

CAN DIGITAL TECHNOLOGY FACILITIES MITIGATE THE VULNERABILITY AND RISK DURING COVID-19? TOWARDS AQUAFARMER ECONOMICS SUSTAINABILITY

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Abstract: Unpredictable weather and the COVID-19 pandemic, as well as financial, management, health and environmental risks, pose significant challenges to aquaculture, threatening the industry's sustainability. This study aims to determine the impact of technology in reducing the vulnerabilities and risks in aquafarming economics during the pandemic. Data was gathered from 297 aquafarmers in the east coast state of Terengganu in Peninsular Malaysia using face-to-face interviews and online questionnaires, results were analysed using SmartPLS software. Financial risk had the greatest influence on aquafarmers' economics, followed by management risk, vulnerability to COVID-19 and health risk. Poor management could result in financial loss, whereas health issues, disease outbreaks, and environmental pollution could cause major stock losses and lower corporate efficiency. The study highlighted the importance of technology in reducing management risk in aquafarming economics. It emphasised the need for aquafarmers to stay updated with the latest knowledge and technology to improve their management skills and identify main risks in the business. This knowledge could be used to develop strategies for long-term sustainability and reduce economic problems. Adoption of technology facilities should not only be promoted to facilitate farm and management operations, but to ensure the long-term sustainability of aquaculture.

Keywords: Digital technology facilities, aquafarmer economy, sustainability.

Introduction

The onset of COVID-19 has led to the decline in aquafarmers' purchasing power and sales turnover, resulting in layoffs and unemployment in the industry. Fish production is limited by low-quality inputs and revenue has suffered due to escalating cost of fish feed and transport (Amoussou *et al.*, 2022). The inability of aquafarmers to pay wages has also hampered production. Movement restrictions and low prices of fish made it difficult to hire more workers and sustain operations. These issues are aggravated by the ensuing economic downturns worldwide, where consumer spending power and seafood demand are severely curtailed (Khan *et al.*, 2023). The problem is not unique to the aquafarming industry. COVID-19 has

also brought significant negative impact on the profit margins of other industries. As the pandemic continues to affect the global economy, companies may need to re-evaluate their operations and adapt to the new normal in order to survive.

Moreover, small- and medium-sized entrepreneurs regard other pandemic business management and risk management issues similarly (Belas *et al.*, 2022). This is especially so when facing higher input prices (Martey *et al.*, 2022). The high costs of feed, transport, and labour have been the main constraints of aquafarming specifically, and the agriculture industry as a whole. Labour shortage had led to harvest delays and lower yield and quality.

Furthermore, the lack of financial resources has been a major constraint for many farmers and agriculture businesses. With reduced demand and lower prices for their products, many have fallen into financial difficulties. Therefore, to cope with future shocks, the use of endogenous and digital technologies for distant sales is recommended for aquafarmers (Amoussou *et al.*, 2022).

However, some businesses have managed to survive thanks to good strategies and technology adoption, geographical location, and government support (Nielsen *et al.*, 2023). Climate change, cost increases, and logistics disruptions will increase the vulnerability of aquafarms (Hai & Speelman, 2023). However, the implementation of strategic improvements in spatial planning can mitigate these vulnerabilities (Soto *et al.*, 2021). Scientific farming practices, digital technology, and minimising export dependence can revive the agriculture sector and help it reach its full potential. These approaches can help farmers boost productivity, optimise resources and practice sustainable, and eco-friendly farming (Jaikumar *et al.*, 2023). Further research on IT support and knowledge-sharing between Western servers/domain providers and digital entrepreneurs can identify prospects to develop entrepreneurial digital competencies and improve decision-making (Ngoasong, 2017). Therefore, this preliminary study is to develop scale to assess digital technology adoption in maintaining the aquafarmers' economy during the pandemic, especially in the Malaysian context.

Thus, this preliminary study is implemented to assess the aquafarmers' perception. The development and validation of a questionnaire to gauge digital technology adoption among aquafarmers will provide crucial insights into adoption patterns and decision-making processes. A reliable and valid measure scale can provide accurate and consistent results, making it easier to interpret and analyse data. Without crisis measures in place, aquafarmers will continue to face labour shortages and high costs that could burden the economy and communities that rely on the industry.

Literature Review

Efficient methods are necessary to promote higher output and expand the fish market to achieve sustainable aquaculture production. Given the consequences of climate change, environmental risks, biosecurity and fish health issues, and the necessity to implement new technology requiring trained workers, this is particularly important.

Vulnerability Assessment

Aquaculture can be vulnerable due to their high reliance on coastal resources, which exposes them to the greatest impact of seasonal weather fluctuations (Albasri & Sammut, 2021). The seasonal changes may influence the ideal period for fish farming as temperature change, daylight hours, and precipitation patterns will affect fish growth. If there is a decrease in market demand, aquafarmers have to keep their stocks longer, which will result in higher feed and production expenses. Inadequate resources also hinder harvest and productivity (Khan *et al.*, 2023). The impact of these changes can affect the growth, reproduction, and overall health of farmed species.

