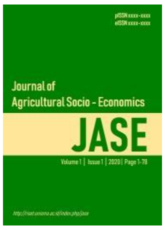

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Rice Farmers and Climate Change: A Vulnerability Study and Adaptation Strategy in Deli Serdang Regency

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Abstract. Rice is a strategic commodity for national food security; however, its production is increasingly threatened by climate change, including shifting rainfall patterns, rising temperatures, and more frequent extreme weather events that create yield uncertainty and reduce farmer welfare. This study aims to analyze the influence of economic, social, and environmental factors on livelihood sustainability and the adaptive capacity of rice farmers in Deli Serdang Regency. The main contribution of this research lies in explicitly modeling livelihood sustainability as a mediating variable linking climate change impacts to farmers' adaptive capacity within an integrated SEM-PLS framework. Unlike previous studies that mainly focus on direct effects, this study examines both direct and indirect relationships, providing a clearer understanding of how environmental pressures translate into adaptive outcomes at the household level. A quantitative approach was employed using data from 95 rice-farming households. The SEM-PLS results indicate that environmental factors significantly affect livelihood sustainability and adaptive capacity. Livelihood sustainability also significantly enhances adaptive capacity, confirming its role as a key mediating variable. In contrast, economic and social factors do not show significant effects. The model demonstrates moderate explanatory power ($R^2 = 0.389$). These findings highlight that adaptation is not solely a direct response to environmental stressors but is strongly mediated by livelihood sustainability, emphasizing the importance of strengthening livelihoods as a central strategy in climate change adaptation policies.

Keywords: Climate Change Adaptation; Livelihood Sustainability; Adaptive Capacity; Rice Farmers; SEM-PLS

INTRODUCTION

Rice is a strategic commodity for Indonesia's national food security, as rice serves as the primary staple food for the majority of the population. Previous rice-farming studies in Indonesia also show that farm performance and technical efficiency remain important concerns in strengthening the sustainability of paddy farming systems (Azis et al., 2024). However, rice production is increasingly challenged by climate change. Rice farming is highly sensitive to climatic variability because it depends heavily on rainfall patterns, water availability, soil conditions, and seasonal stability, all of which are directly affected by climate change (Ansari et al., 2023). Climate change affects rice production through changes in climate, hydrological, and crop-related conditions, including water availability, soil fertility, and crop yield, thereby requiring more reliable data and modeling approaches to support effective adaptation measures in Indonesian rice farming systems (Ansari et al., 2023). Climate change is characterized by rising global temperatures, shifting rainfall patterns, and an increasing frequency of extreme weather events such as floods and droughts. These changes have posed serious threats to food production, particularly for major staple commodities such as rice (Rozci, 2024). In addition, climate change causes uncertainty in planting times and production patterns due to shifts in the rainy and dry seasons, ultimately increasing the risk of crop failure and reducing the stability of agricultural production (Rahayu et al., 2024). In 2023, national rice production reached 53.63 million tons of harvested dry unhusked rice (GKG), a 2.05% decrease from 2022, when 54.75 million tons were recorded. In North Sumatra, Deli Serdang Regency is the largest rice-producing area, with a production volume of 328,854 tons (Statistics Indonesia, 2024).

As a major rice production center in North Sumatra, Deli Serdang Regency plays a crucial role in ensuring regional food supply stability. However, increasing rainfall intensity in the region has been associated with declining rice production and productivity (Chaniago, 2023). In addition to climate pressures, changes in land use due to urbanization and plantation expansion also contribute to the reduction in rice field area, which impacts the sustainability of rice in the future (Siagian et al., 2022). The vulnerability of rice-farming households is closely associated with disruptions in planting practices, water availability, harvest certainty, and the capacity to adjust adaptation strategies under changing irrigation and environmental conditions (Ismail et al., 2025). Farmer vulnerability refers to a condition in which farmers are exposed to multiple pressures that may affect productivity, income, and overall welfare. These pressures may arise from environmental, economic, social, and institutional factors. In the context of climate change, vulnerability reflects the extent to which farmers are affected by adverse impacts such as irregular rainfall, rising temperatures, pest infestations, drought, and flooding (Estiningtyas et al., 2024). This vulnerability is influenced not only by risk exposure but also by farmers' adaptive capacity, which is highly dependent on access to weather information, agricultural technology, and institutional support (Rahayu et al., 2024). Moreover, limited access to modern technology, climate information, and institutional support constrains farmers' adaptive capacity (Asfaw et al., 2016). Although some farmers have implemented adaptation strategies such as adjusting cropping calendars, adopting climate-resilient varieties, or diversifying income sources, these efforts are often insufficient to offset the growing intensity of climate-related stressors (Sanogo et al., 2023).

