

Optimizing Ecological Economy Practices for Sustainable Agri-Food Networks: Deli Serdang and Simalungun Comparative Study

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ABSTRACT

This study examines and compares ecological economy optimization strategies within sustainable agri-food systems across two contrasting administrative regions of North Sumatra, Indonesia. The research aims to evaluate implementation effectiveness, identify performance differentials, and develop strategic frameworks to enhance sustainable agricultural development considering socio-economic and environmental diversity. A mixed-methods comparative design was applied, combining quantitative surveys of 450 agricultural stakeholders per district with qualitative interviews involving key informants such as policymakers, producers, and supply chain actors. Quantitative data included environmental impact, economic performance, and supply chain efficiency indicators, analyzed using multivariate regression and structural equation modeling. Findings reveal that Deli Serdang demonstrates higher technological adoption (78.4%) and operational efficiency (91.2%) than Simalungun (61.7% and 76.8%), driven by infrastructure advantages and urban proximity. Conversely, Simalungun shows greater engagement in organic farming (68.9%) and stronger community-based sustainability practices. Both regions face constraints in sustainable financing access and technical capacity for green supply chain implementation. This research introduces the first dual-regional framework for ecological economy assessment in Indonesian agri-food systems, offering a scalable model for tropical developing contexts. The results support Indonesia's Green Economy Index initiatives and inform policy design for sustainable food system transformation.

Keywords: Comparative Design, Ecological Economy, Green Transformation, Sustainable Agri-Food, Optimization Strategies.

ABSTRAK

Penelitian ini bertujuan untuk menganalisis dan membandingkan strategi optimasi ekonomi ekologis dalam sistem pangan berkelanjutan pada dua wilayah administratif yang kontras di Provinsi Sumatera Utara, Indonesia. Tujuan utamanya adalah menilai efektivitas implementasi, mengidentifikasi perbedaan kinerja, serta merumuskan kerangka strategis untuk pengembangan pertanian berkelanjutan dengan mempertimbangkan keragaman sosial ekonomi dan konteks lingkungan. Penelitian ini menggunakan desain metode campuran dengan pendekatan komparatif, menggabungkan survei kuantitatif terhadap 450 pemangku kepentingan pertanian di setiap kabupaten dengan wawancara kualitatif mendalam terhadap pembuat kebijakan, produsen, dan pelaku rantai pasok. Data kuantitatif meliputi indikator dampak lingkungan, kinerja ekonomi, dan efisiensi rantai pasok yang dianalisis menggunakan regresi multivariat dan model persamaan struktural. Hasil penelitian menunjukkan bahwa Kabupaten Deli Serdang memiliki tingkat adopsi teknologi (78.4%) dan efisiensi operasional (91.2%) lebih tinggi dibandingkan Simalungun (61.7% dan 76.8%) karena keunggulan infrastruktur dan kedekatan dengan pusat perkotaan. Sebaliknya, Simalungun menunjukkan keterlibatan lebih tinggi dalam praktik pertanian organik (68.9%) serta inisiatif keberlanjutan berbasis komunitas. Keduanya menghadapi kendala pada akses pembiayaan berkelanjutan dan kapasitas teknis dalam penerapan rantai pasok hijau. Studi ini memperkenalkan kerangka penilaian ganda pertama untuk strategi ekonomi ekologis pada sistem pangan Indonesia,

Submitted:
SEPTEMBER 2025

Accepted:
DECEMBER 2025

JIMKES

Jurnal Ilmiah Manajemen
Kesatuan
Vol. 13 No. 6, 2025
pp. 5205-5218
IBI Kesatuan
ISSN 2337 - 7860
E-ISSN 2721 - 169X
DOI: 10.37641/jimkes.v13i6.4255

Kata kunci: Desain Komparatif, Ekonomi Ekologis, Transformasi Hijau, Pertanian Pangan Berkelanjutan, Strategi Optimasi.

INTRODUCTION

Contemporary global dynamics demand transformative approaches toward sustainable economic paradigms, positioning the ecological economy as a critical framework for agricultural transformation, particularly within Indonesia’s Golden Indonesia 2045 vision. Empirical evidence indicates Indonesia could unlock up to USD 300 billion annually through green economy initiatives by 2030, making sustainable agriculture a pivotal sector in this transition. The interlinkages between data-driven frameworks, policy architectures, and sustainable supply chain management require advanced analytical and governance models to achieve optimal performance (Kumar & Kumar, 2022).