Seasonal temperature fluctuations can have a significant impact on aquatic organisms. The effects of changes in temperature will adversely affect water quality (Dey *et al.*, 2021). Water conditions need to be monitored to maintain optimal temperatures for the cultivated species. Annual daylight changes will affect aquatic organism growth and behaviour as it triggers feeding, reproduction, and migration in many aquatic species. Increased rainfall or a drought may affect water quality and availability. Since 2015, fish diseases triggered by poor water quality and farm practices, as well as the high cost of local production and competition from cheap imports had all contributed to a stagnation in the Malaysian aquaculture industry (Ragasa *et al.*, 2022).

Small-scale farmers are particularly susceptible climate change as they may not have sufficient resources to equip their fish farms to cope with extreme weather changes. Constraints

to aquaculture expansion also include lack of seed and feed supply, weak extension support, and inadequate credit and markets (Asiedu, 2017).

Demographic factors such as education, income, and access to infrastructure may significantly contribute to aquafarmers' vulnerability. Approximately 85% of the participants believed that there is a relationship between the decrease in precipitation and water resources in a region with an increase in extreme climatic events such as droughts. About one-third of respondents noted a decrease in flooding and frostbite occurrences over the past 30 years (Jamshidi *et al.*, 2019). During the wet season, the high level of water and subsequent floods were favourable conditions for spawning. As a result, fish species will show more restricted movement which makes them more difficult to catch (Offem *et al.*, 2011). In the COVID-19 pandemic, some businesses have encountered difficulties in sustaining their production levels due to labour shortage, supply chain interruptions, and safety precautions. Larger farms may survive by seeking new markets and taking loans from banks, but they find it difficult to replace the workers who were retrenched (Lebel *et al.*, 2021).

Moreover, limited availability of skilled labour is an ongoing challenge for aquaculture firms (Ragasa, 2022). Environmental issues such as unpredictable weather fluctuations can affect the aquafarm's conditions and hinder the ability to maintain appropriate monitoring. Several factors have increased the vulnerability of monitoring work at aquafarms during the pandemic. Social distancing measures and lockdowns have resulted in a limited number of workers available for monitoring aquafarms. Furthermore, travel restrictions make it hard for experts and technicians to inspect aquafarms, which can lead to insufficient monitoring and management.

Communication issues have also risen hindering the ability of aquafarmers, workers, and regulators to exchange crucial information and work together efficiently. Furthermore, the

COVID-19 pandemic has impacted various aspects of the aquaculture sector such as decreased consumption, cancelled export orders, price drop, delayed summer stocking, lack of technical support, and transport challenges (Rafiqzaman, 2020). For example, the seed quality of shrimp was affected due to poor monitoring and maintenance of ponds, which resulted in microbial contamination like white spot disease and other infections (Jaikumar *et al.*, 2023). It is essential for the aquafarming industry, governments, and regulatory bodies to implement innovative solutions like remote monitoring technologies and create contingency plans to maintain the monitoring and management of aquafarms during difficult times.

Risk Assessment

Aquaculture production faces various risks that can impact its sustainability and profitability. Health risks like disease outbreaks, parasites, and poor water quality can lead to significant losses in production and even the death of farmed species. Besides, the aquafarmers may encounter specific health risks during the pandemic, like those faced by other key employment sectors. The main concern involves the possibility of being exposed to the virus through interactions with colleagues, suppliers, and customers. In addition, issues related to labour shortages, high turnover, or inadequate training can lead to health risk for the aquatic species and affect the business.

Aquaculture can have dual effects on the environment. Unsustainable practices including overfeeding, poor waste management, and contamination from pesticides and medicines could harm close-by ecosystems. Another environmental risk is the impact of seasonal change, which can cause alterations in water temperatures, ocean acidification, and changes in currents. The pH and temperature fluctuations in the water column influence the primary outcome of the environment (Dey *et al.*, 2021). These factors can affect the growth and survival of fish species, making it challenging for aquafarmers to maintain stable and profitable operations.

Pollution is another major environmental risk that can impact aquafarmers' economics. Chemical runoff from agricultural activities, industrial waste, and plastic pollution can contaminate water bodies, leading to the decline of fish populations and negatively affecting businesses. Additionally, the poor water quality do not only result in reduced profits, decreased product value, and health risks, but also affects production. Production declines when water contains impurities that can hinder the development, reproduction, and survival of cultured species. Water quality is crucial for consumption, agriculture, aquaculture, and industrial purposes (Lebel *et al.*, 2021).

Inefficient management can lead to decreased productivity, higher costs, and reduced profitability. Difficulties in sourcing and retaining skilled employees may result in productivity problems and higher labour expenses. Aquatic species are vulnerable to disease and parasite outbreaks, which can result in substantial economic losses if not controlled efficiently. Financial risk can significantly impact the economics of aquafarming, as it does in any other industry. The prices of fish and other aquatic products in the market can fluctuate due to various factors such as supply and demand, seasonal trends, and global economic conditions. This can lead to unpredictable income for aquafarmers, making it challenging to plan and manage their finances.

