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Assessing Climate Vulnerability and Its Linkages to Adaptation Strategies and Farm Resilience in Rice Farming Systems

Merna Ayu Sulastri, Yulia Sari, Jerry Antonio, Trissa Silvian

Departement of Socio-Economic Agriculture, Faculty of Agriculture, Universitas Sriwijaya, South Sumatra, Indonesia

Abstract

Rice farming systems in swamp lowland ecosystems are highly vulnerable to climate change due to their dependence on hydrological conditions and limited adaptive resources. This study aims to examine the interaction between vulnerability, adaptation strategies, and farmer resilience to strengthen the sustainability of swamp-based rice farming. Using a mixed-methods approach that integrates Vulnerability and Capacity Assessment, SWOT analysis, and Structural Equation Modeling with data from 80 farmers selected through stratified random sampling, the research evaluates vulnerability components, identifies context-specific adaptive strategies, and tests causal relationships among key variables. The findings show that farmers face high vulnerability driven by strong exposure and sensitivity, while adaptive capacity remains limited. Although farmers possess experiential knowledge and social capital, technological gaps, low climate literacy, and financial constraints reduce adaptive readiness. The SEM results indicate that farmer characteristics significantly shape adaptation strategies, and both factors play a critical role in determining resilience. Overall, the study demonstrates that resilience emerges from the interaction between biophysical pressures and socioeconomic constraints, highlighting the importance of strengthening knowledge, technology access, and institutional support to enhance adaptive capacity and ensure the long-term sustainability of rice farming in vulnerable swamp ecosystems.

Keywords

Adaptation strategies, climate change, resilience, farmers, rice farming, Value Chain Analysis (VCA).

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Introduction

Climate change has emerged as a major challenge for the global agricultural sector, particularly for strategic food commodities such as rice, which serves as a primary pillar of food security in many developing countries. Global temperature surface during the decade of 2006-2015 was 0.87°C, and between 2030 and 2052 it has been predicted that temperature will be 1.5°C. Consequently, the risk of climate change to health is expected to be growing (Fatmawati and Sulistyawati, 2019). Climate change in Indonesia can be seen from the increasing of the temperature above average every year and the decreasing of annual rainfall in some regions. The South part of Indonesia tends to have less rain while the north has more rainfall, even it is always increasing. The temperature average in Indonesia during 1981-2010 was 27°C. However, in May 2019, it was detected that it was increasing up to 0,9°C (BMKG, 2019).

In Indonesia, the agricultural sector plays a vital role in national economic development (Nendissa et al., 2022; Salendu, 2021). However, this sector is confronted with numerous challenges, many of which are driven by climate change ((Maja and Ayano, 2021). Increasingly unpredictable climate variability including the rising frequency of floods, droughts, extreme weather anomalies, and shifts in planting seasons has direct implications for crop productivity, cultivation efficiency, and the income stability of farming households (Malhi et al., 2021; Saikanth et al., 2023). Farmers' vulnerability to climate change is further exacerbated by limited access to adaptive technologies, reliable climate information, and adequate agricultural infrastructure (Ogundeji et al., 2022).

The challenges posed by climate change affect not only agricultural production but also have broader implications for the sustainability of farmers' livelihoods and the stability of rural economies, particularly among smallholder farmers who face significant limitations in accessing technology, information, and productive resources (Habib-ur-Rahman et al., 2022; Zenda, 2024). Studies by Maulu et al. (2021 and Yamin et al. (2025) highlight that the high dependence of smallholder farming systems on natural conditions makes them extremely sensitive to climatic disturbances such as drought and rainfall uncertainty. One of the regions most vulnerable to climate change is the lowland swamp agricultural area (Hashim et al., 2025). This ecosystem comprises three distinct types shallow swamp margin, intermediate swamp lowland, deep swamp lowland (Putra et al., 2025; Qurani and Lakitan, 2021), each exhibiting high susceptibility to climate-related impacts (Ratmini, 2021; Susilawati et al., 2025). Studies by Pathak et al. (2020) indicate that farmers operating within floodplain systems possess unique vulnerability characteristics due to their heavy dependence on water-level dynamics and the duration of inundation.

Research by Belay et al. (2022) further shows that smallholder farmers, who dominate agricultural structures in developing countries, represent the most vulnerable group due to limited formal education, insufficient access to information, and low capacity to comprehend rapidly changing climate dynamics. Low levels of education significantly hinder farmers' ability to identify climate risks and select appropriate adaptation measures when facing floods, droughts, and increasingly erratic planting seasons (Ahmad et al., 2022). Education level is one of the most decisive factors influencing the effectiveness of farmers' climate change adaptation, as it affects their capacity to interpret climate information and adopt adaptive technologies (Marie et al., 2020). These conditions create a deepening cycle of vulnerability, wherein limited adaptive capacity directly contributes to heightened risks of crop failure, declining productivity, and income instability among farming households (Abebaw, 2025).

