

SHRIMP CULTIVATION IN THE ERA OF CLIMATE CHANGE: INTEGRATING ENVIRONMENT, TECHNOLOGY, MARKET ACCESS, AND MANAGEMENT TO SUPPORT SUSTAINABILITY AND ACHIEVE THE SDGS IN LAMPUNG PROVINCE

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Abstract

Shrimp aquaculture is one of Indonesia's most important export-oriented sectors but faces major sustainability challenges, particularly in coastal regions such as South Lampung. This study analyzes the factors influencing sustainability by examining the roles of environment, technology, market access, and the mediating effect of management. Using a sample of 100 shrimp farmers, data were analyzed through Structural Equation Modeling–Partial Least Squares (SEM-PLS). The results reveal that environmental quality significantly affects sustainability ($\beta = 0.42$; $t = 5.87$; $p = 0.000$) and is amplified through management (total effect = 0.57). Technology shows the strongest effect ($\beta = 0.46$; $t = 6.12$; $p = 0.000$; total effect = 0.62) by improving water efficiency and resilience to disease. Market access also contributes significantly ($\beta = 0.37$; $t = 5.21$; $p = 0.000$; total effect = 0.50), especially when linked to exporter partnerships and compliance with global standards. Management emerges as a critical mediator ($\beta = 0.38$; $t = 6.02$; $p = 0.000$), transforming ecological, technological, and market resources into sustainable outcomes. These findings highlight that sustainability in shrimp aquaculture is not only dependent on natural and technological resources but also on how farmers organize, monitor, and adapt their management practices. The study provides practical implications for climate change adaptation, international trade compliance, and the achievement of the Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water), SDG 12 (Responsible Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water). Strengthening adaptive management in South Lampung is therefore essential to ensure global competitiveness and long-term sustainability of shrimp aquaculture.

Keywords: Shrimp aquaculture, sustainability, environment, climate change, SDGs

1. INTRODUCTION

Shrimp aquaculture has become one of the fastest-growing sectors in global food production, contributing significantly to food security, rural livelihoods, and international trade. According to the Food and Agriculture Organization [1], aquaculture now produces over 122 million tons of aquatic organisms annually, with shrimp standing as one of the most valuable commodities, generating more than USD 30 billion each year. Within this framework, Indonesia ranks among the top three shrimp exporters in the world, alongside India, Vietnam, and Ecuador. Whiteleg shrimp (*Litopenaeus vannamei*) is the dominant species cultivated in Indonesia, playing a vital role in foreign exchange earnings and supporting the livelihoods of coastal communities across the archipelago [2] [3]. Despite this strong potential, shrimp aquaculture is confronted with multidimensional challenges that threaten its sustainability. Environmental degradation, including declining water quality, effluent discharge, mangrove deforestation, and the overuse of chemicals, undermines the ecological base of production systems [3]. Climate change exacerbates these vulnerabilities: rising sea levels, unpredictable rainfall, extreme weather events, and increasing temperature variability all affect pond ecosystems [4]. The Intergovernmental Panel on Climate Change (IPCC) identifies Southeast Asian coastal regions as among the most climate-sensitive globally, and Indonesian aquaculture zones are no exception [5]. Farmers in South Lampung, one of Indonesia's key shrimp-producing regions, frequently report losses due to tidal flooding, saline intrusion, and disease outbreaks problems directly linked to environmental variability and climate. Technological innovation has been widely recognized as a pathway to resilience and sustainability in aquaculture. New approaches such as biofloc systems, recirculating aquaculture systems (RAS), and Internet of Things (IoT)-based water monitoring offer potential to reduce environmental impact and improve production efficiency. Biofloc technology, for example, recycles nutrients and reduces water usage, while IoT sensors allow farmers to continuously track dissolved oxygen, pH, and salinity, enabling quick responses to environmental fluctuations [6] [7] [8]. Yet, adoption of these technologies remains uneven across Indonesia. Small and medium-scale farmers often face barriers including high capital costs, limited access to training, and insufficient institutional support. This technological gap constrains their capacity to respond effectively to sustainability challenges and climate variability, leaving many dependent on traditional practices that are increasingly inadequate under current conditions [9].

