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Economic viability of sustainable aquaculture practices for long-term resource management

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Abstract

This paper evaluates the profitability of sustainable resource-based aquaculture and explores the possibility of incorporating long-term resource sustainability as part of integrated aquaculture system profitability. Considering the speed at which the global aquaculture sector is growing, it is still an utmost challenge to address its social and environmental sustainability concerns. Concepts of sustainable aquaculture are put forward to address the sector's blend of social, ecological, and economic objectives. Prior research demonstrates that aquaculture systems perform unevenly across the three dimensions. To position aquaculture as a credible pathway for long-term resource management, it is pertinent to evaluate the conditions in which economically viable aquaculture is practiced. To address this, the paper presents the sustainable aquaculture literature and studies on the economic sustainability of aquaculture, then, based on identifying gaps, proposes integrating cost-benefit analysis, life cycle analysis, and resource sustainability as a new methodological approach. The approach identifies resource economic drivers as feed cost, Yield per area, certification, and ecosystem externalities. The model, documented with illustrative tables and graphs, demonstrates that sustainable systems with moderate productive feed cost, efficient market access and cycles, and premium market access conditions, can be profitable within typical investment horizons. Economically viable sustainable aquaculture requires the systematic consideration of resource management, certification, waste management, and market frameworks. The approach described provides practitioners and policymakers with a mechanism for evaluating and developing frameworks for sustainable, long-term resource management. Future research should prioritize the empirical application of this approach across a range of geographical settings.

Keywords: Sustainable aquaculture, Economic viability, Resource management, Aquaculture certification, Lifecycle assessment

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Introduction

Recognized as one of the pillars of future global food systems, aquaculture the farming of fish, shellfish, and seaweeds offers solutions to the increasing demand for protein sources (Lightfoot *et al*., 1993). It also contributes to the food security, the economy, and the socio-economic development of a region. However, the development of the aquaculture industry and its practice also creates challenges, including nutrient discharge, habitat conversion, and social equity issues. Because of this, the word 'sustainable aquaculture' was invented to signify the desire for production without harming the socio-economic and ecological conditions of a region (Valenti *et al*., 2018).

From an economic perspective, 'sustainable aquaculture' aims to generate profit while managing resource systems, which involves maintaining a sustained, positive balance of water, feed, assimilated waste, and biodiversity and ecosystem services to prevent depletion of the system's resource base. In the reality of aquaculture, many businesses pursue short-term profitability, disregarding ecological imbalances and externalities, which puts long-term business viability and the risk of resource depletion (Wurts, 2000). An analysis of 57 aquaculture systems suggested that while social, economic, and environmental results achieved were, on average, positively correlated, the relationship between financial and ecological results was the weakest of the three. This illustrates the need for direct market forces to achieve sustainable goals (Kumar *et al*., 2023).

Additionally, the limited market access, high input costs, poor infrastructure, and insufficient formal regulatory and certification frameworks in many developing regions continue to impede both economic viability and sustainability.

To effectively manage resources over time i.e., ensuring that, over the years, the productive and healthy aquatic resources required for sustainable aquaculture are available it is necessary to ascertain the conditions that render certain sustainable practices economically feasible and to define an evaluative approach for them (Ferreira, Hawkins and Bricker, 2007).

To address this, the present work surveys the literature on the economics of sustainable aquaculture, identifies key cost and resource management drivers, and proposes a method that draws on economic modeling, integrates resource management and performance tracking, and offers a unified approach (Bailly and Paquotte, 1996). The primary purpose is to enable the integration of evaluative aquaculture systems for the profitability and resource sustainability of practitioners, researchers, and aquaculture policymakers (Ansah, 2014).

Key contributions:

- An overview of the literature on the economic potential of sustainable aquaculture and the sustainable management of linked resources is provided.
- An integrated approach consisting of economic cost-benefit analysis, lifecycle/resource management indicators, and market segmentation is proposed.

