to sustain their operations, such as water, capital, and labor. This deficiency can severely hinder the efficacy of IMTA practices and the overall achievement of sustainability goals. Therefore, it is imperative that policies not only promote the adoption of innovative aquaculture techniques such as IMTA but also ensure that the necessary infrastructure and resources are available to support these practices. The development and implementation of comprehensive, integrated policies are fundamental to advancing IMTA and enhancing the sustainability of the aquaculture sector. These policies should be designed to balance economic growth with environmental preservation and social well-being, thus paving the way for a more sustainable and prosperous aquaculture industry.

When examining economic sustainability indicators within aquaculture, Sipunculus nudus emerged as one of the most profitable species, outperforming even IMTA and other conventional aquaculture methods. This profitability is evidenced by a detailed assessment of various aquaculture investments, which demonstrates differences in financial feasibility among the diverse farming types. IMTA and Sipunculus nudus farming are particularly notable for their high efficiency across most financial indices. IMTA shows an exceptional Profitability Ratio on Total Investment of 2.59, indicating that for every dollar invested, there is a return of $2.59. Similarly, Sipunculus nudus also performed well, with a profitability ratio of 1.93. The internal rate of return (IRR) for these farming methods is equally impressive, at 62.74% for IMTA and 44.98% for Sipunculus nudus. These figures highlight the robust economic potential of these types of aquaculture, reflecting their capacity to generate substantial returns on investment. Conversely, traditional forms of aquaculture, such as fish and oyster farming, still show profitable operations, albeit not at the high levels observed in IMTA or Sipunculus nudus farming. These types of farming continue to generate income and provide livelihoods for farmers, supporting the local economy and sustaining community employment. However, shrimp farming presents a different scenario. It shows the lowest profitability among the surveyed aquaculture types, with a Profitability Ratio on Total Investment of just 1.02. The economic viability of shrimp farming has been particularly volatile since the COVID-19 pandemic, influenced by a combination of environmental challenges and disease outbreaks. The overall economic conditions for shrimp farming in Quang Ninh have shown signs of decline, indicating potential risks and lower returns for both investors and farmers. When considering both profitability and other financial metrics, IMTA and fish farming appear to be the most attractive investment options within the aquaculture sector in Quang Ninh. These methods not only promise higher returns but also offer more stable and sustainable opportunities compared to more volatile shrimp farming. Investors and policy makers are advised to focus on these areas, leveraging their potential to drive economic growth, enhance sustainability, and support the livelihoods of the local communities engaged in aquaculture.

In the realm of environmental sustainability, Integrated Multi-Trophic Aquaculture (IMTA) stands out for its superior performance compared to other aquaculture practices. One key metric where IMTA excels is the "use of space" indicator, where it demonstrates significant efficiency, scoring 20.00 points less than traditional fish farming. This suggests that IMTA makes more efficient use of space, integrating various species into a single system that effectively utilizes vertical and horizontal farming dimensions to maximize productivity per unit area. Additionally, in regard to the "Potential of Global Warming" indicator, IMTA also performed slightly better, with only a 0.50 point difference compared to fish farming. Although this margin is small, IMTA systems may have a marginally lower impact on global warming due to their integrated nature, which can help reduce emissions related to feed usage, waste processing, and other inputs. Conversely, for the "Risk of Farmed Species" indicator, fish farming appears to have an advantage over IMTA, scoring 0.22 points less. This suggests that fish farming might be subject to slightly less biological risk, possibly due to less complexity in managing single-species environments compared to the multispecies setups required in IMTA. Managing health and disease across different species that share the same space can present greater challenges and risks. On the social sustainability front, IMTA shows a clear advantage over traditional fish farming, particularly in terms of employment impacts. IMTA requires less investment in both direct and total employment, indicating that it can achieve higher production levels with less labor input. This efficiency in labor usage not only reduces operational costs but also increases scalability and profitability potential. However, it is important to consider that while requiring less labor could be seen as an economic benefit, it might also mean fewer employment opportunities within a community dependent on aquaculture for jobs. IMTA exhibits strong performance across various sustainability metrics, offering a compelling case for its broader adoption in aquaculture. Its efficient use of space and lower potential impact on global warming align with environmental sustainability goals, while its lower reliance on labor investment highlights its economic efficiency. However, balancing these benefits with the social implications of reduced employment opportunities is crucial for holistic sustainability in aquaculture practices.

Sipunculus nudus is considered among the top contenders for the most sustainable species in aquaculture due to its high performance across the three pillars of sustainability: economic, environmental, and social. This species often performs at levels comparable to those of Integrated Multi-Trophic Aquaculture (IMTA), highlighting its efficiency and potential within the aquaculture sector. Despite this, some differences between IMTA and traditional fish farming methods raise questions about the overall value and viability of investing heavily in IMTA systems for aquaculture farmers. However, when examining long-term sustainability, IMTA has clear advantages, particularly from an environmental perspective. Traditional monoculture farming of Sipunculus nudus, while beneficial in terms of yield and profitability, can contribute to local water contamination through the discharge of nutrient-rich waste, potentially leading to significant ecological consequences. Moreover, extensive aquaculture farms, which are common in some regions, can exacerbate environmental degradation through pollution that may clog waterways and disrupt local ecosystems, including the displacement of marine mammals. On the other hand, intensive farming practices often attract predators and can similarly disrupt local wildlife populations and ecological balance (Würsig and Gailey, 2002; Valenti et al., 2018). In contrast, IMTA systems are designed to mimic natural ecosystems more closely by integrating multiple species at different trophic levels. This design allows the waste from one species to serve as nutrients for another, significantly reducing the potential for pollution. For example, waste products from fish can be utilized by filter feeders such as oysters and nutrient absorbers such as seaweed. This closed-loop system minimizes environmental impact, reduces waste, and enhances the overall sustainability of farming practices. IMTA systems also offer additional benefits beyond environmental sustainability. These systems can potentially provide more stable ecosystems for various species, reducing vulnerability to diseases and environmental changes, which in turn can lead to more consistent yields. This stability is crucial for long-term economic sustainability and can contribute to the social sustainability of local communities by providing a more reliable source of income and employment. Therefore, while the initial investment in IMTA may be greater and the systems more complex to manage than traditional monoculture or extensive farming setups, the long-term benefits they offer make them attractive options for the future of sustainable aquaculture. The ability of IMTA to integrate economically viable practices with strong environmental stewardship exemplifies a forward-thinking approach to aquaculture that can serve as a model for industry worldwide.

