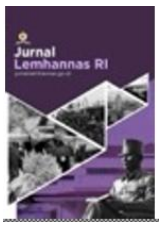

Jurnal Lemhannas RI (JLRI)
e-ISSN : 2830-5728
Vol. 13 No. 2, June 2025: 216-230
DOI: 10.55960/jlri
https://jurnal.lemhannas.go.id/index.php/jkl

Strengthening Sustainable Agricultural Innovation to Support Food Sovereignty and National Resilience

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Article Info:

Keywords:
Agricultural innovation.
Food sovereignty.
Governance.
National resilience.
Sustainability.

Article History:
Received : 1-6-2025
Revised : 14-6-2025
Accepted : 30-6-2025

Article DOI :
10.55960/jlri.v13i2.1243

Abstract

Purpose: This study analyses the role of sustainable agricultural innovation in strengthening food self-sufficiency as a foundation for national resilience in responding to climate change, geopolitical dynamics, and import dependence.

Study Design/Methodology/Approach: The study applies a qualitative descriptive approach combined with policy analysis and a SWOT framework to examine institutional capacity, governance, and innovation pathways through the evaluation of national policies, regulations, and strategic agricultural programmes. The analysis integrates content analysis, SWOT assessment, and data triangulation to ensure consistency of findings, while the *Asta Gatra* framework is used to examine the multidimensional relationship between agricultural innovation, food self-sufficiency, and national resilience.

Findings: The results indicate that sustainable agricultural innovation improves production efficiency through the implementation of smart agriculture, mechanisation, and climate-adaptive practices. However, the impact remains uneven due to low levels of technology adoption, limited human resource capacity, and weak institutional coordination. These structural constraints influence the stability of food production, distribution, and access, particularly under external pressures related to climate change, global price volatility, and dependence on imports.

Originality/Value: The study positions sustainable agricultural innovation as an integrated system linking technology, human capacity, and governance within the *Asta Gatra* framework. The analysis provides conceptual and policy contributions to strengthening food self-sufficiency and national resilience under conditions of global uncertainty.

How to cite: Rahmatiana, R., Daryanto, E., Nasution, I.H., Hartono, D., Yuwono, I. (2025). Strengthening Sustainable Agricultural Innovation to Support Food Sovereignty and National Resilience. Jurnal Lemhannas RI, 13 (2), 216-230. https://doi.org/10.55960/jlri.v13i2.1243

e-ISSN: 2830-5728

INTRODUCTION

Strengthening sustainable agricultural innovation requires an integrated, consistent, and long-term strategic orientation that aligns technological advancement, institutional capacity, and governance effectiveness within a unified development framework. Indonesia positions national resilience in the food sector as a strategic priority due to increasing geopolitical instability, accelerating climate change, and disruptions in global supply chains. Food systems determine the stability of production, distribution, and access, which directly shapes economic performance and social stability. The food system occupies a central position within economic and socio-cultural dimensions while interacting closely with natural resource management, which influences the nation's ability to respond to multidimensional threats. Sustainable development theory explains that food systems integrate economic, social, and environmental dimensions to maintain long-term sustainability (Shi et al. 2019). However, global dynamics indicate that national food systems encounter pressures driven by price volatility, climate variability, and disruptions in international logistics networks. The Sustainable Development Goals place food security at the centre of human development and economic stability while encouraging adaptive agricultural transformation (Atapattu et al. 2024; United Nations 2024). Nevertheless, the interaction between these global pressures and domestic structural conditions creates complexities that extend beyond the capacity of conventional policy responses.

