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Integration of Farming-Livestock Systems in Sustainable Agrocomplex Development in Indonesia

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Abstract

Integrated farming-livestock systems offer a sustainable approach to agrocomplex development in Indonesia. This study analyzes the application of integrated systems in three different agroecosystems: wetlands in Karawang, drylands in Gunung Kidul, and plantations in Central Lampung. Research methods include direct observation, field measurements, and data analysis using Systems Dynamics Modeling, Data Envelopment Analysis, and Structural Equation Modeling. The results show three main typologies of integration: rice-cattle, food crops-horticulture-goats, and oil palm-livestock systems. Integrated systems increase nitrogen use efficiency by 37-52%, reduce chemical fertilizer needs by 45%, and increase farmer income by 43.7 % compared to conventional practices. Environmentally, these systems increase soil organic matter content, reduce greenhouse gas emissions by 2.4-3.7 tons CO_2-eq/ha/year, and increase biodiversity. Implementation challenges include institutional fragmentation, limited post-harvest technology, and lack of standardization of organic fertilizer quality. Critical success factors include institutional support, farmers' technical capacity, and the suitability of technology to the local context. This research contributes to the development of a sustainable agrocomplex model that is adaptive to the diverse conditions of Indonesia's agroecosystems, with important implications for food security and climate change mitigation policies.

Keywords: agriculture-livestock integration, sustainable agrocomplex, resource efficiency, nutrient cycle, food security, climate change mitigation, income diversification

1. Introduction

Indonesia as an agricultural country with abundant natural resources faces significant challenges in achieving food security and environmental sustainability. The agricultural and livestock sectors that have long been the backbone of the national economy are now faced with various problems, ranging from shrinking agricultural land, environmental degradation, to climate change that threatens productivity [1]. Amid these challenges, the concept of integrating agricultural-livestock systems in sustainable agrocomplex development has emerged as a promising holistic approach to addressing these various problems simultaneously.

Integrated farming systems, also known as integrated farming systems, is an approach that integrates agricultural and livestock components into one production system that supports and synergizes each other [2]. This system allows for a cyclic flow of nutrients and energy, where waste from one subsystem becomes valuable input for another. For example, livestock manure can be processed into organic fertilizer for plants, while crop residues can be used as animal feed, creating a system with almost no waste [3]. This approach not only increases the efficiency of resource use, but also reduces environmental impacts and increases the economic viability of farming.

In Indonesia, integrated farming systems have actually long been practiced by traditional farmers in various forms, such as the "mina padi" system which combines rice cultivation with fish, or the "tumpang sari" system which combines various types of plants [4]. However, with the increasing population and increasing demand for food, a more systematic and modern approach is needed to optimize the interaction between agricultural and livestock subsystems on a larger scale, namely in the form of sustainable agrocomplexes.

Sustainable agrocomplex refers to the development of integrated agricultural-livestock areas that not only consider production aspects, but also economic, social, and environmental sustainability [5]. This concept is in line with the Sustainable Development Goals (SDGs) adopted by Indonesia, especially goals number 2 (zero hunger), 12 (responsible consumption and production), and 15 (terrestrial ecosystems) [6]. In the context of Indonesia with its diverse ecosystems and varying socio-economic conditions, a sustainable agrocomplex approach requires adaptation to local conditions and integration of traditional knowledge with modern technology.

Despite its great potential, the implementation of integrated farming-livestock systems on an agrocomplex scale in Indonesia still faces various obstacles. A study conducted by Sukmawati and Dasipah [7] identified several major challenges, including: lack of farmer understanding of integrated system management, limited access to technology and capital, and lack of comprehensive policy support. In addition, research by Susilawati et al. [8] shows that infrastructure disparities between regions in Indonesia are also a significant obstacle to the development of sustainable agrocomplexes evenly.

Several previous studies have proven the significant benefits of integrated farming-livestock systems. Hermawan et al. [9] found that the implementation of crop-livestock integration systems in Central Java can increase farmers' income by up to 45% compared to conventional systems, while reducing the use of chemical fertilizers by up to 30%. Meanwhile, Sutrisno and Wibowo [10] reported that integrated farming-livestock systems contribute to reducing greenhouse gas emissions through the use of biomass and biogas. However, most of these studies still focus on small-scale or household levels, while implementation on a wider agrocomplex scale still requires further study.

This article aims to analyze the potential, challenges, and strategies for developing integrated farming-livestock systems in the context of sustainable agrocomplex development in Indonesia. Specifically, this article will examine: (1) models of integrated farming-livestock systems that are appropriate to the conditions of the Indonesian agroecosystem, (2) the role of technology in optimizing integrated farming systems, (3) institutional and policy aspects that support sustainable agrocomplex development, and (4) implementation strategies that consider socio-economic and environmental aspects. Through this comprehensive study, it is hoped that it can provide theoretical and practical contributions to the development of sustainable farming systems in Indonesia that are able to answer the challenges of food security and environmental conservation simultaneously.