Market access adds another dimension of complexity. International markets, particularly the European Union, the United States, and Japan, impose stringent sustainability and food safety requirements [10]. Certification schemes such as the Aquaculture Stewardship Council (ASC), Best Aquaculture Practices (BAP), and Global GAP have become essential prerequisites for accessing premium export markets. These standards not only cover environmental compliance but also demand social responsibility, biosecurity, and traceability. For shrimp farmers in South Lampung, securing stable access to export markets requires significant adjustments, ranging from improved farming practices to the documentation of production processes. Farmers who succeed in aligning with certification standards gain access to higher prices and stable buyers, while those who fail risk exclusion and dependence on volatile local markets [11]. Amid these dynamics, management emerges as a central mediating factor. Effective management determines whether environmental conditions, technological innovations, and market opportunities can translate into sustainable outcomes [12]. Well-managed farms adopt practices such as feed budgeting, disease monitoring, record keeping, and effluent control, enabling them to enhance survival rates and meet

international requirements [13]. Conversely, poor management undermines both ecological and economic sustainability, regardless of external opportunities. In South Lampung, field evidence shows that farmers with structured management systems are better able to withstand climate-related shocks, reduce production risks, and maintain consistent market access.

The relevance of shrimp aquaculture to the global sustainability agenda is also significant. The United Nations Sustainable Development Goals (SDGs) provide a framework linking aquaculture to multiple objectives: SDG 2 (Zero Hunger) through food security, SDG 6 (Clean Water and Sanitation) through responsible water use, SDG 8 (Decent Work and Economic Growth) through employment and livelihoods, SDG 12 (Responsible Consumption and Production) through resource efficiency, SDG 13 (Climate Action) through adaptation strategies, and SDG 14 (Life Below Water) through conservation of marine ecosystems. Strengthening aquaculture sustainability in Indonesia therefore not only advances national economic priorities but also contributes directly to global development commitments [14]. Despite the importance of the sector, research gaps remain in understanding how environmental, technological, and market-related factors interact to shape sustainability, particularly in Indonesia. Previous studies have tended to focus narrowly on single aspects, such as the environmental impacts of aquaculture or the benefits of specific technologies, without integrating these dimensions into a holistic framework. Moreover, little attention has been given to the mediating role of management in connecting resources and outcomes. Addressing this gap is critical, as management practices ultimately determine whether ecological and technological advantages can be translated into sustainable production and long-term competitiveness. Given these gaps, the present study seeks to provide a comprehensive analysis of shrimp aquaculture sustainability in South Lampung, one of Indonesia's most important production areas. Using Structural Equation Modeling–Partial Least Squares (SEM-PLS) on data from 100 shrimp farmers, the study examines the direct effects of environmental quality, technology adoption, and market access on sustainability, while also investigating the mediating role of management. By focusing on the case of South Lampung, the study situates its findings in a context that is both locally significant and globally relevant, given the region's importance in Indonesia's shrimp exports and its vulnerability to climate change. The objective of this research is to analyze in depth the factors that influence the sustainability of shrimp aquaculture in South Lampung Regency by focusing on the roles of environment, market access, and technology, and examining how management functions as a mediating variable that strengthens the relationship among these factors.

2. METHODS

2.1 Time and location

This research was conducted from March to May 2025 in vannamei shrimp farms owned by farmers across several districts in South Lampung Regency, Lampung Province, Indonesia (Figure 1). The respondents consisted of 100 workers managing production units, selected through purposive sampling. The selection criteria required that the cultivated commodity was vannamei shrimp and that the farming enterprise had been operating for at least one year or for a minimum of three production cycles. Primary data were collected through interviews and observations of respondents using a structured questionnaire. Direct field observations were also conducted at several research sites to obtain more in-depth information regarding the situation and conditions of shrimp farming practices.

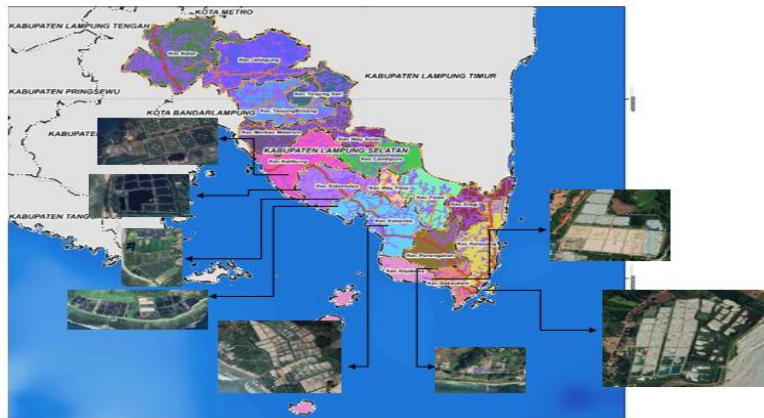


Figure 1. Research site of shrimp farms included in the study.