Recently evolving global and national dynamics in the food sector, particularly climate change, geopolitical pressures, and supply chain disruptions, necessitate a strategic response that prioritises agricultural transformation through innovation, institutional strengthening, and governance reform. Indonesia faces structural climate change, geopolitical pressure, and supply chain disruptions that necessitate a strategic response that prioritises challenges that include disparities in resource distribution, unequal access to technology, and variations in institutional effectiveness across regions. Therefore, agricultural innovation contributes not only to technical instruments but also as a systemic mechanism that integrates knowledge, policy, and implementation. Effective transformation depends on coordination among actors and sectors to ensure that innovation improves productivity while strengthening environmental sustainability and socio-economic stability. The interdependence between agricultural systems and national resilience indicates that improvements in food production require structural adjustments that enhance system adaptability and responsiveness to external pressures. Strengthening agricultural innovation must go beyond technology adoption and address systemic constraints that limit the effectiveness of agricultural transformation, including limited infrastructure, unequal market access, and low farmer training capacity.

National policy direction reflects efforts to strengthen agricultural innovation through science and technology to respond to these pressures. Regulatory frameworks, including Law of the Republic of Indonesia Number 18/2012 and Law of the Republic of Indonesia Number 22/2019, reinforce food governance, while Law of the Republic of Indonesia Number 19/2013 expands farmers' access to technology and information to support agricultural independence. Law of the Republic of Indonesia Number 11/2019 establishes science as a foundation for cross-sectoral development, supported by Presidential Regulation of the Republic of Indonesia Number 38/2018 through the

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National Research Master Plan, which positions agricultural innovation as a long-term strategic agenda. These regulatory instruments collectively establish a policy environment that prioritises innovation-driven agricultural transformation. However, implementation outcomes remain constrained by structural and operational limitations that reduce policy effectiveness and hinder alignment between policy objectives and field-level realities.

While the industrial-use and national reserves demand of rice consumption is steadily increasing to a total of around 36.5 million tonnes, empirical evidence shows that the production is declining from 31.10 million tonnes in 2023 to nearly 30.34 million tonnes due to climate variation and land conversion. The disparity in production capacity versus demand puts stress on the national food system, revealing disconnects between policymaking and implementation. These gaps remain, despite the changes in policy design, suggesting that implementation will be ineffective when institutional capacity and resource allocation misalign with policies designed by decision-makers. However, agricultural innovation has yet to function as an integrated system that balances production supply and demand in response to changing environmental and economic pressures.

The Agricultural Innovation Systems framework explains that innovation develops through interactions among actors, collective learning processes, and institutional integration rather than relying solely on technological adoption. Government institutions, academia, the private sector, and farmers function as key actors in driving agricultural transformation. The effectiveness of innovation depends on the quality of interaction among these actors, which shapes the diffusion of knowledge and technology across agricultural systems. However, empirical evidence indicates uneven coordination among actors, which constrains the distribution and adoption of innovation across regions, leading to disparities in agricultural productivity and limiting the overall effectiveness of transformation efforts. Meanwhile, variations in institutional capacity and access to resources influence how actors engage with innovation processes, particularly in translating available technologies into productive outcomes. Empirical variations indicate that the efficacy of agricultural innovation, alongside the consideration of technological availability, is important for fortifying institutions that facilitate its adoption and dissemination within agricultural regions and production systems.

The concept of food self-sufficiency strengthens domestic production orientation, distribution control, and ecological sustainability through agroecological practices that prioritise local resource utilisation and environmental conservation. The agroecological approach emphasises the role of local actors in maintaining production stability while reducing dependence on external inputs, while agroecological practices improve soil quality, biodiversity, and resource efficiency to support long-term sustainability. However, the integration of agroecological practices into national agricultural systems requires institutional support, capacity development, and coordinated policy implementation to ensure scalability, while institutional capacity constraints and policy fragmentation influence the ability of governance structures to align ecological practices with broader agricultural policies and production systems.

Within the agricultural innovation framework, sustainable agricultural innovation operates as an integrated system linking technology, institutional arrangements, and policy mechanisms. The effectiveness of innovation depends on the quality of

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governance, regulatory coherence, and actors' capacity to adapt to environmental changes, not just on technology alone. Variations in human resource capacity, access to infrastructure, and institutional support create disparities in innovation adoption across regions, while unequal extension services, limited access to finance, and differences in digital literacy impact farmers' ability to engage in innovation processes. The resulting disparities shape differences in production performance and limit innovation's contribution to national food system outcomes. Meanwhile, structural limitations related to institutional coordination and resource distribution continue to impact the extent to which innovation can operate as a cohesive system across agricultural regions.

