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ARTICLE

Enhancing Sustainability in Super-Intensive Shrimp Farming by Implementing a Closed Ecological System

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ABSTRACT

This study aims to assess the sustainability of super-intensive shrimp farming using a sustainability indicators analysis that considers various factors. The indicators were selected based on the current state of super-intensive shrimp farming activities and observations of specific natural conditions in the study area. The study identified 18 indicators across three dimensions for assessing the sustainability of shrimp farming, including economic, environmental, and social. Furthermore, the study proposed and successfully implemented a closed ecological system to improve sustainability in super-intensive shrimp farming. The waste from the shiphong water exchange process includes shrimp shells, shrimp feces, and residual pond waste. Shrimp shells or carcasses are collected for composting. The final organic fertilizer is used for orchard cultivation and as a replacement for chemical fertilizers. The treated water is recirculated to a primary settling pond for further treatment before being returned to the super-intensive shrimp farming ponds. The results show that the implementation of the closed super-intensive farming system, which emphasizes material and energy recycling along with increased farming density, resulted in a total gross outcome index (GO) of $925,717.23. This figure is 11.2 times higher than that of the traditional super-intensive farming system. However, intermediate costs (IC) increased by $723,113.68. The closed system operates on an area of 0.09 ha/kg of shrimp, uses 0.15 m^3 of water, and needs 1.01 MJ of energy. Additionally, the Nitrogen

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to Phosphorus (N:P) ratio is 0.27:0.05, and the use efficiency of N and P reach 87% and 81%, respectively.

Keywords: Sustainability; Environmental Indicators; Closed Ecological System; Super-Intensive Shrimp Farming; Environmental Impacts

1. Introduction

By the end of 2024, Vietnam's total shrimp farming area is approximately 749,777 ha, with shrimp production estimated at 1.29 billion t. In the Mekong Delta region, the shrimp farming area exceeds 700,000 ha, producing about 700,000 t of shrimp, which represents over 90% of the area and 95% of the country's brackish water shrimp production. The shrimp farming industry is experiencing strong growth and is expected to bring significant economic value to the people in the region. However, environmental sustainability issues must be considered. Shrimp farming activities in the area frequently release large amounts of nutrient pollutants into the environment [1,2]. Intensive shrimp farming produces the highest amount of excess nutrients, while the environmental efficiency of super-intensive shrimp farming reaches 40%, significantly higher than that of intensive (23.27%) and semi-intensive (17.08%) farming [3,4]. Typically, shrimp only absorb about 20–25% of the total 30–40% of protein in the feed provided to the pond daily. Estimated ammonia nitrogen emissions from shrimp ponds are 50 g/kg of shrimp feed. The unabsorbed feed accumulates at the bottom of the pond, combining with digestive waste to produce various forms of waste [5]. In shrimp farming, wastewater is generated not only during the harvesting stage but throughout the entire farming process due to daily water exchange. The water exchange activities combined with chemical treatment of the feedwater in the ponds can deteriorate the surface water quality in the area [6,7]. On average, intensive and semi-intensive shrimp farming uses approximately 8.2 t of chemicals and 41.7 t of biological products along with supplemental feed [8,9]. Therefore, managing waste from shrimp farming by reusing and recycling these nutrients is essential to minimize eutrophication of surface water. Over the years, many efforts have been made to reduce nutrient levels in shrimp ponds, contributing to more sustainable shrimp farming practices [10].

Estimating the sustainability and environmental impacts of aquaculture is a challenge. A lack of quantitative sustainability performance data is limiting the industry's ability to demonstrate the potential benefits of aquaculture, which plays a role in the future of the seafood supply. The Environmental Indicators System (EIS) has emerged as a tool to demonstrate the sustainability of complex ecosystems. Impact-specific parameters were defined as Impact, Resource, Target, Limit Reference Point (LRP), and Recovery Timeframe. EIS was used to develop a 0–100 performance scale for key environmental impacts [11]. While previous studies have focused on individual social or environmental aspects of sustainability in shrimp farming, integrated assessments of these factors using social-ecological systems (SES) approaches have been rare. This study is the first to develop and conceptualize a framework for assessing the sustainability of shrimp farming—comprising a set of social and ecological indicators. It uses an integrated, interdisciplinary, and empirical SES approach [12]. The previous study identified 28 indicators across four criteria for measuring livelihood sustainability: economic, social, environmental, and policy. The index reflects the sustainability of livelihoods for various farming groups. The results showed that the sustainability levels for the farming group, the intercropping group, and the cage fish group were approximately nine times lower than the overall index. This study also categorized household sustainability as follows: relatively sustainable (42.3%), slightly sustainable (38.14%), sufficiently sustainable (17.8%), and unsustainable (1.69%). Additionally, the sustainable livelihood strategies for shrimp farmers were investigated in the Mekong Delta in the context of climate change [13]. The study employed 19 criteria to assess the environmental sustainability of shrimp farming and evaluated the Livelihood Vulnerability Index under the Intergovernmental Panel on Climate Change (LVI-IPCC) based on five livelihood assets and 17 indicators. The results indicate that human, natural, and financial assets positively affect environmental sustainability. Notably, shrimp farmers with more experience, reservation ponds, access to financial credit, or higher annual income showed a positive relationship with sustainability. Furthermore, the narrowing of agricultural production, sources of income, and natural food supply contributes to vulnerabilities in the livelihoods of rural communities [14]. They found that shrimp cultivation provided minimal economic benefits to these communities.

The theories of resilience, the circular economy, and ecological modernization were adapted to assess the sustainability of aquaculture activities. The application of these theoretical frameworks aims to enhance the adaptability and sustainable development of livelihoods. The concept of resilience is increasingly being used in farming system research. When assessing shrimp farming in the Mekong Delta, the results show that farmers lack the capacity for transition and exhibit the weakest resilience [15,16]. Furthermore, the transition from a linear to a circular economy at the farm level and across the entire shrimp value chain has been accelerated. The shrimp farming industry is moving towards a more sustainable aquaculture system, aligned with the circular economy, by adopting appropriate waste treatment and recycling technologies [17,18]. Ecological Modernization (EM) is applied as a framework for evaluating the effectiveness of various ecological solutions. The current EM evaluation frameworks used to assess the effectiveness of different ecological solutions focus on ecological efficiency and cleaner production [19]. This means EM focuses on using environmentally friendly technologies as a means to address climate change. Therefore, the EM approach ultimately focuses primarily on mitigation interventions, with very little focus on adaptation options for sustainable goals [20]. In aquaculture, assessing the sustainability of the environment and livelihood within a closed ecological system relies on a range of different indicators. The various water parameters (water depth, transparency, pH, dissolved oxygen, biochemical oxygen demand, and total dissolved solids) and soil parameters (electrical conductivity, organic matter, potassium, and phosphorus) in shrimp ponds were analysed to assess the relationship between shrimp production and environmental sustainability [21]. Additionally, some studies have focused on determining and measuring the quality of bottom soil to evaluate its suitability for aquaculture activities and the impact on soil quality [22,23]. A previous study measured and evaluated soil and water quality indicators across various farming systems in the Mekong Delta. The findings indicated that while the pH and salinity levels were suitable for prawn growth, they fell below the critical thresholds necessary for cultivating black tiger shrimp and white-legged shrimp. Furthermore, water alkalinity, dissolved nitrogen, phosphorus, and chemical oxygen demand did not significantly affect shrimp growth [24].