- Example tables and figures are provided to illustrate the application of this approach and highlight the key variables affecting viability.
- The implications for policy and management of long-term sustainable aquaculture and resource management are articulated.

A literature survey focusing on previous studies on the economic sustainability of aquaculture practices is presented in Section II. Section III outlines the methodology we intend to use, accompanied by a diagram of the proposed methodology framework. Results and discussion are presented in Section IV, where we provide tables and figures demonstrating core relationships, along with sensitivity analyses. Finally, in Section V, we conclude the paper by summarizing the key findings and the proposed directions for future research.

Literature Survey

The expansion of aquaculture has been well documented, and according to the Food and Agriculture Organization (FAO), the sector will continue to expand and intensify. It will continue to grow in significance for livelihoods and employment, particularly in the developing world. However, the sustainability of such growth hinges on a range of technical, environmental, economic, and governance issues. The World Economic Forum review characterizes the challenges of sustainable aquaculture as optimizing feeds, managing aquatic health, addressing environmental interactions, and integrating food production systems. One body of work investigates the three spheres of sustainability economic, environmental, and social and their interactions within aquaculture (Pillay, 1997). For instance, in a recent global study of 57 aquaculture systems, Taryn M. Garlock et al. found that, on average, the systems' sustainability pillars were complementary; indeed, positive correlations were found among each pair of dimensions (Bunting, 2024). The authors, however, noted that the correlation between the environmental and economic dimensions was the weakest (coefficient ~0.33), suggesting that, for many systems, financial benefits will not align with positive environmental outcomes.

The economic viability of aquaculture systems has been the focus of a more direct stream of research (Sonesson *et al.*, 2023). This body of work has found that the significant cost drivers feed, energy, labour, infrastructure, and certification/traceability contribute to unsustainable operations. Inadequate infrastructure and inefficiencies along value chains can result in economic unviability, and, in turn, a positive outlook for market growth will not materialize. Sustainability and cost-effectiveness will continue to be favorably affected by technological advancements. Research conducted by the Institute of Marine and Environmental Technology on fully contained, land-based systems suggests that achieving positive environmental and economic performance outcomes can be realized through the development of enhanced techniques in water treatment, waste conversion, and overall system engineering, with a focus on reducing externalities and improvedimproving resource use efficiency.

Another key area of focus will be governance and certification. Certification and traceability systems, schemes, and frameworks (for example, the Aquaculture Stewardship Council and Best Aquaculture Practices) are perceived and touted in the literature as mechanisms that provide market access, support sustainability, and internalize external costs (Folke and Kautsky, 1992). While the literature suggests that economic viability will be enhanced through premium pricing and market access, resource-constrained environments offer limited mechanisms for sustained applicability. Work on context-specific constraints, especially in developing countries, is nascent and primarily emerging. Sustainable intensification in aquaculture will not be practical in the absence of a favorable local context, including access to feed, infrastructure, smallholder scale, and governance. Research on small-scale aquaculture suggests that a lack of appropriate resource management and institutional context will lead to suboptimal intensification and eventual collapse (Berg *et al*., 1996).

The literature shows that, to an extent, the unsustainable nature of aquaculture can be mitigated and that aquaculture can be a good alternative to the exploitation of wild marine life (Kapoor and Vasudevan, 2025). Given socio-economic factors, the case for aquaculture is strengthened (Begam and Banu, 2025). However, achieving economic, social, and ecological sustainability simultaneously remains a formidable challenge. The economic aspect of sustainability also concerns the aquaculture system's feed and other input costs, technological efficiencies, and market access (Venkadeshwaran *et al*., 2025). Managerial aspects of resource (e.g., waste management and treatment, ecological impacts, certification) are critical, albeit often underappreciated. Most glaring is the absence of research on sustainability within integrated economic and resource management frameworks.