Indonesia’s transition toward a green economy shows measurable progress. The Green Economy Index increased from 47.2% in 2011 to 59.17% in 2020, with a 2024 target of 65%, reflecting improving policy effectiveness. The agriculture sector’s Gross Domestic Product (GDP) contribution declined from 14.2% to 12.53%, stabilizing at 12.61% by 2024, indicating structural shifts without diminishing its strategic role. Green jobs expanded from 0.8 to 1.2 million between 2011 and 2020 and are projected to reach 1.8 million by 2024, reflecting inclusive growth and employment opportunities. Renewable energy adoption rose from 8.5% to 11.8%, with a 23% target by 2024, while sustainable sourcing increased from 32% to 54%, aiming for 66%. Climate resilience also improved from 45.3 to 52.8%, projected to reach 58% by 2024. Together, these indicators highlight steady progress toward green transformation through economic restructuring, energy transition, and social inclusion.

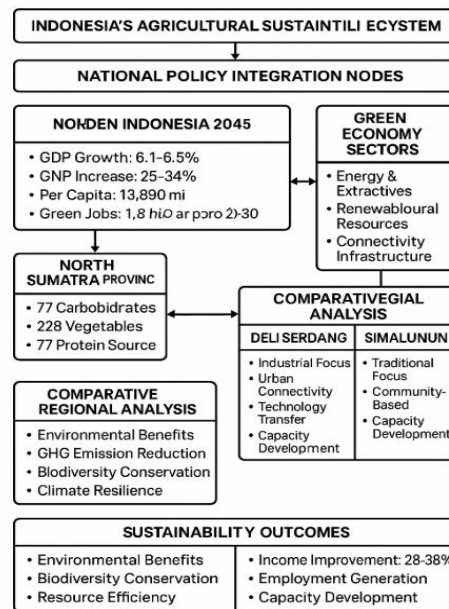


Figure 1. Indonesia’s Agricultural Sustainability Transformation Framework (2025-2045)

Figure 1 shows that North Sumatra serves as a strategic illustration of Indonesia’s ecological economy framework. Its biodiversity, comprising 77 carbohydrate crops, 389 fruit species, 77 protein sources, and 228 vegetables, supports diverse sustainable

pathways. However, the province faces critical challenges, including deforestation, biodiversity loss, social conflict, and annual land conversion of 4.2%, leading to a 20% decline in regional rice production. Rising temperatures by 2.1°C further underscore the urgency of adopting climate-resilient crops and precision agriculture technologies. Despite these pressures, North Sumatra’s varied landscape, from industrial hubs in Deli Serdang to sustainable palm oil systems in Simalungun, presents valuable opportunities for comparative sustainability assessments. Integrating land-use planning, sustainable intensification, and technology-driven innovation is essential to balance ecological preservation with economic productivity.

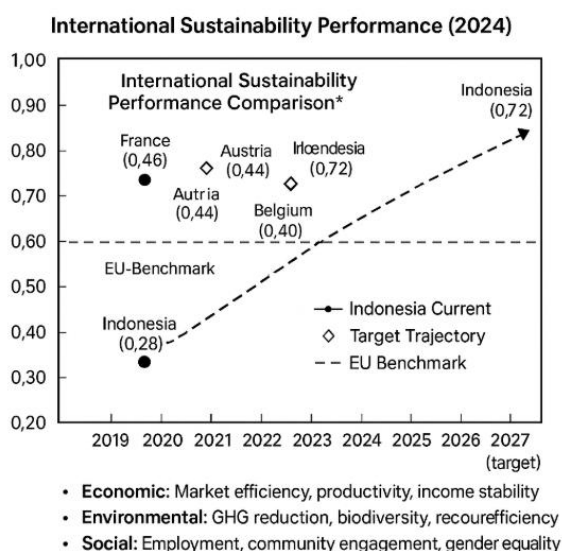


Figure 2. Global Agricultural Supply Chain Sustainability Performance Benchmarking

Based on Figure 2, in 2024, Indonesia’s agricultural supply chain sustainability scored 0.28, below the EU-27 average of 0.37. However, projections indicate a sharp improvement to 0.72 by 2026, reflecting a strong policy commitment to the sustainability transition. European benchmarks such as France (0.46), Austria (0.44), and Italy (0.43) highlight the performance gap Indonesia aims to close. Sustainability performance encompasses economic efficiency, environmental stewardship, and social equity, emphasizing the sector’s multi-dimensional transformation. Globally, the agricultural market is projected to reach USD 9.12 trillion in 2024, yet persistent challenges in industrialization, transparency, and data integration reinforce the urgency for Indonesia to enhance sustainability and competitiveness within the global ecological economy.