To achieve sustainable livelihoods for farmers, it is essential to establish a closed ecological system. This system can help maintain a balance between socio-economic development and environmental protection while reducing vulnerability to climate change. The Recirculating Aquaculture Systems (RAS) are a promising solution for improving waste management. They can also reduce water use, recycle nutrients, and support fish farming in areas with inadequate biophysical conditions (water scarcity, poor water quality, and unfavorable environments) [25,26]. For instance, they designed a sustainable energy system for shrimp farms in the Mekong Delta. This system promotes economically and environmentally sustainable production by utilizing aeration systems powered by renewable energy [27]. Additionally, implementing a hybrid zero water discharge (ZWD) and RAS system improves water quality, growth, survival, and productivity of super-intensive white shrimp culture at low salinity levels [28]. An integrated ecological system for catfish farming that combines livestock and crop cultivation was proposed [29]. This approach aims to treat waste from catfish ponds, effectively circulate nitrogen sources, and minimize nitrogen loss into the environment. Furthermore, the previous studies developed a closed ecological model for intensive catfish farming called AZEIS (Agro-based Zero Emission Integrated System). The system integrates livestock, cultivation, and fish farming within a closed system to address environmental pollution and create new livelihood opportunities for farmers [30,31].

This study utilizes environmental, economic, and social indicators to evaluate the current status of super-intensive shrimp farming households in a province of the Mekong Delta region. Proposing and implementing a closed ecological system that targets zero emissions and enhances sustainability for super-intensive shrimp farming.

2. Materials and Methods

2.1. Research Framework

This study aims to propose and implement a closed ecological system for super-intensive shrimp farming in the Mekong Delta, focusing on efficient material and energy circulation while minimizing environmental waste. The methodological framework is described in **Figure 1.** The study consists of three steps designed to assess the livelihood characteristics and sustainability of super-intensive shrimp farming:

1. Analyzing the livelihood characteristics of individuals involved in super-intensive shrimp farming.
2. Selection indicators to evaluate the environmental, economic, and social sustainability of a closed ecological system that promotes the circulation of materials and energy. The process of analyzing and selecting these indicators will provide insights into the sustainability of the super-intensive shrimp farming model.
3. Proposing and implementing an integrated ecological system to enable practical super-intensive shrimp farming, aimed at achieving sustainable development.

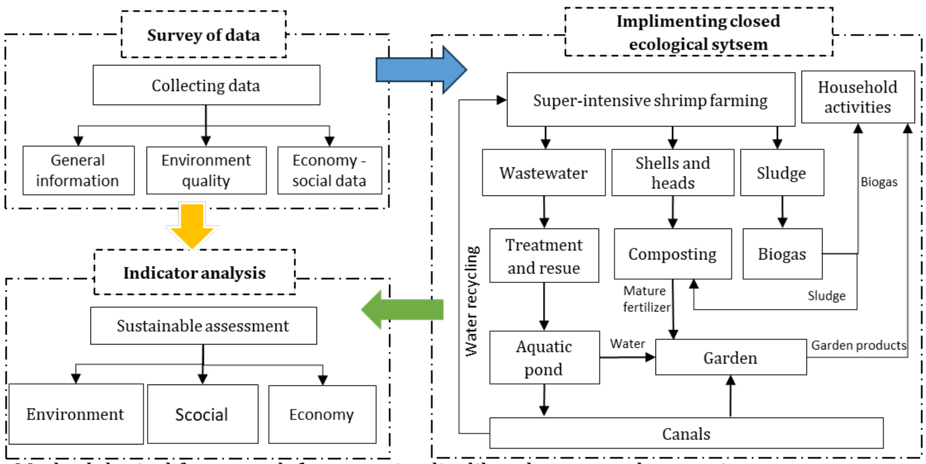

Figure 1. Methodological framework for assessing livelihood status and proposing a waste treatment system.

2.2. Case Study Background

This study surveys and investigates the current status of super-intensive shrimp farming, focusing on aspects such as pond management, stocking density, water supply, feeding practices, water change regimes, shrimp development stages, harvest timing, and shrimp yield (**Figure 2**). It includes collecting samples to assess the quality of the surrounding environment. A total of 36 shrimp farming households in Giao Thanh Commune–Thanh Phu District–Ben Tre Province were surveyed, which is a region known for its significant shrimp farming in the Mekong Delta. The in-depth interviews were supported by information forms that collected data on livelihood capital sources, development strategies, efficiency, and environmental impacts. The Thanh Phu District has been identified as an area for investment in high-tech shrimp farming, with developmental plans from 2021 to 2025. Data collection includes details on shrimp farming areas, sanitation costs, types of breeds, feed, medicine, energy use, costs associated with hiring external versus in-house labor, quantities of seed stocked, stocking density, survival rates, yield, selling prices, and other factors influencing shrimp farming activities. Additionally, the study conducts surveys on sources of waste, assesses water quality in ponds, and indicators of water pollution caused by shrimp farming practices in the research area.

(a) (b) (c) (d)

Figure 2. (**a**) Shimp Pond; (**b**) Sedimentation Pond; (**c**) Output Canal; (**d**) Siphong Canal.

2.3. Sustainability Indicators Selection and Analysis

The sustainability indicators were selected based on a proposed system for super-intensive shrimp farming, as well as observations from field visits in the study area. The indicators were chosen for their convenience and ease of data collection to ensure their effectiveness and significance. Selection involved analyzing the major issues and assessing the sustainability of the farming system. The research employed the dimensions-principles-criteria-indicators framework to develop these sustainability indicators [32]. The method is structured in a hierarchical manner that connects the indicators to the overarching principles of sustainability. Additionally, three dimensions were identified to evaluate sustainability: economic, environmental, and social sustainability. These principles were then broken down into criteria that correspond to the system's specific features or characteristics. A total of 18 indicators grouped into three dimensions (5 economic, 8 environmental, and 5 social), which are proposed for evaluating the sustainability of super-intensive shrimp farming in Ben Tre province, as shown in **Figure 3** and **Table 1**.

Table 1. Explanation of Indicators for Assessing Livelihoods and Environmental Sustainability.

	Standard	Index	Explain, Argue	Data Sources
		A/Economy		
Represents the total economic results brought about by about 2 shrimp farming crops in a year.	Indicators for assessing production value for super-intensive shrimp farming	GO, IC	The sustainability of the economy depends on the efficient use of financial capital to boost shrimp farms' profitability and return on investment, increase reinvestment rates, and improve ecosystem services.	On-site interviews, personal observations, and a combination of formula-based calculations.
Ensure efficient use of capital and profits, including externalities	Capital efficiency	NPe, AI, RII		

Table 1. Explanation of Indicators for Assessing Livelihoods and Environmental Sustainability.