Methodology

As noted in the literature survey, the economic viability of sustainable aquaculture systems, with a focus on long-term management, can be framed with a comprehensive set of methods. Such a comprehensive set can be divided into three interrelated modules as suggested below:

1. Economic Viability Module
2. Resource Management/Environmental Module
3. Market/Certification Module

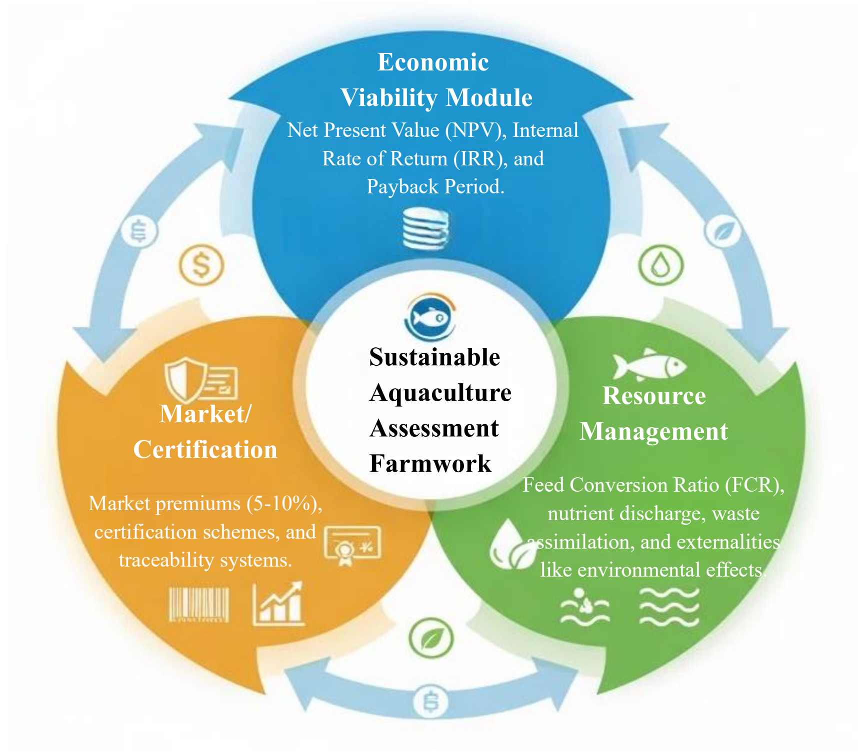


Figure 1: Integrated framework for sustainable aquaculture assessment.

The Integrated Framework for Sustainable Aquaculture Assessment and its three modules are intertwined as illustrated in Figure 1. These modules are: Economic Viability Module (blue), which focuses on profitability indicators such as NPV and IRR; Resource Management/Environmental Module (green), which assesses sustainability using FCR and Nutrient Discharge; and Market/Certification Module (orange), which considers Market Premiums and Certification Schemes. These modules work together to assess the overall economic viability and ecological sustainability of the aquaculture systems.

All together, these parts integrate to form a complete, coherent assessment system of aquaculture, aimed at achieving harmony at the economic, environmental, and market levels. These parts are interconnected relationally. These parts assess aquaculture based on profitability and resource sustainability.

Economic Viability Module

Evaluating the economic aspect of your fish growing is your target goal. It evaluates the profitability of fish farming facilities using certain Indices, primarily the Net Present Value, Internal Rate of Return, and Payback Period. These Metrics help determine the profitability and the speed with which a fish farming system can generate returns. Evaluating the system from an Economic vantage point employs the NPV approach, which is formulated as follows and aims to ascertain the profitability value of the system:

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+r)^t} - C_0 \qquad (1)$$

Where:

- R_t= Cash inflow at time t
- r= Discount rate
- n= Project lifetime
- C_0= Initial investment cost

Finding the IRR requires calculating the NPV at zero, which identifies the return rate such that the present value of the inflows equals the investment cost. The Payback Period is relatively simple, as it determines the time required to recover the initial investment, which is necessary for project risk evaluation.