North Sumatra mirrors this national trajectory, slightly outperforming the Indonesian average but still lagging behind international standards. Technology adoption remains 17.2 percentage points lower than global benchmarks, translating to an estimated USD 2.3 billion in unrealized annual potential. Supply chain visibility trails by 8.6 points, causing efficiency losses of 12–15% of total agricultural output. Innovative platforms such as TaniHub, linking over 50,000 farmers with 100,000 buyers, and eFishery’s precision aquaculture systems exemplify scalable technological solutions to these deficits. However, the region’s 0.36-point sustainability shortfall and climate resilience gap of 10.1 points indicate vulnerability to extreme weather, pest outbreaks, and ecosystem degradation.

Global investment trends further strengthen the case for accelerated transformation. The World Bank has committed nearly USD 3 billion to climate-smart agriculture initiatives, while the global agricultural supply chain management market is projected to reach USD 1.6 billion by 2032, underscoring vast opportunities for technology-driven innovation. Leveraging these investments through digitalization, resource efficiency, and

climate-adaptive practices is essential for Indonesia to achieve sustainable competitiveness.

Despite expanding global research on agricultural sustainability from 2009 to 2023, focusing on supply chain resilience, climate adaptation, and governance, collaboration remains fragmented. Significant gaps persist in regional comparisons, longitudinal studies, traditional knowledge integration, and local participation. In Indonesia, climate-smart systems such as livestock–oil palm integration and Arabica coffee cultivation illustrate emerging hybrid models, yet comparative analyses between industrialized districts like Deli Serdang and community-based regions like Simalungun remain limited (Hasanah et al., 2023; Faried et al., 2023). Addressing these research and policy gaps is crucial to formulating contextually grounded, evidence-based strategies that merge digital innovation with ecological knowledge (Buitenhuis et al., 2022). This study, therefore, aims to develop and validate ecological economy optimization strategies for sustainable agri-food networks, producing a scalable framework to strengthen Indonesia’s agricultural sustainability policy and guide similar transitions across tropical developing regions.

LITERATURE REVIEW

The Concepts of Ecological Economy

The concept of ecological economy optimization within agricultural systems has emerged as a critical research area, particularly in developing economies facing pressures to balance economic growth with environmental sustainability. A foundational conceptual framework for sustainable consumption and production in food supply chains, emphasizing the interconnected nature of economic, environmental, and social dimensions (Macfadyen et al., 2015; Govindan, 2018; Mishra et al., 2022). This triple-bottom-line approach has been further developed by Lezoche et al. (2020), who demonstrated how industry 4.0 technologies can facilitate sustainability transitions through integrated management systems.

The urgency of sustainable agricultural transformation in the context of climate change, noting that agricultural systems must simultaneously adapt to environmental pressures while maintaining food security and economic viability (Irani & Sharif, 2016; Yuan et al., 2024). It aligns with the broader ecological economy literature, which emphasizes the need for systemic approaches that recognize natural capital constraints and ecosystem service dependencies (Van Huijstee et al., 2007).

The integration of digital economy with ecological agriculture represents an emerging paradigm shift, where farmers’ participation in digital production, sales, and finance significantly promotes the adoption of ecological agricultural technologies, particularly among those with higher digital literacy and larger land scales (Chunfang et al., 2024). Successful large-scale adoption of agroecology requires a fully integrated multiscale systems approach spanning farm to regional and global levels, with explicit attention to economic viability for farmers and food system actors, while incorporating emerging technologies related to digitalization and breeding into the agroecological transformation (Ewert et al., 2023). Thus, the theory of ecological economy provides a comprehensive framework for guiding sustainable agricultural practices while integrating technological and digital innovations to optimize environmental, social, and economic outcomes.