	Standard	Index	Explain, Argue	Data Sources
		B/Society		
Improve local economies, jobs, workplace safety and food security.	Payment rate for people in local communities	Ge, LW, PCW	Social sustainability is based on local development, with benefits for local communities, while respecting their culture and habits.	On-site interviews and some secondary data from the shrimp pond area
	Performance level of aquaculture sector	PA, RR		
		B/Environment		
Ensure minimal environmental impact and maximum efficiency in resource use.	Level of use of space, water, energy and raw materials	S, W, E, N, P	Environmental sustainability is based on using the lowest amount of natural resources with maximum efficiency, and minimum negative impact on the surrounding environment.	On-site sample collection and subsequent measurements followed by laboratory analysis
	Efficiency in the use of raw materials and energy	EE, EN, EP		

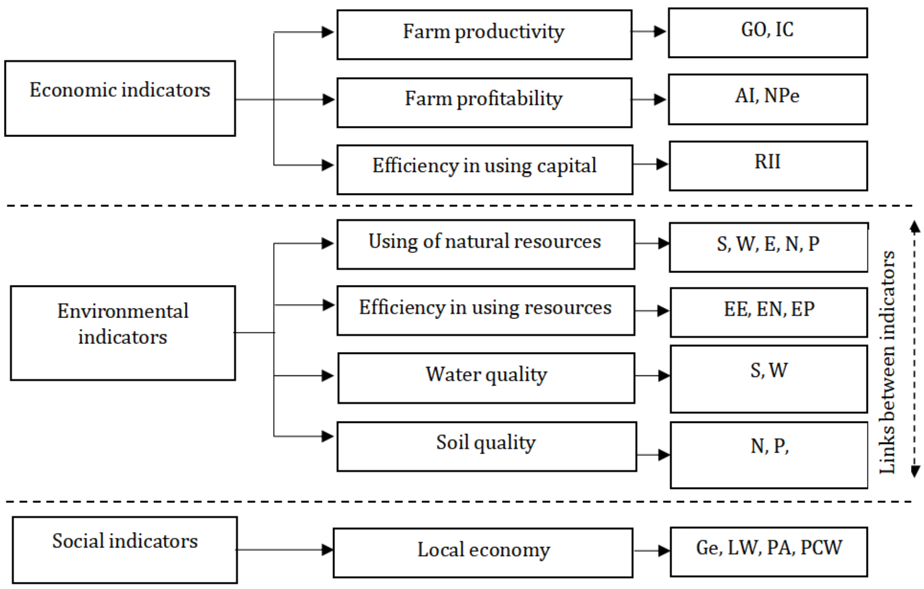

Figure 3. Indicators for Sustainability Assessment of Shrimp Farming.

Note: Abbreviations are presented in the sections below.
Source: Modified from some previous studies [21,32].

2.3.1. Economic Indicators Analysis

Economic indicators show the effective use of capital, economic feasibility, the ability to absorb negative external costs, the capacity of resilience, and the creation of financial resources for reinvestment [32]. The following indicators are proposed to measure and evaluate economic sustainability for shrimp farming.

Total Gross Output (G0)

GO is an index that represents the total results brought to shrimp farming households in a certain period of time.

$$GO = \sum Q_i * P_i \tag{1}$$

Where:

GO—Total Gross Output ($ or VND);

Q_i— Product Output (kg);

P_i—Price of the Corresponding Product ($ or VND/kg).

Intermediary Costs (IC)

The index (IC) is a measure that includes costs for sanitation, pond renovation, breeds, feed, medicine, energy use activities during farming, harvesting, and the costs of hiring outside labor, as well as using in-house labor.

Net Profit (NPe)

Net profit is a measure of shrimp farm profits after deducting all costs. It represents the actual profit and includes operating expenses subtracted from total income.

It can be expressed as:

$$NPe = GR - TPC \quad (2)$$

Where:

NPe—Net Profit ($ or VND);

GR—Total Revenue ($ or VND);

TPC—Total Production Costs ($ or VND).

Ratio between Initial Investment and Net Profit (RII)

The ratio between initial investment and net profit indicates the efficiency of capital investment in shrimp farming.

$$RII = \frac{NPe}{IC} \quad (3)$$

Where:

RII—Ratio between NPe and IC;

NPe—Net Profit ($ or VND);

IC—Intermediary Costs ($ or VND).

Annual Income (AI)

Annual income is defined as the sum of profit and opportunity cost. The taxes and fees vary depending on the location. Therefore, these two variables should be excluded when comparing systems in different areas. The AI index should be divided by farm area to compare farms of different sizes. It can be expressed as:

$$AI = GR - OC - D \quad (4)$$

Where:

AI—Annual Income ($ or VND);

GR—Total Revenue ($ or VND);

OC —Operating Expenses ($ or VND);

D—Depreciation ($ or VND).

2.3.2. Social Indicators Analysis

Social indicators reflected the ability to create benefits for local communities, including the number of jobs generated per ton of product and food security, equitable income distribution, equality of opportunity, and inclusion of vulnerable populations. The following indicators are proposed to measure and evaluate social sustainability for shrimp farming [32].

Participation and Gender Equity (Ge)

The (Ge) index measures the gender structure of employment in the shrimp farming activities of local people.

$$Ge = \sum \min(a,b) \quad (5)$$

Where:

Ge—Participation and Gender Equity (%);

Min—Minimum Value;

a—Number of Females in Total Number of Employees (workers);

b—Number of Males in Total Number of Employees (workers).

Use of Local Worker (LW)

$$LW = \frac{\text{Number of jobs employing local workers}}{\text{Total jobs created}} (\%) \quad (6)$$

Proportional Cost of Work (PCW)

The proportional cost of work shows that super-intensive shrimp farming is either labor-intensive or machine-intensive, which reduces the number of jobs. In family-based shrimp farming systems, family labor should be included.

$$PCW = \frac{\text{Labor cost + home}}{\text{Production costs}} (\$ \text{ or VND}) \quad (7)$$

Permanency (PA)

Average time per worker spent on aquaculture activities.

$$PA = \sum_{i=0}^{n} \frac{F_i}{n} \quad (8)$$

Where,

PA—Permanency (year);

F_i—Shrimp Pond Operation Time (year);

i—Shrimp Pond i^{th};

n—Total Number of Shrimp Ponds.

Risk Rate Assessment (RR)

Risk assessment is a thorough process to identify and analyze potential events that could negatively affect individuals or the environment.

$$RR = \frac{\text{Number of risk factors observed}}{\text{Number of risk factors analyzed}}$$

2.3.3. Environmental Indicators Analysis

Environmental indicators have been developed to reflect the efficient use of natural resources, as well as the composition of waste products and unused by-products that threaten genetic diversity and overall biodiversity. The indicators evaluate the use of natural resources such as space, water, energy, nitrogen, and phosphorus. The indicators measure the number of raw materials and energy required to produce each ton of mature shrimp, and the amount of pollutants from the super-intensive shrimp farming process per unit weight of shrimp. These indicators help assess the potential risks associated with resource consumption and waste generation at super-intensive shrimp farms.

Use of Space/Production (S)

The index (S) measures the area used (ha or m^2) per unit of production (kg or t)

$$S = \frac{\text{Usable area}}{\text{Production output}}(\text{ha/kg}) \quad (9)$$

Dependence on Water (W)

This indicator evaluates water use per unit of production, considering only water consumption (m^3). Water returned to the environment in a similar condition to its withdrawal is not counted as consumption, but if it is re-polluted, it should be considered consumed.

$$W = \frac{\text{Water consumption volume}}{\text{Production output}}(\text{m}^3/\text{kg}) \quad (10)$$

Use of Energy (E)

This index (E) quantifies the total energy used in various forms—including food, fertilizer, electricity, fossil fuels, and others—per unit of production.

$$E = \frac{\text{Energy used}}{\text{Production output}}(\frac{\text{MJ}}{\text{kg}}) \quad (11)$$

Use of Nitrogen (N)

$$N = \frac{\text{Amount of Nitrogen Used}}{\text{Production output}}(\text{gN/m}^3) \quad (12)$$

Use of Phosphorus (P)

$$P = \frac{\text{Amount of Phosphorus Used}}{\text{Production output}}(\text{gP/m}^3) \quad (13)$$

Efficiency in the Use of Energy (EE)

$$EE = \frac{\text{Energy recovery}}{\text{Production Energy}}(\%) \quad (14)$$

Efficiency in the Use of Nitrogen (EN)

$$EN = \frac{\text{Mass of Nitrogen recovered during the process}}{\text{Mass of Nitrogen used}}(\%) \quad (15)$$