Resource Management/Environmental Module

This particular module will evaluate the sustainability of the Environmental/Resource Management module. This module takes into account the FCR, the discharge of nutrients and waste, waste assimilation, and the externalities. The Feed Conversion Ratio is defined as:

$$FCR = \frac{\text{Amount of Feed (kg)}}{\text{Amount of Fish Produced (kg)}} \quad (2)$$

Measures how efficiently feed is transformed into fish biomass. An FCR value that is lower denotes a more efficient system that uses less feed to achieve a particular output, resulting in increased cost-effectiveness. Moreover, from an environmental viewpoint, systems that achieve lower FCR are more sustainable. Regarding environmental impacts, Nutrient Discharge is the most critical parameter in the ecological evaluation of an aquaculture system.

$$Nutrient\ Discharge = \frac{Nutrient\ Inputs}{Aquaculture\ Area} \quad (3)$$

Where:

- Feed, excreta, and chemicals provide nitrogen and phosphorus, which constitute Nutrient Inputs.
- Aquaculture Area denotes the entire surface area of the ponds or tanks and thus the area from which nutrients are released.

The preceding evaluation provides an outline for gauging the degree of nutrient pollution, which serves as an indicator of the degree to which the system contributes to eutrophication, among other ecological damages. Optimally, the discharge of nutrients should be economically justifiable, whilst the output should be of commercially viable fish. This encapsulates the essence of sustainable aquaculture.

Market/Certification Module

The Market/Certification Module explores the profitability and premium pricing opportunities for aquaculture goods derived from sustainable practices. Certified sustainable practices achieve parity with non-sustainable products. This is true whether recognized bodies such as Aquaculture Stewardship Council (ASC) and Best Aquaculture Practices (BAP) certify the product or not. This module examines the system's economic viability as it pertains to certification costs and market premiums. Revenue equations for certified sustainable products:

$$Revenue = (\text{Yield} \times \text{Market Price}) + \text{Certification Premium} \quad (4)$$

Where:

- The market price refers to the value assigned to every unit of a specific fish type or aquaculture product.
- Certification premium denotes the additional revenue, often 5 to 10%, that is accrued from premium markets, which acknowledge sustainability.

The coordination of these three modules sufficiently captures the equilibrium between the financial components, including profitability, and other elements of the environment, including nutrient management and feed efficiency. The market premium provides the motivation for producer to incorporate sustainability and profitability into their practices, which is a key motivator of sustainability. This is because the certification and traceability standards on which the market premium is based.

Integration of Modules

The Sustainable Aquaculture Assessment Framework is made up of three modules, which connect and communicate in an integrated and dynamic manner. Moving in, one economic viability and profitability threshold will influence resource management and certification paths. Notably, if market feed prices are high or if they are managed inefficiently, changes will undoubtedly be necessitated in the economic resource management. Resource management will need reactions such as downward adjustments in feed and/or improvements in the feed conversion ratio (FCR). On the other hand, market access gained through certification and traceability system resources will help improve the profitability of the venture. High-value and high-profitability products will provide access to premium markets. Moving also provides a profitability threshold to the module on 'Economic Viability' due to the self-adjusting nature of feed resources, cost-saving through resource optimization, and increasing the system's overall efficiency. Better resource management will help reduce costs and enhance system efficiency, thus improving the economic viability of the modules. The Market/Certification Module will generate higher revenue and will significantly assist in garnering additional investments toward the practices of sustainability. This is especially true with the premium the market places on certified products.

Key Input & Output Parameters

To analyze the impact of different factors on the system, the following table presents a comparison of the primary input and output parameters for the three chosen aquaculture cases: Conventional, Sustainable Moderate, and Sustainable Intensive. These parameters explain how the implemented sustainable practices influence basic and core business variables.

Table 1: Key input & output parameters for different aquaculture scenarios.

