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RESEARCH

Promoting sustainable shrimp farming: balancing environmental goals, awareness, and socio-cultural factors in the Mekong Delta aquaculture

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Abstract
Shrimp farming in the Mekong Delta significantly impacts the environment, primarily through untreated effluents. This study evaluates environmental effects and socio-cultural factors influencing shrimp farming. Using the theory of planned behavior (TPB), 87 shrimp farming households across six coastal provinces we surveyed and analyzed data with exploratory factor analysis (EFA). Findings reveal critical water pollution concerns, with a substantial gap in adopting effective environmental measures. The feed conversion ratio (FCR) in intensive farming averaged 1.59, indicating feed inefficiencies. Water quality analysis showed 85.7% of farms rely on untreated river water, exacerbating pollution risks. Widespread antibiotic use and the presence of antibiotic-resistant genes highlight the urgent need for sustainable practices. Regression analysis indicated farmer attitudes significantly predict environmental concern and intentions toward sustainable practices, accounting for 66.6% of the variance in environmental concern. The study underscores the need for targeted interventions to enhance sustainable shrimp farming, emphasizing the role of attitude and awareness in environmental stewardship. These results provide a valuable framework for policymakers and practitioners to foster sustainability in aquaculture, benefiting both the environment and shrimp farmers' livelihoods through effective water treatment technologies.

Keywords Environmental impact · Mekong Delta · Shrimp farming · Sustainable aquaculture practices · Theory of planned behavior (TPB)

Introduction

Aquaculture, especially shrimp farming, plays a critical role in Vietnam's economic development, by generating employment and contributing significantly to exports. However, this industry also presents considerable environmental and social challenges. The rapid growth of shrimp farming in the Mekong Delta, with its extensive 750 km coastline, has exposed

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Extended author information available on the last page of the article critical issues in environmental management and protection, particularly regarding water pollution.

By 2022, the shrimp farming area in the region had expanded to 669,945 ha, with most farms cultivating white-leg shrimp (*Litopenaeus vannamei*) and giant tiger prawn (*Penaeus monodon*) (Hossain et al. 2013; Tung et al. 2024). The prevailing use of traditional farming methods often results in the misuse of antibiotics and banned substances to manage disease outbreaks, leading to significant water contamination and a decline in shrimp product quality (Nguyen Tan 2021; Van Khanh et al. 2023). Untreated wastewater discharged directly from shrimp farms is typically released into nearby canals and rivers without prior treatment, contributing to deteriorating water quality, affecting community health and biodiversity in the surrounding ecosystems (Páez-Osuna et al. 1998). Compounding these issues, climate change manifested through unpredictable weather patterns, extended periods of rain or drought, rising temperatures, and increased salinity further compromises shrimp health and overall farm productivity (Tan et al. 2020).

In addition to environmental concerns, shrimp farming faces socio-cultural challenges that influence farming practices. The knowledge and practices of shrimp farmers are shaped not only by environmental factors but also by cultural and social dynamics, including community expectations and economic incentives (Franco et al. 2018). However, there is a notable gap in understanding how these socio-cultural factors affect farmers' behaviors and decisions related to environmental management, creating a need for more comprehensive research (Diep et al. 2022).

Implementing sustainable solutions in shrimp farming requires more than reducing pollution. It is essential to address the underlying behavioral patterns and attitudes of farmers, as these influence the effectiveness of environmental protection measures (Joffre et al. 2018; Tran et al. 2024a). The perception, attitudes, and decision-making processes of farmers determine whether sustainable practices, such as wastewater treatment, are adopted. Research has shown that raising awareness about environmental risks and demonstrating economic benefits can positively impact farmers' willingness to adopt sustainable technologies (Emerenciano et al. 2013).

Central to sustainable shrimp farming is the concept that "farming shrimp is essentially farming water." This philosophy highlights the importance of monitoring and managing water quality to create optimal conditions for shrimp growth while minimizing the need for antibiotics and chemicals (Ng et al. 2018; Van Rijn 2013). Maintaining a clean water environment not only enhances shrimp health but also ensures compliance with environmental standards, thereby supporting long-term farm productivity.

To improve sustainability, it is necessary to revisit farming processes (Cortés et al. 2021), optimize input materials, and reduce environmental stressors, such as nutrient pollution and chemical overuse. Effective water quality management ensures the stability of shrimp habitats and reduces the spread of diseases, contributing to higher product quality and profitability (Seethalakshmi et al. 2021). In this context, comprehensive intervention strategies that address both environmental and socio-cultural factors are essential for promoting sustainable practices. Understanding farmers' motivations whether driven by economic incentives, environmental concerns, or community expectations can guide the design of targeted policies and practical solutions for sustainable shrimp farming.

To effectively address environmental pollution and promote sustainable practices in shrimp farming, it is essential to understand the diverse motivations driving farmers' decisions, including economic incentives, awareness of environmental impacts, compliance with regulations, and social pressures from the community. Recognizing these factors alongside their behavioral patterns enables the development of targeted interventions that align environmental goals with the farmers' practical needs and aspirations. The theory of planned behavior (TPB) provides a robust framework for examining social and behavioral factors influencing farmers' acceptance of sustainable practices (Rozenkowska 2023). TPB focuses on attitudes toward behavior, subjective norms, and perceived behavioral control. Firstly, farmers' attitudes toward adopting wastewater treatment technologies can be improved by raising awareness about their economic and environmental benefits (Khanpae et al. 2020; Le et al. 2024a, b). If farmers perceive that these technologies enhance productivity and reduce environmental impacts, they will have a more favorable attitude toward adoption (Liu et al. 2018; Meijer et al. 2015). Secondly, subjective norms, referring to social pressures from family, friends, and the community, significantly influence behavior (Hall and Rhoades 2010). If farmers feel supported and valued by their social circle and community for adopting wastewater treatment technologies, they are more likely to implement these practices (Biesheuvel et al. 2021). Thirdly, perceived behavioral control, which involves the ease or difficulty of performing the behavior, is crucial (Li et al. 2023). Providing training and technical support increases farmers' confidence in using new technologies (Tama et al. 2021). Additionally, minimizing perceived risks associated with new technologies encourages acceptance, as farmers are more likely to adopt innovations if they believe these technologies are safe and low-risk. Combining TPB insights with sociological surveys will help understand the challenges shrimp farmers face and how socio-cultural factors influence their adoption of environmental protection measures (Ulhaq et al. 2022). This integrated approach can develop effective strategies to promote behavior change toward more sustainable practices. By applying TPB, the study aims to identify key drivers behind shrimp farmers' behavior, facilitating the establishment of effective wastewater treatment systems and promoting sustainable aquaculture practices (Diep et al. 2022; Dong et al. 2022; Ulhaq et al. 2022).

This study offers a comprehensive perspective on the relationship between shrimp farming practices and their environmental impacts from a socio-cultural viewpoint, an area not previously focused on in depth (Tarunamulia et al. 2023). By integrating sociological analysis with the theory of planned behavior, it presents a novel approach to identifying and addressing environmental challenges in shrimp farming. This not only fills a significant knowledge gap in environmental science but also aids in the development of practical, sustainable intervention strategies. Focusing on the socio-cultural factors affecting shrimp farming practices and their environmental impacts (Wang et al. 2019), this research opens up new and significant avenues of study. Moreover, proposing solutions based on scientific evidence contributes to enhancing the sustainability of the shrimp farming industry, not just in the Mekong Delta but also in similarly conditioned regions. This contribution is valuable both scientifically and practically, supporting policy formulation and improved practices aimed at sustainable development.

Materials and methods

Location of research and survey

The research was conducted in the coastal provinces of the Mekong Delta, as shown in Fig. 1. The surveyed provinces, which have significant coastal shrimp farming areas, include Tien Giang, Ben Tre, Tra Vinh, Soc Trang, Bac Lieu, and Ca Mau. Concentrating

Fig. 1 The research area encompasses coastal shrimp farming provinces in the Mekong Delta (Vietnam)

the survey in these regions allows for a focused examination of the environmental and socio-cultural dynamics specific to intensive shrimp farming areas.

To ensure comprehensive data collection, the positions of shrimp farms were recorded using GPS. A total of 95 shrimp ponds were visited and surveyed across these provinces. The selection of these locations was recommended by agricultural extension officers from local government agencies. The officers suggested these particular farms because they are managed by long-standing shrimp farming households, which are likely to provide more accurate perspectives and reliable data. By focusing on these experienced farmers, the research can yield insights that are directly relevant and potentially generalizable to similar contexts, thereby offering practical solutions and informed policy recommendations for sustainable shrimp farming practices.

Survey form and survey content

The questionnaire was composed of five sections, targeting shrimp farming households as the primary respondents. The general information section included questions designed to collect additional details about respondent characteristics, such as gender, age, and years of experience (Trang et al. 2022). The detailed questionnaire is available in the supplementary materials.

Subsequent sections delved into descriptions of the farming operations (Diep et al. 2022; Thi and Ninh 2021). This part aimed to provide basic information about the shrimp farms, utilizing various types of questions, such as informational queries and yes–no formats, to gather data on the scale of shrimp farming operations, the type and model of farming practiced, the species of shrimp being farmed, pond preparation prior to stocking, current conditions of shrimp ponds, control over stocking sizes, and the allocation of area across ponds. Information on farming processes collected included water sources for input, criteria and thresholds for input control, seed stock used, types of feed typically utilized at the farm, and daily feed additives mixed for shrimp.

Management information during the shrimp farming process encompassed daily water quality checks, disease management and treatment, water pumping and recirculation rates throughout the farming period, water treatment or recycling for reuse, and shrimp harvesting.

The final section addressed potential environmental issues surrounding the farms. It included questions designed to collect data on farmers' environmental concerns and attitudes toward sustainable practices, using a 5-point Likert scale ranging from (1) "Not at all concerned," (2) "Not concerned," (3) "Neutral (no opinion)," (4) "Concerned," to (5) "Extremely concerned" (Patin and Riedel 2011). The question design in this section was based on the theory of planned behavior (TPB). The study employed an empirical research model proposed within the TPB framework (Ajzen 1991; Croasmun and Ostrom 2011) which included three main factors influencing environmental concern: "attitude," "awareness," and "objective difficulties." Additionally, the study analyzed the influence of "Concern" on the "Intention to Implement" environmental protection measures. Figure 2 depicts the proposed research model based on the TPB.