Aquaculture is susceptible to disease outbreaks, which can lead to significant financial losses due to high mortality rates, increased costs for treatment, and potential loss of market access. Unpredictable weather conditions, water pollution, and other environmental factors can negatively impact aquafarming operations, leading to reduced productivity and increased costs for mitigation measures. The cost of feed, fish seeds, and other essential inputs can fluctuate sharply, making it difficult for aquafarmers to manage their expenses and keep to their budgets. According to Bashar *et al.* (2022), farmers are facing financial pressures due to the forward (product price) and backward

(input costs) aspects of the value chain. In this study, we demonstrated that farmers have implemented remedial measures such as cutting labour expenses by reducing workforce and diversifying their farm products.

Digital Technology Adoption in Aquaculture Production

Digital technology refers to advanced tools and systems that use automation, Artificial Intelligence (AI) and digital platforms to improve aquafarming (Yoo *et al.*, 2020). These technologies include drones and sensors to automate tasks such as a pond cleaning and feeding, monitoring water quality and fish health, and better decisionmaking through data analysis, besides ensuring food safety and traceability throughout the aquaculture supply chain (Paspalakis *et al.*, 2020). These tools help aquafarms run efficiently, lower costs, improve sustainability, and support the long-term financial stability of the business. Together, these technologies can create a more resilient and profitable aquaculture industry.

The digital economy has a significantly positive effect on economic growth and industrial performance (Guo *et al.*, 2020). COVID-19 has boosted demand for digital industries. Many development strategies have been proposed to bridge the "digital divide" and strengthen the driving effect of the digital economy. Additionally, countries have began to identify strengths and weaknesses to formulate effective development strategies. Many are relying on the digital economy to develop new service trade patterns and improve their technological innovation capabilities, besides expanding cooperation in digital trade (Zhang *et al.*, 2022).

The COVID-19 epidemic has led to constraints on conventional marketing approaches due to social restraints. Utilising digital technology to provide online facilities is a viable method to sustain entrepreneurship. In addition, the utilisation of digital technologies and the Internet for promotional and sales

activities will empower operations to endure the challenges posed by the COVID-19 epidemic. The utilisation of the Internet and Information Technology (IT) provides an opportunity for entrepreneurs to sustain and enhance their revenue (Tasmilah *et al.*, 2022).

Digital technologies can help address these concerns and potentially disrupt fisheries and aquaculture (Rowan, 2023). Digital technologies that facilitate easy access to good agronomic practices, weather information services, input and output market information services, and financial services have been determined as crucial. Continuous advancements in aquaculture technology require skilled professionals to manage and operate these systems. Education and training programmes are essential to equip the workforce with knowledge and skills to maintain and improve the technology-driven aquaculture sector. According to Obiero *et al.* (2019), secondary education, diversified on-farm activities, farm size, production levels, attendance of extension training, ease of understanding, and ease of handling technologies are positive and significant predictors of aquaculture digital technology adoption.

Materials and Methods

Pilot Test

Before final deployment throughout the real sample, a pilot test was conducted among 50 Terengganu aquafarmers using a Likert scale questionnaire with 51 items to identify potential issues, weaknesses, and improvement opportunities. This survey had 10 sections, covering demographics, aquafarm details, and eight constructs with likert scale questions, including (1) seasonal change vulnerability, (2) COVID-19 vulnerability, (3) health risk, (4) environmental risk, (5) management risk, (6) financial risk, (7) digital technology facilities, and (8) aquafarmers' economy. Seven items were removed during the reliability test due to low item-total correlations. Meanwhile, eight items (18.2%) were deleted due to poor outer

loadings. As a result, 36 items were retained, demonstrating convergent and discriminant validity.

Data Collection

This study employs a quantitative survey approach to collect data from 248 aquafarmers in Terengganu. The respondents were selected using a simple random sampling technique. This study included a sample of 248 aquafarmers selected at random from a population of 705 in Terengganu. The selection of the sample was based on the Krejcie and Morgan table (1970). Data is gathered using telephone surveys, face-to-face interviews, and online surveys.

Method of Analysis

The data is analysed using the variance-based structural equation model, which was the PLS-SEM approach in the SmartPLS version 4 software. Data analysis comprised three main stages: Data screening, measurement model, and structural model. Before data screening, it was necessary to confirm that the study sample data had met the criteria specified in Green's Table (1991) to ensure enough data for PLS-SEM analysis.

Additionally, normality tests and Common Method Bias (CMB) were also conducted. The assessment of CMB involved the utilisation of Harman's single-factor test, the full collinearity test (variance inflation factor, VIF), or the variable marker technique. To mitigate the effects of CMB, it was necessary to acknowledge and account for situations, where data was collected from a single source and the same individual provided responses for both the independent and dependent variables. CMB could arise when a single response method was employed to measure both the independent and dependent variables simultaneously and in the same survey location. To ensure the accuracy and reliability of a study, it was crucial to address the issue of common method bias. This bias had the potential to distort the relationship between variables and introduce measurement errors, which could

significantly impact the reliability, validity, and parameter estimations (Podsakoff *et al.*, 2012; Kock *et al.*, 2021).

