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Technical Efficiency of Shrimp Production of the Integrated Mangrove–shrimp Farming System in Vietnamese Mekong Delta

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This study investigates the determinants of productivity and technical efficiency in integrated mangrove–shrimp farming systems in Ca Mau province, Vietnam, using a Cobb–Douglas stochastic frontier production function. Our analysis reveals that pond preparation costs, labor input, natural pest control methods, and mangrove coverage significantly influence shrimp productivity. The mean technical efficiency of 85.6% indicates strong but not optimal performance across farms. Key factors reducing technical inefficiency include farmer education, training participation, and organic certification, while shrimp disease occurrence notably increases inefficiency. The findings demonstrate that the integrated mangrove–shrimp farming model can successfully balance economic viability with environmental conservation. Policy recommendations include infrastructure support, enhanced training programs, disease management protocols, and incentives for organic certification. This research contributes to the growing literature on sustainable aquaculture practices and provides empirical evidence supporting the economic and ecological benefits of integrated mangrove–shrimp farming systems.

Key words: aquaculture, mangrove conservation, organic certification, sustainable farming

INTRODUCTION

Vietnam's fisheries industry stands as a cornerstone of the nation's economy, consistently ranking among the top ten export sectors. Contributing approximately 4–5% to the Gross Domestic Product and 9–10% to national export revenue, the industry's significance is undeniable (Department for International Trade, 2019). Within this sector, aquaculture has emerged as a dominant force, accounting for 53.2% of total fishery production as of 2017 (General statistics office of Vietnam, n.d.).

Shrimp aquaculture, in particular, has experienced remarkable growth, with production surging by 127% between 2002 and 2017, from 186,000 tons to approximately 747,000 tons. This dramatic increase has positioned shrimp as Vietnam's leading seafood export product (Department for International Trade, 2019). The decade from 2008 to 2018 witnessed a near 120% rise in shrimp export turnover, climbing from US$1.6 billion to US$3.55 billion, reflecting an impressive average annual growth rate of 9% (Vietnam Association of Seafood Exporters and Producers n.d.).

While intensive and semi–intensive shrimp farming models dominate the industry, catering to both domestic and export markets, Vietnam also maintains extensive shrimp culture practices that rely on natural ecological services. A noteworthy example is the integrated shrimp–mangrove farming system, an improved extensive culture model where a portion of the farm is dedicated to mangrove preservation. This innovative approach serves a dual purpose: it contributes to mangrove forest conservation while producing high–quality, environmentally sustainable shrimp.

However, the integrated shrimp–mangrove model faces challenges, primarily low productivity due to its heavy reliance on natural processes. To encourage wider adoption of this environmentally friendly approach, it is crucial to support farmers in enhancing the model's productivity. The system typically involves raising shrimp alongside crabs and sometimes fish, with additional wild shrimp and fish entering the ponds through tidal flushing. Shrimp remains the primary product, accounting for 67% of the revenue generated from these integrated farms.

Given the economic and environmental importance of this farming model, this paper aims to analyze the technical efficiency of shrimp production within the integrated mangrove–shrimp culture system. By identifying factors influencing efficiency and potential areas for improvement, this research seeks to contribute to the sustainable development of Vietnam's shrimp aquaculture sector, balancing economic growth with environmental conservation.

METHODOLOGY AND DATA COLLECTION

Theoretical Framework: Stochastic Frontier Production Function

This study employs the stochastic frontier production function approach, pioneered by (Aigner, Lovell, and Schmidt, 1977; Meeusen and Van den Broeck, 1977). The model is specified as:

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$$Y_i = f(X_i\,;\,\beta)\,\exp\,(v_i - u_i) \qquad (1)$$

where Y_i is the output for the i^{th} farm (i = 1, 2, …, n); X_i is a vector of inputs of the i^{th} farm; β is a vector of parameters to be estimated; v_i is assumed to be independently and identically distributed N(0, σ_v^2) random error, and independent of the u_i; u_i is a non–negative random variable which accounts for technical inefficiency in production and is assumed to be independently and identically distributed (Khai *et al.*, 2008; Khai and Yabe, 2011).

Building on this, we defined the inefficiency term u_i as: (Battese and Coelli, 1995; Phuong *et al.*, 2023)

$$u_i = Z_i\,\delta + W_i \qquad (2)$$

where Z_i is a vector of explanatory variables; δ is a vector of parameters to be estimated; W_i are random variables, defined by the truncation of the normal distribution with zero mean and variance σ_u^2, such that the point of truncation is $-Z_i\delta$, i.e., $W_i \geq -Z_i\delta$.