The minimum sample size for the study to achieve reliability was determined using a mandatory formula. The sample size was calculated based on the requirements of exploratory factor analysis (EFA): N (total sample) $= 5 \times \mathrm{m}$, where m represented the number of questions (Tran et al. 2024a, b). This formula, referenced from the research of Hair et al. (1998), suggested that the minimum sample size should be five times the total number of observed variables for the independent factors. This approach was deemed appropriate for studies utilizing factor analysis. This sample size is appropriate for studies utilizing factor analysis (Comrey et al. 1973). Given that shrimp farming households served as the survey subjects, access and data collection were more challenging compared to standard social interviews. The survey comprised a total of 15 questions, resulting in a minimum required

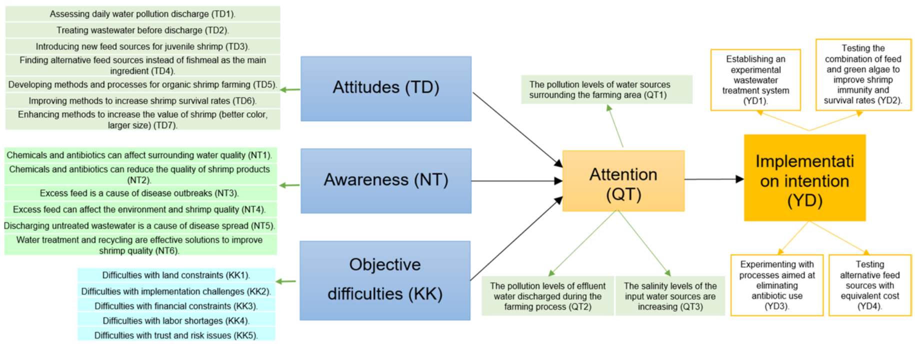

Fig. 2 Proposed research model identifying factors influencing environmental concern and intentions among shrimp farming households, based on theoretical underpinnings

sample size of 15×5=75 responses. Although 95 valid survey responses were collected, only 87 were included in the final analysis due to incomplete information or failure to meet the reliability criteria.

In this study, multiple interrelated variables were collected and analyzed. EFA was employed to examine these relationships and to identify variables that loaded on multiple factors or were initially misclassified (Stapleton 1997). The reliability of the exploratory factors was tested using Cronbach's Alpha (α), with acceptable values ranging between 0.6 and 0.95 (Gebremedhin et al. 2022), which assesses the reliability of each scale by analyzing the fit of each questionnaire item. This method assessed the reliability of each scale by analyzing the fit of individual questionnaire items. Subsequently, EFA was used to condense a set of observed variables into a smaller, more meaningful set of factors, offering insights into the variables influencing environmental concern and intention. These findings provided a foundation for proposing environmental protection solutions, such as wastewater treatment systems.

Additionally, correlation analysis was conducted to understand the relationship between two variables without distinguishing between independent and dependent variables. Regression analysis was performed to predict the dependent variable based on known values of one or more independent variables, indicating the degree of correlation between exploratory factors and the intention to adopt environmental protection measures among shrimp farming households.

Data processing and statistics

The map of the survey locations was compiled using Google Earth Pro and transferred to ArcGIS 10.5 (ESRI) for map construction. Raw data from the questionnaires were carefully inputted into Excel 2021 for preliminary analysis, including data cleaning and basic descriptive statistics to understand the demographic and operational characteristics of the shrimp farming households.

Subsequent in-depth statistical examination was conducted using SPSS 20. Descriptive analysis of all study variables was performed, where frequency and percentage were used for categorical variables, and mean and standard deviation, along with minimum and maximum values, were obtained for continuous variables. EFA was utilized to identify underlying factors affecting environmental concerns and sustainable practices among shrimp farmers. The reliability of measurement scales was evaluated using Cronbach's Alpha to ensure internal consistency. Pearson correlation and regression analyses were conducted to explore the relationships between various factors, such as environmental management practices, operational challenges, and farmers' intentions to implement sustainable measures. Statistical significance was determined with a 95% confidence interval (CI) and a p value of < 0.05.

Results and discussion

Characteristics and experience of shrimp farming households

Table 1 provides an overview of the demographic and professional characteristics of the surveyed shrimp farming households ($N = 87$). The data illustrate key aspects such as age distribution, gender composition, years of experience in aquaculture farming, and familial involvement in the profession.

The demographic and professional characteristics of shrimp farming households offer critical insights into the sustainability and challenges of shrimp farming in the Mekong Delta. The data indicate that shrimp farming is predominantly managed by middle-aged individuals, with 40.2% aged 30 to 45 years and 28.7% aged 45 to 60 years. This demographic trend underscores the physically demanding nature of the profession (Thi and Ninh

Table 1 Sample characteristics of shrimp farming households ($N = 87$)

Characteristics	Number	Percent
Age group (years)		
Less than 18	0	0
18–23	2	2.3
24–29	19	21.8
30–45	35	40.2
45–60	25	28.7
Over 60	6	6.9
Gender		
Female	8	9.1
Male	79	90.9
Aquaculture farming experience (years)		
Less than 2 years	10	11.5
From 2–5 years	23	26.4
From 10–15 years	37	42.5
From 15–20 years	13	14.9
From 5–10 years	3	3.4
Over 20 years	1	1.1
Have family members (relatives) involved in shrimp and aquaculture farming		
No	28	32.2
Yes	59	67.8

2021), requiring robust health and resilience to manage the day-to-day operations and risks involved.

The gender distribution highlights a significant male dominance in shrimp farming, with 90.9% of respondents being male. This gender disparity can be attributed to the technical and physical demands of the job, suggesting a potential area for policy intervention to support and encourage female participation in this sector.

Experience in shrimp farming is a critical factor contributing to the success or failure of a farming cycle. Accumulated over years and through learning from peers, more experience allows individuals to better understand their farming subjects (Ulhaq et al. 2022). Among the 87 surveyed samples, “10 to 15 years” of experience was the most common, with 37 responses accounting for 42.5%. This was followed by “2 to 5 years” at 26.4% and “15 to 20 years” at 14.9%. Longer experience was less common, with “over 20 years” at 1.1% and “less than 2 years” at 11.5%. The accumulation of experience is crucial for the effective management of shrimp farming, as it enables farmers to make informed decisions regarding seeding, feeding, and overall farm management. This wealth of experience contributes to the resilience and adaptability of farmers in the face of environmental and market challenges.

A notable 67.8% of households reported having family members involved in shrimp and aquaculture farming. This familial involvement facilitates the transfer of knowledge and skills across generations, fostering a collaborative and supportive farming environment. Such a network not only enhances the practical expertise of individual farmers but also strengthens the community’s overall capacity to adopt sustainable practices.

The reliability of this survey is bolstered by the comprehensive demographic data and the detailed account of farming experience. By capturing a broad spectrum of age groups, gender, and years of experience, the survey provides a holistic view of the current state of shrimp farming in the Mekong Delta. Understanding these characteristics is pivotal for shaping sustainable farming practices. The predominance of experienced, middle-aged male farmers suggests a need for targeted interventions to support aging farmers and promote gender inclusivity in the region (Van Niekerk et al. 2015). This robust dataset is instrumental in guiding future research and policy development aimed at promoting sustainable aquaculture practices. Additionally, the strong familial connections within the farming community highlight the importance of intergenerational knowledge transfer, which can be leveraged to enhance the adoption of innovative and sustainable farming techniques.

In summary, the insights gained from this survey underscore the critical role of demographic and experiential factors in the sustainability of shrimp farming. By addressing the identified challenges and leveraging the strengths of the farming community, stakeholders can develop more effective strategies to promote sustainable aquaculture practices in the Mekong Delta.

Characteristics and operational characteristics of shrimp farming households

The majority of white-leg shrimp farming areas range from 0.5 to 3 ha, with 0.5 to 1 ha accounting for 40.2%, and 1 to 3 ha comprising 35.6% (Table 2). Areas larger than 3 ha are the least common among the surveyed households. Larger areas can potentially yield higher profits, but they also pose greater management challenges such as disease control, environmental factors, and increased labor costs, leading to higher risks in the profession.

Table 2 Characteristics of shrimp farming practices and models ($N = 87$)

Characteristics	Number	Percent
Pond area (ha)		
Below 0.1	0	0
0.1–0.5	20	23
0.5–1	35	40.2
1–3	31	35.6
Above 3	1	1.1
Types of ponds		
Raising shrimp in earthen ponds or covered with tarpaulin	87	100
Shrimp farming in cement tanks	0	0
Shrimp farming in rice fields	0	0
Stake trap, Cage or Net enclosure farming	0	0
Type of shrimp farming model used		
High-tech greenhouse shrimp farming	1	1.1
Improved extensive shrimp farming	10	11.5
Super-intensive shrimp farming	60	69
Semi-intensive shrimp farming	15	17.2
Extensive shrimp farming	1	1.1
Types of shrimp providing main income		
White-leg shrimp	82	94.3
Black tiger shrimp: 4 (4.7%)	5	5.7
Giant freshwater prawn: 0 (0%)	0	0
Lobster: 0 (0%)	0	0

Consequently, most farmers limit their farming area to a moderate size and opt for high-density farming.

With technological advancements, various modern shrimp farming models have emerged, including intensive and super-intensive systems like Biofloc technology, low water exchange shrimp farming, two-phase shrimp farming, and indoor shrimp farming in greenhouse structures (Emerenciano et al. 2013; Van Wyk 2001). However, traditional farming methods using earthen ponds, where water and feeding are controlled manually, still prevail. All surveyed households use earthen ponds or ponds covered with tarpaulin (Table 2). In these traditional models, farmers often struggle to control the use of chemicals and antibiotics due to a lack of water quality monitoring. Frequent changes in water quality due to the influence of soil properties cause fluctuations in the living environment and pose significant risks to shrimp (Van Tan and Thanh 2021).