The measurement model would then be used to ensure that convergent and discriminant validity were achieved. Convergent validity could be met when the cross-loading value exceeded 0.5, the average extracted variance (AVE) exceeding 0.5, and the composite reliability (CR) exceeding 0.7 (Hair *et al.*, 2019). Meanwhile, discriminant validity could be attained when the heterotrait-monotrait correlation ratio (HT-MT criterion) exceeded 0.85 or 0.90, depending on the outcome (Hair *et al.*, 2019). According to Franke and Sarstedt (2019), the HTMT 0.90 criteria should be applied if the derived construct’s HT-MT values were higher than 0.85, but lower than 0.90. The HT-MT criterion was a rigorous measure for identifying potential non-discriminatory relationships between latent variables. It had been used in various studies to confirm the distinctness of measurement tools (Yusoff *et al.*, 2020).

Confirming discriminant validity entailed analysing HT-MT values, which should not exceed 0.9 (Franke & Sarstedt, 2019; Ringle *et al.*, 2023). In addition, HT-MT inference (the upper limit confidence interval value) needs to be less than one for discriminant validity. The structural model will be tested with 5,000 bootstrap samples after the measurement model

was complete. Determining the direction of the β value (band coefficient), a *t*-value greater than 1.645 and a *p*-value of less than 0.05 were the criteria that should be used to assess the structural model, according to Hair *et al.* (2017).

Lastly, the model’s predictive power was determined by testing it with PLS predict. PLS predict could be measured using the comparison between Root Mean Square Error (RMSE) in the PLS model and Linear Modelling (LM). The model had good predictive power when all RMSE values in the PLS model were lower than the LM. This difference (PLS-LM) would be negative or less than 0. Conversely, when most differences (PLS-LM) were less than 0, the model often exhibited a moderate level of predictive ability. A minority of differences below 0 indicated limited predictability. Predictive power was not established if all items had values greater than 0 (Shmueli *et al.*, 2016; Tuan Mansor *et al.*, 2020; Ngah *et al.*, 2021).

Besides, according to Tuan Mansor *et al.* (2020), if the value of Q² predicted for the PLS model was higher than that predicted for LM, this meant that the model had been all predictive or overfitted. Figure 1 depicts the conceptual framework of this study.

The exogenous constructs in this study were vulnerable to seasonal changes, COVID-19 health risks, environmental risks, management risks, and financial risks. Meanwhile, technology

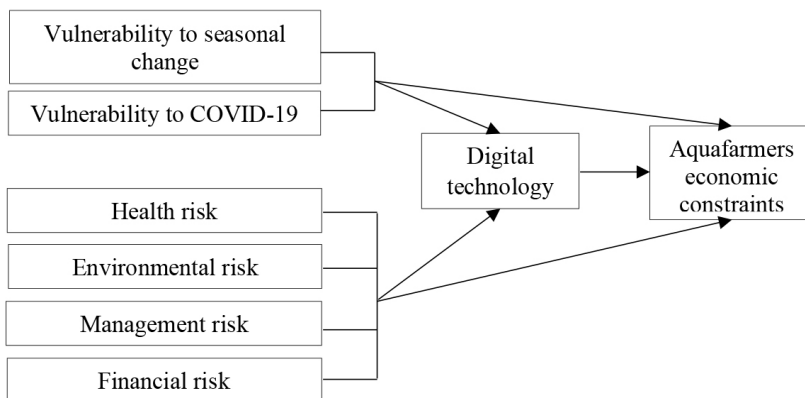


Figure 1: Conceptual framework of study

Source: Created by author

facilities and aquafarmers' economic constraints were the endogenous constructs. A descriptive analysis was also conducted in this study to present the information of demographic profile and aquafarmers' details.

Results

The findings are presented in two sections: The descriptive analysis and the PLS-SEM analysis. The former provides a detailed breakdown of the respondents' demographics and information about the respondents' aquafarms. The latter highlighted the vulnerabilities and risks faced by aquafarmers in Terengganu and explored the potential of new technologies to address their economic challenges.

Descriptive Analysis

Table 1 shows the number and percentage of responders based on their demographics, who were mostly from the state capital Kuala Terengganu. They are followed by respondents from other districts like Besut, Hulu Terengganu, Setiu, Dungun, Kemaman, Kuala Nerus, and Marang. Age wise, most of the responders were between 30 and 39, and only a small number above 70. Furthermore, 95.2% of respondents were born in the state, 88.3% were married, and 89.5% were male. Only 4.4% had never had a formal education, whereas 42.7% had high school qualification.

