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The Role of Ethnoecological Knowledge, Climate Adaptation Strategies, and Farmer Innovation in Achieving Sustainable Agriculture in Indonesia

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ABSTRACT

This study investigates the interrelationships among Ethnoecological Knowledge, Climate Adaptation Strategies, and Farmer Innovation in fostering Sustainable Agriculture in Indonesia. Using a quantitative approach, data were collected from 150 smallholder farmers across Java, Sumatra, and Sulawesi through structured questionnaires measured on a five-point Likert scale. The data were analyzed using Structural Equation Modeling (SEM-PLS 3) to test the direct, indirect, and mediating relationships among the constructs. The findings reveal that ethnoecological knowledge significantly enhances both climate adaptation and farmer innovation, indicating that traditional ecological wisdom remains a critical foundation for modern sustainability practices. Climate adaptation strategies have a dual role—directly strengthening sustainability and indirectly fostering innovation. Furthermore, farmer innovation mediates the relationship between traditional knowledge and sustainability, serving as a transformational bridge from cultural heritage to adaptive modernization. The model explains 69% of the variance in sustainable agriculture, confirming its strong predictive power. The study provides theoretical contributions by integrating the Resource-Based View (RBV) and Dynamic Capabilities Theory (DCT) and offers practical recommendations for policymakers to strengthen local wisdom, participatory innovation, and adaptive learning in rural development. These findings underscore that Indonesia's agricultural transformation depends not on abandoning tradition, but on revitalizing it through innovation-driven adaptation toward sustainability.

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1. INTRODUCTION

Agricultural sustainability in Indonesia lies at the intersection of tradition and transformation. As one of the world's most agrarian nations, Indonesia's agricultural systems are deeply rooted in ethnoecological knowledge—centuries of understanding the environment, biodiversity, and resource management. Yet, rapid environmental changes driven by climate variability pose complex challenges to rural livelihoods. Farmers must now preserve traditional ecological wisdom while integrating innovative and adaptive strategies to sustain productivity and ecological balance. The convergence of indigenous knowledge, adaptive capacity, and innovation is thus pivotal to advancing agricultural sustainability. Ethnoecology offers a framework for linking traditional knowledge with climate adaptation, where indigenous practices provide valuable insights for resilience [1]. Although traditional systems remain vulnerable, their adaptation potential can be strengthened through integration with scientific research [1]. Sustainability-oriented innovation (SOI) is increasingly essential, requiring interdisciplinary collaboration to develop practices that meet environmental, social, and economic challenges [2]. Approaches such as sustainable farming and agroecology help farmers navigate climate variability and globalization pressures [3]. However, shifting weather patterns, water scarcity, and global market dynamics continue to threaten food security and rural livelihoods, demanding adaptive strategies [3]. Moreover, while modernization has boosted productivity, it has also exposed weaknesses in supply chains and distribution, underscoring the urgent need for sustainable agricultural practices [4].

Climate change has significantly altered the dynamics of Indonesia's farming ecosystems, causing shifting rainfall patterns, prolonged droughts, and pest outbreaks that threaten food security and income stability. These climatic disturbances demand adaptive, locally grounded responses. Studies emphasize that smallholder farmers possess rich ethnoecological insights crucial for climate adaptation, including traditional weather forecasting, crop diversification, soil fertility management, and pest control based on local observation and cultural practices [5], [6]. Farmers in Indonesia rely on personal experience and local wisdom to adapt, such as adjusting planting patterns and employing soil cultivation techniques [7]. Local knowledge is also used for predicting natural events, often in conjunction with information from formal institutions [8], while indigenous practices are more successful when supported by community leaders and government collaboration [1].

Despite its value, ethnoecological knowledge faces challenges due to limited policy and institutional support. Drought remains a leading cause of crop failure, affecting up to 70% of farmers in some regions [8], while rising production costs and stagnant income create economic pressures [7]. Integrating traditional knowledge with modern science is essential to strengthen adaptation strategies [9]. Government policies, subsidies, and protection of customary land rights play key roles in enabling sustainable practices [1]. Social adaptation, through indigenous knowledge and strong community networks, enhances resilience [10]. In this context, farmer innovation—emerging through community learning and the adaptation of traditional methods—has become vital for rural resilience and sustainable intensification while maintaining ecological integrity [11]. However, more empirical research is needed to understand how ethnoecological knowledge and adaptive behavior jointly shape farmer innovation and long-term agricultural sustainability.

Theoretically, this research draws upon the Resource-Based View (RBV) and the Dynamic Capabilities framework to explain how local knowledge resources and adaptive capacities are mobilized toward sustainable outcomes. Ethnoecological knowledge serves as a unique intangible asset embedded within social and cultural systems, enabling communities to interpret and respond to environmental changes. When combined with dynamic capabilities—such as innovation and adaptation—these resources empower farmers to reconfigure their practices amid ecological and market uncertainties. Consequently, this study examines the mediating role of farmer innovation in translating traditional ecological knowledge and adaptive strategies into measurable sustainability performance. Empirically, the research advances quantitative understanding of sustainability transitions within smallholder farming systems. Prior studies in Indonesia often isolate socio-cultural or technological adaptation factors, whereas this study integrates both dimensions within a comprehensive model tested using Structural Equation Modeling–Partial Least Squares (SEM-PLS 3) on data from farmers across diverse agroecological regions, thus providing a robust analysis of causal relationships among ethnoecological knowledge, climate adaptation, farmer innovation, and agricultural sustainability.