External pressures further intensify the dynamics of agricultural transformation, as climate change alters production patterns through shifts in rainfall cycles, temperature variability, and increased frequency of extreme weather events. Global market dynamics impact price stability and supply chain reliability, and geopolitical tensions affect access to essential inputs and trade flows. These pressures interact with domestic structural conditions, creating uncertainties in food production, distribution, and access. Meanwhile, the integration of risk management strategies into agricultural innovation systems remains influenced by institutional capacity and policy coordination, particularly in maintaining system stability under changing environmental and economic conditions. The interaction between external pressures and internal system constraints reflects the evolving nature of agricultural systems, which require continuous adaptation in response to multidimensional challenges.

The *Asta Gatra* framework provides a multidimensional perspective on national resilience by integrating natural resources, economic capacity, socio-cultural dynamics, and governance structures. Agricultural systems contribute to this framework through their role in supporting resource sustainability, economic stability, and social cohesion, while innovation processes influence the capacity of these systems to respond to internal and external pressures. However, variations in governance arrangements, institutional capacity, and policy implementation influence how agricultural innovation contributes to resilience outcomes across regions. Meanwhile, the alignment between innovation processes, governance mechanisms, and resilience objectives remains influenced by differences in institutional effectiveness and coordination, particularly in integrating technology development with broader socio-economic and environmental priorities.

Despite the availability of policy frameworks and technological advancements, structural challenges persist in the implementation of agricultural innovation, as limited coordination between central and regional governments, disparities in resource allocation, and variations in institutional capacity continue to constrain the effectiveness of innovation strategies (Amanah et al. 2021). Governance arrangements do not consistently ensure alignment between policy objectives and operational practices, while institutional fragmentation contributes to uneven implementation across regions (Grovermann et al. 2019). Meanwhile, empirical conditions reflect persistent coordination gaps and structural disparities that influence how innovation operates within agricultural systems, particularly in translating policy direction into measurable improvements in production and distribution performance (Gunadi et al. 2019), which limits the ability to explain how governance mechanisms condition the effectiveness of innovation systems in producing consistent resilience outcomes.

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Existing studies frequently examine agricultural innovation, food security, and national resilience as separate domains, while theoretical perspectives emphasise the importance of systemic interaction across these dimensions (Amare and Darr 2020; Hartley and Rashman 2018). Previous research tends to focus on technological adoption or policy evaluation, yet provides limited explanation regarding how innovation systems interact with governance structures in shaping resilience outcomes (Amanah et al. 2021). Empirical findings indicate that institutional capacity, actor coordination, and resource accessibility influence the effectiveness of innovation processes, although these elements often appear fragmented within analytical approaches (Aida et al. 2024; Gunadi et al. 2019). Limited integration across theoretical and empirical perspectives constrains the development of comprehensive strategies capable of addressing structural challenges within agricultural transformation, particularly in linking innovation processes with broader resilience objectives, while the absence of an integrated analytical approach restricts a systematic understanding of how institutional dynamics shape agricultural innovation performance under external pressures.

Sustainable agricultural innovation is positioned within the linkage between innovation systems and national resilience frameworks through the integration of the Agricultural Innovation Systems perspective with the *Asta Gatra* framework, which enables examination of how technological, institutional, and governance dimensions shape food self-sufficiency (Melzatia et al. 2024). Variations in policy implementation, institutional capacity, and technology adoption continue to generate uneven outcomes across regions, while empirical evidence indicates that improvements in innovation capacity do not consistently translate into enhanced food system performance (Mendrofa et al. 2024; Salamah et al. 2025). Analytical limitations remain in explaining how governance arrangements mediate the relationship between innovation processes and resilience outcomes under external pressures, particularly in addressing the interaction between technology, institutional capacity, and actor engagement within diverse agricultural systems. The integration of innovation systems and resilience frameworks provides a basis for examining how institutional dynamics influence agricultural transformation in responding to structural constraints and external pressures. The study therefore examines how sustainable agricultural innovation operates within complex institutional arrangements and how interactions among governance structures, technological capacity, and actor dynamics influence food self-sufficiency and national resilience.