Previous studies have examined the impacts of climate change on agricultural productivity, farmer vulnerability, and adaptation strategies. Recent evidence from Indonesian irrigated rice-farming systems shows that farmers respond to climate change through locally specific adaptation strategies, including the use of local and non-local knowledge to reduce livelihood vulnerability, particularly in areas facing water shortages and rising temperatures (Arifah et al., 2022). In addition, social and human capital have been shown to play important roles in shaping farmers' climate change adaptation, particularly through farmer organizations, social cohesion, education, and localized adaptation responses in agricultural communities (Prayitno et al., 2025). However, most previous studies have addressed adaptation, vulnerability, social capital, or productivity separately and have not sufficiently integrated economic, social, and environmental impacts of climate change with farmers' livelihood sustainability and adaptive capacity in a single analytical framework. In addition, limited studies have explicitly examined livelihood sustainability as a mediating mechanism linking climate-related pressures to farmers' adaptive capacity, particularly among rice-farming households in Deli Serdang Regency. Therefore, this study aims to analyze the economic, social, and environmental impacts of climate change on farmers' livelihood sustainability and adaptive capacity, and to examine the mediating role of livelihood sustainability in strengthening farmers' adaptive capacity.

METHODS

Study Area and Period

This study was conducted in November 2025 in Deli Serdang Regency, North Sumatra, Indonesia. The study site was purposively selected because Deli Serdang is the province's largest rice-producing regency. Data collection was carried out in Lubuk Pakam District, selected for recurring flood events that caused crop failures in several villages in 2020, 2021, and 2023, as well as for climate projections issued by the Meteorology, Climatology, and Geophysical Agency (BMKG).

Population and Sample

The study population comprised 1,872 rice-farming households in Lubuk Pakam District. The respondents were selected using simple random sampling, in which each rice-farming household in the population had an equal probability of being selected as a sample. The sample size was determined using Slovin's formula with a 10% margin of error, assuming a relatively homogeneous population: $n = N / (1 + Ne^2)$, where n is the sample size, N is the population size, and e is the margin of error. With a population of 1,872 rice-farming households, the calculation yielded 94.92, rounded to 95 respondents.

Data Sources

Primary data were collected through face-to-face structured interviews using a questionnaire administered to 95 selected rice-farming households. Additional contextual information was obtained from relevant local stakeholders, such as agricultural extension officers and farmer group representatives, to support the interpretation of local climate-related risks. Prior to full data collection, the questionnaire was piloted with local farmers outside the main sample to ensure clarity and contextual relevance of the questions. Secondary data on local climate projections (rainfall and extreme weather) were obtained from BMKG, while regional rice production statistics for Deli Serdang Regency were obtained from Statistics Indonesia (BPS).

Data Analysis

Data were analyzed using Structural Equation Modeling–Partial Least Squares (SEM-PLS) with SmartPLS software. SEM-PLS was selected because the study examined relationships among multiple latent constructs and aimed to assess both direct and indirect effects within the proposed model. The analysis was conducted in two stages. First, the measurement model (outer model) was evaluated to assess indicator validity and construct reliability through outer loading, Average Variance Extracted (AVE), Cronbach's Alpha, Composite Reliability, and discriminant validity. Indicators with outer loading values below the acceptable threshold were reviewed and removed when necessary. Second, the structural model (inner model) was evaluated to test the hypothesized relationships among Economic Impacts, Social Impacts, Environmental Impacts, Livelihood Sustainability, and Farmers' Adaptive Capacity. The structural model was assessed using path coefficients, t-statistics, p-values, coefficient of determination (R^2), effect size (f^2), and predictive relevance (Q^2). A bootstrapping procedure was applied to determine the statistical significance of direct and indirect effects, including the mediating role of Livelihood Sustainability.

Variables and Indicators

The study model includes climate change impacts across economic, social, and environmental dimensions, as well as farmers' livelihood sustainability and adaptive capacity. The indicators for this study were carefully selected and adapted from Purwanti et al. (2022) and Estiningtyas et al. (2024), as these previous studies successfully measured climate vulnerability and adaptation in similar Indonesian agricultural contexts. All indicators were operationalized as perceptual statements and measured using a five-point Likert scale, ranging from 1 = strongly disagree to 5 = strongly agree. To ensure content validity and contextual fit for Deli Serdang Regency, the adapted indicators were reviewed alongside local agricultural conditions before finalization in the survey instrument.