2. LITERATURE REVIEW

2.1 Ethnoecological Knowledge and Sustainable Agriculture

Ethnoecological knowledge plays a vital role in promoting sustainable agriculture by integrating traditional practices, beliefs, and values that enhance biodiversity, resilience, and community well-being. In Indonesia, this wisdom is reflected in agricultural systems such as intercropping, organic fertilization, and traditional irrigation networks like subak and leuit, which embody deep ecological understanding and social harmony. Practices such as swidden farming and agroforestry in West Java have evolved in response to population pressures and economic changes [12], while sustainable resource management techniques like rotational farming and fishing ensure natural regeneration and long-term environmental balance [13]. However, globalization and modernization threaten the continuity of these traditions, resulting in documentation loss and generational knowledge gaps. Integrating indigenous ecological wisdom with scientific research and modern technologies can strengthen agricultural resilience against climate change and enhance adaptive capacity [14]. The successful adoption of these practices depends on active community participation and supportive government policies, including subsidies and incentives for sustainability [1]. The transition from traditional to modern agricultural systems since the Green Revolution has brought productivity gains but also disrupted agroecosystems, reinforcing the need to preserve valuable local wisdom alongside scientific innovation [12]. Ethnoecological knowledge—transmitted through cultural rituals and empirical observations—thus provides a crucial framework for understanding environmental interactions and guiding sustainable agricultural development [15].

2.2 Climate Adaptation Strategies in Agriculture

Climate adaptation in agriculture for smallholder farmers in tropical developing countries like Indonesia requires an integrated approach that combines behavioral, institutional, and technological changes to mitigate the adverse impacts of climate variability and strengthen resilience. The effectiveness of these adaptations depends on access to knowledge, social capital, and institutional support, which enable the adoption of adaptive practices. Farmers in Indonesia often merge traditional ecological knowledge with modern meteorological information, creating an adaptive co-management system that enhances sustainability. Access to climate information and agricultural extension services encourages the adoption of adaptive techniques such as improved planting systems and climate forecasting [10], [16]. Strong governance, policy alignment, and stakeholder collaboration are equally essential to mainstream adaptation efforts and strengthen farmers' capacity to face climate challenges [10], [16]. Technological innovations—such as drought-tolerant crops, efficient irrigation, and improved soil management—further enhance resilience [17]. However, adaptation is also shaped by socioeconomic and cultural factors, where livelihood diversification, credit access, and insurance improve economic resilience but may be constrained by financial burdens and productivity loss [10]. Moreover, cultural values and traditional beliefs strongly influence the acceptance of adaptive practices, as farmers often combine ancestral forecasting methods with modern techniques to maintain both ecological balance and community identity [7].

2.3 *Farmer Innovation and Its Role in Agricultural Transformation*

Farmer innovation in Indonesia is a vital mechanism that enables smallholder farmers to adapt to environmental and market challenges through context-specific and sustainable solutions. Rooted in the need to enhance productivity, efficiency, and resilience, these innovations are shaped by factors such as relative advantage, compatibility, and observability, as proposed by Rogers' Diffusion of Innovation Theory, while social learning and peer influence further drive adoption within farming communities. In North Lombok, farmers have implemented horticultural innovations tailored to local ecological conditions, highlighting the value of context-specific approaches in improving agricultural outcomes [18]. Similarly, in East Nusa Tenggara, the success of rice innovations depends on external input availability and environmental suitability [19]. Collaborative networks among farmers, governments, and other stakeholders are essential for facilitating communication and cooperation, as seen in the diffusion of greenhouse technologies in China, which underscores the importance of social connectivity for effective innovation dissemination [20]. Peer influence and shared learning platforms enhance behavioral change and productivity gains [20]. In Indonesia, smallholder farmers adopt adaptive strategies such as crop diversification and altered planting patterns to manage climate risks and market uncertainties—practices influenced by education level, land ownership, and market access [21]. Ultimately, farmer innovation acts as a dynamic capability that bolsters resilience through continuous experimentation and resource optimization, strengthening the adaptive capacity of rural communities [21].

2.4 *Sustainable Agriculture as the Outcome of Transformation*

Sustainable agriculture is a multifaceted approach that integrates environmental health, economic profitability, and social equity to ensure the long-term viability of farming systems. In developing countries like Indonesia, this concept aligns closely with the Sustainable Development Goals (SDGs), particularly Zero Hunger, Responsible Consumption and Production, and Climate Action. The shift from input-intensive to knowledge-intensive models requires farmers to combine traditional and scientific knowledge, adopt adaptive practices, and strengthen local innovation networks to achieve sustainability outcomes such as productivity stability, reduced environmental degradation, and improved livelihoods. Environmentally, practices like permaculture, crop rotation, and effective water management are essential for preserving ecosystem health and biodiversity [22]. Economically, sustainable agriculture promotes the efficient use of inputs to maintain yields while conserving resources [23]. From a social perspective, it upholds equity and justice to enhance community resilience and food security [22]. Agroecology and organic farming reduce chemical dependence and improve soil health, while precision agriculture increases resource efficiency and minimizes waste [22], [24]. Local innovation networks also play a pivotal role in fostering adaptive governance and sustainability [24]. However, economic, technological, and sociocultural barriers often hinder widespread adoption, underscoring the need for supportive policies, international collaboration, and investment in farmer education to accelerate the transition toward sustainable agriculture [25].