The farm–level technical efficiency (TE) for the i^{th} farm is then calculated as:

$$TE_i = \exp\,(-u_i) = \frac{Y_i}{f\,(X_i;\,\beta)\,\exp\,(v_i)} \qquad (3)$$

Empirical Model Specification

We apply the Cobb–Douglas stochastic production frontier, specified as:

$$\ln Y = \beta_0 + \sum \beta_j\, lnX_j + v_i - u_i \qquad (4)$$

where ln denotes the nature logarithm, Y is the quantity of shrimp produced per hectare of water–surface area by the i^{th} farmer. The inputs (X_j) included in the model are shrimp seed (j =1), pond–preparation cost (j =2), labor (j =3), the use of tea seed cake or derris roots to kill fish (*D_saponin)* (j =4), lime (*D_lime*) (j =5), and mangrove coverage (j =6). β are the parameters to be estimated.

The inefficiency model incorporates the following variables (Phuong *et al.*, 2023):

$$u_i = \delta_0 + \delta_1\, Education_i + \delta_2\, Experience_i + \delta_3\, D\_Disease_i + \delta_4\, D\_training_i + \delta_5\, Area_i + W_i \quad (5)$$

where, $Education_i$: Years of formal education; $Experience_i$: Years of experience in shrimp production; $D\_Disease_i$: Incidence of shrimp disease (dummy variable); $D\_training_i$: Participation in training programs (dummy variable); $Area_i$: Water–surface area of the farm.

Descriptive statistics for all variables used in both the production frontier and inefficiency models are presented in Table 3.1. The maximum likelihood estimation (MLE) technique is employed to simultaneously estimate the parameters of the stochastic frontier model and those of the technical inefficiency model. This approach allows for a more efficient estimation of the entire model, capturing both the production function and the factors influencing inefficiency.

Data Collection

The study focuses on the Vietnamese Mekong Delta (VMD), the primary shrimp–producing region in Vietnam (General Statistics Office of Vietnam, n.d.). This area also hosts the country's largest remaining mangrove forests. Among the 14 provinces in the VMD, Ca Mau province was selected for data collection due to its extensive mangrove forests (Tran and Ha, 2008) and renowned integrated shrimp–mangrove systems. A cross–sectional survey was conducted, involving in–person interviews with 120 integrated mangrove–shrimp farmers. The sampling strategy aimed to capture a representative cross–section of farms in terms of size, location within the province, and management practices. The survey instrument was designed to collect detailed information on: Farm characteristics (size, mangrove coverage, infrastructure), Production inputs (seed, feed, labor, chemicals), Output (shrimp yield, other aquatic products), Management practices (pond preparation, water management, disease control), Farmer characteristics (age, education, experience, training), Environmental factors (water quality, disease incidence)

Prior to the main survey, a pilot study was conducted with 15 farmers to refine the questionnaire and ensure its clarity and relevance. Enumerators were trained to ensure consistency in data collection and to minimize potential bias. This comprehensive dataset allows for a robust analysis of the technical efficiency of integrated mangrove–shrimp farming systems and the factors influencing their productivity.

RESULTS AND DISCUSSION

Description of the crop

Farmers begin by preparing the pond, a process that includes removing sediment, utilizing tea seed cake or derris roots to eliminate fish (62.5% of farmers), and applying lime to control bacteria (15.8%). This preparation occurs annually from July to September, according to the lunar calendar. Following pond preparation, farmers stock post–larvae multiple times throughout the year, averaging five stockings, with the first stocking typically larger than subsequent ones. After stocking shrimp seeds for 2–3 weeks, farmers then stock crab seeds. Crab seeds are also stocked multiple times, ranging from 1 to 12 times a year, averaging 6 times. The size of crab seeds varies, with larger sizes fetching higher prices.