The type of shrimp farming model used by the households includes super-intensive shrimp farming (69%), semi-intensive shrimp farming (17.2%), improved extensive shrimp farming (11.5%), high-tech greenhouse shrimp farming (1.1%), and extensive shrimp farming (1.1%) (Table 2). Among the surveyed households, super-intensive shrimp farming (69%) was the most prevalent. While this method is highly productive, it poses significant environmental risks due to the intensive use of feed and chemicals, which can lead to water pollution and disease outbreaks. Additionally, many farms that share the same water source exacerbate the spread of pollution and diseases, further highlighting the environmental challenges associated with super-intensive farming. This preference for high-intensity methods reflects a focus on maximizing productivity but underscores the urgent need for sustainable practices to mitigate environmental impacts (Khiem et al. 2022; Nguyen et al. 2019). Achieving sustainable shrimp farming will necessitate the integration of best practices from both intensive and extensive models, supported by appropriate policies and investments in sustainable technologies. Additionally, ongoing education and training for farmers on sustainable practices will be crucial to mitigate environmental impacts while maintaining productivity (Development 2017; Hoa et al. 2011; Tong et al. 2004; Washim et al. 2020).

The data in Table 2 indicate that white-leg shrimp (*Litopenaeus vannamei*) is the predominant species contributing to the main income at the surveyed farms, with 94.3% of households relying on it as their primary source of revenue. This overwhelming preference for white-leg shrimp can be attributed to its faster growth rate, higher survival rate, and adaptability to various farming conditions, which make it a highly lucrative choice for farmers (Ngoc et al. 2023). In contrast, black tiger shrimp (*Penaeus monodon*) accounts for only 4.7% of the primary income sources. Although black tiger shrimp is valued for its larger size and higher market price, its lower prevalence suggests that it may be less favored due to higher susceptibility to disease and more demanding farming requirements. No households reported relying on giant freshwater prawn or lobster as their main income sources, indicating a clear focus on species that are more commercially viable and easier to manage in the local farming conditions. The absence of these species could also reflect the specific market demands and environmental conditions that favor the cultivation of white-leg shrimp and, to a lesser extent, black tiger shrimp.

Table 3 provides a comprehensive summary of pond areas and durations among the surveyed households. The average pond area for each household is 3485.6 m (approximately 0.35 ha), with a standard deviation of 1077 m^2. This indicates that most farms operate within a similar size range, facilitating comparable management practices and operational challenges. The time since the last pond construction, on average, is 0.78 years, suggesting recent expansions or new entries into shrimp farming, while the longest duration of pond usage is 24 years, indicating established farming practices among some households.

The duration of pond usage among households shows significant diversity, with an average of 5.42 years and a range from 1 to 24 years. This variability highlights the mix of both newly established and long-standing ponds within the community. Longer-established ponds benefit from accumulated knowledge and stability, while newer ponds might incorporate modern technologies and practices aimed at improving productivity and sustainability. The recent establishment of new ponds indicates that many farmers are expanding their operations, possibly driven by market demand and advancements in shrimp farming technology. However, this expansion brings environmental considerations. New ponds can be designed with better environmental controls and sustainability measures, but the rapid

Table 3 Statistical summary of pond areas and duration in shrimp farming

Statistics	Average area of each pond (m^2)	Time since last pond construction (years)	Longest pond usage duration (years)
Valid	87	87	87
Mean	3485.6	0.78	5.42
Std. Deviation	1077	0.76	4.01
Min–Max	350–6000	0–3	1–24

increase in pond areas can also lead to greater environmental pressures if not managed properly.

To achieve sustainable shrimp farming, it is essential to balance the introduction of new ponds with the maintenance and optimization of existing ones. Long-term planning, along with investments in sustainable practices such as proper waste management and water quality monitoring, is crucial to mitigate the environmental impact of both new and old ponds.

Current status of water quality management in shrimp aquaculture

Water sources for shrimp ponds are limited, primarily relying on just two types: groundwater and river water. The majority of farmers, at 90.5%, use river water for shrimp cultivation, while the remaining 9.5% use well water. The river water, being the main source, carries risks and is not guaranteed to be free from excess feed, antibiotics, and residual chemicals discharged untreated into the environment by other shrimp farms (Khiem et al. 2022). Farmers generally perceive this water source as "stable" and "clean to a good extent." However, to ensure the stability and sterility of the incoming water, treatment methods are indispensable.

Figure 3 shows that the survey results indicate that most farmers treat the water before stocking shrimp, recognizing this as a crucial step to minimize risks. The primary treatment methods aim to stabilize pH, address turbidity, eliminate pathogens and crustaceans, and create an environment rich in minerals and natural food for shrimp.

Throughout the shrimp farming process, to mitigate risks from poor water quality and enhance productivity, it is vital for farmers to accurately and continuously monitor pond water quality, implementing timely measures in case of anomalies. This also reflects the growing concern among farmers about the quality of the water entering and leaving the ponds and its impact on the surrounding environment. The most monitored parameters by farmers are pH, salinity, and turbidity, with 90.5% of farmers regularly checking these indicators. The control of $N\text{-}NO_3$ levels is less common, with only 78.6% of farmers monitoring this parameter. Furthermore, water quality assessment is not yet comprehensive, lacking important microbiological indicators such as *Coliform* and *Escherichia coli*, which are critical to ensure a disease-free environment in shrimp farming (Devadas et al. 2023).

Figure 4 provides an overview of the frequency with which shrimp farmers monitor key water quality parameters essential for maintaining shrimp health and ensuring product quality. These parameters include pH, dissolved oxygen (DO), alkalinity, salinity, and turbidity, which have a direct impact on shrimp health. Most farmers (67%) monitor these parameters twice daily, except for turbidity, which is monitored with the same frequency by 55% of farmers. Daily monitoring is also prevalent, with 79% of farms monitoring pH, 84% monitoring DO and alkalinity, and 79% monitoring salinity and turbidity. In contrast, parameters that primarily reflect the general condition of the aquatic environment, such as ammonia, nitrite ($N\text{-}NO_2$), nitrate ($N\text{-}NO_3$), and hydrogen sulfide (H_2S), are monitored less frequently.

Figure 5 shows that twice-daily monitoring rates for these environmental parameters are relatively low, with ammonia at 26%, nitrite at 17%, nitrate at 14%, and hydrogen sulfide at 14%. However, daily monitoring rates are higher, with 48% of farmers monitoring ammonia, 43% monitoring nitrite, 38% monitoring nitrate, and 40% monitoring hydrogen sulfide. These findings indicate that farmers prioritize parameters directly associated with shrimp health and productivity over those related to the broader aquatic environment.

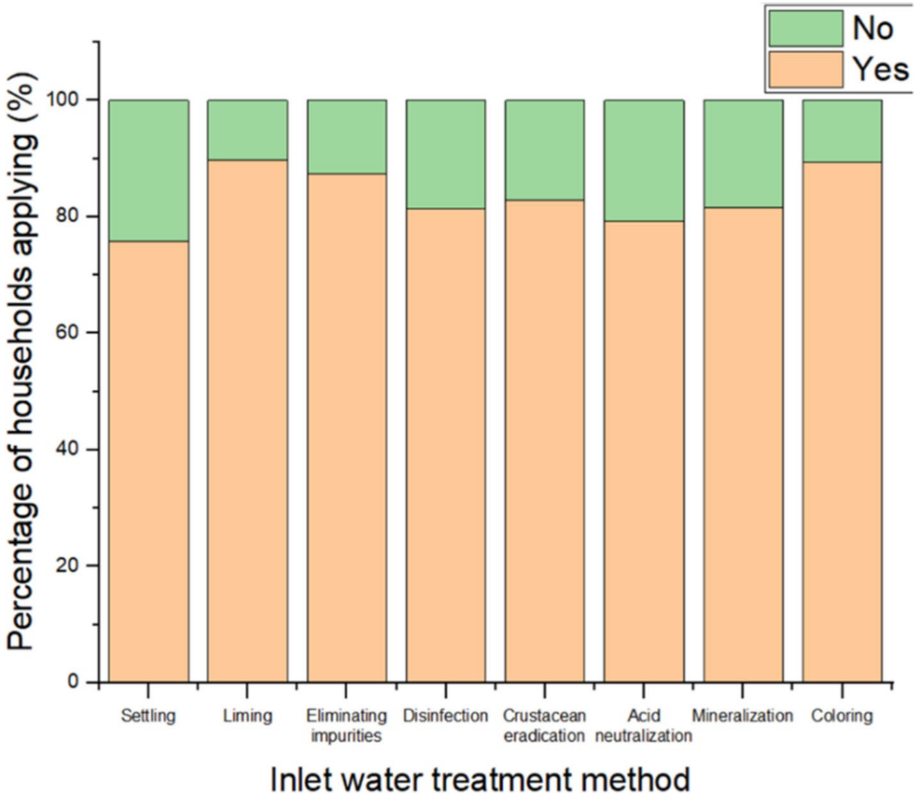

Fig. 3 Water treatment methods employed by shrimp farming households for incoming river water before introduction into shrimp ponds

It is observed that farmers pay less attention to parameters directly indicating the pollution level of pond water, likely due to a lack of technical expertise and the expensive equipment required for such tests. However, this trend can be explained by the farmers' focus on immediately observable indicators that directly affect the shrimp, potentially leading to the risk of sudden water pollution and mass shrimp deaths. Moreover, the uncontrolled discharge of shrimp farming wastewater by many farms can pollute the receiving environment. This wastewater is also the water source for neighboring farms (Khiem et al. 2022); if not properly managed and treated, it can adversely affect the shrimp. Furthermore, the organic waste load in shrimp ponds originates from excess feed, shrimp excrement, antibiotics, etc. The wastewater from shrimp ponds contains high levels of compounds like nitrogen and phosphorus, and nutrients, creating favorable conditions for the growth of pathogenic bacteria and viruses (Iber and Kasan 2021).