2.5 Theoretical Framework and Hypothesis Development

This research integrates the Resource-Based View (RBV) and Dynamic Capabilities Theory to explain how internal resources and adaptive mechanisms drive sustainable agricultural performance. According to the RBV [26], unique and valuable resources—such as local ecological knowledge—create competitive advantage when they are rare, inimitable, and non-substitutable; in this context, ethnoecological knowledge serves as an intangible cultural asset that strengthens environmental stewardship and decision-making. Meanwhile, the Dynamic Capabilities Theory [27] asserts that sustainability arises when organizations or farmers can integrate, build, and reconfigure resources in response to environmental change, with farmer innovation and adaptation representing these dynamic capabilities. Accordingly, this study posits that ethnoecological knowledge positively influences climate adaptation and farmer innovation; climate adaptation enhances innovation and sustainable agriculture; farmer innovation directly contributes to sustainability; and innovation mediates the relationship between ethnoecological knowledge, adaptation, and sustainability. By grounding its framework in these theories, the study bridges traditional ecological understanding with modern management and innovation perspectives, emphasizing that agricultural sustainability stems not only from external support but also from the intrinsic strengths and adaptive capacities of local communities.

3. RESEARCH METHODS

3.1 Research Design

This study employed a quantitative explanatory research design to analyze the causal relationships among ethnoecological knowledge, climate adaptation strategies, farmer innovation, and sustainable agriculture in Indonesia. The explanatory approach was selected to empirically test theoretical linkages derived from the Resource-Based View (RBV) and Dynamic Capabilities Theory using statistical modeling. Structural Equation

Modeling with Partial Least Squares (SEM-PLS 3) was applied to identify both direct and indirect effects among constructs while addressing measurement errors and complex interdependencies. The design utilized cross-sectional data collected from farmers across various agroecological zones in Indonesia, capturing diverse cultural and environmental settings. The use of SEM-PLS was deemed appropriate due to its robustness in handling latent variable relationships, predictive analysis, and relatively modest sample sizes [28]

3.2 Population and Sampling

The population of this study consisted of smallholder farmers actively engaged in agricultural production across rural areas of Java, Sumatra, and Sulawesi—regions chosen for their high agricultural productivity and vulnerability to climate change. Farmers were identified through local agricultural extension offices and cooperatives, and purposive sampling was applied to ensure participants had relevant experience with both traditional ecological practices and modern adaptation or innovation initiatives. The inclusion criteria required that farmers (1) had managed agricultural land for at least five years, (2) participated in or possessed knowledge of community-based adaptation programs, and (3) had implemented innovative crop or resource management practices. A total of 150 valid responses were collected, which met the adequacy standards for Structural Equation Modeling using Partial Least Squares (SEM-PLS). Following Hair et al. (2021), a minimum sample size of ten times the largest number of structural paths directed toward a single construct is sufficient for PLS analysis, confirming that the obtained sample size was statistically appropriate for model estimation and hypothesis testing.

3.3 Data Collection Procedures

Data were collected through structured questionnaires administered between January and April 2025. The instrument was adapted from validated scales in prior studies and refined through expert reviews involving agricultural extension officers and academic researchers specializing in sustainability and rural innovation. A pilot test with 20 respondents was conducted to assess clarity, reliability, and cultural relevance, followed by necessary revisions to enhance comprehension before full deployment. The questionnaire comprised five sections: (1) demographic information covering age, education, farming experience, and land size; (2) ethnoecological knowledge assessing local environmental understanding, traditional farming techniques, and cultural ecological values; (3) climate adaptation strategies measuring behavioral, technical, and institutional responses to climate variability; (4) farmer innovation evaluating experimentation, adoption of new methods, and creativity in farming; and (5) sustainable agriculture assessing environmental, social, and economic dimensions of sustainability. All items were rated on a five-point Likert scale from 1 (strongly disagree) to 5 (strongly agree). To ensure data quality and inclusivity, trained enumerators assisted respondents with low literacy levels, promoting accurate interpretation and consistent responses.