Efficiency in the Use of Phosphorus (EP)

$$EP = \frac{\text{Amount of Phosphorus recovered during the process}}{\text{Amount of Phosphorus used}}(\%) \quad (16)$$

2.4. Design an Integrated Super-Intensive Shrimp Farming System

The idea for developing an integrated shrimp farming system in this study is based on previous studies. The zero-emission integrated system for super-intensive shrimp farming has been successfully implemented to effectively recycle nutrients in the form of matter and energy generated by waste flows. The main advantage compared with other conventional agricultural systems is the minimization of the wastewater treatment process, which meets Vietnamese national standards. Reducing waste treatment investment and operating costs for local farmers. In this study, the proposed system is based mainly on the treatment of wastes generated from super-intensive shrimp ponds (**Figure 4**). The waste generated from a water discharge by the siphoning process includes shrimp shells, shrimp manure, and leftovers from the pond. Shrimp shells or carcasses are collected for the composting process. The final compost is provided for orchard farming and replaces chemical fertilizer. The sediment (mud) contains a high concentration of pollutants, which are mainly nitrogen and phosphorus arising from the bottom of a super-intensive shrimp pond. This waste source is treated using the anaerobic process to create favorable conditions for converting toxic substances into easily absorbable and non-toxic forms. The biogas outlet from the anaerobic process can be used for household activities and reduce energy costs. The sludge sediment from biogas is combined with shrimp shells or carcasses for the composting process, and the effluent can be treated by aquatic ponds. In an aquatic pond, the floating and submerged aquatic plants treat wastewater exchanged from super-intensive shrimp ponds. The aquatic plants absorb the pollutants for their growth and development. Therefore, the pond can be applied as an available natural ecosystem for wastewater treatment in the shrimp pond. That could be considered an optimal solution to achieve economic and environmental benefits.

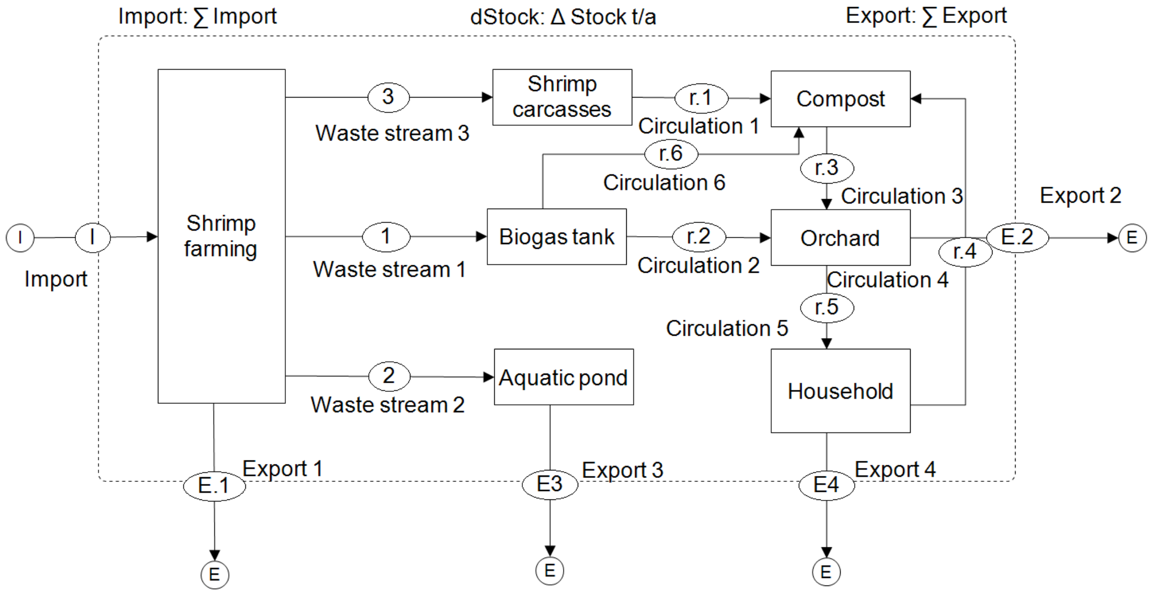

Figure 4. An Integrated Super-Intensive Shrimp Farming System.

3. Results

3.1. Current Status of Shrimp Farming Activities in the Study Area

In intensive farming conditions, larger and deeper ponds have a significantly greater ability to stabilize the environment compared to smaller and shallower ones. The average shrimp pond area surveyed was 0.79 ha. Of the surveyed households, 53% (19 households) had farming areas less than 0.5 ha. Additionally, 11 households had farming areas ranging from 0.5 to 1 ha, while 6 households had areas exceeding 1 ha, representing 17% of the total. The average depth of the white-leg shrimp ponds was recorded at 1.23 m, with the majority (66.7%) of ponds having depths between 1.0 and 1.2 m. All 36 farming households focused on raising white-leg shrimp. The farmers had an average age of 42.9 years, ranging from 30 to 62 years old. The age group from 35 to 45 years made up the largest segment (52.8%), followed by those over 45 years old (25%) and those under 35 years old (22.2%). Most farmers had 4 to 5 years of experience in white-leg shrimp cultivation, accounting for 52.8% of the respondents. The majority of male household owners is 91.7%, and the farming techniques used in their households are rooted in their experience raising black tiger shrimp or learning from one another. They also rely on fisheries extension documents, which reach 63.9%, and training courses, which reach 22.2%, while those who have attained education at the intermediate or university levels account for 13.9%. The government-organized technical training courses are viewed as one of the most effective channels for delivering new advancements in farming techniques to the community.

Despite the relatively large number of trained individuals, none of the households surveyed (100%) keep a diary to monitor their farming processes. A survey of 36 shrimp farming households revealed that all of them cultivate two crops each year: the first crop runs from January to May, and the second from June to December. The quantity of seeds released is determined by the surface area of the water used for shrimp farming and the density of the pond, which indicates the production capacity of each household. This is also closely linked to the amount of capital invested in aquaculture activities and serves as a measure of the risks shrimp farmers encounter.

Among the surveyed households, 22 shrimp farms (61%) use antibiotics to prevent diseases in their farmed shrimp, while 14 farms (39%) do not (**Table 2**). The current challenges in shrimp farming are disease and environmental issues, and many households have opted to periodically add antibiotics to their practices. However, this method poses the risk of antibiotic residues in seafood products, which could harm consumer health and negatively impact the reputation of Vietnamese seafood in the market[21,33].

Table 2. Statistics on the Use of Pesticides and Biological Products.

Factors	Number of Shrimp Farms	Ratio (%)
Wastewater Management and Treatment		
Yes	15	42
No	21	58
Use of Pesticides		
Yes	25	69
No	11	31
Pharmaceutical Products, Chemicals, and Biological Preparations		
Yes	0	0
No	36	100
Use of Antibiotics		
Yes	22	61
No	14	39

3.2. Current Status of Livelihood Sustainability of Shrimp Farmers

3.2.1. Economic Sustainability

The two indicators of total gross outcome (GO) and intermediate cost (IC) represent the total economic results achieved over a period of two crop cycles per year. The GO value ranges from $4686.79 to $421,676.98, with an average production value of $61,527.22. This indicates that the total production value from the two crops is relatively high. The intermediate costs range from $3281.28 to $304,278.57, with an average of $45,676.62. During the 2021 crop season, the focus of intermediate costs was primarily on seed selection and feed to enhance yields in the production process (**Figure 5**).