Table 1. Variables and Indicators of the Study

Variables	Indicators
Economic Impacts of Climate Change	Climate change reduces crop yields (E1)
	Agricultural income decreases due to extreme weather conditions (E2)
	Farmers frequently experience crop failure due to climate change (E3)
	Climate change reduces access to agricultural markets (E4)
	Fertilizer and seed prices increase due to climate change impacts (E5)
	Agricultural production costs increase as a result of climate change (E6)
Social Impacts of Climate Change	Climate change weakens social relationships (cooperation) among farmers (S1)
	Solidarity and mutual assistance among farmers decline when facing climate change (S2)
	Climate change reduces the quality of life of farming communities, particularly through declining agricultural productivity, increased risk of crop failure, higher adaptation costs, and unstable household income (S3)
	Climate change increases social tensions (conflicts) within agricultural communities (S4)
	Farmer group activities are disrupted due to climate change (S5)
Environmental Impacts of Climate Change	Unpredictable rainfall makes it difficult to determine planting schedules (E1)
	Irrigation water availability decreases due to climate change (E2)
	Soil becomes drier or more susceptible to degradation due to extreme weather events (E3)
	Climate change reduces agricultural land quality (E4)
	Crop production outcomes become increasingly uncertain due to weather variability (E5)
Farmers' Livelihood Sustainability	I utilize local resources to sustain farming activities (MP1)
	I attempt to cultivate more than one crop type to reduce the risk of crop failure (MP2)
	I cooperate with other farmers to maintain farm business stability (MP3)
	I adopt new technologies to enhance agricultural resilience (MP4)
Farmers' Adaptive Capacity	I apply farming practices that are appropriate to current weather conditions (A1)
	I am open to agricultural innovations and new technologies (A2)
	I am able to manage resources efficiently to cope with climate-related risks (A3)
	I am willing to make decisions to adopt new farming methods or implement new technologies (A4)
	I learn quickly from experiences in dealing with climate change (A5)
	I am able to anticipate weather impacts on my farming activities (A6)
	I feel prepared to face future climate challenges (A7)

Source: Purwanti et al. (2022) and Estiningtyas et al. (2024).

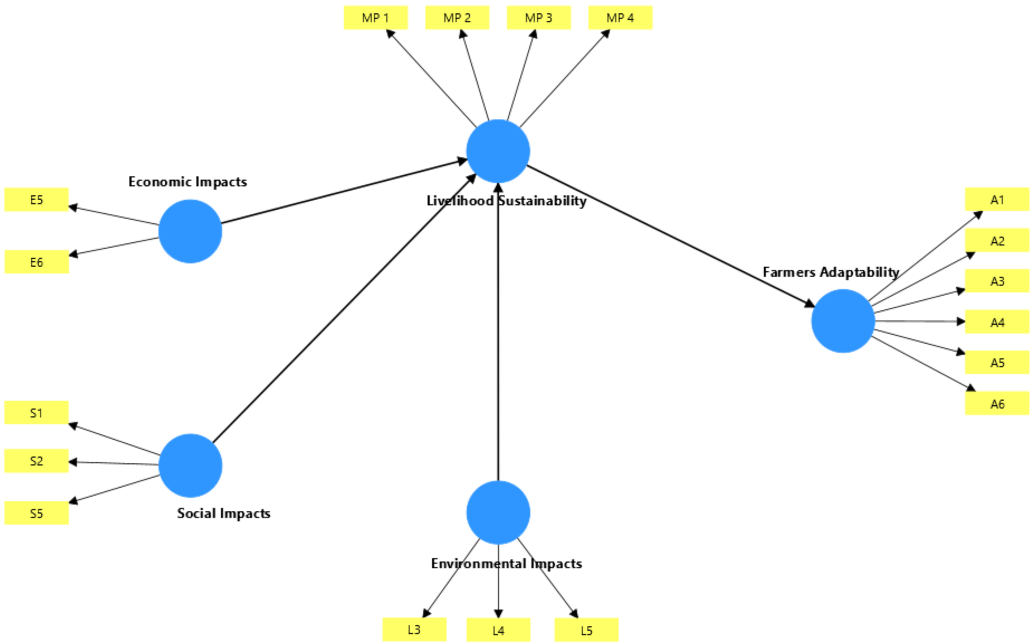

Figure 2. SEM-PLS Model

As shown in Figure 2, the proposed structural model is driven by three exogenous latent constructs representing the impacts of climate change: Economic Impacts, measured by 6 indicators (E1–E6); Social Impacts, measured by 5 indicators (S1–S5); and Environmental Impacts, measured by 5 indicators (L1–L5). These constructs are expected to influence the mediating variable, Livelihood Sustainability, measured by 4 indicators (MP1–MP4). The model ultimately illustrates how these variables predict the endogenous variable, Farmers' Adaptive Capacity, measured by 7 indicators (A1–A7). The arrows represent the directional pathways tested to understand both the direct effects and the mediating role of livelihood sustainability. The indicators listed in Table 1 are the initial measurement indicators used in the questionnaire. Indicators that did not meet the minimum outer loading threshold were removed during measurement model evaluation.

RESULT AND DISCUSSION

Respondent Characteristics

Descriptive exploration included gender, age, educational attainment, land size, income level, farming experience, and sources of climate information. The gender distribution showed that 80 respondents were male (84.21%) and 15 were female (15.79%), indicating a predominantly male sample. This composition suggests that the study findings largely reflect male perspectives. Therefore, interpretations should consider potential gender-based differences in climate change perceptions and agricultural adaptation behavior, as previous studies indicate that adaptation responses may vary according to gender roles, access to resources, and decision-making power within farming households (Haque et al., 2023).