3.4 Measurement of Variables

Each construct in this study was operationalized as a latent variable with multiple observed indicators adapted from established literature to fit the Indonesian agricultural context. Ethnoecological Knowledge (EK) included indicators such as the use of traditional planting calendars (EK1), knowledge of local soil and water systems (EK2), preservation of indigenous crop varieties (EK3), and cultural rituals for environmental balance, adapted from Iskandar & Iskandar (2016) and Kamakaula (2024) who emphasized the ecological and cultural foundations of indigenous agricultural systems. Climate Adaptation Strategies (CA) were measured through adjusting planting time (CA1), crop diversification (CA2), use of climate information (CA3), and participation in local adaptation programs, based on Kusumasari (2016) and Imelda & Hidayat (n.d.), which highlighted behavioral and institutional adaptation mechanisms among smallholder farmers. Farmer Innovation (FI) was assessed through experimenting with new techniques (FI1), adopting new technologies (FI2), collaborating with other farmers (FI3), and demonstrating creativity in resource management, following Abdurrahman et al. (2023) and Sulfiana (2025) who documented farmer-led innovations in local agricultural contexts. Sustainable Agriculture (SA) encompassed efficient resource use (SA1), reduced environmental impact (SA2), improved yield stability (SA3), and enhanced social and economic well-being, based on Sharma & K.C. (2024) and Sutiharni et al. (2024), who outlined key sustainability dimensions aligned with Indonesia's transition toward knowledge-based and ecologically resilient farming. All indicators were validated by three agricultural sustainability experts for content relevance and subsequently tested for reliability using Cronbach's Alpha and Composite Reliability (CR) within the SEM-PLS analysis framework.

3.5 Data Analysis Techniques

The data analysis was conducted using SmartPLS version 3.0, following a two-step approach comprising the evaluation of the measurement model and the structural model. In the measurement model, indicator reliability was confirmed with outer loadings exceeding 0.70, internal consistency reliability was established through Cronbach's Alpha and Composite Reliability values above 0.70, convergent validity was ensured with an Average Variance Extracted (AVE) greater than 0.50, and discriminant validity was verified using the Fornell–Larcker criterion and the Heterotrait–Monotrait (HTMT) ratio below 0.90 (Henseler et al., 2015). In the structural model, collinearity was checked using the Variance Inflation Factor (VIF) with a threshold below 5, while path coefficients (β) were examined for direction, magnitude, and statistical significance through bootstrapping with 5000 resamples. The model's explanatory power was assessed using the Coefficient of Determination (R^2), its predictive relevance through Q^2 values derived from blindfolding, and the effect size (f^2) to determine the contribution of each exogenous construct to the endogenous variables. This analytical framework enabled rigorous testing of both direct and mediating relationships, particularly the mediating role of farmer innovation in linking ethnoecological knowledge and climate adaptation to sustainable agriculture.

4. RESULTS AND DISCUSSION

4.1 Respondent Profile

The respondents of this study comprised 150 smallholder farmers from three major agroecological regions of Indonesia—Java (45%), Sumatra (35%), and Sulawesi (20%)—selected to capture both geographical and cultural diversity. These regions represent distinct environmental conditions and traditional ecological systems, providing an ideal context for examining the interrelationships between ethnoecological knowledge, climate adaptation, and farmer innovation. Demographically, 108 respondents (72%) were male and 42 (28%) female, reflecting the gender imbalance typical in rural agriculture, where men usually dominate decision-making, while women play critical roles in planting and post-harvest processes. The respondents' ages ranged from 25 to 67 years, with an average of 46.2 years, and most (57%) were between 40 and 55 years, representing an experienced and productive farming group. Education levels were relatively low, with 41% completing elementary school, 37% secondary school, and only 22% tertiary education, indicating that agricultural knowledge transfer remains primarily informal and intergenerational. On average, farmers had 17.5 years of experience, with 65% cultivating less than two hectares and 35% managing two to five hectares, confirming their classification as smallholders typical of Indonesia's agricultural landscape.

In terms of agricultural and socioeconomic conditions, 78% of respondents practiced mixed cropping systems—combining rice, maize, or other staples with secondary crops such as chili, peanuts, or cassava—to mitigate climatic and market risks. Farming was the primary livelihood for 82% of respondents, while 18% supplemented income through livestock, handicrafts, or seasonal trading. Around 63% were active members of local cooperatives or farmer groups, which facilitated access to extension services, credit, and knowledge exchange. Ethnoecological practices remained strong: 68% relied on traditional planting calendars (such as pranata mangsa or wariga), 74% preserved indigenous crop seeds, and 61% performed rituals tied to soil fertility and water management. Climate adaptation was evident in widespread measures such as adjusting planting times (72%), adopting drought-tolerant varieties (63%), improving irrigation efficiency (54%), and using weather information (48%). Moreover, 60% of farmers engaged in innovative practices over the past three years, including organic pest control, bio-fertilizer use, and collaborative learning in farmer groups. These patterns demonstrate how Indonesian smallholders are blending ancestral ecological wisdom with modern adaptation technologies, creating a culturally hybrid model of sustainable agricultural transformation.

4.2 Measurement Model Evaluation

The measurement model evaluation was conducted to assess the validity and reliability of the latent constructs used in this study—Ethnoecological Knowledge (EK), Climate Adaptation (CA), Farmer Innovation (FI), and Sustainable Agriculture (SA)—before testing the structural relationships among them. The analysis was performed using SmartPLS version 3.0, following the two-step approach recommended by Hair et al. (2021): (1) evaluation of the outer measurement model, and (2) evaluation of the inner structural model. This section presents the results of the outer model validation, focusing on indicator reliability, internal consistency reliability, convergent validity, and discriminant validity.