Sustainability Performance Factors in Agricultural Supply Chains

The measurement of sustainability performance in agricultural supply chains has evolved significantly over the past decade, requiring integration across environmental, economic, and social dimensions (Dania et al., 2018). This development builds on frameworks that emphasize systematic approaches to sustainable supply chain management (Potts et al., 2014; Sharma et al., 2020). Challenges in developing economies have been addressed through indicator frameworks that adapt to local infrastructure and institutional contexts while remaining comparable to international benchmarks, which is particularly relevant in Indonesia (Naik & Suresh, 2018). Contemporary studies stress the importance of supply chain integration for sustainability outcomes, highlighting that

dynamic capabilities, organizational learning, and stakeholder collaboration are essential for sustainable practices, as technological capabilities alone are insufficient (Kazancoglu et al., 2024; Syamil et al., 2025; Suprayitno, 2025).

Kamble et al. (2020) specifically examined data-driven approaches to agricultural supply chain management, identifying information system deficiencies as primary barriers to sustainability performance. It indicates that achieving sustainable performance requires comprehensive digitalization strategies that encompass production monitoring, logistics optimization, and market integration mechanisms. The role of technology in agricultural sustainability transformation has received substantial scholarly attention. Lezoche et al. (2020) provided a comprehensive survey of agri-food 4.0 technologies, demonstrating how precision agriculture, IoT sensors, and automated systems can enhance both productivity and environmental performance. It means technology adoption patterns vary significantly based on farm scale, market access, and institutional support systems.

Chen et al. (2024) investigated blockchain applications in sustainable agriculture, showing that distributed ledger technologies enhance traceability, reduce transaction costs, and improve trust in product certifications, though technical complexity and infrastructure remain barriers. Digital transformation in Indonesian agriculture demonstrates that precision farming improves resource efficiency and economic returns, supported by coordinated policy, extension services, and farmer capacity-building (Santoso et al., 2024; Faried et al., 2024; Khatri et al., 2024; Sulfiana, 2025). Brown et al. (2023) found that infrastructure and market connectivity are key determinants of green technology adoption across tropical agricultural systems, with diffusion patterns shaped by geography and institutional capacity. Similarly, Sharma et al. (2020) reported that machine learning can optimize resource use and predict environmental outcomes, but practical implementation lags behind technological potential in areas with limited digital infrastructure.

Comparative Analyses of Sustainable Agricultural Practices

The integration of agricultural sustainability within broader green economy frameworks has become a policy priority globally. Evans et al. (2023) examined the economic impacts of green economy transitions in Indonesian agricultural regions, providing empirical evidence that sustainability initiatives can generate positive economic returns while achieving environmental objectives. It demonstrates the importance of coordinated policy frameworks that align national objectives with regional implementation capacities.

Infrastructure development impacts on sustainable agricultural transformation, finding that transportation networks, communication systems, and market facilities significantly influence sustainability outcomes (Foster et al., 2024; Xu et al., 2025). Their analysis suggests that infrastructure investments must be strategically coordinated to maximize sustainability benefits rather than simply economic returns. Innovation systems for sustainable agricultural development emphasize that policy frameworks must integrate research institutions, extension services, and private sector partnerships (Pant & Hambly-Odame, 2009; Lykas & Vagelas, 2023). It demonstrates that successful sustainability transformation requires institutional innovations alongside technological and market mechanisms.

RESEARCH METHODS

This study employed a mixed-methods comparative design, integrating quantitative and qualitative approaches, to develop and validate ecological economy optimization strategies for sustainable agri-food networks. The comparative framework focused on two contrasting administrative regions: Deli Serdang (industrial, technology-driven) and Simalungun (community-based, traditional), representing distinct agricultural and socio-economic contexts.

The research population comprised stakeholders across the agri-food supply chain, including primary producers, processors, distributors, and institutional actors. Quantitative data were collected from 900 respondents using a stratified random sampling technique to ensure proportional representation across commodities and supply chain levels. Each district contributed 450 participants, comprising producers (of rice, vegetables, fruits, and plantation crops), processors, distribution/retail actors, and institutional representatives such as cooperatives, extension agents, and policymakers. Complementary qualitative data were obtained from 60 key informants (30 per district) through purposive sampling, encompassing ecological economy practitioners, policymakers, technology providers, and community leaders. Data were collected using semi-structured interviews and field observation checklists, supported by secondary data analysis of official reports, policy documents, and institutional archives.