Parameter	Conventional Scenario	Sustainable Moderate	Sustainable Intensive
Capital Expenditure (US$/ha)	50,000	60,000	70,000
Annual Feed Cost (US$/ha)	40,000	35,000	30,000
Feed Conversion Ratio (FCR)	1.8	1.5	1.2
Annual Yield (tons/ha)	25	30	35
Market Price (US$/ton)	1,500	1,600	1,700
Certification/Monitoring Cost	–	5,000	10,000
Premium Price Percentage	–	5%	10%
Resource Externality Cost (US$/ha)	10,000	5,000	2,000

The values in Table 1 summarize fundamental input and output metrics pertaining to Conventional, Sustainable Moderates, and Sustainable Intensives, which exemplify various forms of aquaculture. They summarize the differences in capital investments, annual feeding and feeding FCRs, annual production, and annual revenues across the three practices. Besides, it accounts for the costs of certification/monitoring, the premium percentage of price, and externality costs of resources, thus depicting the impact of sustainable practices on the economic and environmental dimensions. Such an overview captures the essence of the trade-off between the financial and ecological aspects of conventional and sustainable aquaculture systems.

Results and Discussion

Economic Viability and Profitability

Evaluating the performance of every scenario in each respective aquaculture setting shows that the moderate focus sustainability systems are the ones that become even more profitable, regardless of the more substantial investments that are needed. On the other hand, the conventional system performs the worst in profitability because it has the most significant investment at $50,000/ha, and the inefficiency in the feed conversion and high cost of feed create a considerable constraint. Conversely, Sustainable Moderate performs much better with a capital investment of $60,000/ha, because it has far lower operational feed costs at $35,000/ha, and a more efficient feed conversion at 1.5, which will further reduce operational costs, and thus improve the profitability and NPV even more in the long run.

While this system requires the most investment of $70,000/ha in the Sustainable Intensive system, financial returns are maximized. The system has an FCR of 1.2, which means feed costs of $30,000/ha, but also generates a more profitable market price of $1,700/ton because of system certification and premium. Because of superior price, feed, Yield, and overall climatic conditions, the payback period is short, making this system more attractive to long-term-oriented investors. Premium market price improves the obvious NPV, increasing profitability. The table below summarizes the capital expenditures, federal costs annually, and market price relative to each scenario.

Table 2: Environmental impact and resource efficiency across aquaculture scenarios.

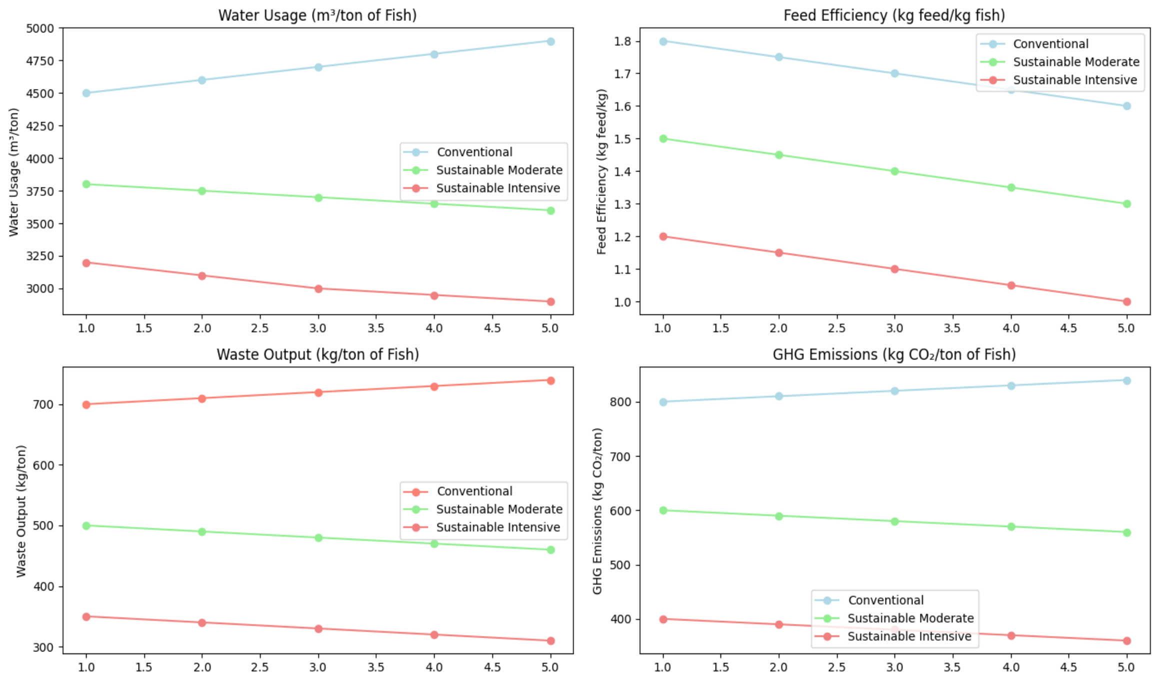
Parameter	Conventional Scenario	Sustainable Moderate	Sustainable Intensive
Water Usage (m^3/ton of fish)	4,500	3,800	3,200
Feed Efficiency (kg feed/kg fish)	1.8	1.5	1.2
Waste Output (kg of waste/ton of fish)	700	500	350
Energy Consumption (kWh/ton of fish)	350	300	250
Greenhouse Gas Emissions (kg CO_2/ton of fish)	800	600	400
Resource Externality Cost (US$/ha)	10,000	5,000	2,000
Sustainability Rating	Low	Moderate	High