Table 2. Respondent Characteristics

Characteristic	Category	Frequency	Percentage (%)
Gender	Male	80	84.21
	Female	15	15.79
Age	30–45 years	29	30.53
	46–60 years	48	50.53
	>60 years	18	18.95
Education	Elementary school	1	1.05
	Junior high school	18	18.95
	Senior high school	67	70.53
	Tertiary education	9	9.47
Landholding size	<0.5 ha	21	22.11
	0.5–1 ha	30	31.58
	>1 ha	44	46.32
Monthly income	<IDR 2 million	25	26.32
	IDR 2–4 million	29	30.53
	>IDR 4 million	41	43.16
Farming experience	<5 years	12	12.63
	5–10 years	30	31.58
	>10 years	53	55.79
Source of climate information	Internet	41	43.16
	Farmer groups	29	30.53
	Television	10	10.53
	Agricultural extension officers	10	10.53
	Village heads	5	5.26

Source: Processed Data

None of the respondents was younger than 30 years. Respondents aged 30–45 years accounted for 29 individuals (30.53%), while the largest group consisted of respondents aged 46–60 years (48 individuals; 50.53%). Respondents aged 60 or older accounted for 18 individuals (18.95%). The dominance of respondents in the 46–60 age group indicates that most participants were in productive and experienced stages of farming, which may influence decision-making and adaptation behavior. However, the limited representation of younger farmers should be considered as a potential limitation. Regarding education, most respondents had completed senior high school (67 respondents; 70.53%). Junior high school graduates accounted for 18 respondents (18.95%), while tertiary education graduates accounted for 9 (9.47%). Only one respondent had completed elementary school (1.05%). This distribution indicates that the sample primarily consisted of individuals with secondary education, which may influence their knowledge, attitudes, and capacity to respond to climate-related risks (Kujur et al., 2026).

Landholding size was predominantly above 1 hectare, with 44 respondents (46.32%). Respondents owning 0.5–1 hectare totaled 30 individuals (31.58%), while 21 respondents (22.11%) owned less than 0.5 hectare. This suggests that the majority of respondents were medium to large-scale farmers, potentially affecting production capacity and adaptation choices. Monthly income distribution indicated that 41 respondents (43.16%) earned more than IDR 4 million, 29 respondents (30.53%) earned IDR 2–4 million, and 25 respondents (26.32%) earned less than IDR 2 million. The dominance of the higher-income group may reflect relatively stronger economic capacity, which can influence technology adoption and resilience. Farming experience was relatively high among respondents. More than half of the respondents (53 individuals; 55.79%) had more than 10 years of farming experience, while 30 respondents (31.58%) had 5–10 years of experience and 12 respondents (12.63%) had less than 5 years. This indicates that the sample largely consisted of experienced farmers who may have developed coping strategies through long-term exposure to climate variability.

Sources of climate information were dominated by internet-based access (41 respondents; 43.16%), followed by farmer groups (29 respondents; 30.53%). Television and agricultural extension officers were each reported by 10 respondents (10.53%), while village heads were reported by 5 respondents (5.26%). These findings suggest an increasing reliance on digital information sources, while institutional channels such as farmer groups and extension services remain important for disseminating climate-related information. Access to weather information and the use of information and communication technologies can strengthen farmers' adaptive capacity by improving their ability to make timely farm-level adaptation decisions (Chetri et al., 2024).

Structural Equation Modeling–Partial Least Squares (SEM-PLS) Results

This study employed Structural Equation Modeling–Partial Least Squares (SEM-PLS) using SmartPLS to examine the relationships among latent constructs. SEM-PLS is a variance-based approach that is particularly suitable for predictive modeling, complex structural relationships, and relatively small sample sizes. The analysis was conducted in two major stages: evaluation of the measurement model (outer model) and the structural model (inner model).

Table 3. Outer Loading and Convergent Validity

Indicators	Farmer Adaptive	Economic Impact	Environmental Impact	Social Impact	Livelihood Sustainability	Description
A1	0.738					Valid
A2	0.769					Valid
A3	0.748					Valid
A4	0.775					Valid
A5	0.678					Valid
A6	0.642					Valid
E5		0.694				Valid
E6		0.941				Valid
L3			0.762			Valid
L4			0.792			Valid
L5			0.787			Valid
MP1					0.725	Valid
MP2					0.687	Valid
MP3					0.651	Valid
MP4					0.607	Valid
S1				0.788		Valid
S2				0.839		Valid
S5				0.794		Valid

Source: Processed Data

Measurement Model (Outer Model)

The measurement model assessment aims to confirm that the indicators used in the study accurately and consistently measure their respective latent constructs. The outer model was evaluated through convergent validity, discriminant validity, and construct reliability.

Convergent Validity

Convergent validity was assessed using outer loading values. Indicators are considered acceptable when the outer loading exceeds 0.60, indicating that the indicator sufficiently represents the intended construct. The results of the convergent validity assessment are presented in Table 3. As shown in Table 3, all retained indicators have outer loading values above the threshold of 0.60, confirming adequate convergent validity for all constructs. Indicators for Farmers' Adaptive Capacity (A1–A6) ranged from 0.642 to 0.775, suggesting moderate to strong indicator contributions. The construct Economic Impacts of Climate Change showed outer loadings of 0.694 (E5) and 0.941 (E6), with E6 representing the strongest indicator within this construct. Indicators for Environmental Impacts (L3–L5) ranged from 0.762 to 0.792, while Livelihood Sustainability (MP1–MP4) ranged from 0.607 to 0.725. Finally, indicators for Social Impacts (S1, S2, S5) ranged from 0.788 to 0.839.