The research was conducted in five sequential phases. The preliminary survey (2 months) included stakeholder mapping and pilot testing with 60 participants through structured interviews. The quantitative data collection phase (4 months) involved digital questionnaires and field-based interviews. The qualitative assessment (3 months) captured in-depth perspectives through semi-structured interviews, followed by field observations across 180 agricultural facilities over 3 months to document supply chain operations. The final data validation phase (2 months) engaged 120 stakeholders in focus group discussions to confirm analytical findings and ensure contextual accuracy. This multi-instrumental, multi-phase framework ensured robust data triangulation, combining statistical reliability with contextual depth to produce an empirically grounded understanding of sustainable agri-food system performance in North Sumatra. Figure 3 illustrates the conceptual research framework for assessing ecological economy optimization.

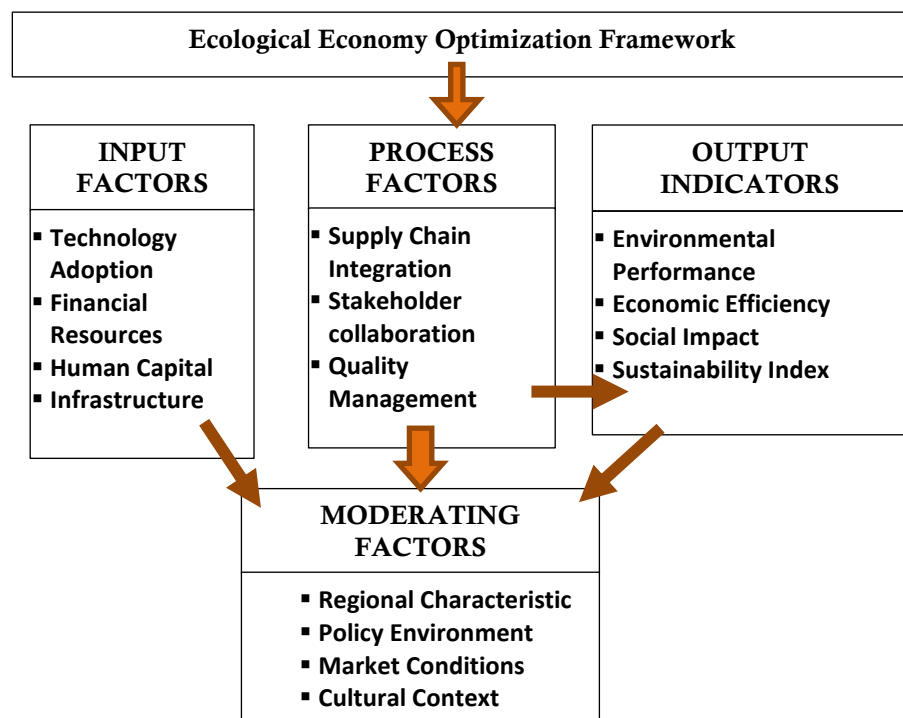


Figure 3. Conceptual Research Framework

RESULTS

The comparative assessment reveals substantial disparities in ecological economy implementation approaches and performance outcomes between the two administrative

regions, with each demonstrating unique competitive advantages and developmental challenges in transforming sustainable agri-food networks (Wildanika et al., 2024).

Table 1. Comprehensive Ecological Economy Performance Indicators - 2024 Assessment

Performance Indicators	Deli Serdang District	Simalungun District	Performance Gap (%)	Statistical Significance
Green Technology Integration Rate (%)	78.4	61.7	16.7	p < 0.001
Supply Chain Operational Efficiency Score	91.2	76.8	14.4	p < 0.001
Environmental Impact Reduction (%)	42.6	56.3	-13.7	p < 0.01
Organic Farming Participation Rate (%)	54.7	68.9	-14.2	p < 0.001
Economic Performance Improvement (%)	38.2	31.4	6.8	p < 0.05
Climate Resilience Index (0-100)	71.8	79.2	-7.4	p < 0.05
Supply Chain Visibility Score	84.7	69.5	15.2	p < 0.001
Stakeholder Collaboration Index	76.3	82.4	-6.1	p < 0.01