LITERATURE REVIEW

Theoretical Studies

Theoretical studies place sustainable agricultural innovation within a national development framework that integrates economic, social, and environmental dimensions as a basis for strengthening food systems. Sustainable development theory emphasises the balance between productivity enhancement and natural resource preservation to maintain long-term sustainability (Shi et al. 2019), which aligns with the *Asta Gatra*-based concept of national resilience that positions food within natural resource and socio-cultural dimensions. Within this framework, national regulations function as normative instruments that guide innovation. Law of the Republic of Indonesia Number 18/2012 emphasises food availability through science and technology and the empowerment of

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key actors, while Law Number 22 of 2019 prioritises research and human resource development as prerequisites for sustainable cultivation systems. Law Number 19 of 2013 expands farmers' access to technology and information, and Law Number 11 of 2019 positions science as a foundation for cross-sectoral development, reinforced by Presidential Regulation Number 38 of 2018 in the National Research Master Plan through the National Research Master Plan as a strategic direction for long-term agricultural innovation. The Agricultural Innovation Systems approach conceptualises innovation as the outcome of interactions among actors, collective learning processes, and institutional support structures (Amare and Darr 2020; Hartley and Rashman 2018), while emphasising that innovation extends beyond technology to include policy arrangements, organisational structures, and socio-economic relations. In parallel, the concept of food self-sufficiency strengthens domestic production orientation, distribution control, and ecological sustainability through agroecological practices that prioritise local resource utilisation and environmental conservation (Holt-Giménez and Altieri 2013). Within this perspective, sustainable agricultural innovation connects technology, institutions, and policy arrangements, while governance quality and actor capacity influence how innovation responds to environmental change.

The relationship between the Agricultural Innovation Systems approach and agroecological perspectives reveals complementary yet partially divergent orientations in explaining agricultural transformation. The Agricultural Innovation Systems framework emphasises institutional coordination, actor interaction, and knowledge diffusion as key drivers of innovation performance, while agroecological approaches prioritise local resource management, ecological sustainability, and farmer-centred production systems. However, the Agricultural Innovation Systems perspective often focuses on structural and institutional efficiency without fully capturing ecological constraints at the local level, whereas agroecological approaches emphasise environmental sustainability but may encounter limitations in scalability and integration within broader policy and market systems. Meanwhile, governance-based perspectives on innovation highlight the role of institutional arrangements, policy coherence, and coordination mechanisms in shaping system effectiveness, while resilience frameworks emphasise system adaptability, stability, and the capacity to respond to external shocks (Melzatia et al. 2024). Differences between governance-oriented approaches and resilience perspectives indicate that institutional effectiveness does not automatically ensure system adaptability under dynamic environmental conditions. The integration of these theoretical perspectives therefore becomes necessary to explain how technological development, institutional capacity, and ecological considerations interact in shaping agricultural systems under external pressures. Analytical separation between innovation systems, ecological approaches, and resilience frameworks limits the ability to capture the complexity of agricultural transformation, particularly in understanding how governance structures mediate the relationship between innovation processes and resilience outcomes across diverse agricultural systems.

Emperical Studies

Agricultural Innovation as a Systemic Driver of Food Independence

Empirical findings indicate that sustainable agricultural innovation in Indonesia develops through a combination of national policies, technology implementation, and

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institutional strengthening. The implementation of smart farming, mechanisation, and agricultural digitalisation increases production efficiency and expands land use across various regional conditions (Salamah et al. 2025); Mendrofa et al. 2024). From a sustainable development theory perspective, these changes reflect the integration of economic, social, and environmental dimensions within the food production system (Shi et al. 2019). Furthermore, the Agricultural Innovation Systems approach positions innovation as the result of interactions between actors supported by institutional coordination. Therefore, the effectiveness of innovation depends on the linkages between government, academia, the private sector, and farmers in the production and distribution processes (Amanah et al. 2021).