Table 2 displays the number and percentage of respondents according to aquafarm details. Most respondents were freshwater farmers,

Table 1: Number and percentage of aquafarmers surveyed in the state of Terengganu, Peninsular Malaysia based on demographic profile

Profile Demographic	Frequency <i>N</i> = 248 (%)
District	
Besut	42 (16.9)
Dungun	25 (10.1)
Hulu Terengganu	41 (16.5)
Kemaman	27 (10.9)
Kuala Nerus	15 (6.0)
Kuala Terengganu	54 (21.8)
Marang	14 (5.6)
Setiu	30 (12.1)
Age (years old)	
20 to 29	27 (10.9)
30 to 39	67 (27.0)
40 to 49	47 (19.0)
50 to 59	59 (23.8)
60 to 69	36 (14.5)
70 and above	12 (4.8)
Gender	
Male	222 (89.5)
Female	26 (10.5)

<i>Educational Level</i>	
No education	11 (4.4)
PMR/SRP (middle school)	63 (25.4)
SPM (high school)	106 (42.7)
STPM/skills certificate/diploma (pre-university)	46 (18.5)
Degree and above	22 (8.9)
<i>Status</i>	
Single	24 (9.7)
Widowed/divorced	5 (2.0)
Married	219 (88.3)
<i>Birth of Place</i>	
Terengganu	236 (95.2)
Others	12 (4.8)

Source: Created by author

Table 2: Number and percentage of respondents based on aquafarm details

Aquafarm Details	Frequency <i>N</i> = 248 (%)
<i>Aquaculture Type</i>	
Freshwater	168 (67.7)
Brackish water	57 (23.0)
Hatchery	6 (2.4)
Freshwater ornamental	17 (6.9)
<i>Aquaculture System</i>	
Pond	48 (19.4)
Cage	132 (53.2)
Tank	27 (10.9)
Fish seed	25 (10.1)
Aquarium	13 (5.2)
Others	3 (1.2)
<i>Duration of Experience</i>	
5 years and below	109 (39.8)
6 to 10 years	78 (28.5)
11 to 15 years	34 (12.4)
16 to 20 years	32 (11.7)
More than 20 years	21 (7.7)

Number of Workers

No worker	208 (78.6)
1 to 2 workers	44 (17.7)
3 to 4 workers	6 (2.4)
5 workers and above	3 (1.2)

Source: Created by author

followed by freshwater ornamental farmers and hatchery farmers. In addition, most respondents used cage-farming as it required minimal land use and allowed fish to remain in their natural environment. Furthermore, most respondents had five years or less experience in aquaculture farming. Approximately 78.6% of respondents worked alone and did not hire workers.

PLS-SEM Analysis

Normality Test

The results show that the data were not multivariate according to Mardia’s multivariate, which was developed by Cain *et al.* (2017). The skewness and kurtosis values were 428.488 and 7.6645, respectively, with a β values of 10.366 and 92.312, respectively, and a p -value less than 0.01. According to Tuan Mansor *et al.* (2020), Ngah *et al.* (2021) and the results could still be used in Smart PLS even though they did not meet the normality criteria.

Common Method Bias

According to Ngah *et al.* (2021), it is generally accepted that CMB would be present if the values of the VIF surpassed 3.3. Table 3 shows that all VIF values were below the 3.3 threshold based on the results of the collinearity tests. It suggests that this study was not affected by the collinearity problem.

Measurement Model

Table 4 shows the results of the convergent reliability assessment for health risk, environmental risk, financial risk, digital technology facility, and aquafarmer economy limit. It also shows the results for vulnerability to seasonal change and COVID-19. The Average Variance Extracted (AVE) for all categories was greater than 0.5 and the composite reliability (CR) was greater than 0.7, except for aquafarmers’ economy. The convergent validity was fulfilled after eight items were omitted from the model. After the model passed

Table 3: Full collinearity testing

Construct	VIF Value
Vulnerability to seasonal change	1.527
Vulnerability to COVID-19	2.270
Health risk	1.546
Environmental risk	1.759
Management risk	2.361
Financial risk	2.033
Digital technology facility	1.224
Aquafarmer’s economy	2.079

Source: Created by author

Table 4: Convergent validity and reliability assessment

Construct	Item	Outer Loading	CR	Cronbach Alpha	AVE
Vulnerability to seasonal change (VS)	A1.1	0.844	0.961	0.917	0.697
	A1.2	0.866			
	A1.3	0.765			
	A1.4	0.877			
	A1.5	0.803			
	A1.6	0.850			
Vulnerability to COVID-19 (VC)	A2.3	0.832	0.924	0.902	0.771
	A2.4	0.895			
	A2.5	0.906			
	A2.6	0.878			
Health risk (HR)	B1.1	0.757	0.799	0.701	0.599
	B1.4	0.697			
	B1.5	0.860			
Environmental risk (ER)	B2.2	0.836	0.841	0.837	0.675
	B2.4	0.711			
	B2.5	0.850			
	B2.6	0.880			
Management risk (MR)	B3.1	0.796	0.818	0.779	0.696
	B3.2	0.924			
	B3.3	0.774			
Financial risk (FR)	B4.1	0.914	0.896	0.855	0.699
	B4.2	0.924			
	B4.6	0.815			
	B4.7	0.665			
Digital technology facilities (TF)	C1	0.816	0.977	0.938	0.722
	C2	0.825			
	C3	0.911			
	C4	0.894			
	C5	0.882			
	C6	0.821			
	C7	0.794			
Aquafarmers' economy (E)	D1	0.720	0.804	0.789	0.541
	D2	0.707			
	D3	0.792			
	D4	0.654			
	D6	0.795			

Source: Created by author

the requirements for convergent validity, it underwent testing to determine its discriminant validity.