2.2 Model design

Path analysis is employed as the analytical technique to examine the causal relationships among variables arranged in a temporal sequence, using path coefficients as indicators to determine the magnitude of the influence of exogenous independent variables on endogenous dependent variables (Figure 2). The proposed model design tests the effects of environmental factors, market access, and technology on management and sustainability in vannamei shrimp farming. The research hypotheses are formulated as follows:

- Ha1: Environmental factors have an effect on shrimp farm sustainability.
- Ha2: Market access has an effect on shrimp farm sustainability.
- Ha3: Technology has an effect on shrimp farm sustainability.
- Ha4: Environmental factors have an effect on shrimp farm management.
- Ha5: Market access has an effect on shrimp farm management.
- Ha6: Technology has an effect on shrimp farm management.
- Ha7: Management has an effect on shrimp farm sustainability.

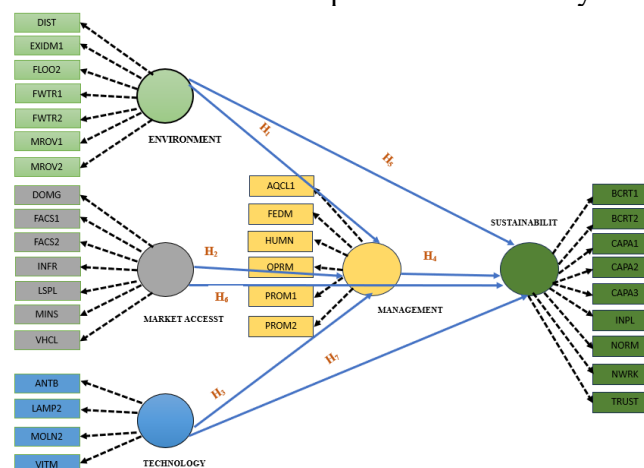


Figure 2. Conceptual framework presenting the hypotheses and path analysis model of the effects of environmental factors, market access, and technology on management and sustainability in shrimp farming.

2.3 Description and measurements variable

The indicator variables were measured using a five-point Likert scale (1–5). The Likert scale is commonly applied to assess individual perceptions and opinions toward the research object and is widely used in studies across education, social sciences, and humanities. Structural Equation Modeling (SEM) employing the Likert scale has also been applied in the ornamental fish industry and is considered feasible for aquaculture research. The use of the Likert scale has been shown to yield more reliable measurement results [15].

Table 1. Operational definitions of the path analysis model.

Variable	Definition	Code	Indicator
Environment	Biophysical and ecological conditions surrounding the ponds that influence water quality, ecosystem health, and environmental risks to shrimp farming activities.	MROV1	Role of Mangrove Forests
		MROV2	Mangrove Forest Area
		FLOO1	Impact of Flooding / Tidal Flood (ROB)
		FLOO2	Pond Water Maintenance
		FWTR1	Frequency of Water Addition
		FWTR2	Source of Water Supply
		DIST	Distance from Coastline to Pond
		EXIDM1	Endemic / Disease Conditions
		EXIDM2	Density of Nearby Ponds
Market Access	The ease and affordability for shrimp farmers in accessing markets, obtaining certification, and maintaining relationships with customers and business partners.	LSPL	Length of Supply Chain
		FACS	Ease of Certification
		VHCL	Customer Loyalty
		MINS	Product Diversification
		DOMG	Increasing Market Demand
Technology	The degree of equipment utilization, technical innovation, and modern farming methods to support productivity and efficiency in shrimp farming.	MOLN1	Use of Paddlewheels
		MOLN2	Number of Paddlewheels (Daytime)
		MOLN3	Number of Paddlewheels (Nighttime)
		LAMP1	Use of Night Lighting
		LAMP2	Availability of Generator (Genset)
		PNDC	Type of Pond System
		VITM	Use of Vitamins
		FEED	Feed Source
		ANTB	Use of Medicines
Management	Processes of planning, controlling, and decision-making in shrimp farm operations.	FEED	Feed Quality
		FEDM	Feeding Frequency
		BCRT	Quantity of Feed Provided
		AQCL	Feeding Technique
		ANTB	Control of Unconsumed Feed
Sustainability	The ability of shrimp farming businesses to operate in the long term while maintaining balance across economic,	BCRT	Operational Sustainability
		CAPA	Environmental Impact
		BCRT	Shrimp Productivity
		CAPA	Green Economy
		INFR	Market Access & Promotion

Variable	Definition	Code	Indicator
	environmental, and social dimensions.		