However, empirical evidence indicates that these interactions between actors are not yet optimal and are still partial, resulting in uneven innovation diffusion. The multifunctionality agriculture perspective asserts that limited institutional integration will reduce the linkages between technological innovation and the overall production system (der Ploeg and Oep 2003). Meanwhile, the adoption rate of agricultural technology remains limited and uneven among farmer groups, influenced by limited access to technology, low digital literacy, and inequality in human resource capacity (Aida et al. 2024; Gunadi et al. 2019). From an innovation theory perspective, the success of technology implementation depends on the ability of actors to adopt and adapt technology according to production needs (Junaidi 2022; Poth 2018), so the relationship between technology and increased productivity shows variations influenced by adaptive capacity at the farmer level.

Furthermore, the agroecological approach positions farmers as key actors in production systems by strengthening local control over production and distribution processes (Holt-Giménez and Altieri 2013). Meanwhile, farmer involvement in the innovation process remains limited, resulting in innovation being more top-down and less responsive to local conditions, which can hinder the effectiveness of agricultural practices tailored to specific regional needs. The discrepancy between technological potential and farmers' adaptive capacity demonstrates that agricultural transformation processes are influenced by factors including education, experience, and access to supporting resources, which contribute to variations in production performance across regions.

Institutional Fragmentation and Policy Implementation Gap

Empirical findings indicate that the development of sustainable agricultural innovation is influenced by the level of integration between research, policy, and implementation (Grovermann et al. 2019). Studies show that suboptimal cross-sectoral coordination leads to uneven distribution of innovation and is dependent on institutional capacity at the regional level (Amanah et al. 2021). Within the public policy framework, regulatory effectiveness is determined by consistent implementation and integration between institutions, while incompletely structured coordination mechanisms impact the linkage between policies and practices in the field and operational needs at the farmer level.

Furthermore, environmentally friendly and organic farming approaches show potential in maintaining sustainable production through more efficient resource management (Maun and Kaleka 2024; Parmila, Suardike, and Prabawa 2022). However, their implementation remains limited to specific regions and relies on policy support and

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the capacity of farming operators, which can vary significantly based on local governance structures and available resources. At the same time, climate change and global market dynamics impact the stability of agricultural systems through pressures on production and distribution. Therefore, agricultural system performance is influenced by the interaction between institutional factors, policies, and the external environment in managing the interrelationships between these factors.

METHODS

This study applies a qualitative descriptive approach combined with policy analysis and a SWOT framework (Leigh 2009) to examine the development of sustainable agricultural innovation through the evaluation of institutional capacity, governance, and innovation diffusion based on national policies, regulations, and strategic programmes. Data selection follows purposive criteria, which prioritise relevance to agricultural innovation, food self-sufficiency, and national resilience, including policy documents, official regulations, and empirical studies that reflect recent developments in the agricultural sector. Literature sources are selected based on their analytical contribution to innovation systems, governance, and sustainability, while regulatory documents are identified according to their alignment with national food policy and agricultural development strategies.

The analytical process integrates content analysis with a structured SWOT framework to examine the performance of agricultural innovation systems. Indicators of institutional capacity, technological development, human resources, and policy support constitute internal factors, while climate change dynamics, global market conditions, and geopolitical influences represent external factors. Each factor is systematically classified into strengths, weaknesses, opportunities, and threats based on its impact on agricultural system performance. This is then followed by a weighting and scoring procedure to evaluate its relative importance in shaping innovation outcomes. The analytical framework then systematically maps the strategic position of the agricultural innovation system and provides a coherent basis for assessing its capacity to respond to internal constraints and external pressures.