Indicator reliability was evaluated using the outer loading values of each observed indicator on its corresponding latent construct, with a minimum threshold of 0.70 considered acceptable to ensure that each indicator explains at least 50% of the variance of its underlying construct (Hair et al., 2021). As presented in Table 1, all indicators achieved loading values above this threshold, ranging from 0.714 to 0.876, confirming that every measurement item reliably represents its respective construct and that no indicator required removal from the analysis.

Table 1. Outer Loading Values of Construct Indicators

Construct	Indicator	Loading	Interpretation
Ethnoecological Knowledge (EK)	EK1: Use of traditional planting calendar	0.812	Reliable
	EK2: Knowledge of local soil and water systems	0.841	Reliable
	EK3: Preservation of indigenous crop varieties	0.785	Reliable
	EK4: Cultural rituals for environmental balance	0.733	Reliable
Climate Adaptation (CA)	CA1: Adjustment of planting time	0.856	Reliable
	CA2: Crop diversification practices	0.832	Reliable

	CA3: Utilization of climate information	0.744	Reliable
	CA4: Participation in adaptation programs	0.718	Reliable
Farmer Innovation (FI)	FI1: Experimentation with new techniques	0.876	Reliable
	FI2: Adoption of new agricultural technologies	0.821	Reliable
	FI3: Collaboration with other farmers	0.792	Reliable
	FI4: Creativity in managing resources	0.741	Reliable
Sustainable Agriculture (SA)	SA1: Efficient resource utilization	0.854	Reliable
	SA2: Reduced environmental degradation	0.816	Reliable
	SA3: Improved productivity stability	0.773	Reliable
	SA4: Social and economic well-being	0.740	Reliable

Table 1 presents the outer loading values of all construct indicators, demonstrating that each measurement item met the reliability threshold with loadings ranging from 0.718 to 0.876. Indicators for Ethnoecological Knowledge (EK) showed strong representation, particularly EK2 (0.841) and EK1 (0.812), confirming that local ecological understanding and traditional calendars are key dimensions of this construct. Climate Adaptation (CA) indicators also performed well, with CA1 (0.856) and CA2 (0.832) showing the highest reliability, indicating that adjustments in planting time and diversification are dominant adaptive behaviors among farmers. Farmer Innovation (FI) exhibited the strongest loadings overall, especially FI1 (0.876) and FI2 (0.821), suggesting that experimentation and adoption of new technologies are central to innovative capacity. Meanwhile, Sustainable Agriculture (SA) indicators showed consistent reliability, led by SA1 (0.854) and SA2 (0.816), reflecting that efficient resource use and reduced environmental degradation are core elements of sustainability. Overall, the results confirm that all indicators effectively capture their respective constructs, ensuring measurement validity and reinforcing the robustness of the model.

Internal consistency reliability assesses how closely related the items within each construct are, indicating the degree to which they measure the same underlying concept. This study employed Cronbach's Alpha (α) and Composite Reliability (CR) as evaluation criteria, with values above 0.70 considered acceptable (Hair et al., 2021). As shown in the results, all constructs demonstrated strong reliability, with Cronbach's Alpha values ranging from 0.845 to 0.898 and CR values from 0.883 to 0.921. Specifically, Sustainable Agriculture (SA) exhibited the highest internal consistency (α = 0.898; CR = 0.921), followed by Farmer Innovation (FI), Climate Adaptation (CA), and Ethnoecological Knowledge (EK). The consistently higher CR values relative to Cronbach's Alpha indicate that the constructs maintain strong reliability even after accounting for the varying indicator loadings, confirming that the items effectively and consistently represent their respective latent variables.

Convergent validity evaluates the extent to which a group of indicators collectively measures the same construct, with the Average Variance Extracted (AVE) serving as the key criterion. According to Fornell and Larcker (1981), an AVE value above 0.50 indicates acceptable convergent validity. As shown in the results, all constructs met this threshold, with Ethnoecological Knowledge (EK) = 0.625, Climate Adaptation (CA) = 0.641, Farmer Innovation (FI) = 0.712, and Sustainable Agriculture (SA) = 0.687. These findings confirm that the indicators within each construct share more common variance than error variance, signifying that each construct is a valid and coherent representation of the underlying theoretical concept it was designed to measure.

Discriminant validity was evaluated using two complementary approaches: the Fornell–Larcker Criterion and the Heterotrait–Monotrait Ratio (HTMT). Based on the Fornell–Larcker Criterion, the square roots of the Average Variance Extracted (AVE) for each construct were greater than their corresponding inter-construct correlations, confirming that each construct measured a distinct conceptual domain (Fornell & Larcker, 1981). Specifically, the diagonal values—Ethnoecological Knowledge (0.787), Climate Adaptation (0.800), Farmer Innovation (0.843), and Sustainable Agriculture (0.825)—were all higher than the off-diagonal correlations, indicating strong discriminant validity and clear conceptual separation among constructs.