During the culture process, farmers often exchange water based on tidal movements through water control gates. Water exchange brings several benefits. Firstly, wild seeds and natural feed enter the shrimp pond with the tide. Secondly, it removes waste from the shrimp ponds. In ponds with static water, the accumulation of waste can harm shrimp, resulting in lower yields (ASEAN National Coordinating Agency of the Philippines, n.d.). Particularly, frequent water exchange dilutes waste products formed by decomposing mangrove leaves, ensuring adequate oxygen levels in the

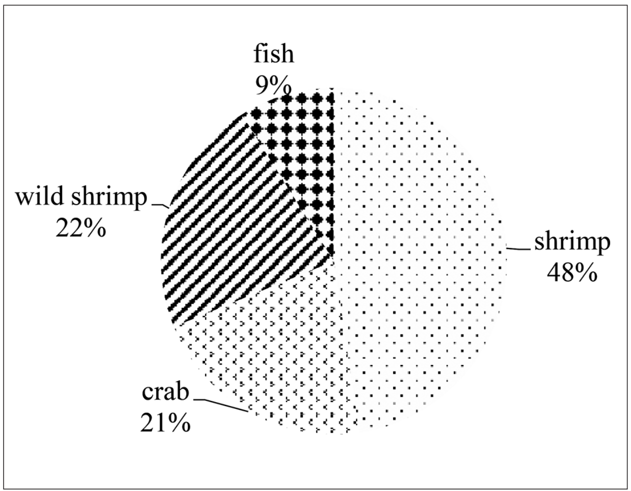

Fig. 1. Structure of harvested products.
Source: Authors' own estimates

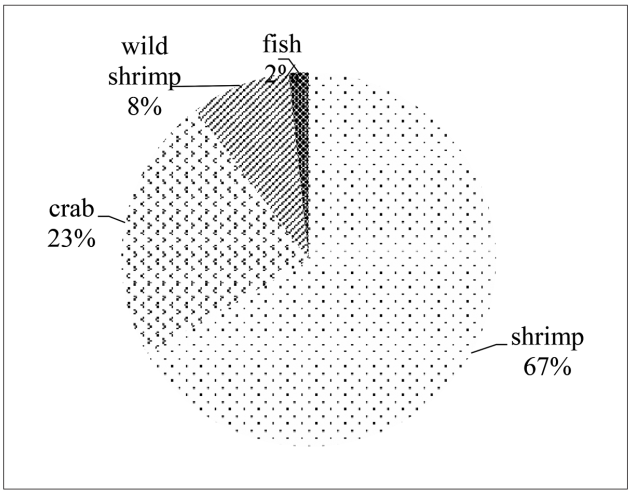

Fig. 2. Structure of revenue of the crop.
Source: Authors' own estimates

pond water. Finally, water exchange helps regulate salinity levels, especially when heavy rains dilute pond water (ASEAN National Coordinating Agency of the Philippines, n.d.).

After farming for about 3–5 months (average of 4 months), farmers start harvesting shrimp for the first time, followed by several harvests throughout the year. Shrimp are harvested according to tidal patterns (2 tides per month and several days per tide). Shrimp raised in this model are typically large in size (less than 20 shrimps/kg), with larger shrimp commanding higher prices. Crabs are harvested for the first time after about 4–5 months and are also harvested several times a year. Crab full of fat is usually priced much more than normal crab, but the proportion of crab full of fat is small. Regarding the structure of harvested products, farmed shrimp constitute a significant portion of production (48%). Crabs account for (21%). In addition, farmers also harvest wild shrimp (22%) and fish (9%), having entered the pond through tidal waters and grown there (Figure 1). In terms of revenue, farmed shrimp generates the largest revenue, accounting for 67% (Figure 2).

Table 1. Farmers' perspectives on constraints to shrimp farming

Constraints	Percentage (%)
Disease	53
Impact of climate change	39
Degradation of water quality	33
Lack of capital	18
Reduction in natural seed sources	8
Insufficient quality seed	5
Reduction in natural feed sources	3
Other	5

Source: Authors' own estimates

Constraints to shrimp farming

The challenges faced by shrimp farmers are outlined in Table 1. Disease poses a significant threat, affecting nearly half of the farmers surveyed. Climate change, particularly excessive rainfall, is a concern for 39% of farmers, while 33% report worries about water quality degradation due to waste from intensive farming and other sources. Other constraints include limited access to capital, quality seeds, and a decline in natural seed and feed availability.

Determinants of the productivity of integrated mangrove–shrimp culture model

Table 2 presents the descriptive statistics of variables used in the Cobb–Douglas production function. All inputs and outputs are calculated per hectare of water–surface area. The average shrimp yield is 252.756 kg/ha of water–surface area. The average amount of post larvae used for stocking is 174.866 thousand post larvae/ha of water–surface area. Farmers typically prepare the pond before starting a new crop, especially by removing sediment at the bottom to prevent disease sources from the previous crop and to create a favorable living environment for shrimp. The pond–preparation cost for shrimp production is calculated by multiplying the total cost of sediment removal by 67% (67% being the proportion of revenue from harvested shrimp). The average cost for pond preparation is 6.050 million VND/ha of water–surface area. Family labor is used for day–to–day management of shrimp ponds. The labor variable in the model represents the total farming days for shrimp production, calculated by multiplying the number of laborers (main laborer + other laborers *0.5) by the number of farming days (one year) and 67%. The average labor required is about 260 days/ha of water–surface area.