Data analysis incorporates source triangulation to strengthen validity by comparing findings across policy documents, empirical studies, and theoretical references. Consistency across sources is examined through iterative comparison, while discrepancies are interpreted as part of structural variation within the agricultural system rather than treated as anomalies. Analytical validity is further supported by linking empirical findings with theoretical frameworks, including the Agricultural Innovation Systems approach, sustainable development theory, and agroecological perspectives. The *Asta Gatra* framework (Melzatia et al. 2024) is applied to examine the relationship between agricultural innovation, food self-sufficiency, and national resilience within a multidimensional perspective.

The regulatory framework includes Law of the Republic of Indonesia Number 18 of 2012, Law of the Republic of Indonesia Number 22 of 2019, Law Number 19 of 2013, and Law Number 11 of 2019. Policy analysis refers to the National Food Plan 2025 to 2029, the National Research Master Plan 2017 to 2045 , and the Climate-Smart Agriculture approach to examine the relationship between productivity, climate change

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adaptation, and resource efficiency. Integration between policy analysis, SWOT evaluation, and theoretical interpretation enables a comprehensive examination of how institutional arrangements, technological capacity, and governance structures influence the performance of sustainable agricultural innovation.

RESULT AND DISCUSSION

Result

The results derive from a structured SWOT analysis based on policy documents, empirical studies, and institutional indicators as outlined in the methodological framework. The analysis of production conditions, covering inputs and production factors in Indonesia, indicates that the development of sustainable agricultural innovation is supported by strong resource endowments, including abundant natural resources, high biodiversity, and extensive agricultural land potential. These factors encourage commodity diversification and increase domestic food production. National policies, including the Food Law, the Sustainable Agricultural Cultivation System, and the National Research Master Plan, reinforce the direction of science and technology-based innovation, particularly through the application of smart agricultural technologies, mechanisation, precision irrigation, and adaptive crop varieties. However, the level of technology adoption remains limited, with only approximately 46.84 per cent of farmers utilising modern technology, which constrains productivity growth and reflects disparities between technological availability and system-wide adoption capacity.

The analysis of demand conditions indicates that increasing national food demand continues to drive the development of agricultural innovation while simultaneously creating pressure on domestic production systems. The size of the domestic market provides opportunities to strengthen food self-sufficiency through increased production; however, the gap between production and consumption persists, indicating that improvements in efficiency do not consistently translate into sustainable fulfilment of food needs. The analysis of firm strategy, structure, and rivalry shows that the agricultural sector remains dominated by small-scale farmers with limited operational capacity, which restricts efficiency and innovation adoption. Although empowerment programmes, including READSI, Agricultural Extension Centers, and Kostratani, have expanded access to technology and information, the distribution of extension services remains uneven, with approximately 45.1 per cent of farmers not receiving adequate assistance, which contributes to disparities in innovation adoption and production performance across regions.

The analysis of related and supporting industries indicates increased support for research and technology development through contributions from BRIN, universities, and digital integration within the agricultural system. However, coordination among research institutions, local governments, the private sector, and farmers remains limited, which constrains the diffusion of innovation and reduces the scalability of technological implementation. Government initiatives, including the National Food Plan, the National Research Master Plan, GERINA, and the climate-smart agriculture approach, demonstrate policy commitment to strengthening agricultural systems. Nevertheless, policy implementation continues to encounter institutional fragmentation, limited coordination between central and regional authorities, and operational constraints at the

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local level, which affect the consistency of innovation delivery. External analysis identifies opportunities arising from digital technology development, global support for sustainable agriculture, and increasing domestic demand, while climate change, global price fluctuations, dependence on imported inputs, and regional disparities continue to exert pressure on food system stability.