However, to date, most research on climate change within the agricultural sector has predominantly focused on biophysical dimensions or merely described its impacts on crop production Piontek et al. (2021), In contrast, studies that comprehensively examine the interlinkages between farmers' vulnerability, adaptation strategies, and agricultural resilience remain limited (Kapitza). Previous studies have largely assessed vulnerability using conventional quantitative approaches, without integrating participatory perspectives capable of capturing the social ecological dynamics experienced by farmers at the local level (Alfie-Cohen and Garcia-Becerra, 2022). Moreover, holistic vulnerability assessment frameworks such as the Vulnerability and Capacity Assessment (VCA) remain rarely applied in research on rice farming systems in Indonesia, particularly in efforts to understand how the dimensions of exposure, sensitivity, and adaptive capacity interact to shape farmers' overall vulnerability. Earlier research has also tended to focus solely on vulnerability mapping, without further linking these assessments to the actual adaptation strategies implemented by farmers or to the resulting resilience outcomes (Kuchimanchi et al., 2021). Yet the connection between adaptation strategies and the level of resilience is essential for understanding the extent to which adaptive actions can reduce climate-related risks and enhance the long-term sustainability of farming systems (Loboguerrero et al., 2019).

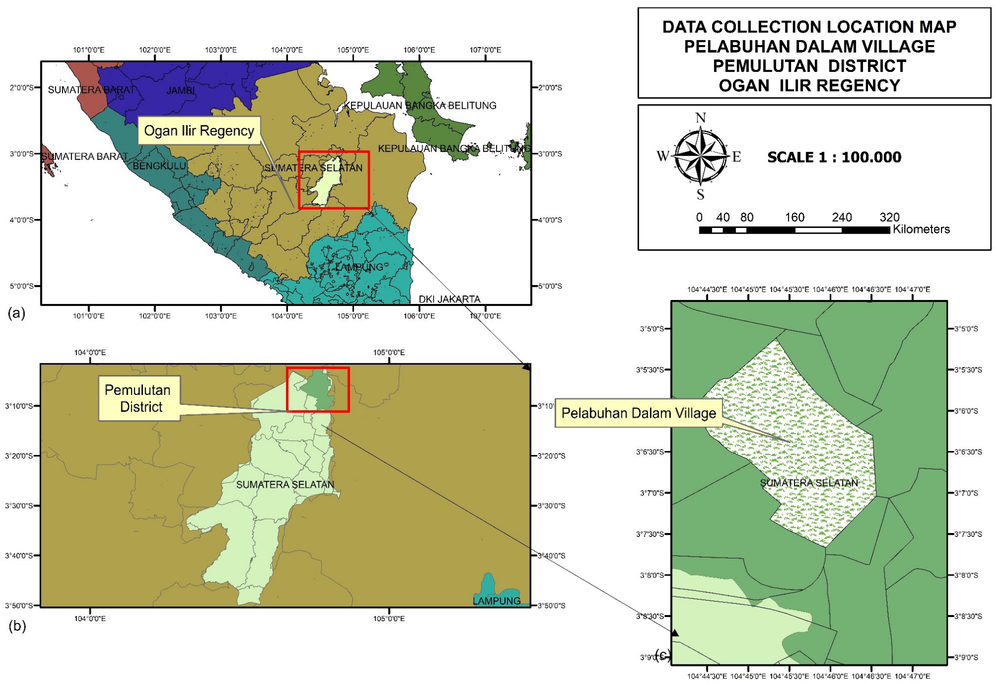
Therefore, this study offers a methodological and conceptual contribution by pursuing three key objectives: (1) to conduct an in-depth assessment of rice farming vulnerability based on the three core dimensions of the Vulnerability and Capacity Assessment (VCA) exposure, sensitivity, and adaptive capacity; (2) to evaluate the adaptation strategies implemented by farmers in response to climate-related risks, not only descriptively but also in terms of their relevance and effectiveness; and (3) to examine the relationship between adaptation strategies and the level of resilience in rice farming systems, in order to understand how adaptive actions contribute to farmers' capacity to cope with and recover from climate-induced stresses. Integrating these three objectives provides a more comprehensive analytical framework and addresses the gaps identified in previous research, thereby generating a more holistic understanding of vulnerability, adaptation, and resilience.