Based on Table 1, the 2024 assessment highlights distinct performance patterns between Deli Serdang and Simalungun in advancing ecological economy practices. Deli Serdang excels in green technology integration (78.4% vs. 61.7%), supply chain efficiency (91.2% vs. 76.8%), economic performance gains (38.2% vs. 31.4%), and supply chain visibility (84.7% vs. 69.5%), all showing statistically significant differences. In contrast, Simalungun demonstrates stronger outcomes in environmental impact reduction (56.3% vs. 42.6%), organic farming participation (68.9% vs. 54.7%), climate resilience (79.2 vs. 71.8), and stakeholder collaboration (82.4 vs. 76.3). These gaps reveal that while Deli Serdang prioritizes technological adoption and market efficiency, Simalungun emphasizes environmental sustainability, resilience, and collaborative practices, reflecting complementary strengths in ecological economy performance.

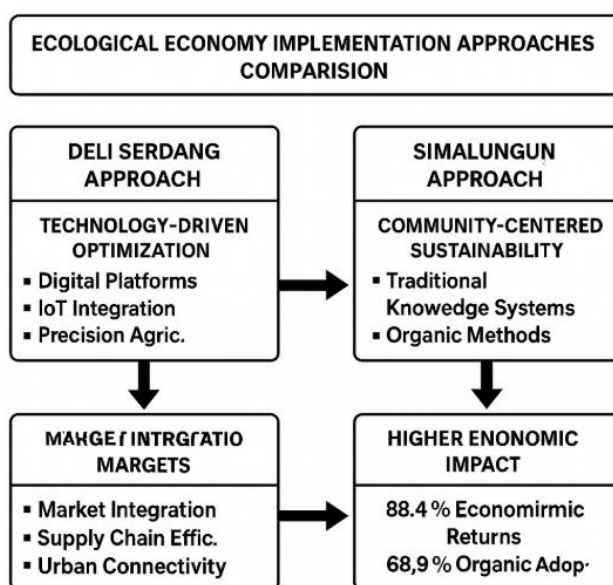


Figure 4. Ecological Economy Implementation Approaches Comparison

The comparison framework in Figure 4 illustrates two distinct approaches to implementing an ecological economy. Deli Serdang adopts a technology-driven

optimization strategy, emphasizing digital platforms, IoT integration, and precision agriculture to strengthen market integration, supply chain efficiency, and urban connectivity, ultimately generating higher economic returns with 78.4% technology adoption. In contrast, Simalungun follows a community-centered sustainability pathway that relies on traditional knowledge systems and organic methods, reinforced by community participation and cultural values, leading to stronger environmental outcomes with 68.9% adoption of organic practices. This demonstrates how differing regional characteristics can shape sustainability trajectories, striking a balance between economic efficiency and ecological resilience.

Table 2. Supply Chain Sustainability Performance Metrics by Stage - 2024

Supply Chain Stage	Deli Serdang Sustainability Score (0-100)	Simalungun Sustainability Score (0-100)	Regional Average	Best Practice Gap
Primary Production	85.2	89.7	87.5	-4.5
Processing & Value Addition	82.6	73.1	77.9	9.5
Distribution & Logistics	88.4	74.2	81.3	14.2
Retail & Consumer Interface	79.8	76.5	78.2	3.3
Reverse Logistics	71.3	68.9	70.1	2.4
Overall Sustainability Index	81.5	76.5	79.0	5.0

According to Table 2, evaluation of supply chain sustainability shows that Deli Serdang performs better in most stages, particularly in processing and value addition (82.6 vs. 73.1) and distribution and logistics (88.4 vs. 74.2), with notable best practice gaps of 9.5 and 14.2 points respectively. Simalungun, however, leads in primary production (89.7 vs. 85.2), slightly above the regional average, while both regions record relatively close scores in retail and consumer interface (79.8 vs. 76.5) and reverse logistics (71.3 vs. 68.9). The overall sustainability index places Deli Serdang higher at 81.5 compared to Simalungun’s 76.5, indicating that while Deli Serdang excels in downstream efficiency, Simalungun’s strength remains in upstream agricultural production.