This suggests that wastewater treatment from shrimp ponds is crucial (Ng et al. 2018), as the effluents are negatively impacting the natural environment, particularly in the Mekong Delta region. For small-scale shrimp farming households and family-owned ponds, there is an absence of specialized wastewater treatment systems. Consequently, organic waste and medications used in the ponds are often directly discharged into external sources without any treatment. The survey results shown indicate that a staggering 85.7%

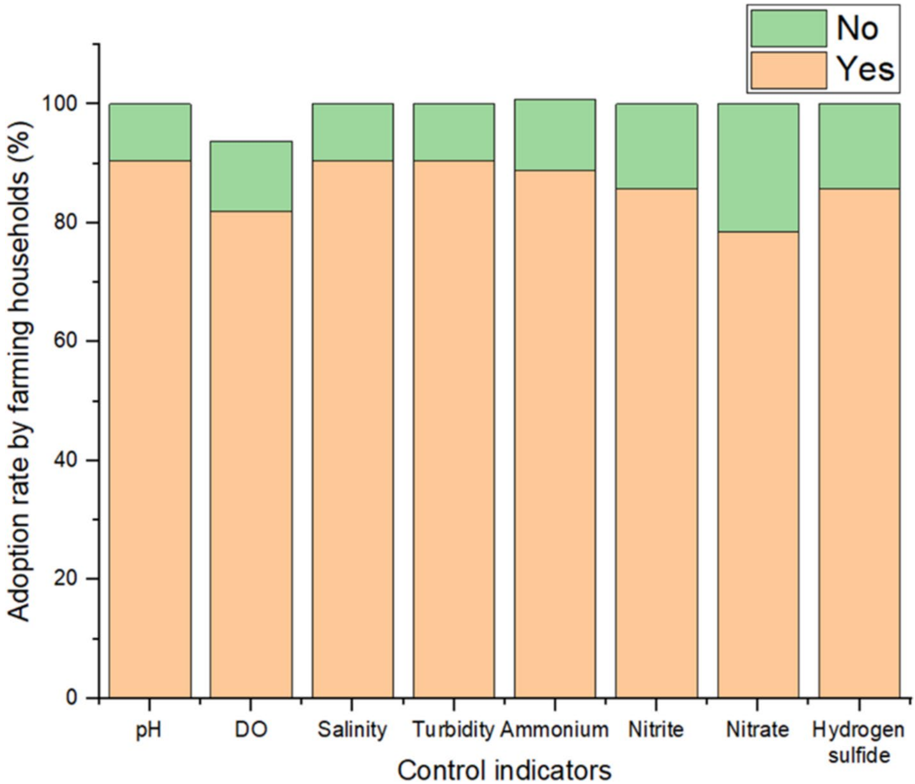

Fig. 4 Proportion of water quality parameters monitored by shrimp farmers during cultivation

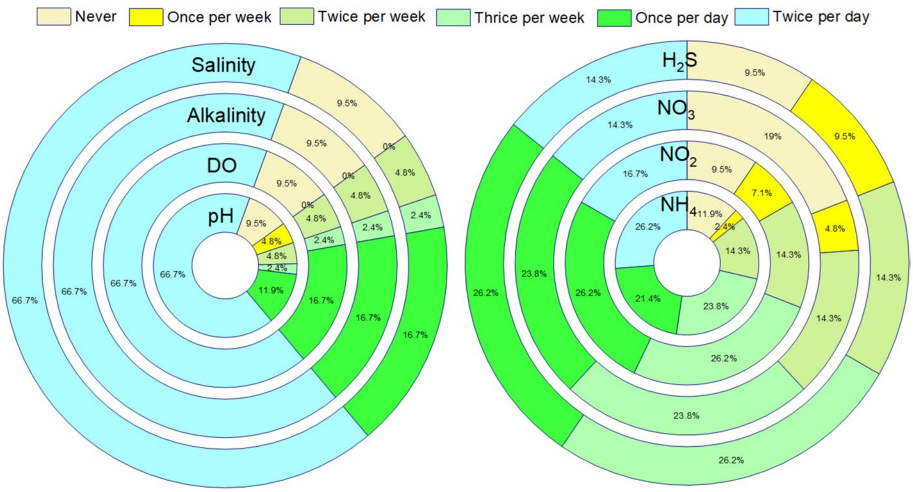

Fig. 5 Frequency of water quality control by shrimp farming households for pH, dissolved oxygen (DO), alkalinity, salinity, turbidity, ammonia, NO_2, NO_3, and H_2S monitoring by shrimp farming households

of shrimp farming households do not treat their wastewater. The survey results highlight a contradiction: although farmers are aware of pollution levels in their pond water, most do not treat their wastewater effectively due to various challenges, including limited access to advanced treatment technologies and the costs associated with water management. Only 14.3% of households have adopted basic treatment methods such as sedimentation and filtration using nets. While these methods help remove suspended solids and debris, they fail to address more complex pollutants like dissolved organic compounds, such as ammonia and nitrates, as well as antibiotic residues, which accumulate over time and degrade water quality (Jones et al. 2001). This incomplete treatment creates an environment conducive to disease proliferation and environmental deterioration.

An additional challenge lies in feed management. Farmers often struggle to control the amount of feed introduced into the system, leading to uneaten feed accumulating at the pond bottom. This excess organic matter not only accelerates water pollution but also fosters favorable conditions for the outbreak of shrimp diseases (El-Saadony et al. 2022). In response, farmers frequently rely on antibiotics, which temporarily mitigate disease symptoms but contribute to further pollution by introducing chemical residues into the water without addressing the underlying cause of poor pond management. Compounding these issues, microbiological monitoring of pond water is often neglected, leaving disease-causing pathogens undetected and untreated.

The failure to adequately treat wastewater and control feed usage perpetuates a cycle of environmental degradation and disease within shrimp farming systems. Despite some awareness among farmers about the deteriorating state of pond water, untreated wastewater continues to be reused in shrimp farming, increasing the risk of disease outbreaks and lowering the overall sustainability of the industry. This cyclical pattern highlights the urgent need for better water management practices, the adoption of sustainable feeding strategies, and the use of effective treatment methods to break the current high-risk loop in the shrimp farming sector.

Moreover, this scenario can lead to a chain reaction of disease outbreaks (Khiem et al. 2022). Assessments of pollution in shrimp farming areas in Thanh Phu district, Ben Tre province, have shown that pollution accumulates toward the end of the river. Similarly, disease pathogens also accumulate in this manner. If antibiotics are used excessively upstream, the resulting wastewater flows downstream to other farms. These downstream farmers, who use river water for shrimp farming without controlling microbiological indices, inadvertently introduce both pathogens and residual antibiotics into their ponds. This leads to widespread and interconnected disease outbreaks and a high accumulation of antibiotics in the shrimp, exacerbating the situation and further increasing the risks associated with shrimp farming.

Environmental problems from shrimp farming

Current status of pathogen control and antibiotic use in shrimp farming

Shrimp farming is inherently risky due to the high susceptibility of shrimp to diseases, often leading to unexplained mortalities (Kabir et al. 2020). Farmers generally attribute these losses to diseases, but the root causes often lie in the pond environment, the farming practices, and careless practices in water sourcing and uncontrolled waste disposal (Macusi et al. 2022). Certain dangerous diseases can lead to mass shrimp deaths, while others may reduce shrimp quality, significantly impacting the farmers' economic situation. Addressing these issues requires a comprehensive approach that includes improving water management, adopting sustainable farming practices, and enhancing disease prevention measures.

The issue pertains to the spread of diseases and various influencing factors in water sources. Most areas directly use water from surrounding rivers, which also serve as recipients of wastewater discharge. According to the OIE (World Organisation for Animal Health) list, there are seven types of viruses severely affecting shrimp, including White Spot Syndrome Virus (WSSV), Yellow Head Virus (YHV), Taura Syndrome Virus (TSV), Spherical Myonecrosis Virus (SMV), Baculovirus Penaeid (BP), Monodon Baculovirus (MBV), and Infectious Hypodermal and Hematopoietic Necrosis Virus (IHHNV) (Lightner 2011). Environmental incidents are likely to occur as numerous studies have shown that these pathogens can easily spread through water currents. Just one source of infection can disperse into the environment through inadequately treated wastewater. Particularly dangerous viruses for white-leg shrimp, such as WSSV, TSV, BP, and IHHNV, can rapidly infect and spread to other natural shrimp species in the area (Desai et al. 1997). Simultaneously, black tiger shrimp are also considered as potential carriers of diseases to other shrimp species, harboring viruses like WSSV, YHV, GAV, IHHNV, MBV, BMNV, LPV (Malczewski et al. 2003). The survey results presented in Fig. 6 show that most shrimp farms experience various diseases, with white feces syndrome being the most common, affecting 64.3% of farms. This is followed by white spot disease at 47.6%, with yellow gill disease being the least common at 2.4%. Alarmingly, diseases arising from poor pond environments are prevalent, with white spot disease at 47.6% and yellow head disease at 26.2%. One significant disease caused by nutrient-rich water with high organic matter and detritus

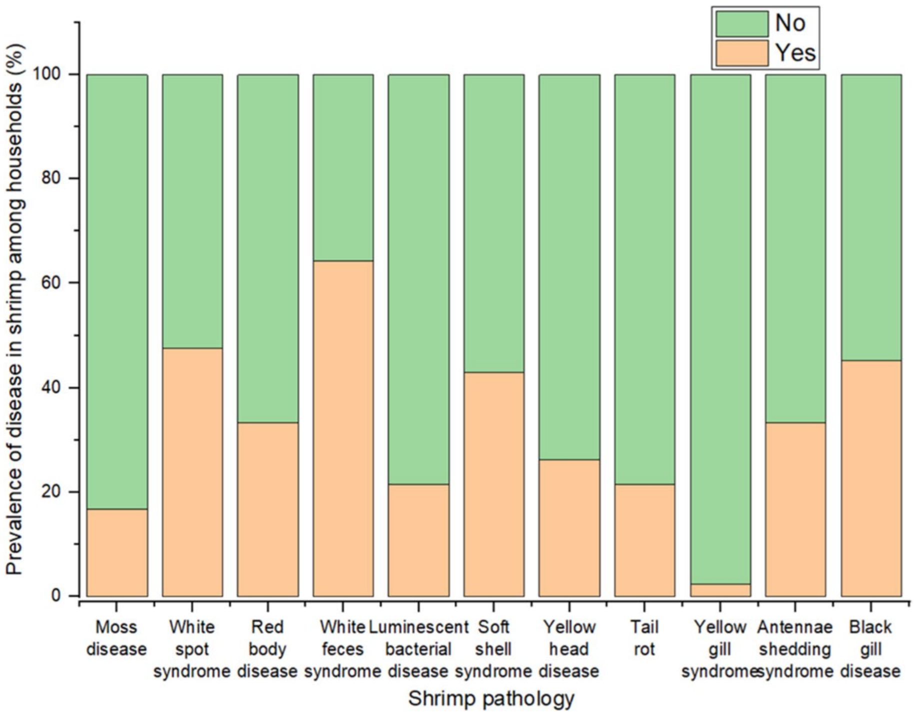

Fig. 6 Common shrimp diseases in ponds and the incidence rate among households as recorded

is luminous bacteria disease, affecting 21.4% of farms. These findings highlight the critical need for improved pond management and environmental control in shrimp farming to reduce the incidence of diseases and mitigate their economic impact on farmers.