Materials and methods

The study was conducted in Pelabuhan Dalam Village, Pemulutan Subdistrict, Ogan Ilir Regency, an area characterized by swamp lowlands, which comprise three distinct types: shallow swamp margin, intermediate swamp lowland, and deep swamp lowland. The unique characteristics of these landscapes coupled with their high exposure to climate-related risks make farmers particularly vulnerable to the impacts of climate change. Therefore, this research aims to assess the extent of farmers' vulnerability to climate change and to identify the adaptation strategies required for sustaining their agricultural activities. The detailed research location is presented in Figure 1 below.

This study employs a mixed-methods approach, integrating quantitative and qualitative analyses through the application of three analytical frameworks: VCA, SWOT, and SEM. These methods were selected to provide a comprehensive understanding of vulnerability, adaptation strategies, and resilience among rice farmers in lebak swamp lowland ecosystems. The VCA analysis is used to assess vulnerability based on the dimensions of exposure, sensitivity, and adaptive capacity (Nadeem et al., 2024), thereby offering empirical insights into farmers' levels of climate exposure and their capacity to adapt (Abdollahzadeh et al., 2023). The SWOT analysis complements these findings by identifying the strengths, weaknesses, opportunities, and threats that shape the formulation of realistic and context specific adaptation strategies for farmers (Magondu et al., 2025). Furthermore, the SEM approach is employed to examine the causal relationships among farmer characteristics, the adaptation strategies they implement, and the resulting levels of farming resilience. This enables a more holistic understanding of the key determinants influencing the sustainability of rice farming systems within swamp environments (Hidayat and Wulandari, 2022; Stoffels et al., 2023).

The population of this study consists of rice farmers cultivating swamp lowlands across the three land types in Pelabuhan Dalam Village, Pemulutan Subdistrict, Ogan Ilir Regency. A total of 80 farmers were selected as respondents using a random sampling technique stratified by land type, ensuring proportional representation of each swam category (Noor et al., 2022). Indicators used to identify internal factors including strengths and weaknesses and external factors including opportunities and threats were examined through a descriptive qualitative SWOT analysis. All items were measured using a five-point Likert scale ranging from "strongly disagree" to "strongly agree" (Zheng et al., 2024). Details of the research variables and indicators are presented in Table 1 and Table 2.



Source: Autors

Figure 1: Site study sampling: a) South Sumatra, b) Pemulutan Subdistrict, c) Pelabuhan Dalam Vilage.

Variable	Indicator	Measurement
Farmer Characteristics (X1)	Age	Years
	Education Level	Years
	Household Dependents	Persons
	Length of Farming Experience	Years
	Cultivated Land Area	Hectares
Adaptation Strategies (X2)	Adjustment of Planting Schedules	Likert Scale
	Climate-Tolerant Varieties	Likert Scale
	Farm Diversification	Likert Scale
	Adaptive Technologies	Likert Scale
	Access to Climate Information	Likert Scale
Resilience (Y)	*Absorptive Capacity*	Likert Scale
	Adaptive Capacity	Likert Scale
	Transformative Capacity	Likert Scale

Source: Autors

Table 1: Variables and indicators for SEM–PLS analysis.

Component	Fokus Indicator
Strengths	Farmers' Experience
	Local Knowledge
	Social Support
	Presence of Farmer Groups
Weaknesses	Limited Access to Technology
	Insufficient Capital
	Low Climate Literacy
Opportunities	Government Program
	Market Access
	Availability of Adaptive Agricultural Technologies
Threats	Extreme Climate Variability
	Price Fluctuations of Agricultural Products
	Natural Resource Degradation

Source: Autors

Table 2: Identification of SWOT Element.

Result and discussion

Socioeconomic and demographic characteristics of respondents

Table 1 summarizes the respondents' socioeconomic characteristics. Most farmers were mature adults, with 60% aged 31–45 and the rest above 46, a pattern consistent with rice-farming demographics reported in Vietnam (Tran et al., (2020). Over half had 10–20 years of farming experience, indicating strong practical knowledge of swamp rice systems. Education levels were generally low, as 62.5% had only basic schooling, which may limit access to modern technologies. Household size was moderate (4–7 members), providing family labor but also increasing economic responsibility. Farm sizes varied, with 53.75% cultivating less than one hectare and 33.75% managing more than two hectares, reflecting a mix of semi-subsistence and semi-commercial production.