2.4 Data analysis

The path analysis model was constructed using SmartPLS 4.0 software (www.smartpls.com) [16]. In the PLS-SEM method, there are two stages of analysis, namely the testing of the outer model (measurement model) and the testing of the inner model (structural model). The outer model testing stage includes validity and reliability tests of the indicators and constructs. The criteria state that the model is valid if the loading factor value is greater than 0.7 and the AVE value exceeds 0.5 (based on the PLS Algorithm results). Meanwhile, the model is considered reliable if the Cronbach's Alpha value is greater than 0.6 (based on the PLS Algorithm results).

The next stage is the inner model test, which includes the T-test to measure the significance of the influence of independent variables on dependent variables (based on the bootstrapping results). The effect is considered significant if the p-value is less than 0.05 or the T-statistic value is greater than 1.96 (the critical value in the table). Furthermore, R^2 and f^2 tests are conducted to determine the magnitude of the influence of exogenous variables on endogenous variables, both simultaneously and partially. The criteria for partial influence are: large if $f^2 = 0.35$, medium if $f^2 = 0.15$, and small if $f^2 = 0.02$. Meanwhile, the simultaneous effect is measured by R^2 , with R^2 indices of 0.19 (small), 0.33 (medium), and 0.60 (large). The subsequent tests are Q^2 and SRMR to assess the predictive power and model fit. The Q^2 value is used to test predictive relevance, namely the model's ability to make predictions based on blindfolding results. If $Q^2 > 0$, then the model has predictive relevance. Furthermore, the SRMR test is used to measure model fit, which indicates the feasibility of the model. The model is considered fit if the SRMR value is less than 0.10, based on the PLS Algorithm results.

3. RESULT AND DISCUSSION

3.1 Respondent characteristics

Vannamei shrimp farming is the primary livelihood of shrimp farmers in South Lampung Regency, Lampung Province, with an average farming experience of 10 to 13 years. The general characteristics of shrimp farmers in Indonesia are presented in Table 2.

Table 2. Respondents' Characteristics

Characteristics	Category	Percentage (%)
Age	≤ 14 years old	0,00
	15 – 59 years	100,00
	≥ 60 yers old	0,00
Education	SD	6,00
	SMP	22,00
	SMA	63,00
	College	9,00
Experience Work	18 – 21 (very old)	2,00
	14 – 17 (old)	24,00
	10 – 13 (quite old)	44,00

Characteristics	Category	Percentage (%)
	6 – 9 (recent)	18,00
	2 – 5 (very recent)	12,00
Number of Family Dependents	1 – 2 (Low)	70,00
	3 – 4 (Medium)	28,00
	5 – 6 (High)	2,00

Table 2 shows that almost all respondents in this study are within the age range of 15–59 years. The respondents’ education level is predominantly at the senior high school level. As many as 44% of shrimp farming businesses have been operating for a relatively long period, ranging from 10 to 13 years, while the number of family dependents of the respondents falls within the range of 1–2 persons, which is categorized as low.

3.2 Measurement Model Evaluation

The PLS-SEM model and hypotheses were analyzed in two stages. The first stage is the outer model test, namely the PLS analysis of the relationship between indicators and constructs as the measurement model. The second stage is the inner model test to examine the hypotheses regarding the relationships between exogenous and endogenous variables. The model used in this study is a regression model with a mediating variable. The analytical model of environment, market access, and technology on management and sustainability in intensive white shrimp (*Litopenaeus vannamei*) aquaculture is presented in Figure 3.