In response to various shrimp diseases, farmers have resorted to using antibiotics as a primary treatment method (Luu et al. 2021). However, this practice has led to significant concerns regarding antibiotic residues in shrimp products, creating barriers to exporting Vietnamese seafood to international markets (Thornber et al. 2020). Antibiotic residues such as Oxytetracycline (OTC), Sulfamethoxazole (SMX), and Levofloxacin (LEOF) have been found in shrimp muscle, ranging from 41.8 µg/kg in juvenile shrimp to 134 µg/kg in mature shrimp. In pond water, these residues fluctuated between 33.0 and 64.4 ng/L, with sediment concentrations increasing nearly fivefold over time (Li et al. 2021; Luu et al. 2021).

The misuse of antibiotics has multiple consequences, affecting not only the quality of exported seafood but also consumer health and the environment. Fluoroquinolones and enrofloxacin have been linked to permanent blindness and vision loss, while chloramphenicol can cause bone marrow suppression (Holmström et al. 2003). Antibiotics leaking into natural water bodies can alter ecosystems and lead to the emergence of antibiotic-resistant genes in bacteria, posing severe risks to humans and other animals (Hossain et al. 2022; Suyamud et al. 2021). Research has shown a significant presence of antibiotic-resistant genes like sul1, qnrD, cmlA, and floR in shrimp and pond mud, with adult shrimp harboring 4.48–19.0 times more resistant genes than juveniles (Hoa et al. 2008; Su et al. 2017).

Most shrimp farming households (81%) use antibiotics preventatively, especially during disease outbreaks in neighboring farms. This practice, driven by fear, raises concerns about the legality and safety of these antibiotics. To mitigate these issues, it is essential to address the root causes of disease outbreaks by improving water quality management, adopting better farming practices, and enhancing biosecurity measures. By reducing reliance on antibiotics, farmers can protect human health, preserve the environment, and ensure the sustainability of the shrimp farming industry.

Impact of feed conversion ratio on shrimp farming

Feed is a crucial factor in the success of aquaculture. For juvenile shrimp, various industrial feeds are predominantly used, including brands like LARIVA, LAVIVA, and ANNAMEI, as well as powdered and TIGER feed. This reliance on specialized, formulated feeds ensures optimal health and growth rates during early development stages. For adult shrimp, the feed types are more diverse, featuring brands such as SUPER NICP, LA CRYSTALS, HI AQUA, and UP PRO. This diversity suggests farmers use a range of commercial feeds to meet the specific dietary needs of mature shrimp, aiming to maximize growth efficiency and market value (Tran et al. 2023).

The extensive use of commercial feeds for both juvenile and adult shrimp highlights the critical role of tailored nutrition in aquaculture. These feeds are designed to provide balanced nutrients, enhancing shrimp growth, survival rates, and productivity. The willingness to experiment with different feed brands indicates that farmers are actively seeking optimal farming outcomes. However, this heavy reliance on industrial feeds has significant environmental and economic implications (Le et al. 2024a, b). The production and use of these feeds can lead to nutrient runoff and water pollution if not managed properly. Additionally, the cost of commercial feeds constitutes a substantial portion of operational expenses for shrimp farmers. The dependency on industrial feeds underscores the need for sustainable alternatives. Exploring natural feed sources or developing eco-friendly feed formulations could help mitigate environmental impacts and reduce costs, promoting long-term sustainability in the shrimp farming industry.

Table 4 provides comprehensive data on various metrics related to shrimp farming among 87 surveyed households. The average stocking density is 116.9 units/m^2, with a range from 30 to 400 units/m^2. The stocking period averages 3.1 months, indicating a relatively short cultivation cycle. The average survival rate is 81.94%, with values ranging from 69 to 90%, demonstrating a generally high success rate in shrimp survival. The average harvest yield is 10.93 t, with a considerable range from 1.5 to 33.5 t, reflecting variability in production efficiency among farms. The feed amount per crop averages 14.85 t, with significant variation from 2 to 50.2 t.

The data presented in Fig. 7, along with the one-way ANOVA analysis, reveal a significant gap between the actual and desired feed conversion ratios (FCR) in shrimp farming. The actual FCR averages 1.31, while the optimal FCR is lower 1.2, a value derived from industry benchmarks and previous studies indicating efficient feed utilization (Chaikaew et al. 2019; Ihsanario and Ridwan 2021). This gap highlights inefficiencies in feed management. This discrepancy suggests that farmers are using more feed than necessary, leading to increased production costs and contributing to environmental issues such as excess organic matter accumulation. Improving feed efficiency to reach the desired FCR would not only enhance profitability but also reduce the ecological impact of shrimp farming by minimizing waste and nutrient pollution in pond environments. The ANOVA analysis confirms the significant difference between actual and desired FCR with a high degree of confidence 99% (F value = 33.12, p value = 0.000). The mean actual FCR is 1.3071, significantly higher than the mean desired FCR of 1.120. The Tukey pairwise comparisons further support this finding, indicating distinct groupings (Actual FCR = A, Desired FCR = B) with no overlap. Efforts to improve FCR are crucial to enhancing both economic efficiency and environmental sustainability in shrimp farming. Addressing feed management inefficiencies can minimize resource wastage, reduce reliance on antibiotics, and mitigate negative environmental impacts. Achieving the desired FCR of 1.12 is essential for minimizing organic waste, reducing the need for antibiotics, and creating healthier pond environments, thereby promoting both economic efficiency and sustainable shrimp farming.

In intensive shrimp farming in Soc Trang, the average FCR is 1.59, with tiger shrimp at 1.6 and white-leg shrimp ranging from 1.1 to 1.2 (Nguyen et al. 2019; Son et al. 2014).

Table 4 Summary of stocking density, survival rate, harvest yield, feed amount, and feed conversion ratios in shrimp farming

Key farming parameters in shrimp cultivation	*N*	Range	Minimum	Maximum	Mean	
	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error
Average stocking density (unit/m^2)	87	370	30	400	116.9	10.5
Stocking period (months)	87	2	3	5	3.1	0.1
Average survival rate (%)	87	31	69	90	81.94	0.7
Harvest yield (tons)	87	33.5	1.5	33.5	10.93	1.4
Feed amount per crop (tons)	87	48.2	2	50.2	14.85	2.0
Actual FCR	87	0.8	0.9	1.7	1.31	0.03
Desired FCR	87	0.5	1	1.5	1.12	0.01

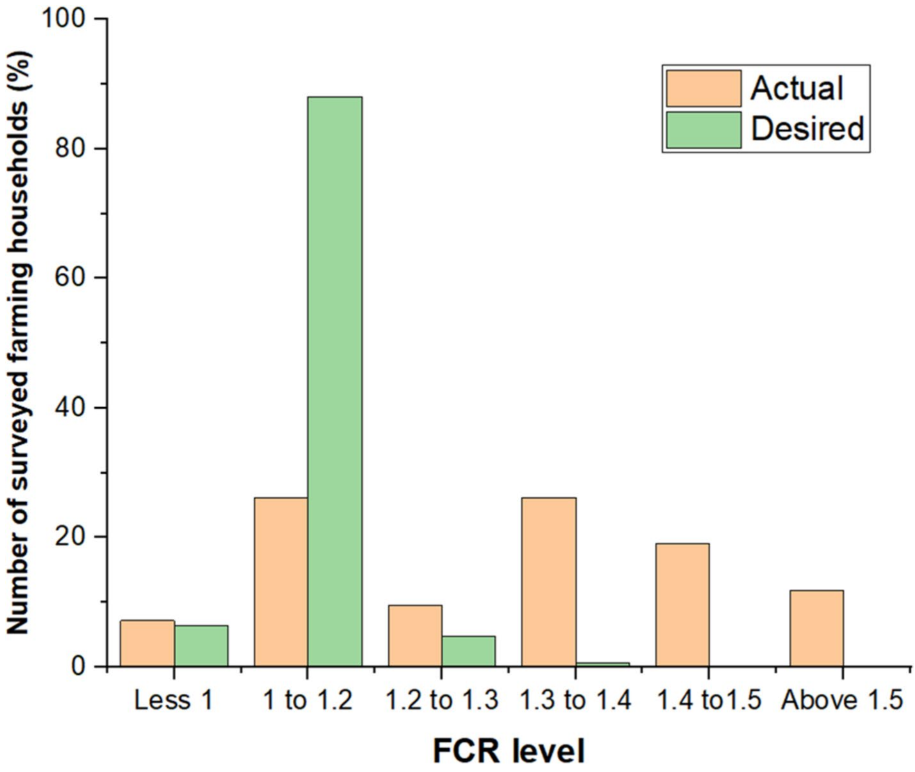

Fig. 7 Desired feed conversion ratio (FCR) by the community (**A**) and actual FCR calculated from recorded data among shrimp farming households (**B**)

Other studies suggest that the appropriate FCR for shrimp farming ranges from 1.18 to 1.3 (Junda 2018). Suitable probiotics can further reduce FCR to as low as 1.22 (Jefri et al. 2020). Farmers report that maintaining an FCR between 1.2 and 1.3 ensures profitability, while an FCR above 1.3 often signals slower growth rates, which may result from the presence of predator fish, disease outbreaks, or low survival rates. The current elevated FCR indicates inefficient feed management, leading to higher production costs and reduced economic efficiency. Excess feed not only contributes to nutrient runoff but also deteriorates water quality by promoting the growth of algae and harmful microorganisms (Kumari et al. 2024). This nutrient-rich environment fosters the proliferation of pathogens, significantly increasing the likelihood of disease outbreaks. To address these challenges, farmers often rely on chemicals and antibiotics, which offer temporary relief but compound environmental pollution and threaten food safety by leaving chemical residues in both water and shrimp (Hossain et al. 2022). Reducing FCR to optimal levels is essential for improving feed efficiency, lowering production costs, and minimizing the ecological footprint of shrimp farming, thereby promoting long-term sustainability.