Further assessment using the HTMT ratio also confirmed discriminant validity, with all HTMT values below the recommended threshold of 0.90 (Henseler et al., 2015). The values ranged from 0.624 to 0.785, demonstrating that correlations between constructs were not excessively high and that each construct remained empirically distinct. These findings validate that the measurement model effectively distinguishes among Ethnoecological Knowledge, Climate Adaptation, Farmer Innovation, and Sustainable Agriculture, ensuring that each construct captures unique aspects of the broader theoretical framework.

4.3 Structural Model Evaluation

After confirming that the measurement model met all reliability and validity requirements, the analysis proceeded to the evaluation of the structural (inner) model to test the proposed hypotheses and assess the strength of relationships among the latent variables—Ethnoecological Knowledge (EK), Climate Adaptation (CA), Farmer Innovation (FI), and Sustainable Agriculture (SA). Using SmartPLS version 3.0 and following the procedures recommended by Hair et al. (2021), the assessment included examining collinearity, coefficient of determination (R^2), effect size (f^2), predictive relevance (Q^2), and path coefficients obtained through a bootstrapping process with 5000 resamples. Prior to testing the path relationships, collinearity among predictor variables was evaluated using the Variance Inflation Factor (VIF), with all values found to be below the recommended threshold of 5.00, confirming the absence of multicollinearity and ensuring that the subsequent structural analysis would yield reliable and unbiased parameter estimates.

Table 2. Collinearity Assessment (VIF Values)

Predictor Variable	VIF	Interpretation
EK → CA	1.000	No collinearity
EK → FI	1.732	No collinearity
CA → FI	1.846	No collinearity
CA → SA	1.932	No collinearity
FI → SA	2.067	No collinearity

Table 2 shows the results of the collinearity assessment, indicating that all Variance Inflation Factor (VIF) values ranged from 1.000 to 2.067, well below the recommended threshold of 5.0. This confirms that multicollinearity among predictor variables is not a concern and that each construct—Ethnoecological Knowledge (EK), Climate Adaptation (CA), Farmer Innovation (FI), and Sustainable Agriculture (SA)—is statistically independent. The low VIF values suggest that the explanatory variables do not overlap excessively in explaining the endogenous constructs, ensuring the stability and accuracy of the path coefficient estimates in the structural model. These results provide a strong foundation for subsequent hypothesis testing and interpretation of causal relationships within the model.

The R^2 value indicates the proportion of variance in endogenous constructs explained by their predictor constructs, with thresholds of 0.26, 0.50, and 0.75 representing weak, moderate, and substantial explanatory power, respectively (Cohen, 1988). As shown in the results, Climate Adaptation (CA) had an R^2 of 0.473, meaning 47% of its variance was explained by Ethnoecological Knowledge (EK), reflecting a moderate level of explanation. Farmer Innovation (FI) achieved an R^2 of 0.622, indicating that 62% of its variance was jointly explained by EK and CA, representing a moderate to substantial relationship. Meanwhile, Sustainable Agriculture (SA) recorded an R^2 of 0.696, showing that 69% of its variance was explained by CA and FI, signifying substantial explanatory power. Overall, these results demonstrate that the integration of traditional ecological knowledge, adaptive capacity, and farmer innovation provides a robust predictive framework for understanding and enhancing sustainability outcomes in Indonesian agriculture.

The effect size (f^2) measures the relative impact of each exogenous construct on the endogenous variable. Following Cohen's (1988) guideline, f^2 values of 0.02, 0.15, and 0.35 represent small, medium, and large effects, respectively.

Table 3. Effect Size (f^2) Results

Relationship	f^2	Effect Size Interpretation
EK → CA	0.892	Large
EK → FI	0.123	Small to medium
CA → FI	0.275	Medium
CA → SA	0.116	Small to medium
FI → SA	0.392	Large

Table 3 presents the effect size (f^2) results, which measure the individual contribution of each exogenous variable to its corresponding endogenous construct. Following Cohen's (1988) guidelines—where f^2 values of 0.02, 0.15, and 0.35 indicate small, medium, and large effects, respectively—the analysis reveals that Ethnoecological Knowledge (EK) has a large effect on Climate Adaptation (CA) (f^2 = 0.892), emphasizing its central role in shaping adaptive behavior among farmers. The influence of EK on Farmer Innovation (FI) is small to medium (f^2 = 0.123), while CA exerts a medium effect on FI (f^2 = 0.275), indicating that adaptive practices contribute meaningfully to the emergence of innovation. The impact of CA on Sustainable Agriculture (SA) is small to medium (f^2 = 0.116), suggesting an indirect pathway through innovation, whereas FI demonstrates a large effect on SA (f^2 = 0.392), highlighting innovation as the strongest driver of sustainability outcomes. Collectively, these results confirm that while traditional knowledge and adaptation provide the foundation, farmer innovation serves as the pivotal mechanism linking ecological wisdom to sustainable agricultural transformation.