Climate vulnerability of rice farmers

The vulnerability assessment conducted in the study area reveals that rice farmers experience a high level of climate-related vulnerability, as summarized in Tables 2 and 3. Table 2 shows that the vast majority of respondents (88.75%) fall into the very high vulnerability category, with only a small proportion categorized as high (6.25%), moderate (1.25%), or low (3.75%). Notably, no respondents were classified as having very low vulnerability, indicating that climate stressors

Category	Frequency	Percentage (%)	Standard Deviation
Age (years)			
15-30	0	0	6.9
31-45	48	60	
>46	32	40	
Farming Experience (years)			
1 - 10	17	21.25	8.9
10-20	41	51.25	
>20	22	27.5	
Years of Schooling			
6- 9	50	62.5	3.3
10 -12	29	36.25	
> 12	1	1.25	
Household Size			
1-3	30	37.5	1.3
4-7	48	60	
>7	2	2.5	
Farm Siza (ha)			
0-1	43	53.75	1.2
1-2	10	12.5	
>2	27	33.75	

Source : Primary data (2025)

Table 3: Socioeconomic and demographic characteristics of respondents.

Score Range	Frequency	Percentage (%)	Category
0 - 1	0	0	Very Low
1.1- 1.5	3	3.75	Low
1.6 - 2.5	1	1.25	Moderate
2.6 - 3	5	6.25	Hight
> 3.1	71	88.75	Very High
Total	80	100	Very High

Source: Primary data (2025)

Table 4: Vulnerability level data.

overwhelmingly affect all farmers in the region. This pattern is consistent with findings from flood-prone and hydrologically unstable rice ecosystems across Asia and Africa. Studies in Bangladesh Islam et al., (2022); and Jamal et al., (2023) similarly report that rice farmers are disproportionately vulnerable due to their strong dependence on climate-sensitive production systems and limited access to adaptive resources.

The component-level analysis (Table 5) shows that exposure (4.12) and sensitivity (4.11) are the dominant drivers of vulnerability. The high exposure score reflects farmers' continual interaction with climate hazards such as erratic rainfall, prolonged inundation, and fluctuating swamp water tables conditions that are widely acknowledged as major stressors in lowland rice production systems. Comparable results were reported by Mohammed and Favretto., (2025) in Nigeria's floodplain agriculture, where climate extremes directly undermine production stability and household food security. High sensitivity in this study further indicates the strong reliance of farmers on rice as their primary livelihood, which heightens the impact of climatic disturbances on income and welfare. This relationship has also been highlighted in (Gardezi et al., 2021), who observed that rice-dependent households are particularly vulnerable to seasonal hydrological shifts driven by climate change.

In contrast, the adaptive capacity index (3.32) is considerably lower than exposure and sensitivity, suggesting that the ability of farmers to adjust or mitigate climate impacts remains constrained. This finding aligns with Aqib et al., (2024), who reported that limited education, insufficient financial capital, and weak institutional support commonly restrict adaptive capacity in rural agricultural communities. Similar constraints have been identified in Southeast Asian rice systems, where access to climate information, improved seed varieties, and extension services remains uneven (Bell et al., 2018).

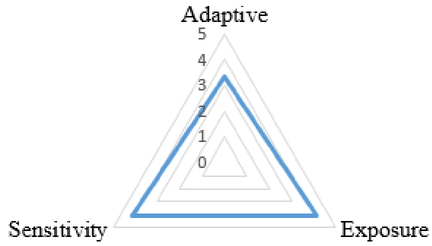
Component	Vulnerabillity Index
Adaptability	3.32
Sensitivity	4.11
Exposure	4.12

Source: Primary data analysis (2025)

Table 5: Key component of vulnerabillity index of area study.

Figure 2 further illustrates the imbalance among the three vulnerability components, with exposure and sensitivity extending more prominently than adaptive capacity. This triangular configuration highlights the structural and persistent nature of climate vulnerability in swamp-based rice farming systems. Such a pattern has similarly been reported in other coastal and inland wetland rice ecosystems, where farmers face simultaneous pressures from hydrological variability, extreme climatic events, and ecological fragility (Aalst et al., 2023) The convergence of high climatic exposure, elevated sensitivity, and constrained adaptive capacity reflects a vulnerability trap commonly found in lowland rice systems, particularly those dependent on highly climate-sensitive water regimes.

Overall, the findings indicate that rice farmers in the study area experience systemic and multi-dimensional climate vulnerability driven by both biophysical and socioeconomic constraints. These results are consistent with contemporary Scopus-indexed literature, which emphasizes that strengthening adaptive capacity through the adoption of climate-smart technologies, improved climate information services, livelihood diversification, and enhanced institutional support remains essential for building long-term climate resilience among smallholder rice farmers (Islam et al., 2022). The evidence therefore underscores the urgent need for integrated adaptation strategies tailored to the unique ecological conditions of swamp-based rice production.