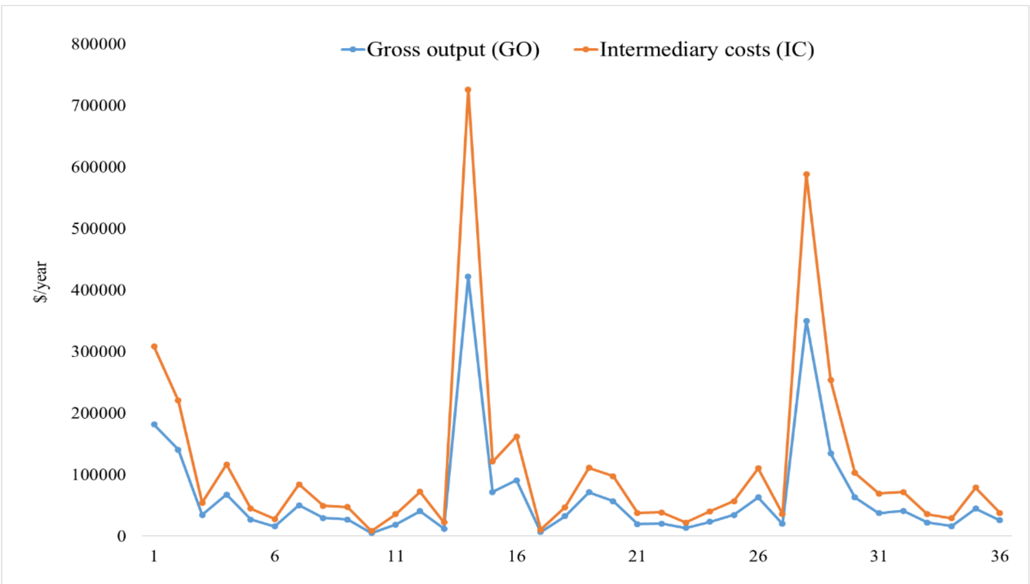

Figure 5. Graph showing total production value and intermediate costs.

The Net Income Index (NPe) values range from $1344.47 to $117,398.41, with an average net income of $16,762.79. The Annual Income (AI) values vary from $1187.40 to $76,502.10, resulting in an average annual income of $13,307.45. This indicates that the profit earned after deducting expenses such as capital, taxes, and depreciation is relatively high. The ratio between initial Investment and net Income (RII) is directly proportional to net income. Intermediary costs range from $3281.10 to $304,261.75. The average initial investment ratio is 0.44, demonstrating that intermediary costs can fluctuate significantly, constituting a large portion of the initial investment. The efficient use of capital and profit reflects the level of capital efficiency and externalities (**Figure 6** and **Table 3**). Compared with the productivity of organic shrimp, which was 383 lb/ha, the benefit-cost ratio was 1.91, indicating that organic shrimp farming is highly profitable [34].

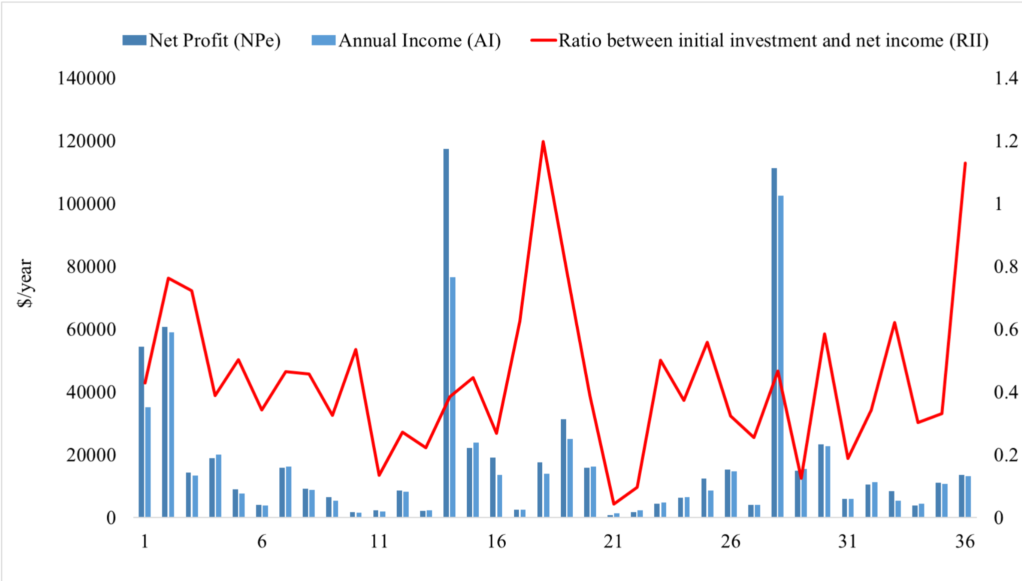

Figure 6. Graph showing net income and annual income.

Table 3. Indicators of Economic Sustainability.

Indicator	Value
Gross Output (GO)	64,619.59 $/year
Intermediary Costs (IC)	45,674.10 $/year
Net Profit (NPe)	18,945.50 $/year
Annual Income (AI)	16,374.40 $/year
Ratio between Initial Investment and Net Income (RII)	0.44

Note: Average values of the indicators of 36 shrimp farms.

3.2.2. Environmental Sustainability

The space used for production (S) and dependence on water (W) indicators are inversely proportional to production output. This means that (S) and (W) indicators increase, the required area and amount of water also increase to support the shrimp farming process. The average ratio of area used is 0.46 m^2/kg, while the average ratio of water used is 0.54 m^3/kg. The fluctuation for area used ranges from 0.32 to 0.58 m^2/kg, and for water used, it ranges from 0.38 to 0.7 m^3/kg. The farming with the highest area used ratio is at 0.58 m^2/kg, while the highest water used ratio is 0.7 m^3/kg, with the lowest water used at 0.38 m^3/kg. Therefore, this analysis assists in ensuring resource utilization at minimal levels while maximizing efficiency (**Figure 7**).

The energy use (E) and energy efficiency (EE) are measured at 45.32 MJ and 35.57%, respectively. The values ranged from 1.83 to 59.07 MJ for energy use and from 27.94% to 92.02% for energy efficiency. The primary sources of energy consumption are the energy used by the hourly working machines and the shrimp feed activity (**Figure 8**). The average nitrogen concentration in the pond environment is 19.26 g/m^3, with a range of 0.4 to 30.65 g/m^3. The highest nitrogen use efficiency of the three farms is reaching 76%, while one farm has the lowest at 57% (**Figure 9**).