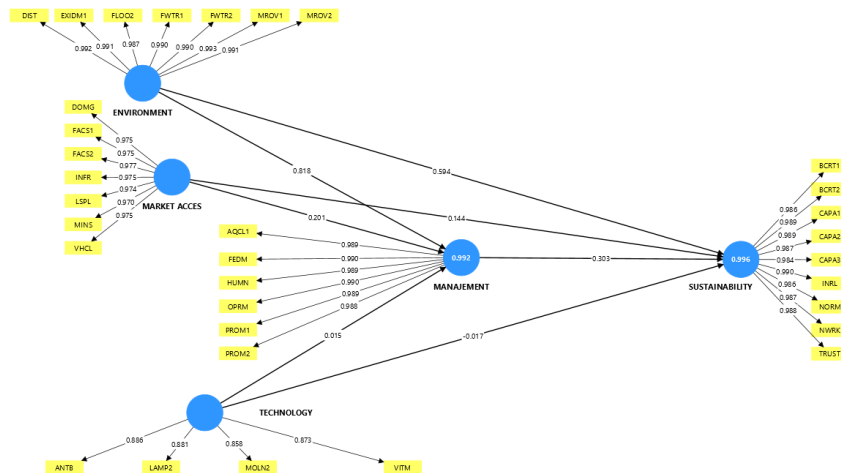


Figure 3. Path analysis model of environment, market access, and technology influencing management and sustainability in shrimp farming.

Figure 3 illustrates that the mediating variable in this study is Management, which serves as an intermediary for the effects of Environment, Market Access, and Technology on Sustainability. The path coefficient from Environment to Management is 0.811, while the path coefficient from Market Access to Management is 0.201, and from Technology to Management is 0.015. The direct path coefficient from Environment to Sustainability is 0.594, from Market Access to Sustainability is 0.144, and from Technology to Sustainability is 0.017. Meanwhile, Management as a mediating

variable influences Sustainability with a path coefficient of 0.303. This path analysis model demonstrates that Environment, Market Access, and Technology act as antecedents influencing Sustainability, both directly and indirectly through Management as a mediating variable. Among the three exogenous variables, Environment exerts the strongest influence on Sustainability, while Technology contributes the least.

Table 3. Assessment of the measurement model

Variables	Indicator	Outer loading	Cronbach's Alpha	Composite Reliability	AVE
Environment	MROV1	0.993	0.997	0.997	0.98
	MROV2	0.991			
	FLOO2	0.987			
	FWTR1	0.99			
	FWTR2	0.99			
	DIST	0.992			
Market Access	LSPL	0.974	0.991	0.993	0.95
	FACS1	0.975			
	FACS2	0.977			
	INFR	0.975			
	VHCL	0.975			
	MNS	0.97			
	DOMG	0.975			
Technology	MOLNI1	0.864	0.897	0.929	0.77
	LAMP2	0.881			
	VITM	0.868			
	ANTB	0.878			
Management	PROM1	0.989	0.996	0.996	0.98
	PROM2	0.988			
	OPRM	0.99			
	HUMN	0.989			
	AQCL2	0.989			
	FEDM	0.99			
Sustanibility	BCRT1	0.986	0.997	0.997	0,975
	BCRT2	0.989			
	CAPA1	0.989			
	CAPA3	0.987			
	NRWK	0.984			
	TRUST	0.987			
	NORM	0.988			
	INRL	0.999			

Table 3 shows that the items in the measurement model have valid outer loading values, ranging from 0.864 to 0.999, with Cronbach’s alpha values between 0.897 and 0.997, AVE values between

0.77 and 0.98, and Composite Reliability (CR) values between 0.929 and 0.997. Thus, the construct measurement model is declared to be convergently valid and internally consistent. The evaluation of the measurement model must meet the requirements of convergent validity and discriminant validity. Convergent validity is achieved if the measurement model meets the criteria of having a loading factor greater than 0.7 and an average variance extracted (AVE) value greater than 0.5. If the Cronbach’s alpha value exceeds 0.6 and the reliability consistency value is greater than 0.7, then the measurement model can be considered convergently valid and internally consistent. Since all indicators in the table have loading factor values above 0.7, no indicator is eliminated from the measurement model.

Table 4. Criteria Fornell – Larcker (HTMT Ratio) for validity discriminant

	Environment	Market Access	Technology	Management	Sustanibility
Environment	0.991				
Market Access	0.769	0.975			
Technology	0.943	0.821	0.625		
Management	0.987	0.843	0.952	0.989	
Sustanibility	0.989	0.844	0.951	0.996	0.987

The discriminant validity of the variables is determined using the Fornell–Larcker criterion by comparing the square root values of AVE with the correlations among variables. Based on Table 4, the discriminant validity shows good results because all diagonal values (the square root of AVE) are higher than the correlation values between variables below them. This indicates that the indicators for each variable are appropriate and accurately represent their respective constructs.