The Stone-Geisser's Q^2 test, conducted through the blindfolding procedure, was used to evaluate the predictive relevance of the structural model, where Q^2 values greater than zero indicate acceptable predictive capability (Hair et al., 2021). The results show that Climate Adaptation (CA) achieved a Q^2 value of 0.312, indicating moderate predictive relevance, while Farmer Innovation (FI) and Sustainable Agriculture (SA) recorded Q^2 values of 0.453

and 0.526, respectively, reflecting strong predictive relevance. These findings confirm that the model possesses robust predictive power, particularly in explaining and forecasting outcomes related to innovation and agricultural sustainability, thereby validating the model's effectiveness in capturing the dynamic relationships among ethnoecological knowledge, adaptation, and innovation within Indonesia's agricultural systems.

To test the proposed hypotheses, the bootstrapping method with 5,000 subsamples was employed to calculate path coefficients (β), t-values, and p-values. A path is considered statistically significant when $t > 1.96$ and $p < 0.05$.

Table 4. Hypothesis Testing

	Path Relationship	Path Coefficient (β)	t-value	p-value	Result
H1	EK → CA	0.685	9.742	<0.001	Supported
H2	EK → FI	0.318	3.965	<0.001	Supported
H3	CA → FI	0.451	5.324	<0.001	Supported
H4	CA → SA	0.289	3.210	0.001	Supported
H5	FI → SA	0.502	6.537	<0.001	Supported
H6	EK → FI → SA (Mediation)	0.159	3.812	<0.001	Supported

Table 4 summarizes the results of the path coefficient analysis and hypothesis testing, demonstrating that all hypothesized relationships in the structural model are statistically significant. Ethnoecological Knowledge (EK) strongly influences Climate Adaptation (CA) ($\beta = 0.685$, $t = 9.742$, $p < 0.001$), confirming that traditional ecological understanding plays a vital role in shaping adaptive behavior. EK also has a positive effect on Farmer Innovation (FI) ($\beta = 0.318$, $t = 3.965$, $p < 0.001$), while CA further enhances FI ($\beta = 0.451$, $t = 5.324$, $p < 0.001$), indicating that adaptive strategies foster innovative practices. Additionally, both CA ($\beta = 0.289$, $t = 3.210$, $p = 0.001$) and FI ($\beta = 0.502$, $t = 6.537$, $p < 0.001$) significantly contribute to Sustainable Agriculture (SA), highlighting that adaptation and innovation are key drivers of sustainability. The mediation analysis also confirms that FI mediates the relationship between EK, CA, and SA ($\beta = 0.159$, $t = 3.812$, $p < 0.001$), underscoring the role of innovation as a transformative mechanism that connects traditional knowledge and adaptive capacity to long-term agricultural sustainability.

4.4 Discussion

The results reveal that Ethnoecological Knowledge (EK) exerts a strong positive influence on Climate Adaptation (CA) and a moderate effect on Farmer Innovation (FI), reaffirming that traditional ecological wisdom remains a cornerstone of adaptive capacity in rural Indonesia. Rooted in indigenous observations, cultural rituals, and localized farming systems, ethnoecological knowledge enables farmers to interpret environmental cues such as rainfall patterns, soil fertility cycles, and pest dynamics. This finding aligns with [12], [29], who emphasized that local ecological systems are dynamic and continuously evolve through intergenerational learning and cultural adaptation. Farmers who continue to practice pranata mangsa calendars, preserve traditional seeds, and manage soil organically were found to be more responsive to climate variability. Moreover, the influence of EK on innovation demonstrates that traditional wisdom provides the foundation for modernization rather than opposing it. Farmers often adapt inherited practices into innovative forms—for example, modifying compost compositions, integrating herbal pest repellents, or producing bio-fertilizers using local materials. These creative acts represent "innovation from within" as observed by [18], [21], where adaptation and creativity arise organically from cultural experience and local experimentation.

The structural results further indicate that Climate Adaptation (CA) significantly affects both Farmer Innovation (FI) and Sustainable Agriculture (SA), positioning adaptation as both a connecting bridge and a direct driver of sustainability. Indonesian smallholders have long combined indigenous and scientific knowledge to cope with environmental changes—adjusting planting schedules, rotating crops, improving irrigation efficiency, and using local weather cues alongside digital information. These adaptive behaviors reflect hybrid systems where traditional and modern insights coexist in synergy, consistent with [7], [10], who highlighted that adaptation in agriculture emerges from both social learning and institutional support. In this context, adaptation is not merely reactive but a proactive and dynamic capability that mobilizes local knowledge to address uncertainty. Furthermore, adaptation contributes directly to sustainability by improving ecological and economic resilience. Diversifying crops and optimizing water management reduce reliance on vulnerable monocultures and enhance long-term food security, reinforcing findings by [1] that integrated adaptation strategies strengthen productivity stability and resource efficiency in Indonesian farming communities.

Among all tested relationships, Farmer Innovation (FI) demonstrated the strongest direct effect on Sustainable Agriculture (SA), underscoring innovation as the core driver of agricultural transformation. Farmers who experiment, collaborate, and creatively manage resources exhibit superior productivity, ecological conservation, and livelihood outcomes. This finding aligns with [18], [24], who identified farmer innovation and local knowledge networks as central mechanisms in promoting sustainability through continuous learning and diversification. Respondents in this study reported developing compost from organic waste, designing water-saving irrigation systems, and integrating mobile-based farm monitoring—forms of grassroots innovation that are socially embedded and contextually relevant. The mediation analysis further confirms that FI mediates the relationship between EK, CA, and SA ($\beta = 0.159$, $p < 0.001$), illustrating that innovation emerges from accumulated knowledge and adaptive learning. This finding supports the view of [9] that innovation operationalizes traditional wisdom into measurable improvements in sustainability performance through adaptive learning cycles.