Source: Primary data analysis (2025)

Figure 2: Triangle diagram of the vulnerability index.

Climate change adaptation strategies of rice farmers

The IFE and EFE matrices outline farmers' adaptive readiness and the external conditions shaping climate change adaptation (Table 6). An IFE score of 2.26 reflects moderate internal strength, mainly supported by long-term experience in swamp rice farming and strong farmer-group institutions. These findings align with studies showing that experiential knowledge, social capital, and community cohesion are central to rural climate resilience (Okolie et al., 2024). Farmer collaboration and active groups facilitate information sharing, peer learning, and coordinated action, reinforcing their role as key adaptation assets. Local wisdom in managing hydrological variability further strengthens adaptive capacity. Despite these strengths, notable weaknesses persist. Limited access to improved technologies, low financial capacity, and insufficient climate-risk awareness constrain farmers' ability to shift from traditional to more technical adaptation strategies. Such constraints mirror patterns observed in other developing-country rice systems where financial and informational barriers inhibit adoption of climate-resilient innovations (Khan et al., 2021). With a total weakness score of 1.00, these structural limitations continue to restrict farmers' adaptive flexibility.

The EFE results (Table 7) indicate an opportunity score of 1.08, showing that the external environment provides meaningful support for adaptation. Government agricultural programs represent the strongest opportunity (0.60), consistent with evidence that subsidies, credit, and extension services enhance adaptive capacity and technology adoption (Gardezi et al., 2021). Climate-oriented technologies (0.38) also offer potential, although limited market access (0.10) constrains broader benefits.

In contrast, the threat score of 1.25 reflects significant external pressures. Unpredictable weather (0.45)

Internal Factor	**Rating**	**Weight**	**Score**
Strengths			
Farmers experience in managing swamp land	4	0.15	0.60
Local wisdom that contributes to agricultural activities	4	0.13	0.53
Collaboration among farmers	4	0.11	0.45
Farmer groups activities	4	0.17	0.68
Total Score			**2.26**
Weakness			
Limited access to improved agricultural tools and technologies	1	0.17	0.17
Farmers' financial capacity	1	0.09	0.09
Farmers exhibit limited awareness regarding climate change and its implications for agricultural production	1	0.17	0.17
Total Score		**1.00**	**0.43**

Source: Primary data (2025)

Table 6: IFE Matrix.

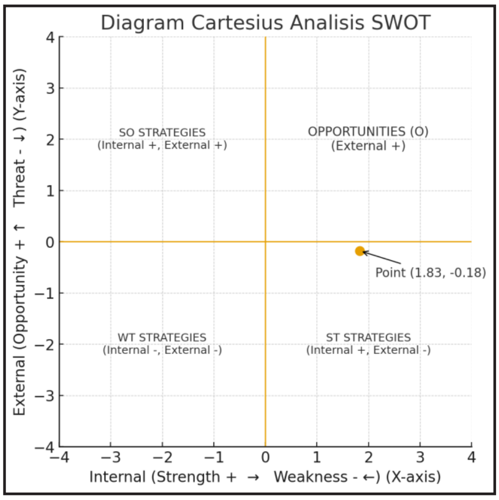
Exernal Factor	**Rating**	**Weight**	**Score**
Opportunities			
Government-supported programs provide assistance that strengthens agricultural activities	4	0.15	0.60
Harvested rice has market access beyond the local area	1	0.10	0.10
Availability of equipment and technologies designed to address climate-related challenges	3	0.13	0.38
Total Score			**1.08**
Threats			
Increasingly unpredictable weather patterns affect crop performance	2	0.23	0.45
Fluctuating and unstable paddy prices	2	0.20	0.40
Declining soil and water quality in rawa agricultural areas	2	0.20	0.40
Total Score		**1.00**	**1.25**

Source: Primary data (2025)

Table 7: EFAS Matrix.

poses the greatest threat, echoing patterns across Indonesia's swamp-based agricultural regions, where extreme hydrological fluctuations reduce planting windows and heighten crop failure risks (Das et al., 2025; Yuliantina et al., 2024). . Price volatility (0.40) and degradation of soil and water quality (0.40) further intensify vulnerability, similar to conditions in other floodplain and deltaic systems in Bangladesh, Myanmar, and Vietnam, where climate shocks and market stressors jointly increase livelihood risks (Ahmed et al., 2021; Tran et al., 2020).