Overall, the convergent validity criterion was satisfied, and all indicators were retained for further analysis. During the convergent validity assessment, several indicators were removed because their factor loadings were below the minimum threshold of 0.60. The removed indicators included A7 from Farmers' Adaptive Capacity, E1–E4 from Economic Impacts, L1–L2 from Environmental Impacts, and S3–S4 from Social Impacts. After removing these indicators, all retained indicators had outer loading values above 0.60 and were considered valid.

Discriminant Validity

Discriminant validity was evaluated using cross-loadings, where each indicator should load higher on its associated construct than on other constructs. The results demonstrate that all indicators showed the highest loadings on their respective constructs, with no cross-loadings on other constructs. This indicates that each construct captures a distinct concept and that there is no substantial overlap among constructs. Therefore, the measurement model meets the requirement for discriminant validity. The results of the discriminant validity assessment are presented in Table 4.

Table 4. Discriminant Validity

Indicators	Farmer Adaptive	Economic Impact	Environmental Impact	Social Impact	Livelihood Sustainability	Description
A1	**0.738**	-0.231	0.264	-0.123	0.543	Valid
A2	**0.769**	-0.100	0.357	0.120	0.512	Valid
A3	**0.748**	-0.174	0.327	-0.140	0.456	Valid
A4	**0.775**	-0.114	0.252	-0.100	0.404	Valid
A5	**0.678**	-0.304	0.324	-0.113	0.317	Valid
A6	**0.642**	-0.107	0.318	-0.023	0.421	Valid
E5	-0.156	**0.694**	-0.132	0.506	-0.160	Valid
E6	-0.218	**0.941**	-0.405	0.383	-0.341	Valid
L3	0.360	-0.331	**0.762**	-0.062	0.496	Valid
L4	0.419	-0.344	**0.792**	-0.085	0.381	Valid
L5	0.234	-0.208	**0.787**	-0.052	0.542	Valid
MP1	0.250	-0.327	0.511	-0.114	**0.725**	Valid
MP2	0.412	-0.212	0.378	-0.160	**0.687**	Valid
MP3	0.421	-0.258	0.526	0.020	**0.651**	Valid
MP4	0.577	-0.073	0.215	-0.070	**0.607**	Valid
S1	-0.029	0.502	-0.136	**0.788**	-0.059	Valid
S2	-0.056	0.253	-0.051	**0.839**	-0.109	Valid
S5	-0.098	0.495	-0.044	**0.794**	-0.096	Valid

Source: Processed Data

Construct Reliability

Construct reliability was assessed using Cronbach's Alpha and Composite Reliability (CR). In SEM-PLS, Composite Reliability is typically emphasized because it provides a more accurate estimate of reliability by accounting for indicator loadings. As shown in Table 5, all constructs demonstrate acceptable reliability. Farmers' Adaptive Capacity showed strong internal consistency (Cronbach's Alpha = 0.821, CR = 0.870). Environmental Impacts (Alpha

= 0.684, CR = 0.824) and Social Impacts (Alpha = 0.741, CR = 0.849) also met the reliability criteria. Although Economic Impacts (Alpha = 0.580) and Livelihood Sustainability (Alpha = 0.588) had slightly lower Cronbach's Alpha values, both constructs remained acceptable due to Composite Reliability values exceeding 0.60 (CR = 0.808 and 0.763, respectively). Thus, all constructs were considered reliable and suitable for structural model evaluation.

Table 5. Construct Reliability

Variables	Cronbach's Alpha	Composite Reliability (rho-r)	Description
Farmer Adaptive	**0.821**	**0.870**	Reliable
Economic Impact	0.580	**0.808**	Reliable
Environmental Impact	**0.684**	**0.824**	Reliable
Social Impact	**0.741**	**0.849**	Reliable
Livelihood Sustainability	0.588	**0.763**	Reliable

Source: Processed Data

Multicollinearity Assessment

Multicollinearity was examined using the Variance Inflation Factor (VIF). VIF values below 5.0 (or more conservatively below 3.3) indicate that multicollinearity is not a concern. The VIF values ranged from 1.174 to 2.188, suggesting no multicollinearity issues in the model. The highest VIF was observed for indicator A4 (VIF = 2.188), which remains within acceptable limits. Therefore, all indicators contribute unique information to the model without excessive redundancy.

Model Fit

Although SEM-PLS primarily focuses on predictive accuracy rather than global model fit, model fit indices can serve as supportive information. The model fit results indicate that the model is acceptable. The SRMR value of 0.111 indicates that the model does not fully meet the strict model fit criterion of 0.08. However, because SEM-PLS primarily emphasizes prediction rather than global model fit, the model was evaluated primarily based on measurement validity, reliability, explanatory power, and the significance of structural paths. The values of d_ULS (2.095) and d_G (0.809) indicate an adequate model approximation. The NFI value of 0.477 suggests moderate fit, which is acceptable in predictive SEM-PLS models, particularly when the model is complex and exploratory. Overall, the model fit indices support the adequacy of the proposed model for subsequent hypothesis testing.