2. Analysis of Methods

Direct observation of integrated farming-livestock practices was conducted using standardized observation protocols to document technical aspects of the system, including the technology used, waste management, and interrelationships between system components. In addition, field measurements were conducted to quantify parameters of crop and livestock productivity, soil quality (including organic matter content, pH, and cation exchange capacity), and greenhouse gas emissions using the closed chamber method. Secondary data were obtained from the Central Bureau of Statistics, the Ministry of Agriculture, agrocomplex project reports, and related scientific publications to enrich the contextual analysis and validate the findings.

Data analysis applied the Systems Dynamics Modeling (SDM) framework to understand the complex interrelationships between components in an integrated farming-livestock system. The SDM model was developed using Vensim PLE software to map and quantify the flows of materials, energy, and economic value in the system. The technical efficiency analysis of the integrated system was conducted using Data Envelopment Analysis (DEA) with the assumption of Variable Returns to Scale (VRS), while the sustainability analysis used the Multi-Criteria Decision Analysis (MCDA) framework that includes 15 sustainability indicators developed based on FAO principles for sustainable agriculture, adapted to the Indonesian context.

To identify factors influencing the adoption and sustainability of integrated farming-livestock systems, this study applied Structural Equation Modeling (SEM) with Partial Least Squares (PLS) approach. Hypothesis model was developed based on Unified Theory of Acceptance and Use of Technology (UTAUT) modified for agrocomplex context, considering social, economic, institutional factors, and innovation characteristics. Comparative analysis was conducted to identify differences in integration patterns, implementation challenges, and sustainability levels across the three study areas, as well as to develop typologies of integrated farming-livestock systems that are appropriate to various Indonesian agroecosystems.

The validity and reliability of the study were strengthened through triangulation of data sources and methods, peer review by integrated agricultural experts, and validation of the model by key stakeholders through Focus Group Discussions (FGDs) conducted in each study area. These FGDs also served as a forum to validate initial findings and develop policy recommendations with stakeholders. The ethical aspects of the study were maintained by obtaining informed consent from all respondents and informants, and ensuring the confidentiality of personal data in presenting the research results. Limitations of the study include the relatively short observation time to capture the seasonal dynamics of the farming system and limited geographic coverage, although efforts were made to select representative locations for various Indonesian agroecosystems.

3. Results

Characteristics and Typology of Agricultural-Livestock Integration Systems

The results of the study identified three main typologies of agricultural-livestock integration systems that developed in the study area, with characteristics and adoption levels that varied based on agro-ecosystem conditions. In the Karawang wetland area, the rice-cattle integration system dominates (72.4 %) with a pattern of utilizing rice straw as animal feed and cow dung as organic fertilizer for rice fields. Land use efficiency analysis shows that this system increases the Land Equivalent Ratio (LER) by up to 1.67 compared to the monoculture system. In Gunung Kidul, which is a dryland area, the food crop-horticulture-goat livestock integration system is more dominant (68.3 %), with local innovations in the form of water harvesting technology and the manufacture of organic fertilizer plus (POP) enriched with local microorganisms. Meanwhile, in the Central Lampung plantation area, the oil palm-cattle integration model (54.7%) and oil palmgoat (37.2%) are the main choices of farmers, with the utilization of ground cover vegetation and oil palm fronds as feed, as well as integration with food crops in the oil palm sward area at the immature plant stage (TBM).

The results of nutrient flow measurements in the integrated system showed an increase in nitrogen utilization efficiency of 37-52% compared to conventional systems in the three study locations. In Karawang, the use of fermented cow manure reduced the need for chemical fertilizers by 45%, while the use of rice straw as feed and mulch reduced the burning of agricultural waste by 78%. SEM analysis identified that the relationship between the agricultural and livestock subsystems (path coefficient = 0.67 , $p < 0.001$) was a key factor determining system efficiency. In Gunung Kidul, the integration of legume plants as animal feed and nitrogen fixers increased soil nitrogen content by 32% over a period of three years, which was positively correlated with increased food crop productivity ($r = 0.73$, $p < 0.001$). The biogas system developed in 23% of farmer households in Central Lampung produced energy equivalent to 2.7 liters of kerosene per day per unit, with residue in the form of bio-slurry that increased oil palm yields by 17% compared to the control.