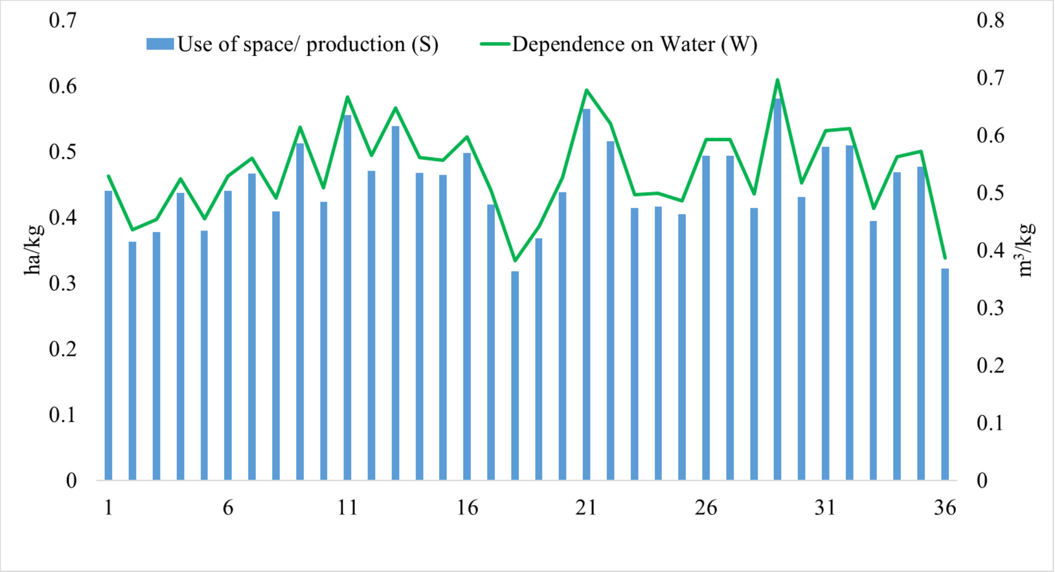

Figure 7. Area and Water Usage.

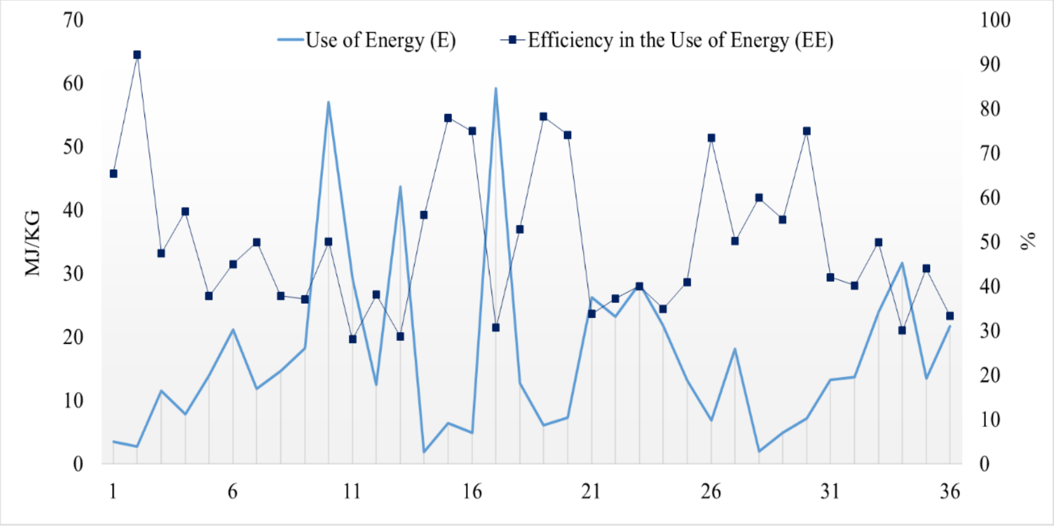

Figure 8. Energy and Energy Efficiency.

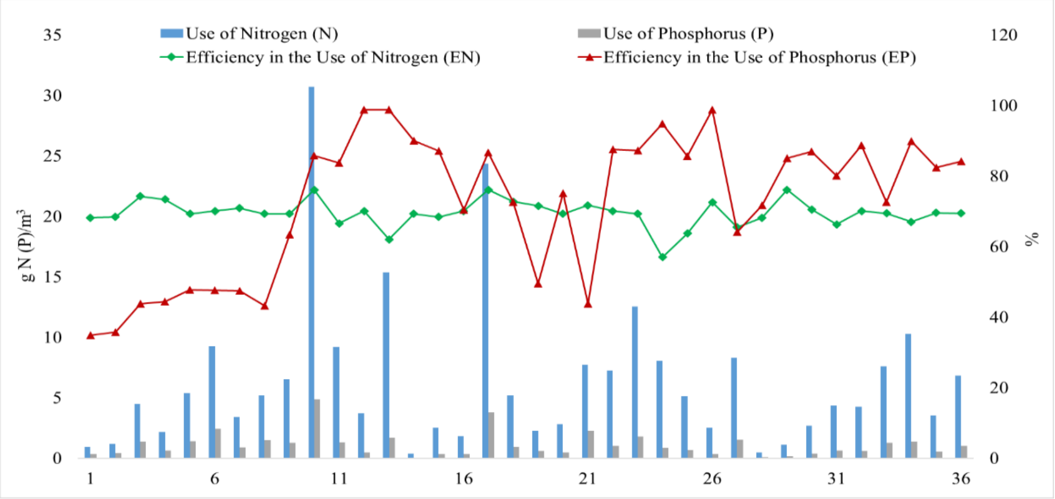

Figure 9. The Amount of Nitrogen, Phosphorus, and the Efficiency of Using Nitrogen Phosphorus.

Phosphorus levels in pond environments average 1.1 g/m^3, with a range of 0.05 to 4.85 g/m^3. The average phosphorus utilization efficiency is 72%, varying between 35% and 99%. The highest recorded phosphorus level on a farm is 4.85 g/m^3, while the lowest is 0.05 g/m^3. The highest phosphorus utilization efficiency is 99% among shrimp farms, while three farms have achieved the lowest recorded efficiency of 35% (**Figure 9** and **Table 4**). In general, the accumulation of organic and inorganic materials in ponds is unavoidable [4]. These accumulated substances originate from various sources: excess feed, animal waste, and organic matter from surrounding shorelines that wash into the pond with rainwater. The materials that accumulate in the pond can serve as both direct and indirect food sources for the cultured organisms.

Table 4. Indicators of environmental sustainability.

Indicator	Value
Use of Space/Production (S)	0.45 ha/kg
Dependence on Water (W)	0.54 m^3/kg
Use of Energy (E)	17.03 MJ/kg
Efficiency in the Use of Energy (EE)	49.86%
Use of Nitrogen (N)	6.37 g N/m^3
Efficiency in the Use of Nitrogen (N)	69.5%
Use of Phosphorus (P)	1.10 g P/m^3
Efficiency in the Use of Phosphorus (P)	72.5%

Note: Average values of the indicators of 36 shrimp farms.

3.2.3. Social Sustainability

The gender equality rate (Ge) is at 100%, indicating that the male and female workers are balanced. Equality is enhancing productivity and competitiveness by ensuring that both men and women workers have fair access to education and employment opportunities. The changing traditional livelihoods may affect gender imbalances in local employment [35]. When society minimizes stigma and discrimination against genders in the workplace, it can focus on evaluating individuals based on their skills and performance (**Figure 10**).

The farmer typically grows shrimp in ponds for an average of 4.5 years. They generally work around 8.5 h per day, though small-scale farmers may work longer hours by using family labor at home. The local workforce remains fully engaged in this process, as the demand for labor in shrimp farming is 100%. Despite this high demand, labor costs account for only 14% of total expenses, primarily because many farmers minimize these costs by employing family members for most tasks (**Figure 11**).