To address these issues, farmers should adopt better feed management practices, including the use of high-quality feed and appropriate feeding techniques (White et al. 2018). Regular water quality monitoring and probiotic treatments can help maintain optimal conditions for shrimp growth, reducing feed waste and improving farm efficiency. The current

FCR levels in shrimp farming in the Mekong Delta highlight significant challenges related to resource wastage and environmental impacts. By reducing FCR through improved management and optimized feed use, farmers can achieve more sustainable shrimp farming practices. This approach will enhance profitability while mitigating negative environmental effects, promoting a more resilient aquaculture industry. Addressing feed management inefficiencies is crucial not only for economic reasons but also for reducing the proliferation of pathogenic microorganisms, thus reducing the reliance on antibiotics and promoting overall environmental health.

Current status of wastewater treatment systems and challenges in establishment

The survey results in Fig. 8 show that "Land availability difficulties" and "Financial investment difficulties" significantly impact respondents' environmental concerns in shrimp farming, both scoring 4.4/5 on average. In contrast, "Fear of negative impacts on shrimp and marine life" scored the lowest with an average rating of 4.1/5. These findings underscore the practical challenges that farmers prioritize over environmental concerns.

Farmers prefer expanding shrimp farming ponds over investing in wastewater treatment systems due to the higher short-term income potential. Establishing and maintaining

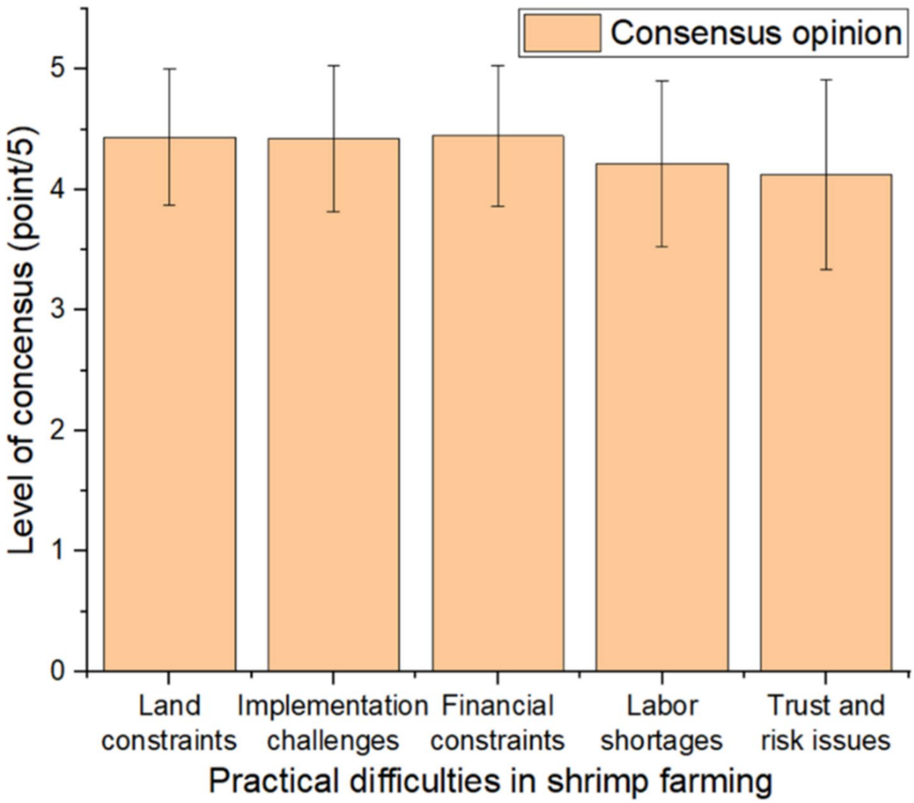

Fig. 8 Evaluation of difficulties encountered in establishing current shrimp farm wastewater treatment systems

wastewater treatment systems require significant initial and ongoing costs, posing a barrier for small-scale farmers with limited capital. Additionally, many farmers lack the necessary knowledge for effective wastewater treatment (Anh et al. 2010). This trend restricts space for environmental objectives and highlights the need for targeted interventions.

The data reveal a concerning trend: out of 87 surveyed households, only 3 have preliminary treatment using settling ponds, while 84 discharge wastewater directly into the environment daily. This widespread practice of direct discharge exacerbates environmental pollution and the spread of diseases, highlighting a critical gap in sustainable farming practices. The significant barriers include financial constraints, with a mean score of 4.218 and a standard deviation of 0.689, and implementation challenges, with a mean of 4.448 and a standard deviation of 0.586 (Table 5). These high scores reflect the substantial difficulty farmers face in adopting effective wastewater management systems.

Technical aspects of wastewater management necessitate comprehensive strategies and planning from local authorities (Neiland et al. 2001). Policies encouraging investment in environmentally significant projects, such as low-interest loans with better incentives, technical support from professionals, and regular workshops on shrimp farming issues, are essential to address these challenges (Huitric et al. 2002). These measures can help overcome the financial and technical barriers that currently hinder the adoption of effective wastewater treatment systems. For instance, the mean score for land constraints is 4.437 with a standard deviation of 0.565 (Table 5), indicating widespread agreement on the

Table 5 Reliability analysis of measurement scales using Cronbach's Alpha

Factors	Item	Mean	Std. error	Corrected item–total correlation	Reliability (Cronbach's Alpha)
Attitudes (TD)	TD1	3.885	0.813	0.763	0.915
	TD2	3.839	0.913	0.768	
	TD3	4.161	0.608	0.653	
	TD4	3.897	0.732	0.824	
	TD5	3.862	0.794	0.737	
	TD6	4.161	0.608	0.653	
	TD7	3.897	0.732	0.824	
Awareness (NT)	NT1	4.035	0.637	0.441	0.872
	NT2	4.149	0.620	0.597	
	NT3	4.184	0.656	0.671	
	NT4	4.012	0.739	0.810	
	NT5	4.080	0.766	0.719	
	NT6	4.011	0.739	0.810	
Objective difficulties (KK)	KK1	4.437	5.645	0.418	0.780
	KK2	4.448	0.586	0.461	
	KK3	4.218	0.689	0.708	
	KK4	4.126	0.789	0.714	
	KK5	3.839	0.834	0.511	
Attention (QT)	QT1	3.931	0.789	0.883	0.922
	QT2	3.908	0.802	0.921	
	QT3	3.828	0.930	0.742	

difficulty of accessing sufficient land for both farming and wastewater treatment. Labor shortages also present a significant challenge, with a mean score of 4.126 and a standard deviation of 0.790. This indicates variability in how labor issues affect different farmers, but overall, it remains a critical barrier to effective farm management and environmental practices. Trust and risk issues scored a mean of 3.839 with a standard deviation of 0.834, suggesting a lack of confidence among farmers in implementing new systems or technologies without assurances of their efficacy and benefits.

Given this information and the overconfidence in the environment's self-cleansing ability, along with the farmers' complacency, a widespread outbreak is entirely possible in the event of a risk occurrence. Such an outbreak would result in significant economic losses for the region and shrimp farmers. Therefore, there is a need for effective management of breeding stocks and rational planning of farming areas to prevent epidemic outbreaks that could be detrimental to shrimp farmers.

In summary, the current status of wastewater treatment in shrimp farming is inadequate, with the majority of households lacking proper systems. Addressing the financial, technical, and knowledge gaps through targeted policies and support can significantly improve environmental sustainability in shrimp farming. The statistical insights reinforce the need for interventions to address the practical difficulties faced by shrimp farmers, promoting a more sustainable and environmentally friendly industry.

Factors affecting interest and intention to implement environmental protection measures

Analyzing values and testing the scales of factors affecting shrimp farmers

Table 5 presents the reliability analysis of measurement scales using Cronbach's Alpha for the factors of Attitudes (TD), Awareness (NT), Objective Difficulties (KK), and Attention (QT). Each factor's reliability and validity are examined to ensure the robustness of the measurement scales.

The Attitudes factor has a Cronbach's Alpha of 0.915, indicating excellent internal consistency. The Corrected Item-Total Correlation values for items TD1 to TD7 range from 0.653 to 0.824, all surpassing the acceptable threshold of 0.5 (Arbab et al. 2024). The mean scores for these items range from 3.839 to 4.161, with reasonable variability within responses, effectively measuring the underlying attitude construct. The Awareness factor has a Cronbach's Alpha of 0.872, demonstrating high reliability. The Corrected Item-Total Correlation for items NT1 to NT6 ranges from 0.441 to 0.810, confirming their validity. The mean scores for these items range from 4.011 to 4.184, with consistent responses, indicating reliable measurement of respondents' awareness levels. The Cronbach's Alpha for Objective Difficulties is 0.780, suggesting good reliability. The Corrected Item-Total Correlation for items KK1 to KK5 ranges from 0.418 to 0.714, validating the items. The mean scores range from 3.839 to 4.448, with some variability, indicating consistent measurement of the objective difficulties faced by farmers. The Attention factor shows a Cronbach's Alpha of 0.922, indicating excellent reliability. The Corrected Item-Total Correlation for items QT1 to QT3 ranges from 0.742 to 0.921, confirming strong internal consistency. The mean scores range from 3.828 to 3.931, with slight variability, indicating effective measurement of respondents' attention to critical factors impacting shrimp farming.