D_saponin is a dummy variable, equal to 1 if a farmer used tea seed cake or derris roots to kill fish, and 0 otherwise. Certified organic farmers use tea seed cake rather than derris roots because tea seed cake is very safe. 62.5% of surveyed farmers use tea seed cake or derris roots. *D_lime* is a dummy variable, equal to 1 if a farmer used lime, and 0 otherwise. 15.8% of farmers use lime to control bacteria and adjust the pH level of water in shrimp ponds. Mangroves are considered an input in shrimp production because mangroves in shrimp ponds provide food inputs, water filtration, and shading in mixed systems (Rönnbäck, 1999; Tendencia *et al.*, 2012). Thus, mangrove coverage is included in the stochastic frontier production model as a variable. Mangrove coverage is expected to have a positive effect on shrimp productivity. The average mangrove coverage is about 55%. Surveyed farmers have an average education level and years of experience in shrimp production of about 7 years and 20 years, respectively. *D_disease* is a dummy variable, equal to 1 if a farmer faces shrimp disease, and 0 otherwise. 60.8% of surveyed farmers face shrimp disease. *D_training* is a dummy variable, equal to 1 if a farmer participated in any training course about shrimp production, and 0 otherwise. 90% of farmers responded that they participated in at least one training course about shrimp production. The average water–surface area (excluding mangrove area) is 2.056 hectares.

The empirical results from the stochastic frontier production function and technical inefficiency models are presented in Table 3. The estimation reveals several statistically significant determinants of both shrimp production and technical efficiency. In the stochastic frontier production model, four variables emerge as statistically significant determinants of shrimp productivity:

– *Pond–preparation cost* exhibits a positive coefficient (β = 0.130) significant at the 10% level, indicating that a 1% increase in pond–preparation investment is associated with a 0.13% increase in shrimp yield, ceteris paribus. This finding suggests that capital investments in pond infrastructure and preparation contribute to creating optimal growing conditions for shrimp cultivation.

– *Labor* shows a positive relationship (β = 0.121) significant at the 10% level, suggesting that increased labor allocation enhances production outcomes. This likely reflects the importance of careful monitoring and management in intensive shrimp farming systems.

– *D_saponin* (Saponin application) is significant at the 5% level, with farms utilizing tea seed cake or derris roots for pest control achieving higher yields compared to non–users. While both methods prove effective, tea seed cake is recommended over derris roots due to its superior safety profile and environmental compatibility.

– *Mangrove coverage* demonstrates a positive coefficient (β = 0.007) significant at the 5% level, underlining the crucial role of natural ecosystem services in sustainable aquaculture. This finding provides empirical support for integrated mangrove–aquaculture systems as a viable approach to enhancing both productivity and environmental sustainability.

The technical inefficiency model identifies three key determinants of farm–level efficiency:

– *Education* exhibits a negative coefficient (δ = –0.363) significant at the 5% level, indicating that an increase in farmers' education could reduce technical inefficiencies in shrimp production. This finding aligns with previous studies (Khai and Yabe 2011; Begum *et al.*, 2013; Iliyasu *et al.*, 2014; Islam *et al.*, 2014) and highlights the importance of human capital in optimizing farm management practices.

– *D_disease* (Disease occurrence) shows a positive relationship with technical inefficiency (δ = 1.484) significant at the 10% level, suggesting that disease outbreaks substantially impair farm efficiency. This result corroborates findings from previous research (Asche and Roll, 2013; Iliyasu *et al.*, 2014) and emphasizes the critical importance of disease prevention and management protocols.