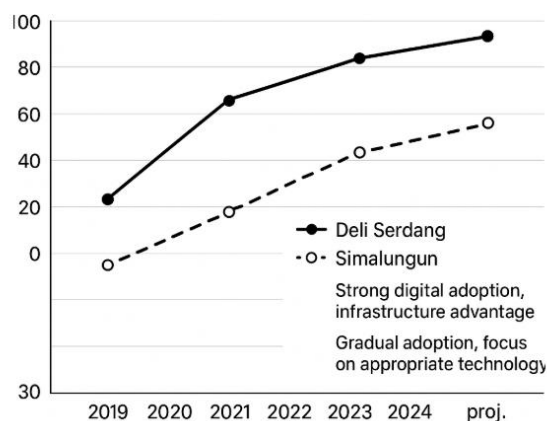


Figure 5. Agricultural Technology Adoption Patterns - Comparative Analysis

The comparative analysis of agricultural technology adoption shows a clear divergence between the two regions, illustrated in Figure 5. Deli Serdang demonstrates a rapid and

consistent increase, beginning with moderate adoption levels in 2019 and climbing steadily to above 90% by 2024, reflecting strong digital adoption supported by better infrastructure. Meanwhile, Simalungun starts from a much lower base and progresses more gradually, reaching just above 55% by 2025. This pattern highlights how Deli Serdang benefits from infrastructure and resource advantages to accelerate modernization, while Simalungun focuses on more appropriate and incremental technology adoption, balancing growth with local capacity and community needs.

The analytical results demonstrate that Deli Serdang's technology-oriented approach yields superior economic performance improvements (38.2% vs 31.4%) and operational efficiency gains, primarily attributed to enhanced digital platform integration and metropolitan market proximity. Conversely, Simalungun's community-centered approach achieves greater environmental impact reduction (56.3% vs 42.6%) and demonstrates stronger biodiversity conservation outcomes, reflecting traditional knowledge integration with sustainable practices.

Table 3. Financial Performance and Investment Analysis - 2024

Financial Indicators	Deli Serdang	Simalungun	Regional Benchmark	Investment Priority
Average ROI on Green Investments (%)	24.7	19.3	22.0	High
Green Technology Investment (USD/hectare)	847	623	735	Medium
Supply Chain Cost Reduction (%)	15.8	12.4	14.1	High
Productivity Improvement (%)	28.4	22.7	25.6	High
Market Premium for Sustainable Products (%)	18.6	25.2	21.9	Medium
Access to Green Finance (% of farmers)	34.7	28.9	31.8	Critical

Based on Table 3, the 2024 financial and investment assessment reveals that Deli Serdang generally surpasses Simalungun in several performance indicators. It records a higher average ROI on green investments (24.7% vs. 19.3%), greater investment in green technology per hectare (USD 847 vs. USD 623), stronger supply chain cost reductions (15.8% vs. 12.4%), and better productivity improvements (28.4% vs. 22.7%). These outcomes highlight that Deli Serdang places a stronger emphasis on technology-driven investment and efficiency enhancement, positioning it above the regional benchmark in most categories, particularly in areas of cost management and resource optimization.

On the other hand, Simalungun demonstrates a comparative advantage in the market premium for sustainable products (25.2% vs. 18.6%), suggesting stronger consumer trust and demand for its environmentally friendly commodities. However, both districts face a critical challenge in access to green finance, with only 34.7% of farmers in Deli Serdang and 28.9% in Simalungun having access, which remains below optimal levels for scaling sustainable initiatives. This indicates that while Deli Serdang leads in investment and efficiency, Simalungun's strength lies in its market positioning, and both require improved financing mechanisms to sustain long-term ecological economic growth.

DISCUSSION

The research findings reveal fundamentally different strategic approaches to ecological economy optimization, reflecting the influence of geographical positioning, infrastructure development, and cultural contexts on the selection of sustainable development pathways (Cotter et al., 2014; Ma & Liu, 2023). Deli Serdang's superior performance in technology integration and supply chain efficiency supports theoretical frameworks emphasizing innovation diffusion patterns in regions with enhanced connectivity and market access.