Table 5 indicates the result of HT-MT. All constructs showed less than 0.85 and achieved the requirement of HT-MT 0.85. Therefore, discriminant validity was satisfied and fulfilled and free from multicollinearity problems. Then, the next step was implemented to evaluate the structural model.

Structural Model

Before conducting the structural model analysis, it is essential to perform a collinearity test to assess the VIF. This test determined whether there was multicollinearity (or collinearity) among the primary constructs (latent variables) in the model. High VIF values might indicate a problem with collinearity, which could distort the results of the model. Hair et al. (2017) stated that collinearity was assessed by calculating VIF values for each endogenous construct. The correlation between two constructs was generally considered free of collinearity issues if the VIF score did not exceed 3.3. In this analysis, the VIF values for all direct effect relationships ranged from 1.3 to 2.116, indicating that there were no significant collinearity problems.

Subsequently, the structural model analysis examines the relationships between the variables and their predictive capacities. PLS-SEM

evaluated the structural model’s predictability and variable relationships. Each path in the model was evaluated by determining coefficients, beta values, Standard Errors (SE), *t*-values, *p*-values, and confidence intervals (Hair et al., 2021; Ringle et al., 2023). Table 6 presents the direct effect of vulnerability to seasonal change, vulnerability to COVID-19, health risk, environmental risk, management risk, financial risk, technology facility, and the aquafarmers’ economic constraints, respectively. There was a positive significant impact of vulnerability to COVID-19, health risks, management risk, and financial risks on aquafarmers’ economy constraints at the significant level of 0.05, except vulnerability to seasonal change and environmental risk. Meanwhile, there was a significant negative impact of digital technology facility on aquafarmers’ economy constraints. However, there was no significant impact of all constructs on digital technology facility adoption except management risk.

Financial risk showed the highest impact on aquafarmers’ economic constraints ($\beta = 0.318$, $t = 4.259$, $LL = 0.170$, $UL = 0.461$, p -value < 0.01), followed by digital technology facility ($\beta = -0.286$, $t = 6.091$, $LL = -0.378$, $UL = -0.194$, p -value < 0.01), vulnerability to COVID-19 ($\beta = 0.166$, $t = 2.000$, $LL = -0.010$, $UL = 0.318$, p -value < 0.05), management risk ($\beta = 0.153$, $t = 2.346$, $LL = 0.030$, $UL = 0.283$, p -value < 0.05),

Table 5: Discriminant validity assessment (HT-MT)

Construct	VS	VC	HR	ER	MR	FR	T	E
VS								
VC	0.482							
HR	0.189	0.609						
ER	0.566	0.606	0.247					
MR	0.309	0.720	0.622	0.592				
FR	0.415	0.571	0.310	0.603	0.737			
T	0.104	0.105	0.168	0.142	0.211	0.137		
E	0.218	0.584	0.497	0.464	0.715	0.617	0.390	

VC = vulnerability to COVID-19, VS = vulnerability to seasonal change, MR = management risk, HR = health risk, FR = financial risk, ER = environmental risk, E = aquafarmers’ economic constraints, and T = digital technology adoption. Source: Created by author

Table 6: The direct effect

Direct Effect	β	SE	t-value	p-value	LL	UL	VIF	R ²	F ²
VS → E	-0.071	0.058	1.219	0.223	-0.178	0.050	1.517	0.519	0.007
VC → E	0.166	0.083	2.000	0.046	-0.010	0.318	2.212		0.026
HR → E	0.124	0.052	2.357	0.018	0.022	0.229	1.514		0.021
ER → E	0.085	0.068	1.244	0.213	-0.049	0.216	1.744		0.009
MR → E	0.153	0.065	2.346	0.019	0.030	0.283	2.312		0.021
FR → E	0.318	0.075	4.259	0.000	0.170	0.461	1.822		0.116
T → E	-0.286	0.047	6.091	0.000	-0.378	-0.194	1.054	0.052	0.161
VS → T	0.077	0.097	0.792	0.428	-0.117	0.262	1.510		0.004
VC → T	0.017	0.104	0.167	0.868	-0.191	0.216	2.212		0.000
HR → T	-0.080	0.075	1.075	0.282	-0.231	0.063	1.507		0.005
ER → T	0.036	0.096	0.372	0.710	-0.147	0.233	1.743		0.001
MR → T	-0.226	0.099	2.288	0.022	-0.420	-0.031	2.259		0.024
FR → T	0.060	0.103	0.581	0.561	-0.145	0.264	1.818		0.002

VC = vulnerability to COVID-19, VS = vulnerability to seasonal change, MR = management risk, HR = health risk, FR = financial risk, ER = environmental risk, E = aquafarmers' economic constraints, and T = digital technology adoption.