The reliability analysis using Cronbach's Alpha confirms that all the factors—Attitudes, Awareness, Objective Difficulties, and Attention—have high internal consistency, with Alpha values well above the acceptable threshold of 0.7. The Corrected Item-Total Correlation values further validate the reliability of the individual items within each factor. The high reliability scores across all factors indicate that the survey items are robust and consistent in measuring the respective constructs. The reliability analysis using Cronbach's Alpha provides strong evidence for the robustness and validity of the measurement scales used in this study. The high internal consistency across all factors indicates that the survey items are effective in measuring the respective constructs, providing a solid foundation for further analysis and research in shrimp farming practices.

Exploratory factor analysis of factors affecting shrimp farmers

After four rounds of exploratory factor analysis (EFA) and eliminating unsuitable variables, the results showed the Kaiser–Meyer–Olkin Measure of Sampling Adequacy is 0.655, meeting the condition $0.5 \leq KMO \leq 1$, which indicates that the sample size is adequate for factor analysis (Table 6). Additionally, Bartlett's Test of Sphericity has a significance value (Sig.) of 0.000, which is less than 0.05. This confirms that the observed variables are correlated and suitable for structure detection.

The cumulative variance explained by the factors is 73.086%, exceeding the 50% threshold. This suggests that the factors extracted explain a substantial amount of the total variance (Table 7). The Eigenvalue for the first factor is 2.755 and for the second factor is 1.630, both greater than 1, satisfying the criteria for significant factors. In addition, the factor loadings for all variables are greater than 0.5, indicating that the variables are well represented by the factors (Table 8).

The first factor (F1) includes four observed variables: TD1 (Assessing water pollution levels every time wastewater is discharged into the environment daily), TD2 (Implementing a wastewater treatment system for shrimp ponds before discharge into the environment), TD4 (Enhancing methods to increase the value of shrimp such as better color and larger size), and NT1 (Chemicals and antibiotics can affect surrounding water quality). The high loadings of TD1 (0.896), TD2 (0.899), TD4 (0.811), and NT1 (0.568) suggest that this factor is strongly related to environmental concerns and water quality management in shrimp farming. Thus, this factor can be named "Environmental Management and Enhancement."

The second factor (F2) includes two observed variables: KK3 (Difficulties with labor shortages) and KK4 (Difficulties with trust and risk issues, including fears that implementation will negatively impact shrimp and aquaculture). The high loadings of KK3 (0.924) and KK4 (0.930) indicate that this factor is related to operational challenges and risk management in shrimp farming. Hence, this factor can be named "Operational Challenges and Risk Management."

The strong factor loadings in the Environmental Management and Enhancement (F1) factor indicate that farmers are highly concerned with environmental management practices. The need to regularly assess water pollution (TD1) and implement wastewater treatment systems (TD2) is paramount. Recognizing that chemicals and antibiotics can affect water quality (NT1) highlights the awareness of potential environmental impacts. Additionally, improving

Table 6 Values of Kaiser–Meyer–Olkin criteria and Bartlett's test of sphericity

Kaiser–Meyer–Olkin measure of sampling adequacy		0.655
Bartlett's test of sphericity	Approx. Chi-Square	250.440
	df	15
	Sig	0.000

Table 7 Factors extracting and their participation in variance

Component	Initial eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	2.755	45.914	45.914	2.755	45.914	45.914	2.604	43.397	43.397
2	1.630	27.173	73.086	1.630	27.173	73.086	1.781	29.689	73.086
3	0.794	13.237	86.323						
4	0.459	7.651	93.975						
5	0.232	3.864	97.839						
6	0.130	2.161	100.000						

Extraction method: principal component analysis

Table 8 Rotated pattern matrix

	Component	
	F1	F2
TD2	0.899	
TD1	0.896	
TD4	0.811	
NT1	0.568	
KK4		0.930
KK3		0.924

Extraction method: principal component analysis. Rotation method: Varimax with Kaiser normalization

Rotation converged in 3 iterations

shrimp quality (TD4) aligns with the economic incentives to produce higher-value products while maintaining sustainable practices.

In contrast, the Operational Challenges and Risk Management (F2) factor highlights significant operational challenges, including labor shortages (KK3) and trust issues regarding new practices (KK4). The high factor loadings for these variables reflect the practical difficulties farmers face in managing labor and the apprehension toward adopting new methods due to perceived risks. This underscores the need for supportive policies and training programs to address these operational hurdles and build confidence among farmers.

Regression and correlation of factors

The regression and correlation analysis aims to understand the relationships between various factors influencing shrimp farming. This section evaluates three primary pathways: the impact of F1 (Environmental Management and Enhancement) and F2 (Operational Challenges and Risk Management) on QT (Concern), the influence of QT on YD (Intention to Implement), and the combined effect of F1 and F2 on YD.

Hypothesis 1 discusses the impact of F1 and F2 on QT. The Pearson correlation analysis (Table 9) shows a strong positive correlation between F1 and QT, with a Pearson correlation coefficient of 0.821, significant at the 0.01 level. This suggests that improvements in environmental management practices (F1) are closely associated with heightened concerns regarding environmental impacts (QT). Conversely, F2 shows a weak correlation with QT ($r = 0.122$), indicating that operational challenges and risk management have a lesser influence on environmental concerns. The regression analysis in Table 10 confirms these findings. Model 1, which predicts QT using F1 and F2, has an adjusted R square of 0.666, indicating that 66.6% of the variance in QT is explained by these factors. The Durbin-Watson statistic of 2.138 suggests no autocorrelation in the residuals, affirming the model's reliability. The ANOVA results in Table 11 show a significant F test value ($p < 0.000$), validating the model's overall fit. Table 12 reveals that only F1 significantly impacts QT, with a standardized regression coefficient (Beta) of 0.823 and a p value of 0.000. F2, with a p value of 0.799, does not significantly influence QT. This indicates that enhancing environmental management practices strongly raises environmental concerns among shrimp farmers, while operational challenges do not have a notable effect.

Table 9 Pearson correlation analysis

Correlations					
		YD	QT	F1	F2
YD	Person correlation	1	0.650**	0.717**	0.105
	Sig. (2-tailed)	–	0.000	0.000	0.332
	N	87	87	87	87
QT	Person correlation	0.650**	1	0.821**	0.122
	Sig. (2-tailed)	0.000	–	0.000	0.261
	N	87	87	87	87
F1	Person correlation	0.717**	0.821**	1	0.168
	Sig. (2-tailed)	0.000	0.000	–	0.121
	N	87	87	87	87
F2	Person correlation	0.105	0.122	0.168	1
	Sig. (2-tailed)	0.332	0.261	0.121	–
	N	87	87	87	87

**. Correlation is significant at the 0.01 level (2-tailed)

Table 10 Model summary of multivariate regression analysis

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Walson
1. Predictors (F1, F2) and (QT)	0.821[a]	0.674	0.666	0.453	2.138
2. Predictors (QT) and (YD)	0.650[b]	0.423	0.416	0.582	1.645
3. Predictors (F1, F2) and (YD)	0.717[c]	0.514	0.502	0.538	1.722

Table 11 ANOVA analysis of variance

Coefficients						
Model		Sum of squares	df	Mean square	F	Sig
1	Regression	35.586	2	17.793	86.753	0.000
	Residual	17.229	84	0.205		
	Total	52.815	86			
2	Regression	21.108	1	21.108	62.245	0.000
	Residual	28.824	85	0.339		
	Total	49.932	86			
3	Regression	25.652	2	12.826	44.373	0.000
	Residual	24.280	84	0.289		
	Total	49.932	86			

Hypothesis 2 discusses the impact of QT on YD. The relationship between QT and YD is also significant. The Pearson correlation coefficient between QT and YD is 0.650, significant at the 0.01 level (Table 9), indicating a strong positive correlation. This implies that increased concern (QT) is associated with a higher intention to implement sustainable practices (YD). Model 2 in Table 10, which uses QT to predict YD, shows an Adjusted R

Table 12 Regression coefficients—detailed analysis of variable effects

Coefficients								
Model		Unstandardized coefficients		Standardized coefficients	t	Sig	Colinearity statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	−0.090	0.397		−0.227	0.821		
	F1	1.029	0.079	0.823	13.026	0.000	0.972	1.029
	F2	−0.018	0.072	−0.016	−0.255	0.799	0.972	1.029
2	(Constant)	1.358	0.318		4.272	0.000		
	QT	0.632	0.080	0.650	7.890	0.000	1.000	1.000
3	(Constant)	0.442	0.472		0.938	0.351		
	F1	0.874	0.094	0.719	9.318	0.000	0.972	1.029
	F2	−0.017	0.085	−0.15	−0.198	0.844	0.972	1.029

Square of 0.416. This means that 41.6% of the variance in YD is explained by QT, with the remaining 58.4% attributable to other factors and random errors. The Durbin-Watson statistic of 1.645 confirms the absence of autocorrelation in the residuals. The regression coefficients in Table 12 further validate the significance of QT's impact on YD. The standardized regression coefficient (Beta) for QT is 0.650, with a *p* value of 0.000, indicating a substantial and statistically significant influence. Therefore, heightened concern about environmental issues significantly increases the likelihood of farmers' intention to implement sustainable practices.