Structural Model (Inner Model)

The structural model evaluation assesses the model's predictive power and the significance of hypothesized relationships among latent constructs. The inner model was evaluated using R^2 values and path coefficients, with significance assessed via bootstrapping.

The coefficient of determination (R^2) measures the extent to which the model's predictors explain the endogenous constructs. The results of the analysis indicate that Farmers' Adaptive Capacity has an R^2 of 0.389 (adjusted $R^2 = 0.382$), explaining 38.9% of the variance in adaptive capacity. Meanwhile, Livelihood Sustainability has an R^2 of 0.395 (adjusted $R^2 = 0.375$), indicating that the predictor variables explain 39.5% of its variance. Overall, these R^2 values suggest moderate explanatory power, indicating that the model has adequate predictive capability. Nevertheless, a substantial proportion of the variance remains influenced by external factors not included in the model, which may also affect both constructs.

The analysis of direct effects reveals several important relationships among the constructs, as presented in Table 6. The results show that Economic Impacts have a negative but non-significant effect on Livelihood Sustainability ($\beta = -0.109$, $t = 1.127$, $p = 0.260$). This indicates that the economic impacts of climate change do not significantly influence livelihood sustainability in the study context. In contrast, Environmental Impacts demonstrate a positive, statistically significant effect on Livelihood Sustainability ($\beta = 0.578$, $t = 6.686$, $p = 0.000$), suggesting that environmental conditions and climate-related changes are key determinants of livelihood sustainability among rice-farming households. Meanwhile, Social Impacts show no significant relationship with Livelihood Sustainability ($\beta = -0.013$, $t = 0.092$, $p = 0.927$), implying that social factors included in this model do not meaningfully explain variations in livelihood sustainability. Furthermore, Livelihood Sustainability exhibits a strong, statistically significant positive effect on Farmers' Adaptive Capacity ($\beta = 0.624$, $t = 9.351$, $p = 0.000$), indicating that improved livelihood sustainability enhances farmers' adaptive capacity to climate change. Overall, these findings highlight that Environmental Impacts significantly improve Livelihood Sustainability, which, in turn, significantly strengthens Farmers' Adaptive Capacity. In contrast, Economic and Social Impacts do not have a significant direct effect on Livelihood Sustainability.

Table 6. Direct Effects

Relationship	β	t-statistic	p-value	Decision
Economic Impacts → Livelihood Sustainability	-0.109	1.127	0.260	Not supported
Environmental Impacts → Livelihood Sustainability	0.578	6.686	0.000	Supported
Social Impacts → Livelihood Sustainability	-0.013	0.092	0.927	Not supported
Livelihood Sustainability → Adaptive Capacity	0.624	9.351	0.000	Supported

Source: Processed Data

The indirect effects were examined to evaluate the mediating role of Livelihood Sustainability in the relationship between the exogenous variables and Farmers' Adaptive Capacity. The results of the indirect effect analysis are presented in Table 7. As shown in Table

7, the indirect effect of Economic Impacts on Farmers' Adaptive Capacity through Livelihood Sustainability is negative and not statistically significant (β = −0.068, t = 1.114, p = 0.265), suggesting that economic impacts do not significantly influence adaptive capacity through livelihood sustainability. In contrast, Environmental Impacts exhibit a positive and statistically significant indirect effect on Farmers' Adaptive Capacity (β = 0.360, t = 5.249, p = 0.000), indicating that environmental factors affect farmers' adaptive capacity through the mediating role of livelihood sustainability. Meanwhile, the indirect effect of Social Impacts on Farmers' Adaptive Capacity is not significant (β = −0.008, t = 0.092, p = 0.926), implying the absence of a mediation effect. Overall, these findings confirm that livelihood sustainability acts as a significant mediator in the relationship between environmental impacts and farmers' adaptive capacity. In contrast, the mediating roles for economic and social impacts are not supported.

Table 7. Indirect Effects

Relationship	β	t-statistic	p-value	Decision
Economic Impacts → Livelihood Sustainability → Adaptive Capacity	-0.068	1.114	0.265	Not supported
Environmental Impacts → Livelihood Sustainability → Adaptive Capacity	0.360	5.249	0.000	Supported
Social Impacts → Livelihood Sustainability → Adaptive Capacity	-0.008	0.092	0.926	Not supported

Source: Processed Data

The SEM-PLS model can be represented through two structural equations. The first equation defines Livelihood Sustainability as a function of Economic, Environmental, and Social Impacts. Among these predictors, Environmental Impacts exhibit the strongest and the only statistically significant positive effect, indicating their dominant role in determining livelihood sustainability. The second equation describes Farmers' Adaptive Capacity as being influenced by Economic Impacts, Environmental Impacts, Social Impacts, and Livelihood Sustainability. The results reveal that Livelihood Sustainability is the most significant and strongest predictor of adaptive capacity. In addition, Environmental Impacts contribute significantly to adaptive capacity through indirect pathways mediated by livelihood sustainability. Overall, the SEM-PLS findings suggest that the environmental impacts of climate change play a crucial role in enhancing livelihood sustainability, thereby significantly strengthening farmers' adaptive capacity. Furthermore, livelihood sustainability serves as an important mediating variable in the relationship between environmental impacts and adaptive capacity. In contrast, economic and social impacts do not demonstrate statistically significant direct or indirect effects within the proposed model.