Economic and Social Impact of Integration Systems

Economic analysis shows a significant increase in household income of farmers through the implementation of integrated farming-livestock systems. In Karawang, farmers with integrated rice-cattle systems earned 43.7% higher income (average IDR 47.8 million/year) compared to non-integrated farmers (IDR 33.3 million/year). Production cost efficiency was achieved through reduced use of external inputs, with savings in chemical fertilizer costs of IDR 3.2 million/ha/planting season and reduced livestock feed costs of IDR 4.7 million/unit of livestock/year. The structure of farmers' income also became more diversified, with contributions from food crops (55%), livestock (35%), and derivative products such as organic fertilizer and biogas (10%), which increased household economic resilience to fluctuations in agricultural commodity prices.

Financial feasibility analysis using Net Present Value (NPV) and Benefit-Cost Ratio (BCR) showed that all three integration models were economically feasible (NPV>0, BCR>1), with the oil palm-cattle integration model in Lampung having the highest BCR value (2.4). Sensitivity analysis showed that the integration system was more resilient to external shocks such as input price increases and output price decreases compared to the non-integration system. Interestingly, the logistic regression results identified that market access ($OR=3.2$, $p<0.01$) and family labor availability ($OR=2.7$, $p<0.01$) were significant determinants of the adoption of the integration system, more influential than the land area factor ($OR=1.4$, $p<0.05$).

From a social aspect, the integration system contributes to strengthening community social capital, especially through farmer-livestock groups that manage shared facilities such as communal biogas installations and organic fertilizer banks. The results of Social Network Analysis (SNA) show an increase in social network density from 0.34 to 0.67 during the five years of program implementation in Gunung Kidul, which is positively correlated with the level of technology adoption ($r=0.62$, $p<0.001$). The integration system also creates new job opportunities, especially for women and youth, in processing activities such as organic fertilizer production, waste processing, and biopesticides. Gender analysis shows that women's involvement in farm business decision-making increased from 23% to 47% after the implementation of the integration system, with greater control over small livestock management and processing of derivative products.

Environmental Impact and Sustainability

Environmental impact evaluation shows the positive contribution of the integrated farming-livestock system to resource conservation and climate change mitigation. Soil parameter measurements showed a significant increase in soil organic matter content in all three locations, with the highest increase in Gunung Kidul (from 1.2 % to 3.5% during the five years of implementation). The increase in organic matter was positively correlated with the water holding capacity of the soil which increased by an average of 27%, which is very important for adaptation to climate variability. Carbon footprint analysis using the Life Cycle Assessment (LCA) approach showed that the integrated system reduced greenhouse gas emissions by 2.4 -3.7 tons CO_2-eq/ha/year compared to the conventional system, mainly through chemical fertilizer substitution, agricultural waste utilization, and biogas production.

In Lampung, the use of livestock in an integrated oil palm plantation system contributed to a reduction in herbicide use of up to 62% through vegetation control by livestock grazing in the plantation area, while increasing the biodiversity of flora (Shannon index increased from 1.34 to 2.67) and soil fauna (earthworm population increased 3.8-fold). Nutrient efficiency analysis showed that the closed nitrogen cycle in the integrated system reduced nitrate leaching into water bodies by 47% compared to conventional systems, which had a positive impact on surface water quality around the study site.

Sustainability assessment using the MCDA framework with 15 indicators shows that the integrated system has a higher sustainability score (average score of 7.8 on a scale of 10) compared to the non-integrated system (average score of 4.3). The radar chart of sustainability analysis shows that the integrated system excels especially in the ecological (score of 8.6) and economic (score of 8.2) dimensions, but still needs strengthening in the institutional dimension (score of 6.7), especially related to access to credit and agricultural insurance. Hierarchical cluster analysis identified three groups of farmers based on the level of sustainability of their systems: innovators (23%), early adopters (42%), and late adopters (35%), with significant differences in terms of access to information ($p<0.01$) and participation in farmer groups ($p<0.001$).

Challenges and Success Factors

Despite showing various advantages, the implementation of integrated farming-livestock systems on an agrocomplex scale faces several significant challenges. Stakeholder analysis identified that institutional fragmentation at the government level (between the farming and livestock sectors) is a major obstacle to developing coherent policies, with an institutional fragmentation index of 0.67 (scale 0-1). The results of the regression analysis showed that the lack of coordination between institutions has a significant negative impact on program sustainability ($\beta=-0.43$, $p<0.01$). The identified technical challenges include: limited post-harvest technology for processing agricultural waste (identified by 67% of respondents), lack of standardization of organic fertilizer quality (identified by 54% of respondents), and limited water availability during the dry season, especially in dryland areas (identified by 72% of respondents in Gunung Kidul).