Table 1. SWOT, EFAS, and IFAS

Internal Factor Analysis Summary (IFAS)		Weight	Rating	Score
S1	Availability of natural resources and high biodiversity	0.12	4	0,48
S2	National policy support (Food Law, RIRN, National Food Plan)	0.13	3	0,39
S3	Agricultural technology development (smart farming, mechanisation, digitalisation)	0.12	3	0,36
S4	Farmer empowerment and extension programmes (READSI, BPP, Kostratani)	0.11	3	0.33
S5	Large domestic market potential	0.12	3	0.36
	Total Strength	**0.60**		**1.92**
W1	Low technology adoption by farmers	0.10	2	0.20
W2	Limited human resource and extension capacity	0.08	2	0.16
W3	Weak integration of research with implementation	0.08	2	0.16
W4	Limited access to financing and infrastructure	0.07	2	0.14
W5	Policies not yet integrated between central and regional governments	0.07	2	0.14
	Total Weakness	**0.40**		**0.80**
IFAS TOTAL		**1.00**		**2.72**

External Factor Analysis Summary (EFAS)		Weight	Rating	Score
O1	Development of digital technology and precision agriculture	0.14	4	0.56
O2	Global support for sustainable agriculture	0.13	3	0.39
O3	Potential for regional and international cooperation	0.11	3	0.33
O4	Increasing domestic food demand	0.12	3	0.36

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Internal Factor Analysis Summary (IFAS)		Weight	Rating	Score
O5	Investment opportunities in the sustainable agriculture sector	0.10	3	0.30
	Total Strength	**0.60**		**1.94**
T1	Climate change and extreme weather (El Niño)	0.12	2	0.24
T2	Dependence on food and input imports	0.10	2	0.20
T3	Fluctuations in global food prices	0.09	2	0.18
T4	Regional development gaps	0.09	2	0.18
Total Threat		**0.40**		**0.80**
EFAS TOTAL		**1**		**2.74**

Source: processed by the author

The IFAS score of 2.72 and the EFAS score of 2.74 position sustainable agricultural innovation in a configuration reflecting both internal strengths and external opportunities, although significant structural weaknesses remain. Natural resource availability, policy support, technological development, and market potential constitute strengths, while limited technology adoption, low human resource capacity, weak integration between research and implementation, and limited access to financing and infrastructure represent weaknesses. Digital transformation, the global sustainability agenda, and increasing domestic demand create opportunities, while climate change, price volatility, import dependence, and regional disparities constitute threats. These findings suggest that innovation capacity exists but has not consistently translated into system-wide performance due to structural and institutional constraints.

Various policy documents, empirical studies, and analytical frameworks demonstrate patterns of interconnectedness in agricultural innovation performance, particularly through the interaction between institutional capacity, governance structures, and technology adoption. The identified configurations demonstrate that sustainable agricultural innovation improves production efficiency, strengthens human resource capacity, and promotes adaptation to climate variability. However, the effectiveness of these mechanisms remains affected by gaps in institutional integration, limited access to resources, and weak coordination among actors within the agricultural system, which can hinder the overall progress and sustainability of agricultural innovation efforts.

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Discussion

The IFAS and EFAS scores of 2.72 and 2.74 indicate that sustainable agricultural innovation in Indonesia operates within a configuration characterised by internal strengths and external opportunities, while structural weaknesses continue to constrain system performance. Resource availability, policy support, and technological development align with the principles of sustainable development, which emphasise the integration of economic, social, and environmental dimensions in supporting long-term system sustainability (Shi et al. 2019). National regulatory frameworks, including Law Number 18 of 2012 on Food and Law Number 22 of 2019 on Sustainable Agricultural Systems, reinforce the role of science, technology, and institutional support in strengthening food production and resilience. Empirical findings showing increased efficiency through smart farming and mechanisation (Salamah et al. 2025); Mendrofa et al. 2024) correspond with these regulatory and theoretical orientations, while the *Asta Gatra* framework positions resource utilisation and economic capacity as key elements in supporting national resilience (Melzatia et al. 2024).

However, uneven improvements in production capacity indicate that technological development does not consistently translate into system-wide performance, particularly in areas where socio-cultural factors and human resource capacity influence the ability to adopt innovation. The Agricultural Innovation Systems perspective explains that innovation effectiveness depends on the quality of interaction among actors and the strength of institutional coordination (Amanah et al. 2021) , while empirical evidence indicates that limited technology adoption and disparities in human resource capacity continue to restrict innovation diffusion (Aida et al. 2024; Gunadi et al. 2019). The interaction between technological availability and actor capacity reflects a non-linear relationship between innovation and productivity, indicating that institutional and human factors shape how innovation contributes to food system performance.