– *D_training* (Training participation) demonstrates a negative association with technical inefficiency (δ = –2.832) significant at the 1% level. Farmers who participate in technical training programs exhibit higher effi-

Table 2. Descriptive statistics of variable used in the production function

Variables	Description	Mean	S.D
Shrimp yield	Yield in kilograms per hectare of water–surface area	252.756	119.695
Seed	Quantity of post–larvae used for stocking (thousand post–larvae per hectare of water–surface area)	174.866	135.238
Pond Preparation cost	Cost for removing sediment at the pond bottom, calculated as 67% of total costs (million VND per hectare)	6.050	3.357
Labor	Total farming days for shrimp production, computed as (main laborer + other laborers *0.5) * number of farming days *67%	260.189	185.485
D_saponin	Dummy variable: 1 if tea seed cake or derris roots are used to eliminate fish; 0 otherwise	0.625	0.486
D_lime	Dummy variable: 1 if lime is used; 0 otherwise	0.158	0.367
Mangrove coverage	Proportion of mangrove area to total pond area (%)	55.525	12.090
Education	Average years of schooling	7.450	2.858
Experience	Years of experience in shrimp production	19.791	8.136
D_Disease	Dummy variable: 1 if the farmer encounters shrimp disease; 0 otherwise	0.608	0.490
D_Training	Dummy variable: 1 if the farmer has participated in any shrimp production training courses; 0 otherwise	0.900	0.301
Area	Size of the pond's water–surface area excluding mangrove areas (hectares)	2.056	1.224

Source: Authors' own estimates

Table 3. Parameter estimators of stochastic production frontier and technical inefficiency models

Variables	Coefficient		Standard Error
Stochastic production frontier			
Ln (seed)	0.084		0.057
Ln (pond–preparation cost)	0.130	*	0.072
Ln (labor)	0.121	*	0.067
D_saponin	0.155	**	0.071
D_lime	0.075		0.094
Mangrove coverage	0.007	**	0.003
Constant	3.841		0.401
Technical inefficiency model			
Education	–0.363	**	0.185
Experience	–0.053		0.059
D_disease	1.484	*	0.902
D_training	–2.832	***	1.034
Area	0.048		0.391
Constant	1.491		1.612
Log likelihood	–52.423		
Wald χ^2 *(6)*	30.72		
σ_v	0.344	0.028	
Observations	120		

Source: Authors' own estimates
****, **, and * indicate significance level at 1%, 5%, and 10% levels, respectively*

Table 4. Distribution of technical efficiency (TE)

TE levels	Number of farms (N)	Percentage (%)	Cumulative (%)
<0.5	6	5.0	5.0
0.5–0.6	1	0.8	5.8
0.6–0.7	5	4.2	10.0
0.7–0.8	9	7.5	17.5
0.8–0.9	34	28.3	45.8
>=0.9	65	54.2	100.00
Mean of TE		0.859	
Minimum		0.197	
Maximum		0.974	

Source: Authors' own estimates

Table 5. Technical efficiency of certified organic farms vs. non–certified farms

	Certified farms	Non–certified farms
Mean of Technical Efficiency (TE)	0.898	0.767
Standard Deviation	0.064	0.221
Difference in TE between groups	0.131***	

Source: Authors' own estimates

ciency levels, suggesting that structured knowledge transfer effectively complements practical experience. This finding supports previous research (Iliyasu *et al.*, 2014) and underscores the value of extension services in disseminating best practices and innovative techniques.

Table 4 illustrates the distribution of technical efficiency (TE) among shrimp farms, ranging from 19.7% to 97.4%. Notably, 5% of farms fall below a 50% TE level. Approximately 28% and 54% of farms achieve TE levels of 80–90% and above 90%, respectively. The mean TE stands at 85.9%, indicating a potential 14.4% increase in output with current inputs. Moreover, certified organic farms demonstrate higher TE, averaging 89.8%, compared to 76.7% for non–certified farms (Table 5). Figure 3 further emphasizes that a greater proportion of certified organic farms achieve TE above 80%, highlighting the benefits of certification in enhancing efficiency.

CONCLUSION POLICY IMPLICATION

This study employed a Cobb–Douglas stochastic frontier production function to analyze the determinants of productivity in integrated mangrove–shrimp farming systems in Ca Mau province, Vietnam. Our findings offer