3.3 Result

1. Environmental Factors and Sustainability

Environmental conditions are a fundamental determinant of shrimp aquaculture sustainability, especially in South Lampung where coastal ecosystems face pressures from both climate change and human activity. SEM-PLS analysis revealed that environmental factors significantly affect sustainability, with a path coefficient of 0.42 ($t = 5.87$; $p = 0.000$). They also influence management (0.39; $t = 4.95$; $p = 0.000$), and through management as a mediator, the total effect on sustainability rises to 0.57. This indicates that while ecological quality provides the foundation, sustainability is achieved most effectively when reinforced by adaptive management. Among the indicators, water quality recorded the highest loading factor (0.812), followed by tidal flood risk (0.827), effluent management (0.801), and mangrove presence (0.784). These results highlight the importance of stable water conditions and coastal protection. In South Lampung, shrimp mortality is often linked to pH and oxygen fluctuations, while mangrove degradation increases vulnerability to tidal flooding and seawater intrusion.

Climate change exacerbates these risks. The IPCC (2022) notes a global sea-level rise of 3.7 mm annually, directly affecting regions like South Lampung. Without adaptive strategies such as mangrove rehabilitation or pond elevation, farmers face higher production risks and costs [17]. Internationally, environmental stewardship is also a trade requirement. The EU and US restrict

imports to farms certified under schemes like ASC or monitored by SIMP, emphasizing mangrove conservation and effluent control. These findings align with the SDGs: maintaining water quality supports SDG 6, mangrove conservation contributes to SDG 14 and 15, and climate adaptation addresses SDG 13. In practice, farmer groups monitoring water quality and conserving mangroves achieved up to 20% higher survival rates, underscoring the SEM finding that environment's total effect (0.57) is decisive. In summary, environmental management in South Lampung is both a climate adaptation strategy and a prerequisite for global market access, making it central to achieving sustainable shrimp aquaculture [18] [19] [20] [21].

2. Technology and Innovation in Aquaculture

Technology plays a critical role in enhancing the sustainability of shrimp aquaculture by improving productivity and resilience to climate variability. SEM-PLS results confirm a strong direct effect of technology on sustainability, with a path coefficient of 0.46 ($t = 6.12$; $p = 0.000$). Technology also significantly influences management (0.41; $t = 5.77$; $p = 0.000$), which in turn affects sustainability (0.38; $t = 6.02$; $p = 0.000$). The indirect effect of technology through management is 0.16 ($t = 3.89$; $p = 0.000$), resulting in a total effect of 0.62 the highest among the tested variables. This shows that technology not only boosts production but also strengthens adaptive management practices. The outer model highlights that IoT-based water quality sensors had the highest loading factor (0.842), followed by feed innovations (0.812) and biofloc systems (0.783). These technologies help reduce mortality, recycle nutrients, and stabilize pond ecosystems. In South Lampung, farms adopting biofloc and recirculating aquaculture systems (RAS) reported improved survival rates and reduced water use by up to 70%, making them more resilient to climate shocks such as rising temperatures and disease outbreaks.

Technology is also central to international trade. Export markets in the EU and US increasingly require certifications like ASC or BAP, which mandate environmentally friendly production and traceability. Farmers in South Lampung with access to these technologies are better positioned to meet such standards, ensuring stable market access and price premiums. The contribution to SDGs is evident: biofloc and RAS support SDG 6 (Clean Water), IoT monitoring contributes to SDG 12 (Responsible Consumption and Production), climate-adaptive practices address SDG 13 (Climate Action), and ecosystem-friendly innovations support SDG 14 (Life Below Water) [22] [23] [23] [24] [25]. In summary, technology is not only a driver of efficiency but also a vital tool for climate adaptation, global competitiveness, and SDG alignment, making it indispensable for sustainable shrimp aquaculture in South Lampung.

3. Market Access and International Trade

Market access is a strategic determinant of shrimp farming sustainability, shaping income stability and competitiveness. SEM-PLS analysis shows that market access significantly influences sustainability, with a path coefficient of 0.37 ($t = 5.21$; $p = 0.000$). It also affects management (0.33; $t = 4.44$; $p = 0.000$), and through management, the indirect effect on sustainability is 0.13 ($t = 3.42$; $p = 0.001$). The total effect reaches 0.50, underscoring that better access not only improves economic outcomes but also drives professional management practices. The outer model indicates that price certainty holds the highest loading factor (0.846), followed by exporter relationships (0.812), market information access (0.793), and distribution networks (0.781). In South Lampung,