Limited involvement of farmers in innovation processes further reflects a structural imbalance between policy-driven initiatives and local implementation. Agroecological perspectives emphasise the importance of local resource control, farmer participation, and ecological sustainability in maintaining production systems (Holt-Giménez and Altieri 2013), while regulatory frameworks including Law Number 19 of 2013 on Farmer Protection and Empowerment promote the role of farmers as active actors in agricultural development. Empirical findings indicating top-down implementation patterns suggest that innovation processes do not consistently incorporate local knowledge and production conditions, which influences the effectiveness of agricultural practices and limits the adaptability of innovation across regions. The interaction between institutional design and farmer engagement therefore influences the capacity of agricultural systems to sustain production and distribution.

Institutional analysis indicates that policy fragmentation and limited cross-sectoral coordination continue to influence the effectiveness of innovation implementation. Public policy perspectives highlight that regulatory presence alone does not ensure effective outcomes without institutional integration and coordination mechanisms. Regulatory instruments, including the National Research Master Plan and the National Food Plan, provide a strategic direction for agricultural innovation; however, empirical findings indicate that coordination among research institutions, local governments, the private sector, and farmers remains uneven (Amanah et al. 2021). Variations in institutional

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capacity and governance arrangements shape the extent to which innovation can be implemented consistently across regions, reflecting the interaction between policy design and operational capacity.

External pressures also affect how well agricultural systems work by interacting with both global and local factors. Climate change, global price fluctuations, and reliance on imported inputs impact production stability and supply chain reliability. Conversely, policy frameworks such as climate-smart agriculture seek to improve adaptive capacity and resource efficiency. Food security literature emphasises the importance of risk management in maintaining system stability under uncertain conditions (Zahri et al. 2024) , while empirical conditions indicate that the integration of risk management strategies remains influenced by institutional capacity and governance coordination. The interaction between external pressures and internal system constraints reflects the dynamic nature of agricultural systems that require adaptive responses across multiple dimensions.

Sustainable agricultural innovation contributes to food self-sufficiency through improvements in production efficiency, enhancement of human resource capacity, and adaptation to climate variability, while the effectiveness of these mechanisms depends on the interaction between technological development, institutional capacity, and governance structures. The integration of natural resources, economic capacity, socio-cultural dynamics, and governance within the *Asta Gatra* framework reflects how agricultural systems operate as interconnected components of national resilience. Variations in institutional integration, access to resources, and coordination among actors influence how innovation contributes to stable production, distribution, and access to food, particularly under conditions shaped by both internal limitations and external pressures.

CONCLUSION

Sustainable agricultural innovation in Indonesia develops through the integration of technological advancement, policy support, and farmer empowerment to improve production efficiency and strengthen the national food system. However, innovation processes have not yet operated as a fully integrated system, which constrains their contribution to food self-sufficiency. Limited technology adoption, disparities in human resource capacity, weak linkages between research and field implementation, and fragmented institutional coordination continue to influence the performance of agricultural systems. These structural conditions affect the balance between domestic production and demand and reinforce dependence on external factors within the framework of national resilience. Sustainable agricultural innovation improves food self-sufficiency through production efficiency, capacity development, and adaptation to environmental change, while the effectiveness of these mechanisms depends on the strength of institutional integration and governance arrangements.

Strengthening sustainable agricultural innovation therefore requires improving human resource capacity, expanding access to technology and financing, and enhancing coordination across policy and institutional structures. Interaction among government institutions, the private sector, academia, and communities supports the development of an adaptive innovation ecosystem that responds to global and domestic pressures. The present study identifies limitations related to the use of a qualitative descriptive approach

and reliance on secondary data, which restrict the examination of causal relationships between variables. Future research can extend this analysis by applying mixed-methods approaches, strengthening empirical measurement, and examining collaborative models among actors to evaluate the effectiveness of innovation strategies in supporting food self-sufficiency and national resilience.

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