This study examined the effects of climate change impacts, economic, social, and environmental, on farmers' livelihood sustainability and adaptive capacity using SEM-PLS. The results indicate that environmental impacts are the primary driver of livelihood sustainability, while livelihood sustainability is the strongest predictor of farmers' adaptive capacity. In contrast, economic and social impacts do not show statistically significant direct effects on livelihood sustainability, nor do they show indirect effects on adaptive capacity through livelihood sustainability. These findings suggest that biophysical and environmental pressures largely shape the adaptation of rice-farming households in Deli Serdang, and that the ability to adapt depends on whether farmers can maintain stable, sustainable livelihood systems under climate stress.

Environmental Impacts as the Dominant Determinant of Livelihood Sustainability

The SEM-PLS results indicate that environmental impacts have a significant and positive effect on livelihood sustainability ($\beta = 0.578$; $p < 0.001$). This finding suggests that environmental conditions such as rainfall variability, irrigation constraints, land degradation, and unstable crop production play a crucial role in shaping farmers' livelihood sustainability. Conceptually, this result is consistent with the characteristics of rice farming systems, which are highly dependent on water availability and seasonal climate stability. (Chowdhury et al., 2024). In rice-based agricultural systems, environmental disturbances often lead to direct adjustments in farming practices, including changes in planting schedules, crop management decisions, and input allocation. (Tran et al., 2022). Therefore, environmental pressures can be considered the most immediate and observable manifestations of climate change at the farm level. From a livelihood perspective, environmental conditions serve as fundamental assets that determine whether agricultural activities can be sustained over time. As environmental stress increases, farmers are more likely to face greater uncertainty, reduced production stability, and increased livelihood vulnerability, thereby threatening livelihood sustainability. (Singh, 2021).

These findings are further supported by recent studies published in reputable international journals. For example, farmers' perceptions of climate change and livelihood vulnerability are strongly influenced by climate variability, such as irregular rainfall and increasing temperatures, which significantly elevate livelihood risks. (Tohidimoghadam et al., 2023)**.** Similarly, research on rural livelihood resilience shows that strong dependence on climatic conditions makes rural communities highly vulnerable to environmental change, underscoring the importance of adaptive capacity. In addition, research on climate-smart agriculture demonstrates that extreme weather events caused by climate change significantly affect agricultural productivity and income stability. Overall, these findings reinforce the results of this study, highlighting that environmental impacts are a key determinant of farmers' livelihood sustainability. However, their effects remain context-specific, as they are strongly influenced by farmers' adaptive capacity, access to technology, and institutional support in responding to climate change.

Livelihood Sustainability as a Strong Predictor of Farmers' Adaptive Capacity

The structural model shows that livelihood sustainability has a strong, significant positive effect on farmers' adaptive capacity ($\beta = 0.624$; $p < 0.001$). This finding implies that farmers who sustain their livelihoods through diversification, collaboration, local resource use, and technology adoption tend to exhibit greater adaptive capacity (Arifah et al., 2022). This relationship is consistent with the idea that adaptation is not solely a technical process, but also a socio-economic capability. Farmers with sustainable livelihoods are more likely to possess the necessary resources and flexibility to implement adaptive strategies, such as investing in improved technologies, adjusting farming practices, or adopting climate-resilient crop varieties. In other words, livelihood sustainability strengthens adaptive capacity by improving farmers' ability to respond proactively rather than reactively (Tran et al., 2022). Furthermore, this finding suggests that adaptation is closely tied to resilience mechanisms at the household level. Sustainable livelihoods provide economic and social buffers that reduce exposure to climate-related shocks, allowing farmers to maintain productivity and household welfare under changing climatic conditions (Mehraj et al., 2024).

The non-significant effects of economic impacts suggest that economic pressures, such as declining income and rising production costs, may function more as indirect consequences of environmental stress than as primary drivers. In many cases, these economic challenges emerge as downstream effects of climate-related shocks, including floods, droughts, and pest outbreaks, which are already represented in the model's environmental dimension. (Haldar & Pearlin, 2023). Additionally, farmers often adopt coping strategies such as informal borrowing, reliance on savings, and income diversification, which may buffer the immediate impact of economic stress and reduce its observable effect on livelihood sustainability. (Mehraj et al., 2024). Limited variation in economic conditions among respondents may also contribute to the weak statistical relationship. Similarly, the absence of significant effects from social impacts indicates that factors such as reduced cooperation, disrupted farmer group activities, and declining social cohesion may not directly translate into short-term livelihood outcomes. Social dimensions are more likely to operate as long-term structural factors that influence adaptation gradually through mechanisms such as knowledge sharing, collective action, and institutional support. However, in situations requiring rapid responses to climate shocks, farmers may prioritize individual coping strategies over collective approaches, relying more on household-level resources and personal experience. Moreover, the effectiveness of social capital may depend on institutional variables not explicitly included in the model, such as extension services and policy support. (Purwanti et al., 2022).