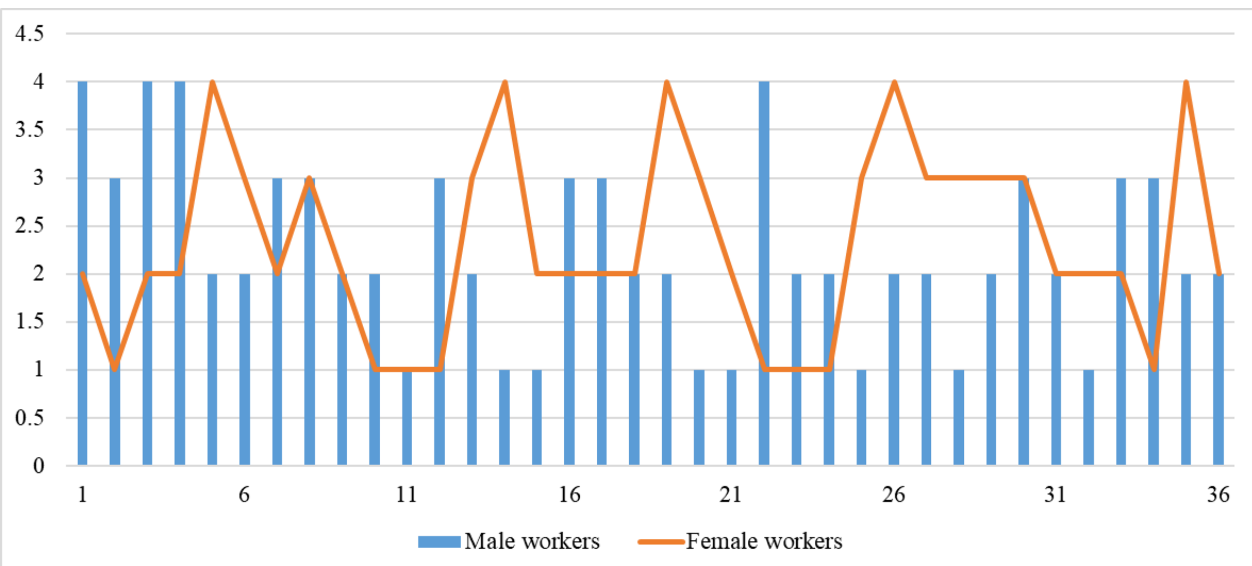

Figure 10. Gender Worker Ratio.

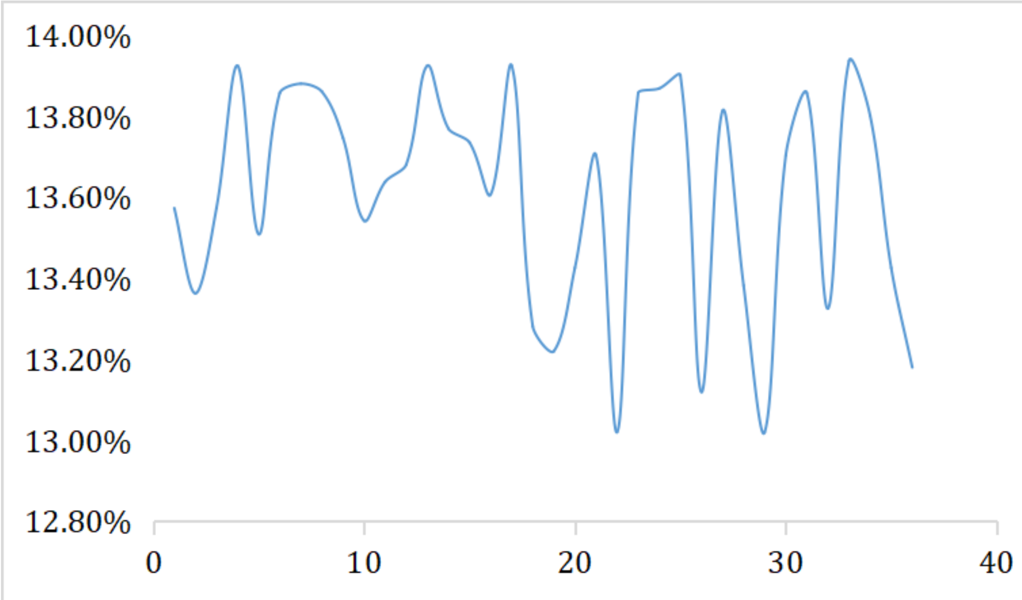

Figure 11. Proportional Cost of Work.

The five factors of risk rate assessment (RR) were identified as species extinction, diseases affecting species, saltwater intrusion into groundwater, water quality, and erosion of rivers and coastlines. If shrimp farming is managed properly by practitioners, the risk factors will be controlled (**Table 5**). This means that the activities in shrimp farming do not harm the environment. Sustainable management can lead to improvements in the local economy, job creation, workplace safety, and food security, ultimately helping local communities to thrive. Whiteleg shrimp farming is susceptible to 27 risks, with probabilities ranging from very low to very high and impacts on production and income ranging from mildly negative to catastrophic [36].

Table 5. Indicators of Social Sustainability.

Indicator	Value
Participation and Gender Equity (Ge)	100%
Use of Local Worker (LW)	100%
Proportional Cost of Work (PCW)	13.61%
Permanency (PA)	29.1 years (each pond)
Risk Rate Assessment (RR)	5 (number of risk factors observed)

Note: Average values of the indicators of 36 shrimp farms.

3.3. Sustainability of Closed Ecological System for Super-Intensive Shrimp Farming

Based on the results of the field survey, it was evident that the initial investment cost was lower than the total production value, indicating efficient capital use as reflected in the ratio between net income (NPe) and the initial investment. For small-scale shrimp farming households, the annual income index (AI) reached $253,565.19, which is 14 times higher than the income from the super-intensive system, which was $235,456.82. Implementing the closed super-intensive system improved material and energy circulation, positively impacting the household economy and increasing the workload associated with shrimp farming. Moreover, both male and female workers are able to engage in this work, which allows for 100% local employment, thereby reducing labor costs [21,33].

The super-intensive system of material and energy circulation requires an area of 0.09 ha per kilogram of water used, with a water consumption of 0.15 m^3/kg and an energy usage of 1.01 MJ. The nitrogen to phosphorus (N:P) utilization ratio is 0.27 to 0.05 (**Table 6**). The high efficiency in nutrient usage, with rates of 87% for nitrogen and 81% for phosphorus, indicates that the system fully utilizes these nutrients. This system demonstrates environmental sustainability, as assessed by various sustainability indicators based on production value. Aquaculture, while an inherently risky agricultural sector, fulfills its labor needs locally. The stability of operations is assured for a period of six years or more, allowing local workers to remain in their jobs without relocating. However, the proportional cost of work (PCW) is only 1.3%, suggesting that most labor is provided by family members. The younger generation is generally less interested in this work due to its demanding nature, even though the associated costs are relatively low. Improvements in equipment have led to a reduction in working hours to 16.77 h per week per laborer. Overall, the indicators for the closed super-intensive system of material and energy circulation are lower than those of the general super-intensive system. Notably, the super-intensive system shows greater efficiency in energy use, reflecting improvements in the energy consumption process throughout the operation.

Table 6. Economic, Social, and Environmental Sustainability.