The SWOT Cartesian diagram (Figure 3) positions the farming community in the Quadrant II (Weakness–Opportunity) strategic zone, with a coordinate of (1.83 – 0.18). This position indicates that although farmers possess access to external opportunities, internal limitations weaken their ability to fully utilize those opportunities.



Source: Primary data analysis (2025)

Figure 3: SWOT analysis.

Strategically, this suggests a WO strategy priority, emphasizing the need to address internal constraints (limited technology access, financial capacity, and climate awareness) by leveraging external supports such as government programs, emerging technologies, and institutional partnerships. This strategic orientation aligns with sustainability frameworks that view climate adaptation as a function of both endogenous capacity-building and exogenous resource mobilization.

Overall, the integrated IFE–EFE and SWOT assessment reveals that while farmers benefit from strong social structures and experiential knowledge, their adaptation is hindered by financial, technological, and informational constraints. Enhancing institutional support, improving farmer access to climate-smart technologies, and strengthening extension-based climate literacy emerge as central priorities for reducing vulnerability and enabling more robust and transformative adaptation pathways.

The adaptation strategies formulated in Table 8 demonstrate a coherent integration of farmers' internal capacities with the external opportunities and challenges shaping climate resilience in swamp-based rice systems. The SO strategies highlight the optimization of experiential knowledge, farmer-group collaboration, and local wisdom through alignment with government programs and climate-smart technologies. Recent studies confirm that strengthening endogenous capacities through institutional support significantly enhances adaptive responses in smallholder agriculture (Ishtiaque, 2021). The WO strategies address structural weaknesses limited technological access, insufficient financial resources, and low climate literacy by leveraging available institutional and technological opportunities. This approach is consistent with contemporary evidence showing that targeted external interventions, including microfinance, digital extension services, and climate-oriented innovations, are crucial for reducing capacity gaps in vulnerable farming

Internal Factor / External Factor	**Strengths (S)**	**Weaknesses (W)**
	1. Farmers possess substantial experience in managing lowland swamp rice fields. 2. Local knowledge remains widely practiced and continues to support agricultural activities. 3. Strong mutual assistance exists among farmers in day-to-day farming operations. 4. Farmer groups are active and provide both technical and social support to their members.	1. Farmers have limited access to modern agricultural tools and technologies. 2. Financial capital among farmers remains insufficient 3. Knowledge of climate change and its agricultural impacts is still limited.
Opportunities (O) 1. Government programs and assistance schemes are available to support agricultural development. 2. Harvested rice can be marketed to external regions, offering wider market access. 3. Support for agricultural tools and climate-adaptive technologies is increasingly available.	**SO Strategies (Strength–Opportunity)** 1. Leverage farmers' experience and collaborative networks (S1, S3, S4) to maximize the benefits of government programs (O1) aimed at improving technologies for swamp-based rice cultivation. 2. Integrate local knowledge (S2) with available climate-adaptive technologies (O3) to enhance farmers' resilience without disregarding traditional practices. 3. Improve production and product quality (S1, S2) to meet external market demand (O2) by establishing cooperative-based marketing systems.	**WO Strategies (Weakness–Opportunity)** 1. Utilize government-supported agricultural technologies (O1, O3) to address farmers' limited technological capacity (W1). 2. Access government programs (O1) to obtain additional financial support (W2) through microfinance or rural credit institutions. 3. Involve farmers in climate-adaptation training initiatives (O3) to strengthen their knowledge and risk-management skills (W3).
Threats (T) 1. Increasingly unpredictable weather patterns negatively affect crop yields. 2. Rice grain prices fluctuate frequently and lack stability. 3. Soil and water quality in swamp-based farming areas show signs of deterioration.	***ST Strategies (Strength–Threat)*** 1. Mobilize farmer groups (S4) to improve coordination and collective action in responding to unpredictable weather conditions (T1). 2. Utilize farmer-to-farmer solidarity (S3) to establish minimum selling-price agreements that reduce the impact of price fluctuations (T2). 3. Maintain and promote local knowledge practices (S2) that help sustain soil and water quality in swamp ecosystems (T3).	**WT Strategies (Weakness–Threat)** 1. Develop partnerships with cooperatives or financial institutions (addressing W2) to strengthen farmers' resilience to grain-price volatility (T2). 2. Implement training programs on soil and water management (addressing W3) to mitigate declining land quality in swamp-based farming areas (T3). 3. Promote crop diversification (W1, T1) to reduce dependency on a single climate-sensitive commodity.