The indirect effects analysis further highlights the central role of livelihood sustainability as a mediating variable. Environmental impacts have a significant indirect effect on farmers' adaptive capacity through livelihood sustainability ($\beta = 0.360$; $p < 0.001$), whereas economic and social impacts do not mediate this effect. This finding suggests that environmental stressors influence adaptive capacity not only directly but also indirectly by shaping the sustainability of farmers' livelihoods. In practical terms, environmental challenges encourage farmers to strengthen their livelihood strategies, such as diversification, the adoption of adaptive technologies, and improved resource management, thereby enhancing their adaptive capacity. Overall, these findings underscore the importance of livelihood sustainability as a key pathway linking environmental pressures to adaptive capacity. While environmental impacts emerge as the primary driver in the model, their effects are mediated by farmers' ability to maintain and adapt their livelihood systems. Therefore, policy interventions should not only focus on mitigating environmental risks, such as improving irrigation systems and managing climate-related hazards, but also prioritize strengthening livelihood sustainability through access to resources, technology, and institutional support, thereby fostering long-term resilience among farming households. (Amandaria et al., 2025).

The main contribution of this study is to demonstrate the mediating role of livelihood sustainability in the relationship between environmental impacts and farmers' adaptive capacity. This finding extends previous studies on climate change adaptation by showing that environmental pressures do not directly translate into adaptive capacity in isolation; rather, they operate through farmers' ability to maintain sustainable livelihood systems. Thus, strengthening livelihood sustainability becomes a critical pathway for improving rice farmers' resilience to climate change.

Limitations

This study has several limitations. First, the sample was limited to rice-farming households in Lubuk Pakam District, which may restrict the generalizability of the findings to other rice-producing regions. Second, the model focused on economic, social, and environmental impacts, while institutional support, access to extension services, and farmers' technological readiness were not explicitly included. Future studies should incorporate these variables and compare different agroecological zones to provide a more comprehensive understanding of climate change adaptation among rice farmers.

CONCLUSION

This study demonstrates that environmental impacts of climate change play a significant role in shaping livelihood sustainability and enhancing rice farmers' adaptive capacity in Deli Serdang Regency. Livelihood sustainability was found to act as a key mediating mechanism, whereas economic and social impacts did not show significant effects within the proposed model. The main contribution of this study is the empirical confirmation that livelihood sustainability serves as a mediating pathway through which environmental climate pressures are translated into farmers' adaptive capacity. This finding highlights that climate adaptation is not only determined by environmental exposure but also by farmers' ability to maintain and adjust sustainable livelihood systems.

The results also imply that strengthening adaptive capacity should be understood as a multidimensional process involving production stability, access to resources, household resilience, and farmers' ability to respond to climate-related disturbances. In this context, livelihood sustainability becomes an important foundation for reducing vulnerability, particularly when farmers face unpredictable rainfall, water scarcity, flooding, and other environmental pressures. The insignificant effects of economic and social factors do not necessarily indicate that these dimensions are unimportant; rather, they suggest that their influence may be indirect, context-specific, or dependent on other supporting variables not fully captured in the present model.

From a policy perspective, the findings suggest that climate adaptation programs should prioritize environmental risk management, including improved water resource management, flood control, and accessible climate information services. In addition, farmer empowerment programs should strengthen long-term adaptive capacity by promoting livelihood diversification, adaptive technology adoption, institutional support, and sustainable livelihood strategies, rather than focusing solely on short-term productivity gains. These efforts should be integrated with local agricultural extension programs, farmer group development, and participatory planning so that adaptation strategies are more responsive to farmers' actual needs and local agroecological conditions.

This study is limited to rice-farming households in Lubuk Pakam District; therefore, the findings may not fully represent other rice-producing regions with different agroecological and institutional conditions. Future studies should incorporate institutional support, extension services, farmers' technological readiness, access to climate-smart agriculture, and comparative analysis across different rice-producing areas to provide a more comprehensive explanation of adaptive capacity. Further research may also apply longitudinal data to examine how farmers' vulnerability and adaptation strategies change over time in response to increasing climate variability.

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Author Contribution

Herlyna Novasari Siahaan contributed to the conception and design of the study, data collection and curation, analysis and interpretation of the results, and preparation of the initial draft of the manuscript. Mia Wananda Varwasih contributed to data collection, statistical analysis, and the critical revision of the manuscript to strengthen its scientific substance. Hendris Syah Putra contributed to the interpretation of the research results, validation of the methodology, and refinement of the manuscript through academic revision. M. Fariz Afif Hasibuan played a role in project supervision and administration, field coordination, and strengthening the conceptual framework of the study. All authors gave final approval to the published version of the manuscript and take full responsibility for the integrity and accuracy of the content of this scientific work.

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