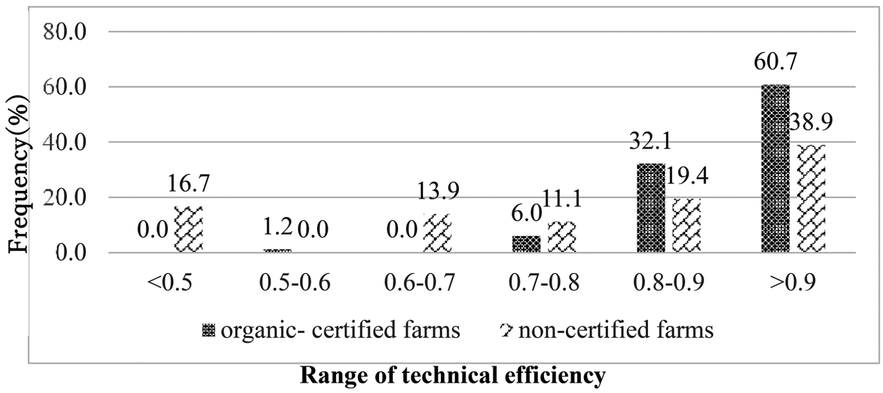

Fig. 3. Distribution of technical efficiency for certified organic farms and non–certified farms.
Source: Authors' own estimates

valuable insights into the factors influencing both productivity and technical efficiency in this unique aquaculture model, which balances economic objectives with environmental conservation. The empirical results reveal that pond preparation costs, labor input, the use of tea seed cake or derris roots for fish control, and mangrove coverage significantly influence shrimp productivity. These findings underscore the importance of investment in pond infrastructure, optimal labor allocation, and judicious use of natural pest control methods in enhancing production outcomes. Our analysis confirms the positive effect of mangrove coverage on shrimp production, providing empirical support for the synergistic relationship between mangrove conservation and aquaculture productivity. This result reinforces the ecological rationale behind the integrated mangrove–shrimp farming model.

The mean technical efficiency of 85.6% indicates that, on average, farmers are operating relatively close to their production frontier. However, there remains potential for a 14.4% increase in output given current input levels, pointing to opportunities for efficiency gains. The technical inefficiency model highlights the crucial role of human capital in farm performance. Specifically, higher levels of farmer education and participation in training courses are associated with reduced technical inefficiencies. Conversely, the incidence of shrimp disease significantly increases inefficiency, underscoring the importance of disease management in aquaculture. Certified organic farmers demonstrate higher technical efficiency compared to their non–certified counterparts, suggesting that organic certification practices may contribute to improved farm management and productivity.

Based on these findings, we propose the following policy recommendations: Policymakers should consider programs to support farmers in improving pond preparation and maintenance, potentially through targeted subsidies or low–interest loans for infrastructure upgrades; Extension services should focus on educating farmers about optimal labor allocation techniques to maximize productivity while minimizing costs; Promote the appropriate use of natural pest control methods, such as tea seed cake or derris roots, through guidelines and training programs that emphasize both effectiveness and environmental sustainability; Develop and implement incentive schemes that reward farmers for maintaining or increasing mangrove coverage on their farms, recognizing the dual benefits for productivity and ecosystem services; Expand access to education and specialized training programs for shrimp farmers, focusing on best practices in integrated mangrove–shrimp farming, disease management, and sustainable aquaculture techniques; Invest in research and extension services aimed at improving disease prevention and management in shrimp aquaculture, potentially including early warning systems and rapid response protocols; Encourage and facilitate the process of organic certification for shrimp farmers, potentially through subsidies for certification costs or preferential market access for certified products; Foster knowledge sharing and technology transfer among farmers, particularly from high–performing (certified organic) farms to less efficient operations, to disseminate best practices and improve overall sector performance.

While this study provides valuable insights, several areas warrant further investigation: Longitudinal studies to assess the long–term impacts of integrated mangrove–shrimp farming on both productivity and environmental sustainability; Comparative analyses of different aquaculture models to quantify the economic and ecological trade–offs; In–depth examination of the mechanisms by which organic certification enhances technical efficiency; Analysis of market dynamics and value chain implications for certified organic shrimp products.

In conclusion, the integrated mangrove–shrimp farming model in Ca Mau province demonstrates considerable promise as a sustainable aquaculture system. By addressing the identified determinants of productivity and technical efficiency, policymakers and stakeholders can work towards optimizing this model, ensuring its economic viability while preserving critical mangrove ecosystems. This balanced approach is crucial for the long–term sustainability of Vietnam's shrimp aquaculture sector and could serve as a model for other coastal regions facing similar challenges in reconciling economic development with environment.

AUTHOR CONTRIBUTIONS

Duyen Thi Thu Tran designed the study questionnaire, collected and analyzed the data. Duyen Thi Thu Tran and Huynh Viet Khai drafted the manuscript. Yoshifumi Takahasi and Mitsuyasu Yabe supervised the research and made critical revisions to the manuscript. All authors read and approved the final manuscript.

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