Source: Primary data analysis (2025)

Table 8: SWOT-derived adaptation strategies.

communities (Antwi-agyei et al., 2022). The ST strategies utilize farmers' social cohesion and local ecological knowledge to mitigate major threats such as weather unpredictability, market volatility, and environmental degradation. Recent literature underscores that community-based networks and farmer mechanisms improve adaptive behavior by enabling coordinated responses to climatic shocks (Osumba et al., 2021). Similarly, the continuation of local knowledge practices is recognized as a key factor in maintaining ecological stability in wetland agricultural systems (Barman et al., 2025).

Lastly, the WT strategies act as defensive measures aimed at minimizing climate-related risks by simultaneously addressing internal limitations and external threats. Strategies such as crop diversification, improved soil–water management, and financial partnerships align closely with recommended adaptive pathways for climate-sensitive rice ecosystems, particularly in hydrologically vulnerable landscapes (Tran et al., 2020). These strategies directly correspond to the high levels of vulnerability previously identified in the study area. Overall, the SWOT-derived adaptation strategies reflect a balanced and context-specific framework that reinforces the need for integrated, institutionally supported, and community-driven approaches to strengthen resilience in swamp-based rice farming systems.

Structural Equation Modeling (SEM)

Structural Equation Modeling (SEM) was employed to examine the structural relationships among farmer characteristics, adaptive strategies, and the resilience of rice farmers in floodplain (rawa lebak) areas (Faruk and Maharjan, 2022; Saleh et al., 2024). This method was selected for its ability to simultaneously evaluate complex causal relationships among latent variables. The construct model analysis focused on the interrelations between Farmer Characteristics, Adaptive Strategies, and Resilience, with results summarized in Table 9.

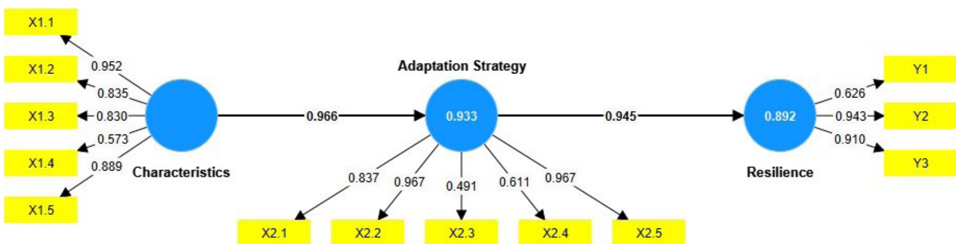
Variable	Outer loadings
X1.1 <- X1. Characteristics	0.952
X1.2 <- X1. Characteristics	0.835
X1.3 <- X1. Characteristics	0.830
X1.4 <- X1. Characteristics	0.573
X1.5 <- X1. Characteristics	0.889
X2.1 <- X2. Adaptive Strategies	0.837
X2.2 <- X2. Adaptive Strategies	0.967
X2.3 <- X2. Adaptive Strategies	0.491
X2.4 <- X2. Adaptive Strategies	0.611
X2.5 <- X2. Adaptive Strategies	0.967
Y1 <- X3. Resilience	0.626
Y2 <- X3. Resilience	0.943
Y3 <- X3. Resilience	0.910

Source: Primary data (2025)

Table 9: Factor loadings of latent constructs.

Outer loadings were used to assess the strength of the relationships between latent constructs and their manifest indicators, following the conventional threshold of 0.70 (Hair Jr. et al., 2020).

The low outer loading values indicate limited contributions of several indicators to their latent constructs. Farming Experience (0.573) shows weak association, reflecting that long experience does not necessarily support adaptation when farmers remain attached to traditional practices (Bouttes; de Boon). Adaptive Technologies (0.491) also has minimal influence due to low adoption driven by limited access, high perceived risks, and inadequate technical (Fyka et al., 2025). Access to Climate Information (0.611) contributes moderately, as climate data is not consistently transformed into adaptive decisions because of limited climate literacy and information barriers (Nugroho et al., 2025). Absorptive Capacity (0.626) further suggests restricted ability to internalize new knowledge. Overall, these results underscore the need to strengthen information access, technological readiness, and adaptive support to improve construct representation in the model (Figure 4).



Source: Primary data analysis (2025)

Figure 4: Results of data analysis (after reconstruction).

Hypotesis testing

Hypothesis testing in the SEM-PLS framework employed bootstrapping to obtain stable parameter estimates and reliable confidence intervals, using a 5% significance level and SmartPLS 4. This approach enabled a clearer evaluation of the causal pathways afnmong the latent constructs and strengthened the interpretation of how exogenous and mediating variables influence the endogenous variables within the model (Table 10).