Indicators	Traditional Shrimp Farming	Closed Ecology System for Shrimp Farming
	A. Economy	
Gross Output (GO)	$90,488.19	$1,015,935.30
Intermediary Costs (IC)	$67,535.03	$790,456.50
Net Profit (NPe)	$22,929.10	$191,290.76
Ratio between Initial Investment and Net Income (RII)	33.95%	17.16%
Annual Income (AI)	$18,103.55	253,497.78
	B. Social	
Participation and Gender Equity (Ge)	100%	100%
Use of Local Worker (LW)	100%	100%
Proportional Cost of Work (PCW)	14%	1.3%
Permanency (PA)	33.57 h/week	16.77 h/week
Risk Rate Assessment (RR)	5	4
	B. Environment	
Use of Space/Production (S)	0.50 ha/kg	0.09 ha/kg
Dependence on Water (W)	0.60 m^3/kg	0.15 m^3/kg
Use of Energy (E)	4.86 MJ	1.01 MJ
Efficiency in the Use of Energy (EE)	71%	87%
Use of Nitrogen (N)	1.84 g N/m^3	0.27 g N/m^3
Efficiency in the Use of Nitrogen (N)	70%	81%
Use of Phosphorus (P)	0.33 g P/m^3	0.05 g P/m^3
Efficiency in the Use of Phosphorus (P)	0.95	1.15

4. Discussion

The super-intensive shrimp farming system, which emphasizes material and energy circulation, has been successfully piloted at a typical shrimp farm. This approach allows farmers to proactively manage the water environment and control disease outbreaks while significantly increasing stocking density. In conventional super-intensive ponds, the stocking density ranges from 80 to 150 shrimp per square meter. However, with the new system focusing on material and energy circulation, this density can reach 200–500 shrimp m^{-2}, and in some cases, even up to 1000 shrimp m^{-2} [37]. Additionally, to reduce labor costs and enhance production efficiency, farmers can now use remote-controlled electronic equipment to automate key operations, such as the oxygen fan system and shrimp feeding machine. This automation enables farmers to manage these systems remotely, eliminating the need to be physically present at the pond. As a result, the number of workers needed has been reduced by half compared to previous practices [13].

The implementation of the closed super-intensive farming system, which emphasizes material and energy recycling along with increased farming density, resulted in a total production value index (GO) of $925,717.23. This figure is 11.2 times higher than that of the super-intensive farming system. However, intermediate costs (IC) increased by $723,113.68. The main contributor to this rise was the high feed cost, which accounted for 69.36% of the expenses, followed by seed purchases at

12.11%, and costs for medicine, chemicals, and biological products at 10.35%. Energy costs made up 1.87%, pond renovation costs accounted for 2.75%, and labor costs represented 1.29% [34]. To effectively reduce these costs, it is essential to enhance the water circulation and filtration capacity in the ponds as increased density necessitates better water management. This improvement would help save on the costs of chemicals, microorganisms, minerals, and overall energy consumption. The economic sustainability indicators will reflect differences in management capacity, the ability to use family labor, and the efficiency of resource use. The disparities also stem from factors such as selling prices and shrimp farming processes based on the farmer's accumulated experience. Thus, it can be affirmed that total costs are only a necessary condition for maintaining production, while revenue efficiency depends primarily on the scale of the aquaculture farm. Revenue efficiency is strongly influenced by the size and water surface area of the farm, the average selling price, and the ability to organize and manage resources. Therefore, super-intensive shrimp farms can achieve high economic efficiency even with low input costs if they optimize operational processes, recycle waste, increase product value, and manage costs effectively [36].

The closed ecological system for super-intensive shrimp farming includes waste treatment solutions aimed at nutrient circulation. The process for circulating matter and energy is organized as follows: Water is sourced from the canal and passed through a settling pond before entering the shrimp pond. During the water change process—where the normal exchange rate is 20–30%—wastewater generated is directed to the pond's wastewater tank. Additionally, sludge generated from the pond bottom during siphoning is pumped into the tank before being processed in the biogas system. A filter net with a mesh size smaller than 0.5 cm is used to collect dead shrimp and molted shrimp heads. The collected sludge is sent directly to the biogas system, which produces gas for household activities [2,7]. The wastewater that exits the biogas system is treated in a four-compartment treatment tank, which consists of: Settling, Catalyst, Microorganism, and Settling. Shrimp carcasses and the sludge remaining after biogas production are stored in a compost area, where they are composted along with biological products. This compost is then used by households as a substitute for chemical fertilizers, thereby improving soil quality with organic fertilizers. The sustainability of shrimp farming livelihoods is maintained through the closed ecological system of material and energy circulation at the household level. This system also addresses key issues related to socio-economic sustainability for families implementing it. The nitrogen remaining in the pond can be transformed into various forms, including dissolved inorganic nitrogen, organic nitrogen, or absorbed and converted by microorganisms. Previous research indicates that black tiger shrimp convert 15.6% of the nitrogen in their feed into shrimp nitrogen during the rainy season, and 24.8% during the dry season [38]. It is also estimated that only about 23–30% of nitrogen is converted from feed into shrimp biomass, while approximately 67.71–69.23% of the nitrogen from feed remains in the pond environment.

The gender equality rate (Ge) is 100% because the male and female populations are equal. This balance indicates increased productivity and competitiveness when both men and women have equal access to education and employment. The society reduces stigma and discrimination between men and women in the same workplace, evaluating job performance based on competence and efficiency rather than gender. As a result, fairness and justice in labor are promoted. The survey results show that most establishments have 2–4 workers, half of whom are part-time. The primary workforce remains family farm labor. The average period of shrimp farming activity (PA) for people in the intensive shrimp farming area is 29.1 years, reflecting their commitment to their livelihood from the past to the future. Difficulties affecting the long-term sustainability of livelihoods include the time and cost of operating ponds to ensure water quality meets standards, water supply treatment, and energy costs. The local worker rate (LW) in shrimp farming is 100%, explained by the fact that all labor is mobilized from local sources, mainly part-time workers, with the remainder coming from family members of the farming. The proportion of work (PCW) rate is 13.61% for super-intensive farming households, and most households utilize their own labor to minimize labor costs throughout the process [12]. The implemented system has proven effective in terms of environmental, economic, livelihood, and social benefits. However, without policy and financial support to bring the models to other localities, the scaling-up effect will not be significant. The lack of supportive policy will affect the sustainability of the implemented closed ecological system. Localities are looking to adopt the closed system and replicate it in similar-scale shrimp farms. Therefore, in the initial phase of expanding and developing the closed ecological system, support from local governments through production projects is needed to make the closed system easier for farmers and other localities to access.

5. Conclusions

Super-intensive shrimp farming in the Mekong Delta plays a significant role in increasing income and improving the livelihoods of local households. The research developed a theoretical framework for a closed ecological system for super-intensive shrimp farming. The system was implemented to evaluate actual efficiencies. The current state of super-intensive shrimp farming consumes a lot of energy and surface water resources and generates a relatively high amount of waste. After applying a closed ecological system for recycling materials and energy, the waste generated from shrimp farming is converted into a valuable product, minimizing environmental impact. This not only ensures sustainability but also increases productivity in shrimp farming in the region. The findings indicate that this system is not only feasible for large-scale commercial shrimp farming but also suitable for small-scale shrimp farming. This system is based on high market demand, available labor, and promising economic indicators. In this study, due to data and sample size limitations, the results could only assess the current status of super-intensive shrimp farming in one commune within the province. Although this commune is designated as a point shrimp farming area and planned for development into a high-tech shrimp farming zone, the farming processes and closed-loop ecological system are not yet suitable for the entire province due to differences in natural characteristics and livelihoods around the farming. In the future, a comprehensive study on environmental, economic, and social sustainability for the entire province needs to be conducted. The solutions for treating and recovering waste from shrimp ponds need further research, especially the effect of salinity in limiting the effectiveness of recovering nutrients from shrimp pond waste.

Author Contributions

Conceptualization, D.M.L.; methodology, D.M.L.; validation, N.T.P.T.; formal analysis, N.T.P.T. and N.V.T.; investigation, N.V.T.; data curation, N.T.P.T. and N.V.T.; writing—original draft preparation, D.M.L. and T.T.K.; writing—review and editing, T.T.K.; project administration, T.T.K. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Any data related to this study will be made available upon reasonable request.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

During the preparation of this work, the authors used Grammarly in order to check grammar, spelling, and improve sentences. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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