Source: Created by author

and health risk ($\beta = 0.124, t = 2.357, LL = 0.022, UL = 0.229, p\text{-value} < 0.05$). These indicated that increases in vulnerability to COVID-19, health risk, management risk, and financial risk would correspondingly increase the aquafarmers' economic constraints. Meanwhile, the increase in digital technology adoption could reduce the aquafarmers' economic constraints. Besides, management risk also negatively affected the digital technology facility adoption $\beta = 0.124 (t = -2.288, LL = -0.420, UL = -0.031, p\text{-value} < 0.05)$. Therefore, an increase in management risk would reduce the digital technology facility adoption.

Preacher and Hayes (2008) and Hair *et al.* (2017) recommended using bootstrapping to test the indirect effects of mediation analysis. According to Preacher and Hayes (2008), if the Lower Limit (LL) and Upper Limit (UL) of the confidence interval did not include zero, this indicated the presence of a significant mediation effect between the independent and dependent variables. Based on Table 7, all relationships showed zero within the lower and upper bounds

of the confidence intervals, except for the relationship between management risk → digital technology facility → aquafarmers' economic constraints. This indicated a significant mediation effect of the digital technology facility in the relationship between management risk and aquafarmers' economic constraints ($\beta = 0.065, t = 2.107, LL = 0.035, UL = 0.129, p \leq 0.05$).

The structural model of the study is illustrated in Figure 2. The structural model demonstrated the result of direct and indirect effects based on the bootstrapping technique (the details could be referred to in Tables 6 and 7). Since the R² value was 0.519, this indicated that vulnerability to seasonal change, vulnerability to COVID-19, health risk, management risk, financial risk, and digital technology facility could explain 51.9% of variance for aquafarmers' economy. Meanwhile, the R² value of 0.052, it indicated that vulnerability to seasonal change, vulnerability to COVID-19, health risk, management risk, and financial risk explained 5.2% of variance for digital technology facility.

Table 7: Indirect effect

Indirect Effect	β	SE	t-value	p-value	LL	UL
VS→T→E	-0.022	0.028	0.780	0.435	-0.066	0.055
VC→T→E	-0.005	0.030	0.163	0.870	-0.078	0.033
HR→T→E	0.023	0.022	1.039	0.299	-0.018	0.071
ER→T→E	-0.010	0.028	0.372	0.710	-0.067	0.044
MR→T→E	0.065	0.031	2.107*	0.035	0.009	0.129
FR→T→E	-0.017	0.030	0.568	0.570	-0.081	0.039

VC = vulnerability to COVID-19, VS = vulnerability to seasonal change, MR = management risk, HR = health risk, FR = financial risk, ER = environmental risk, E = aquafarmers' economic constraints, and T = digital technology adoption.
 Source: Created by author

Since the blindfolding technique had limitations in evaluating predictive relevance, the approach suggested by Shmueli *et al.* (2019) was adopted and PLS was applied to estimate measurement errors by comparing the RMSE with that of the linear model. A model could be deemed to have strong predictive power when all differences between PLS model and

LM were negative. If most of the differences were negative, the model was considered to have moderate predictive relevance. A small proportion of negative differences indicated low predictive power. On the other hand, if all differences were positive, this suggested that the model's predictive relevance could not be confirmed. Table 8 indicated the results of the