Synthesizing these findings illustrates a coherent transformation pathway in Indonesian agriculture: Ethnoecological Knowledge → Climate Adaptation → Farmer Innovation → Sustainable Agriculture. This sequence captures how traditional ecological wisdom evolves through learning and creativity into sustainable outcomes. The results emphasize that Indonesia's agricultural sustainability depends not on external inputs but on endogenous knowledge systems strengthened by adaptation and innovation. This pattern resonates with [13], who described local ecological wisdom as inherently sustainable and capable of guiding adaptive transitions in modern contexts. The integration of the Resource-Based View (RBV) and Dynamic Capabilities Theory (DCT) offers a robust theoretical lens: EK represents a valuable and inimitable cultural resource (RBV), while CA and FI function as dynamic capabilities enabling resource reconfiguration (DCT). Consequently, SA emerges as the ultimate outcome of capability enhancement, empirically validated by the model's strong explanatory power ($R^2 = 0.69$) and predictive relevance ($Q^2 = 0.52$). These results illustrate how "tradition becomes transformation"—where local wisdom acts as a renewable strategic asset driving Indonesia's transition toward sustainable agricultural futures.

4.5 Practical Implications

The findings yield several practical implications for policymakers, development agencies, and community organizations seeking to strengthen agricultural sustainability in Indonesia. First, mainstreaming local wisdom into agricultural extension programs is essential—ethnoecological knowledge such as seed conservation, intercropping, and organic fertilization should be institutionalized within training curricula as valid and complementary to modern sustainability approaches. Second, participatory adaptation training that emphasizes peer-to-peer learning, farmer field schools, and co-creation of technology can enhance farmer agency and collective resilience. Third, the establishment of innovation hubs and digital knowledge-sharing platforms can facilitate experimentation, exchange of best practices, and scaling of successful innovations. Fourth, improving access to climate and market information through mobile applications and digital advisory tools can enhance adaptive decision-making. Finally, agricultural policies should adopt an integrative perspective that balances modernization and cultural preservation, promoting hybrid systems that value both scientific and indigenous approaches to resource management.

This study also contributes directly to Indonesia's progress toward achieving the Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) through the promotion of sustainable food production systems, SDG 12 (Responsible Consumption and Production) through efficient and circular resource use, and SDG 13 (Climate Action) by enhancing climate resilience and adaptation capacity. By empirically demonstrating how traditional knowledge and farmer-led innovation interact to sustain agricultural performance, the study provides a scientific foundation for community-driven approaches to sustainability. It highlights that empowerment, inclusivity, and ecological justice are indispensable elements in transitioning toward resilient agri-food systems—underscoring that sustainable transformation in Indonesia must emerge from within, through the synergy of local wisdom, adaptive learning, and continuous innovation.

5. CONCLUSION

This study provides empirical evidence that sustainable agriculture in Indonesia emerges from the synergistic interaction between ethnoecological knowledge, climate adaptation, and farmer innovation. The SEM-PLS results confirm that Ethnoecological Knowledge (EK) strongly influences Climate Adaptation (CA) and moderately affects Farmer Innovation (FI); Climate Adaptation significantly enhances both Farmer Innovation and Sustainable Agriculture (SA); and Farmer Innovation exerts the strongest direct effect on sustainability while mediating the relationships between knowledge, adaptation, and sustainability. The model's explanatory power ($R^2 = 0.69$) and predictive relevance ($Q^2 = 0.52$) further validate the robustness of these relationships, demonstrating that Indonesia's agricultural sustainability is rooted in a continuum from tradition to transformation—where ancestral ecological wisdom evolves through adaptive learning and innovation to address environmental and socio-economic challenges. Theoretically, this study integrates the Resource-Based View (RBV) and Dynamic Capabilities Theory (DCT) by positioning ethnoecological knowledge as a valuable, rare, and culturally embedded resource (RBV) and identifying climate adaptation and farmer innovation as dynamic capabilities that reconfigure and mobilize these resources to achieve sustainability (DCT). This integration advances sustainability theory by framing local knowledge as a living system of transformation rather than static heritage. Practically, the findings offer guidance for policymakers and agricultural stakeholders: integrating traditional knowledge into national frameworks, promoting farmer-led innovation through participatory hubs, strengthening adaptation networks via digital platforms, and fostering hybrid systems that blend scientific and indigenous practices. These strategies support inclusive agricultural transformation that values cultural heritage as a foundation for resilience. Furthermore, the study contributes directly to Indonesia's achievement of the Sustainable Development Goals (SDGs)—notably SDG 2 (Zero Hunger) through sustainable food production, SDG 12 (Responsible Consumption and Production) through efficient resource management, and SDG 13 (Climate Action) through enhanced climate resilience—highlighting that traditional wisdom and farmer innovation are indispensable pillars of community-driven sustainable development.

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