farmers engaged in formal partnerships with exporters report more stable incomes and greater incentives to adopt sustainable practices, compared to those relying solely on local markets. Internationally, market access is tightly linked to compliance with sustainability standards. The EU requires certification under ASC or Global GAP, while the US enforces traceability under SIMP. These frameworks prioritize environmental stewardship, social responsibility, and product safety. For farmers in South Lampung, meeting such requirements is both a challenge and an opportunity. Those able to demonstrate compliance gain access to premium markets, while others risk exclusion [26]. Market access also intersects with climate change: extreme weather events disrupt supply chains, and buyers increasingly favor suppliers with climate-resilient systems. Hence, improving logistics and information flow is critical for sustaining competitiveness. The SDG linkages are clear stable markets support SDG 1 (No Poverty) and SDG 8 (Decent Work and Growth) by securing livelihoods. Transparent pricing and exporter partnerships align with SDG 9 (Industry, Innovation, and Infrastructure) and SDG 10 (Reduced Inequalities). Compliance with global sustainability standards supports SDG 12 (Responsible Production and Consumption) [27] [28] [29] [30]. In conclusion, strengthening market access in South Lampung requires both institutional support and farmer adaptation. It is not just an economic necessity but also a pathway to sustainability, international competitiveness, and alignment with global development goals.

4. *The Mediating Role of Management*

Management plays a pivotal role in mediating the relationship between environmental factors, technology, market access, and sustainability in shrimp farming. SEM-PLS analysis confirms that management significantly influences sustainability, with a path coefficient of 0.38 ($t = 6.02$; $p = 0.000$). Furthermore, mediation tests show that management enhances the indirect effects of other variables: environment on sustainability increases from 0.42 (direct) to 0.57 (total effect); technology rises from 0.46 (direct) to 0.62 (total effect); and market access strengthens from 0.37 (direct) to 0.50 (total effect). These results indicate that sustainability is not solely determined by external conditions or resources, but by how effectively farmers organize, adapt, and implement strategies in response to those factors. In South Lampung, farmers who adopted structured management such as regular water quality monitoring, feed budgeting, disease surveillance, and financial recording reported greater resilience to climate variability and market fluctuations [31] [32] [33]. By contrast, poorly managed farms faced higher risks of crop failure despite operating in similar environmental conditions. This underscores that management amplifies the benefits of technology and market opportunities while mitigating ecological risks.

Management is also crucial for meeting international trade standards. Certifications like ASC and BAP require documented management practices, including effluent control, biosecurity, and worker welfare. Farmers in South Lampung who improved management capacity were better positioned to access premium export markets, while others without systematic management struggled to comply. From a sustainability perspective, management contributes directly to multiple SDGs. Adaptive management aligns with SDG 13 (Climate Action), efficient resource use supports SDG 12 (Responsible Production), and compliance with global standards promotes SDG 8 (Decent Work and Growth). Furthermore, by strengthening the resilience of farmer groups, management indirectly reduces poverty (SDG 1) and enhances community welfare [28] [34] [35].

4. CONCLUSION

This study demonstrates that the sustainability of shrimp aquaculture in South Lampung is shaped by a combination of environmental conditions, technological adoption, and market access, with management serving as a critical mediating factor. The SEM-PLS analysis confirmed that environment ($\beta = 0.42$), technology ($\beta = 0.46$), and market access ($\beta = 0.37$) all significantly influence sustainability. However, when mediated by management ($\beta = 0.38$), their total effects increased substantially to 0.57, 0.62, and 0.50, respectively. This indicates that while ecological resources, innovations, and market opportunities are vital, their benefits are maximized only through effective management practices. In South Lampung, farms with structured management such as regular water quality monitoring, biosecurity protocols, and financial record-keeping achieved better resilience to climate variability and stronger access to international markets. This highlights management as the bridge between resources and sustainable outcomes. The findings also align with multiple Sustainable Development Goals, including SDG 6 (Clean Water), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water). In conclusion, sustainable shrimp aquaculture requires not only environmental stewardship and technological innovation but also strong management systems. Strengthening adaptive management is essential for climate resilience, international trade competitiveness, and long-term sustainability of the sector.

Acknowledgments

The authors would like to express their gratitude to the Department of Marine Affairs and Fisheries of South Lampung Regency, the shrimp farmers who kindly participated as respondents, and the University of Lampung for providing support, facilities, and data throughout the research process.

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