Table 2 presents the comparative analysis of the three systems: Conventional, Sustainable Moderate, and Sustainable Intensive aquaculture systems, on their systems' ecological footprint and resource utilization efficiencies. Their systems' environmental sustainability, or lack thereof, can primarily be assessed and meaningfully compared based on the indicators of water withdrawal, feed conversion ratios, effluent waste generation, energy expenditure, and greenhouse gas emissions. The Systems' Sustainability Rating demonstrates that, of all systems examined, Sustainable Intensive practices utilize resources and sustainability of water and energy use and waste and emission reduction efficiencies, relative to other systems, more optimally. Conversely, the Conventional System manifests the most significant ecological inefficiencies as a result of inferior fodder utilization, excessive waste generation, and excessive energy use. Resource Externality Cost exhibits much greater financial viability of more sustainable aquaculture systems versus Conventional aquaculture systems.

Resource Management and Environmental Sustainability

The Sustainable Moderate and Sustainable Intensive systems show lower Resource Externality Costs, which reflect their sustainability practices. Sustainable Intensive with an FCR of 1.2 relative to the Conventional System with an FCR of 1.8 uses the most feed efficiently and minimizes nutrient discharge and waste assimilation issues. Sustainable Intensive system Resource Externality Cost is US$2,000/ha and is lower than the Conventional System by US$10,000/ha since the Conventional System has higher feed input and nutrient discharge.

Moreover, the Sustainable Moderate system has a Resource Externality Cost of US$5,000/ha, which demonstrates that the system's environmental impact improvement is mainly due to better feed conversion and sustainable waste management. This is evidence of the remarkable ecological improvement that can be realized by designing more sustainable systems in aquaculture. This is with the economic benefit of lower costs and demand, and higher prices to be obtained in the market, for certified sustainable products.