The SEM analysis indicates that the structural relationships among the variables exert a highly significant and robust influence in explaining the dynamics of adaptive strategies and the resilience of rice farmers to climate change. The magnitude of the path coefficients, combined with substantial t-statistics and highly significant p-values, confirms the reliability and validity of the estimated structural model. The path linking farmer characteristics (X1) to adaptive strategies (X2) exhibits a coefficient of 0.966, demonstrating that individual attributes constitute a primary determinant of adaptive decision-making. Factors such as educational attainment, farming experience, managerial competency, and access to agricultural information significantly enhance farmers' capacity to respond effectively to climatic stressors, emphasizing the pivotal role of human capital in shaping adaptation outcomes.

The relationship between farmer characteristics (X1) and resilience (X3) yields a coefficient of 0.912, suggesting that resilience is influenced not only by the implementation of adaptive strategies but also by the intrinsic socio-economic and personal capacities of the farmers. Stronger characteristics enable more effective risk management, recovery from extreme climate events, maintenance of production stability, and preservation of income streams (Lawrence et al., 2020). These results underscore the critical importance of personal and socio-economic capacity in fostering long-term farm-level resilience. The linkage between adaptive strategies (X2) and resilience (X3) shows a coefficient of 0.945 (t = 113.435; p = 0.000), confirming that adaptation strategies represent a central mechanism directly determining resilience outcomes. Strategies such as adjustments to planting calendars, adoption of climate-resilient varieties, water-efficient technologies, livelihood diversification, and utilization of climate information substantially enhance farmers' ability to cope with climatic variability and extreme events (Gowdhaman, 2024; Malhi et al., 2021; Amaka et al., 2025). Improvements in these strategies are reflected in increased production capacity, income stability, and recovery potential. the estimated SEM model indicates that farm resilience is primarily shaped by two interrelated pillars: the inherent capacities embedded in farmers' socio-economic and personal characteristics, and the effectiveness of the adaptation strategies they implement (Mirzaei et al., 2022). Stronger characteristics facilitate the selection and adoption of appropriate adaptive measures, while effective strategies directly enhance resilience. These findings highlight the necessity of policy interventions focused on human capital development, knowledge dissemination, and the provision of accessible adaptive technologies to strengthen resilience in climate-vulnerable rice-farming system.

Conclusion

This study demonstrates that rice farming systems in swamp lowland areas face substantial vulnerability due to high exposure to climatic stressors, strong sensitivity to environmental disturbances, and limited adaptive capacity. Through the integration of VCA, SWOT, and SEM analyses, the research reveals that farmers' characteristics, the adaptation strategies they adopt, and the resilience they achieve are closely interconnected. In essence, the sustainability of rice farming is shaped not only by ecological

Variable	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
X1. Characteristics> X2. Adaptive Strategies	0.966	0.968	0.007	131.256	0
X1. Characteristics> X3. Resilience	0.912	0.916	0.013	71.222	0
X2. Adaptive Strategies > X3. Resilience	0.945	0.946	0.008	113.435	0

Source: Primary data (2025)

Table 10: Path analysis.

conditions but also by the quality of human capital and the effectiveness of adaptive actions undertaken by farmers. The findings indicate that farmers possess valuable experiential knowledge and social capital, yet constraints related to technology access, climate information, and financial resources reduce their ability to fully capitalize on available adaptation opportunities. This creates a clear causal pathway: limited adaptive capacity leads to suboptimal adaptation strategies, which in turn restrict the development of resilience. Conversely, stronger personal attributes and more appropriate adaptation strategies enable farmers to reduce risks and recover more effectively from climate-related disturbances. Overall, this study emphasizes that strengthening resilience in swamp-based rice farming systems requires continuous enhancement of farmers' adaptive capacity through improved knowledge, technological support, and institutional reinforcement that aligns with local needs. Such efforts are essential to ensure that farmers are not only able to withstand climatic pressures but also capable of advancing within an increasingly dynamic and uncertain agricultural landscape. The research concludes that resilience is not an inherent condition but a product of deliberate, integrated, and sustained adaptation processes.

Corresponding author:
Merna Ayu Sulastri
Departement of Socio-Economic Agricuture, Faculty of Agriculture, Universitas Sriwijaya
Jl. Raya Palembang-Prabumulih KM.32, Indralaya, Ogan Ilir, South Sumatra, 30662
Phone: + 0813-7936-2834, E-mail: mernaayusulastri@fp.unsri.ac.id

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