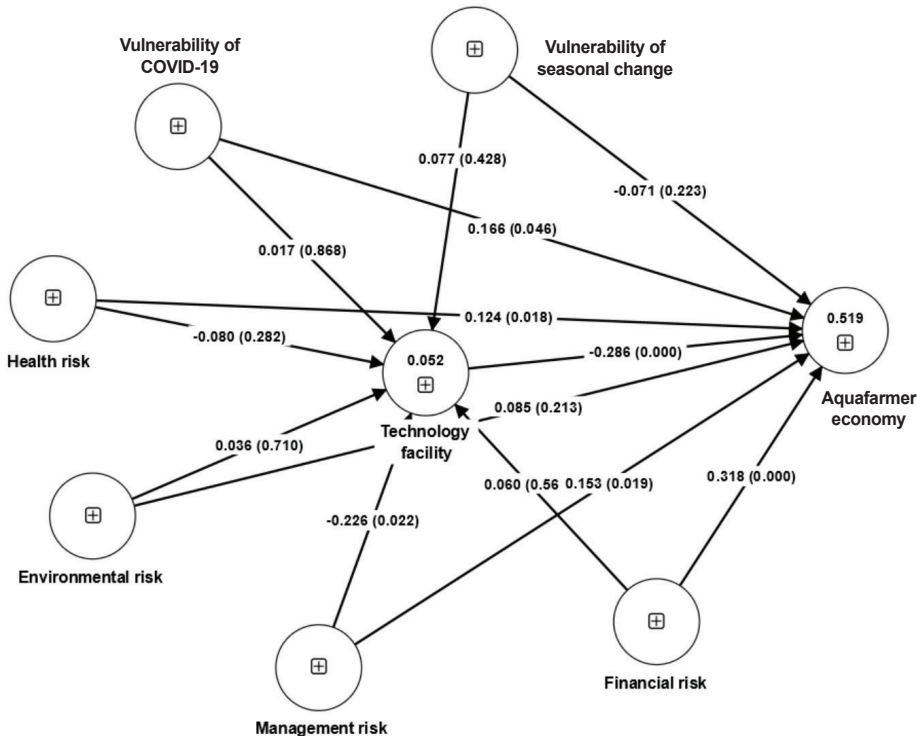


Figure 2: The structural model of the study showing the relationship between constructs
 Source: Created by author

Table 8: PLS predict

Item	PLS RMSE	LM RMSE	PLS-LM	Q ² predict
D1	1.142	1.173	-0.031	0.135
D2	1.194	1.182	0.012	0.125
D3	0.951	1.003	-0.052	0.359
D4	1.099	1.123	-0.024	0.155
D6	0.956	1.014	-0.058	0.263
C1	1.378	1.482	-0.104	-0.029
C2	1.273	1.342	-0.069	0.000
C3	1.274	1.287	-0.013	-0.015
C4	1.226	1.231	-0.005	0.011
C5	1.237	1.257	-0.020	-0.025
C6	1.305	1.299	0.006	-0.063
C7	1.293	1.298	-0.005	-0.026

Source: Created by author

PLS predictions. Most items showed a higher RMSE in PLS model than LM. Since most of the differences for all exogenous variables were negative in comparison to the linear modelling values, it could be concluded that the PLS model had demonstrated moderate predictive power.

Discussion and Conclusions

The study showed that vulnerability to seasonal change and environmental risk did not directly impact the economic sustainability of aquafarmers in Terengganu in the short term. However, the long-term consequences could compromise the industry's profitability and viability, emphasising the need for sustainable practices. The business resilience of Terengganu's aquafarmers to seasonal variations was a key factor in maintaining economic stability, achieved through the diversification of species, implementing temperature control systems, and developing strategies to mitigate market volatility (Runnebaum *et al.*, 2023). While seasonal changes had traditionally affected aquafarmers' businesses,

the COVID-19 pandemic exacerbated these challenges by disrupting supply chains, causing unemployment, and increasing market volatility (Van Senten *et al.*, 2021; Basett *et al.*, 2022). To achieve business sustainability, aquafarmers need steady conditions and stability, which could be achieved through climate-resilient practices that minimise the impact of seasonal variations on water temperature, fish development, and market demand (Jusoh *et al.*, 2022; Mayulu *et al.*, 2022; Alam *et al.*, 2023). By adopting sustainable practices, aquafarmers could ensure the long-term viability of their operations and contribute to a more sustainable future for the industry.

On the other hand, financial risk positively affected the aquafarmers' business sustainability, followed by vulnerability to COVID-19, management risk, and health risk. An increase in these risks can exacerbate the economic constraints faced by aquafarmers, potentially compromising their ability to maintain sustainable aquaculture practices. For instance, financial risk can impact the stability of aquafarmers' revenue, which is essential for

long-term sustainability. Fluctuations in expenses such as feed cost, equipment maintenance, and labour cost could also undermine the financial stability of aquafarmers, making it challenging to achieve sustainable production levels. Moreover, a shortage of funding could force them to prioritise short-term needs over long-term sustainability goals, compromising their ability to adopt environmental friendly and socially responsible practices (Berio & Salugsugan, 2022).

Sustainability in aquaculture is heavily reliant on effective management practices that mitigated risks and promoted environmentally conscious operations. Aquafarmers faced various management risks, including insufficient infrastructure, poor resource management, market fluctuations, disease outbreaks, and environmental issues (Kyule-Muendo *et al.*, 2022). To ensure long-term sustainability, it was crucial for aquafarmers to invest in training programmes that focused on fish health and environmental management. By acquiring the necessary knowledge and expertise in disease prevention and water quality monitoring, aquafarmers could minimise the impact of these risks and improve their operations' sustainability and profitability.

Moreover, responsible farming practices that prioritised environmental stewardship could have a positive impact on the sector (Kenconojati *et al.*, 2023). Additionally, sustainable aquaculture practices could also contribute to broader environmental sustainability by reducing the risk of disease transmission to humans and protecting biodiversity. Furthermore, health risks such as those posed by COVID-19 could also be mitigated through sustainable practices, reducing the economic impacts on aquafarmers and the community (Amoussou *et al.*, 2022).

Furthermore, the digital technology facility had a profound impact on the sustainability of aquafarming by mitigating the effects of management risk and economic constraints, thereby promoting environmentally-friendly

and socially responsible practices that ensured long-term viability of aquaculture (Singh *et al.*, 2022).

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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