The 14.4-point differential in operational efficiency between regions indicates substantial variations in supply chain optimization capabilities, aligning with European agri-food sustainability research, which demonstrates the critical importance of

infrastructure development for supply chain performance. These findings corroborate established supply chain management theories, which emphasize the necessity for integrated measurement systems that address multiple sustainability dimensions simultaneously (Rezaee, 2018; Negri et al., 2021).

Simalungun's demonstrated superiority in organic farming participation (68.9% vs 54.7%) and environmental impact reduction reflects the region's cultural affinity for traditional sustainable practices and enhanced social capital supporting collective environmental stewardship. This finding supports contemporary research on agricultural supply chain resilience, which emphasizes the importance of diversification and community-based adaptation strategies in climate change contexts (McNamara & Buggy, 2017; Suhaeb et al., 2024).

The environmental performance advantages observed in Simalungun align with global sustainability research, indicating that communities with stronger traditional knowledge systems often achieve superior environmental outcomes despite lower technology adoption rates. This supports theoretical frameworks emphasizing the complementary nature of traditional knowledge and modern sustainability practices in agricultural supply chain optimization (Adefila et al., 2024; Sekhar et al., 2024).

Deli Serdang demonstrates its advantages through high levels of technology adoption (78.4%), efficiency (91.2%), market access, and digital integration. Meanwhile, Simalungun emphasizes organic participation (68.9%), environmental performance (56.3%), strong community collaboration (82.4%), and the preservation of traditional knowledge. These strengths converge in an integration zone, where best practices are combined through hybrid models, supportive policies, knowledge exchange, and investment optimization, with the ultimate goal of achieving a sustainability index of 84.2 for both regions. This model aligns with the theory of sustainable supply chain management which argues that integrating economic, environmental, and social dimensions produces optimal performance outcomes (Coopmans et al., 2021; Davis et al., 2021). The hybridization of technology-driven efficiency in Deli Serdang and community-centered sustainability in Simalungun reflects the principle of contextualized sustainability pathways, where different local advantages complement each other. By fostering collaboration and policy alignment, the model ensures that ecological resilience and economic productivity are not seen as competing goals, but as mutually reinforcing pillars for long-term regional sustainability (Mensah, 2019; Zhu et al., 2021).

The research findings provide critical insights for Indonesian green economy policy development, supporting differentiated regional approaches that leverage local competitive advantages while addressing contextual limitations. The economic performance variations between regions underscore the importance of tailored investment strategies that take into account regional infrastructure capabilities and market dynamics. Future policy development should prioritize hybrid approaches combining technological advancement with traditional knowledge preservation, reflecting global trends toward integrated sustainability frameworks in agricultural supply chain management. The research supports multi-dimensional sustainability assessment approaches that recognize the complementary nature of different optimization strategies rather than promoting uniform implementation models.

CONCLUSION

This dual-regional comparative study confirms that ecological economy optimization in sustainable agri-food systems is highly context-dependent and cannot be achieved through a one-size-fits-all approach. Deli Serdang and Simalungun demonstrate two viable yet contrasting pathways: the former leverages technological innovation, infrastructure proximity, and market integration to achieve superior operational efficiency and economic returns, while the latter excels in environmental stewardship, organic practices, and community-driven resilience rooted in traditional knowledge. By recognizing these complementary strengths, policymakers can move away from uniform national strategies and instead design differentiated, region-specific interventions that

maximize local advantages while addressing shared bottlenecks in financing and technical capacity.

The findings carry practical implications for Indonesia's green transformation agenda, particularly in supporting hybrid models that blend digital efficiency with community-based sustainability to accelerate progress toward the national Green Economy Index targets. However, the study is limited to two districts in North Sumatra, which may not fully represent the diversity of Indonesia's archipelago, and the 14-month data collection period might overlook longer-term seasonal or climatic variations. Future research should expand the comparative framework to additional provinces, adopt longitudinal designs to track sustainability outcomes over multiple years, and explore the scalable integration of emerging technologies such as blockchain and artificial intelligence to further strengthen ecological economy performance across varied tropical contexts.

Acknowledgment

The researcher gratefully acknowledges Universitas Pembangunan Panca Budi, local administrations of Deli Serdang and Simalungun, and all participants whose cooperation, insights, and support made this sustainable ecological economy research possible.

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*Ecological Economy in
Sustainable Agri-Food
Systems*

5218