The urgent need for policy reform to foster the sustainable development of aquaculture in Quang Ninh, Vietnam, is clear. Addressing the obstacles that impede sustainable practices is essential and requires a shift toward innovative, smart, and sustainable solutions. IMTA offers a particularly promising approach, capitalizing on the ecological benefits of cocultivating species from different trophic levels. This method leverages natural processes for waste management and nutrient recycling, enhancing overall ecosystem functionality without the reliance on advanced technologies (Chopin et al., 2012). Despite the low technological demands of IMTA, incorporating renewable energy sources such as solar panels, wind turbines, and wave energy can increase the operational sustainability of an aquaculture farm. This holistic integration can enable farms to operate off-grid, potentially generating enough energy to sustain both farm operations and the associated residential needs. Adding water quality monitoring, local weather forecasting systems, and advanced water filtration can further enhance the efficacy and sustainability of farm management by utilizing the energy produced onsite. However, several barriers impede the widespread adoption of IMTA and similar sustainable practices. Among these challenges are those related to capital, policy, and education. Many farmers in Vietnam have limited formal education, with many not surpassing nine years of schooling (Ngoc et al., 2021). This educational shortfall leads to a limited understanding of sustainable practices and their long-term benefits, often resulting in the prioritization of short-term gains over sustainable development. This can manifest in practices such as excessive chemical use or the destruction of critical habitats such as mangroves. Additionally, the complexity of accessing government support and preferential loan rates further complicates the transition to sustainable practices. Farmers often face daunting legal barriers and bureaucratic processes that require legal and language assistance, which they frequently cannot afford or access (Ngoc et al., 2021). The stringent requirements for obtaining financial support, such as detailed business plans and collateral, are often beyond the reach of small-scale farmers who dominate Vietnam's aquaculture landscape. Moreover, issues in the food safety market exacerbate sustainability challenges. There is often a disconnect between buyers' trust in product safety and the actual conditions of production, which are affected by poor water quality and frequent disease outbreaks (Xuan et al., 2021). This situation can drive financially desperate farmers to sell substandard or even contaminated products, which jeopardizes both market demand and the reputation of the sector. To effectively promote sustainable aquaculture practices such as IMTA, policies to address these multifaceted challenges are crucial. This involves enhancing educational opportunities for farmers, simplifying access to financial resources, and improving quality control within the sector. By strengthening these aspects, policy reforms can provide substantial support to farmers at the individual level while also promoting the economic and environmental sustainability of the broader aquaculture industry in Vietnam. Such strategic policy interventions are essential for transitioning to a more sustainable and prosperous aquaculture future.

5. Conclusions

This study provides a detailed quantitative analysis of the sustainability of the multibenefit aquaculture sector in Quang Ninh Province, Vietnam, utilizing a comprehensive set of indicators to assess the economic, social, and environmental aspects of the industry. The findings show that while the aquaculture industry in this region has substantial potential for growth and development, it continues to rely heavily on traditional and classical farming methods. This reliance poses a significant barrier to maximizing the industry's full potential, highlighting the urgent need for modernization through the adoption of advanced scientific and technological practices alongside increased capital investment.

The implications of such advancements are profound and promising not only for bolstering the sustainability of aquaculture practices but also for significantly boosting the local economy of Quang Ninh Province. By modernizing aquaculture techniques, there is a potential to create numerous employment opportunities, thereby alleviating unemployment in the area and addressing broader social and familial issues. Furthermore, the integration of contemporary, environmentally friendly farming methods can play a critical role in preserving and enhancing the region's natural resources, contributing to broader conservation efforts.

The study notably points to the IMTA as an exemplary model that represents the direction in which the industry could head. IMTA promotes the simultaneous cultivation of species from different trophic levels, effectively recycling nutrients and minimizing waste, which underscores the potential for enhanced efficiency and sustainability in aquaculture.

Additional research is necessary to further explore innovative and efficient aquaculture techniques. Future research should focus on practical applications of scientific and technological advancements that could revolutionize the sector. It is essential for stakeholders, including government bodies, educational institutions, and private investors, to collaborate to foster an environment conducive to research and development in aquaculture technologies. Such collaborative efforts will be crucial in ensuring the successful transformation of aquaculture practices in Quang Ninh Province, making the industry more competitive, sustainable, and resilient in the face of global challenges.

Ethical considerations

The study correctly followed the ethical policies for a study that included human subjects, in addition to confirming the consent of all the respondents involved.

Conflict of interest

The authors declare no conflicts of interest.

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