Hypothesis 3 discusses the impact F1 and F2 on YD. The final hypothesis examines the combined effect of F1 and F2 on YD. The Pearson correlation coefficients in Table 9 indicate a strong positive correlation between F1 and YD ($r = 0.717$), while F2 has a weaker correlation with YD ($r = 0.105$). Model 3 in Table 10, which includes F1 and F2 as predictors for YD, has an adjusted R square of 0.502, indicating that 50.2% of the variance in YD is explained by these factors. The Durbin-Watson statistic of 1.722 suggests no autocorrelation issues. The ANOVA results in Table 11 confirm the model's significance, with an *F* test value ($p < 0.000$). However, Table 12 shows that only F1 significantly impacts YD, with a standardized regression coefficient (Beta) of 0.719 and a *p* value of 0.000. F2, with a *p* value of 0.844, does not significantly influence YD. This finding indicates that improvements in environmental management practices (F1) strongly encourage the intention to implement sustainable practices, whereas operational challenges and risk management (F2) do not play a significant role.

To explain this result, numerous studies have confirmed that attitude can positively influence environmental intention (Kumar 2019; Wang 2021; Zhang et al. 2019). However, some researchers argue that a stronger attitude may not always lead to stronger intention (Bechler et al. 2021; Collado et al. 2015, 2017; Šorytė and Pakalniškienė, 2021). Bechler et al. (2021) noted that attitude affects behavior only when it crosses the valence threshold noted that attitude affects behavior only when it crosses the valence threshold. Collado et al. (2017) also observed that older groups are more likely than younger ones to translate their attitude into behavior. In summary, the insights from this study emphasize the importance of focusing on environmental management to promote sustainable shrimp farming practices. The significant impact of environmental management practices (F1) on both environmental concerns (QT) and the intention to implement sustainable practices (YD) underscores the need for continuous assessment and improvement of environmental practices. The strong influence of concern (QT) on the intention to implement (YD) highlights the critical role of awareness and attitude in driving sustainable behavior among shrimp farmers. Therefore, enhancing environmental management and raising awareness about environmental issues are essential strategies to foster sustainable practices in shrimp farming.

Enhancing sustainable shrimp farming through awareness and action

The adjusted empirical model based on the survey results integrates the factors of Environmental Management and Enhancement (F1) and Attention (QT), significantly influencing both the "Concern" and "Intention to Implement" aspects in shrimp farming. Factor F1, which includes crucial elements like assessing daily water pollution (TD1), treating wastewater before discharge (TD2), recognizing the impact of chemicals and antibiotics on water quality (NT1), and finding alternative feed sources (TD4), has a substantial impact on the "Concern" variable, with a high standardized regression coefficient of 0.823. Additionally, F1 strongly influences the 'Intention to Implement' variable, with a coefficient of 0.719. Simultaneously, the factor of "Concern," denoted as QT in the model, significantly influences the "Intention to Implement" environmental improvements in shrimp farming, with a standardized regression coefficient of 0.650. QT includes variables related to the pollution levels in surrounding water sources (QT1), pollution in the discharged water during farming (QT2), and the rising salinity levels of incoming water (QT3).

This adjusted model in Fig. 9 underscores the crucial roles that farmers' environmental management practices and concerns play in their willingness to implement sustainable practices in shrimp farming. The strong factor loadings in F1 indicate that farmers are highly aware of and concerned about the environmental impacts of their farming practices. This awareness translates into a significant intention to adopt sustainable practices, driven by their recognition of the importance of environmental health in maintaining productive and profitable shrimp farming operations.

The comprehensive assessment of environmental monitoring data and various studies reveal serious pollution levels in the external river water (Bull et al. 2021; Le et al. 2022; Zheng et al. 2024). Despite this, most locals believe that the river water in their shrimp farming area is adequate, usable for shrimp cultivation with basic treatments like sediment removal and liming, and even suitable for household use after sedimentation. This has led to a perception that the water can be used without extensive treatment and that the environment can self-purify pollutants. However, when proposing the construction of a treatment system, locals often perceive many challenges related to cost, land availability, management, and concerns about potential impacts on shrimp or the system's effectiveness (Fig. 8), which is consistent with other studies (Iber and Kasan 2021). Despite recognizing water pollution and the need for a treatment system, these issues hinder the motivation to implement environmental protection measures (Tom et al. 2021).

To address the challenges faced in shrimp farming, several objective solutions are recommended with a focus on adjusting farmers' attitudes and promoting sustainable practices. Key factors identified through the analysis include the importance of assessing water pollution before discharging wastewater (TD1) and the necessity of implementing wastewater treatment systems for shrimp ponds (TD2). However, the technical complexity of these systems, combined with the persistence of traditional farming practices, poses

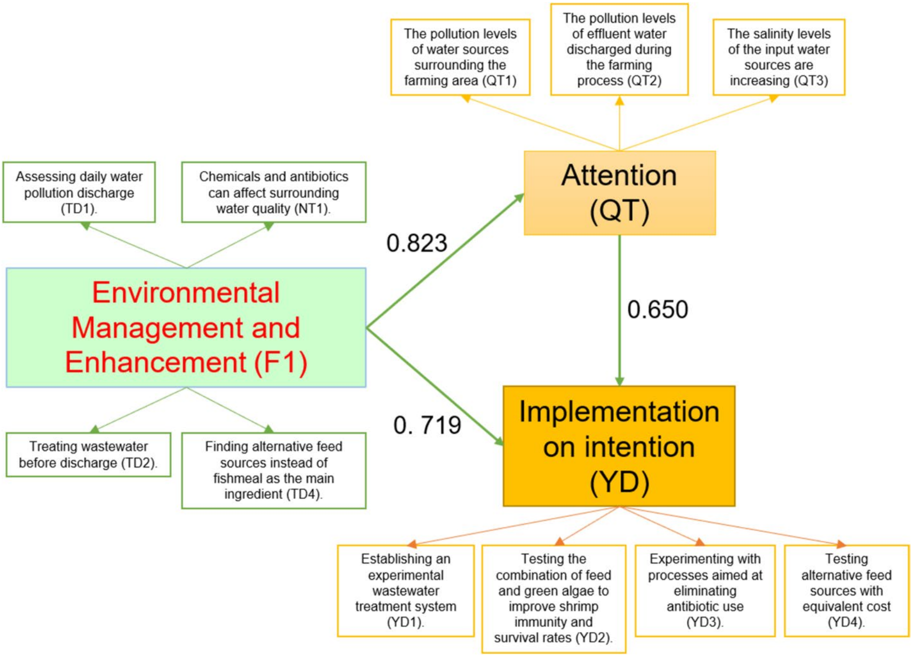

Fig. 9 Survey model following experimental adjustments

significant barriers to effective management and implementation (Bull et al. 2021). To overcome these challenges, solutions should enhance shrimp value (TD4) while reducing antibiotic use (NT1).

A promising approach is the adoption of algae-based wastewater treatment systems. These systems offer simplicity, effectiveness, and the dual benefits of treating waste while generating cost savings. Algae and wetland systems are easy to manage, contribute to improved shrimp health, and allow farmers to optimize space and resources (Deane and O'Brien 1981; Giang et al. 2020; Nguyen et al. 2023; Quang-Tuong and Thanh 2021). Among these, high-rate algal ponds (HRAP) combined with electrocoagulation technology offer an innovative solution tailored for rural areas. The HRAP design mirrors traditional pond systems, making it easy to integrate into existing farming operations (Kishi et al. 2018). This combination not only provides effective water treatment but also aligns with circular economy principles. Electrocoagulation facilitates the recovery of biomass from algae, transforming it into valuable by-products that can be used in agriculture or bioenergy production (Do et al. 2024). The simplicity of HRAP systems, coupled with the economic potential of biomass recovery, makes this approach accessible to small-scale farmers, addressing environmental challenges while promoting sustainable, profitable practices.

Raising environmental awareness is another critical element in promoting sustainable practices. Research highlights that farmers' concern over environmental issues influences their motivation to adopt protective measures. Therefore, efforts to change attitudes and increase awareness of the environmental impact of discharging untreated water are (Primavera 1994). Integrating environmental education into farming communities is a strategic step in this process. Curriculums should include topics related to environmental protection, and student involvement through farm visits, observations of algae-based treatment systems, and participation in volunteer activities can cultivate awareness and responsibility within local communities (Tarunamulia et al. 2023).

Additionally, employing diverse outreach strategies is necessary to ensure widespread adoption of eco-friendly practices. Media campaigns, workshops, and partnerships with farmer associations can effectively disseminate information and foster environmental responsibility (Anand et al. 2021).

Sustainable shrimp farming also requires practical solutions that empower farmers to address environmental concerns effectively. Educational programs, technical support, and financial incentives are essential to encourage farmers to adopt best practices in environmental management (Suzuki and Hoang Nam 2018; Tran et al. 2025). By demonstrating the economic advantages of improved shrimp quality and reduced environmental impact, farmers can be motivated to integrate sustainable practices into their operations. This holistic approach, combining awareness, education, and technical solutions, will contribute to the development of a more sustainable shrimp farming industry.

Conclusion

This study highlights a significant gap between shrimp farmers' environmental awareness and practices in the Mekong Delta, driven by economic constraints, limited technical knowledge, and insufficient support systems. While farmers recognize the negative impacts of untreated effluent discharge, sustainable methods are not widely adopted due to financial limitations and practical challenges. The research demonstrates that farmers' knowledge and positive attitudes explain 66.6% of the variance in environmental concern, underscoring the critical role of education and awareness in fostering sustainable practices. Key recommendations include improving wastewater management and enhancing feed efficiency to achieve an optimal feed conversion ratio (FCR), which can reduce feed costs, improve water quality, and minimize the prevalence of disease-causing microorganisms, thereby decreasing reliance on antibiotics. Addressing these barriers requires holistic strategies that align environmental stewardship with economic sustainability, ensuring both short-term viability and long-term resilience in shrimp farming. By integrating the theory of planned behavior, this study offers a framework for understanding the socio-cultural factors influencing farming practices and provides actionable insights for developing innovative, targeted solutions. These findings contribute to the sustainability of shrimp farming in the Mekong Delta and offer valuable lessons for global aquaculture systems aiming to balance economic growth with environmental conservation.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interest The authors declare no competing interests.

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