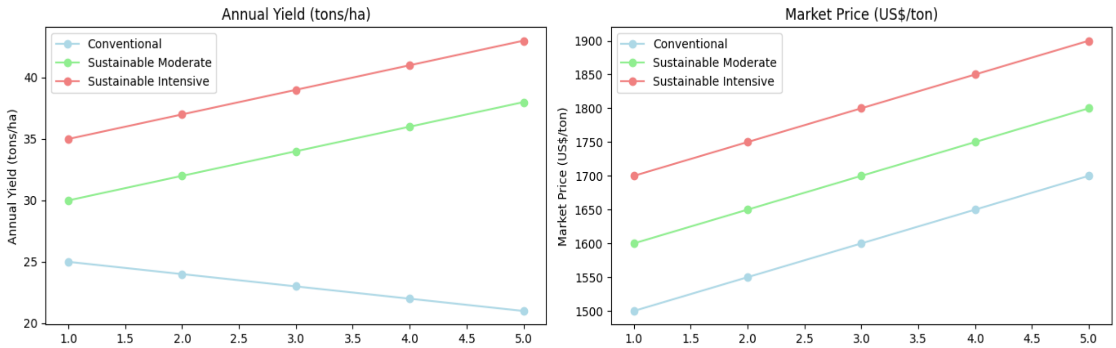


Figure 2: Comparison of environmental impact and resource efficiency across aquaculture scenarios.

Figure 2 compares the five-year performance metrics of Conventional, Sustainable Moderate, and Sustainable Intensive aquaculture systems. This demonstrates the extent to which sustainable practices improve the systems with respect to water use, feed conversion, waste generation, greenhouse gas emissions, yearly output, and market value. Sustainable aquaculture systems maximally improve the environmental impact, and Sustainable Intensive systems derive the most economic benefits, with Sustainable Intensive systems outperforming the others on most metrics.

Market Access and Premium Pricing

The Sustainable Moderate and Sustainable Intensive systems' profitability hinges significantly on market access and premium pricing attainable through certifications. Unlike the Conventional System, which has no access to premium markets, the Sustainable Moderate and Sustainable Intensive systems enjoy premium pricing. For example, the Sustainable Moderate system has a 5% market premium (US$1,600/ton), but the Sustainable Intensive system has a 10% market premium (US$1,700/ton). This gives them a competitive advantage in consumer markets that prefer and are willing to pay a premium for sustainably farmed products. Sustainable systems profit more during the payment, compared to conventional systems, despite the costs of certification and monitoring, because they pay less for monitoring, and certification systems profit more.

The certification costs for the Sustainable Moderate systems and the Sustainable Intensive System (US$5,000/ha and US$10,000/ha) are outweighed by the revenue generated from selling your product at a premium. This shows sustainable practices in aquaculture are viable from a business perspective. Key to long-term profitability and economic viability is the revenue aquaculture systems will make from the market opportunities that arise, making system revenue sustainable from the revenue aquaculture systems make. This allows for new market opportunities, suggesting that long-term profitability stems from system revenue.

Sensitivity Analysis and Risk Factors

A sensitivity analysis evaluates the economic impact of different systems by assessing changes in feed prices, market prices, and FCRs. For example, with a 10% increase in feed prices, the

Conventional System NPV dropped 12% while the decline for the Sustainable Intensive System was 8% and then 6%. This demonstrates the relative sustainability of these systems, particularly when market feed prices are volatile, as in traditional aquaculture systems.

Also, market prices for the Conventional System were 5% lower, which predicted a 10% NPV drop. This loss was minor for the Sustainable Moderate and Sustainable Intensive systems, which dropped 5% to 7%. Due to certification, these systems have a market price volatility safety net. This highlights the expected stability and profitability of these systems. This underscores the profit-generating stability for systems, affirming that these systems are economically sustainable, reliable, and profitable.

Conclusion

Current sustainable aquaculture practices, most notably the Sustainable Intensive systems, provide the best affordable and viable options when compared to previous systems. Indeed, these systems may require a greater upfront cost, but profitability in the long run, primarily through profit premiums associated with certification, is guaranteed due to gains in feed conversion efficiencies, improved waste management systems, and systems with less greenhouse gas emissions. Enhanced resource and waste management systems provide greater market and financial stability by less variable and/or improved price protection, which reduces the risk of price volatility. Therefore, sustainable aquaculture is an optimal strategic response to the anticipated challenges of climate change and food insecurity.

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