The application of Structural Equation Modeling (SEM) identified key factors influencing the adoption and sustainability of the integrated system. The SEM model with adequate goodness of fit ($\chi^2/df=2.34$, CFI=0.92, RMSEA=0.058) showed that institutional support (path coefficient=0.64, $p<0.001$), farmers' technical capacity (path coefficient=0.57, $p<0.001$), and technology suitability to the local context (path coefficient=0.49, $p<0.001$) were the main determinants of successful implementation. Social factors such as collective norms (path coefficient=0.38 , $p<0.01$) and local leadership (path coefficient=0.36, $p<0.01$) also had significant effects, emphasizing the importance of socio-technical approaches in sustainable agrocomplex development.

Comparative analysis between the three study sites resulted in the identification of contextual prerequisites for sustainable agrocomplex development in Indonesia. The success of the integrated system in Karawang is supported by good irrigation infrastructure (water sufficiency index = 0.87) and proximity to the urban market in Jakarta (average distance 68 km), while in Gunung Kidul it is influenced by strong social capital and adaptive innovation to resource constraints. In Lampung, the integration of agriculture-livestock is supported by the availability of relatively large land (average 2.7 ha per household) and the presence of large companies as off-takers of agricultural products. These findings indicate the importance of a differentiated agrocomplex development strategy based on the characteristics of the agroecosystem and socio-economic areas.

4. Discussion

The findings of this study confirm the significant potential of integrated farming-livestock systems as a basis for sustainable agrocomplex development in Indonesia, but with several nuances and complexities that need to be considered in its implementation. The success of the integration model in three different agroecosystem regions shows that this approach has the flexibility to be adapted to local conditions, but still requires adjustments to the specific characteristics of local ecology, society, and economy. These results are in line with previous studies by Devendra [11] who emphasized the importance of a "context-specific" approach in the development of integrated farming systems in Southeast Asia, but this study provides a more detailed empirical contribution regarding the adaptation mechanisms and integration models that are appropriate for various Indonesian agroecosystems.

Increased efficiency of resource use, especially nutrients and biomass, is a major advantage of the integrated system that is consistently found in all three research locations. Reducing external input requirements by 37-52% not only improves the economic sustainability of farming but also reduces farmers' dependence on fluctuations in agricultural input prices. This is increasingly relevant in the context of the global crisis that has resulted in unstable prices for fertilizers and other agricultural inputs. Interestingly, although previous research by Devendra and Thomas [12] predicted the nutrient efficiency of the integrated system to be around 25-30%, the findings of this study indicate a higher potential (37-52%), which is likely due to the optimization of the integration of fermentation and biogas technologies in the nutrient cycle. The implication is that agrocomplex development strategies in Indonesia should not only focus on the physical integration of farm-livestock components, but also on the application of process technologies that increase the efficiency of the nutrient cycle.

The socio-economic dimensions of integrated farming-livestock systems revealed in this study have important implications for rural development strategies in Indonesia. The 43.7% increase in income in Karawang and the diversification of income sources for farming households provide a more stable economic foundation, especially in the face of climate and market uncertainties. However, the finding that market access (OR=3.2) and availability of family labor (OR=2.7) are more influential on the adoption of integrated systems than land size (OR=1.4) has important implications for agrocomplex development policies. This indicates that the policy focus needs to shift from land consolidation to strengthening value chains and increasing labor efficiency. In contrast to the assumption often used in Indonesian agricultural development planning that economies of scale are the main factor, these findings suggest that “economies of scope” through diversification and integration may be more relevant to the context of family farming in Indonesia.

The contribution of the integrated farming-livestock system to environmental aspects, especially increasing soil organic matter content, reducing greenhouse gas emissions, and increasing biodiversity, shows its potential as a low-carbon farming practice that can be integrated into the national strategy for climate change adaptation and mitigation. The emission reduction of 2.4-3.7 tons CO_2-eq/ha/year is in line with Indonesia's commitment to reduce greenhouse gas emissions by 29% by 2030 [13].

5. Conclusion

This study confirms that integrated farming-livestock systems are a promising approach for sustainable agrocomplex development in Indonesia, with tangible benefits in economic, social, and environmental dimensions. The typology of integrated systems developed in three different agroecosystem areas (rice-cattle in wetlands, food crops-horticulture-goats in drylands, and oil palm-livestock in plantations) demonstrates the flexibility of this approach to be adapted to local contexts. Increased resource efficiency, especially reduction of external inputs by 37-52%, is the main advantage of the system that is consistently found in all three study sites.

From an economic perspective, the integration system has been shown to increase farmers' income by up to 43.7 % compared to conventional systems, with a more diversified income structure and higher resilience to market shocks. The finding that market access and availability of family labor have a greater influence on adoption than land area indicates the importance of an "economy of scope" approach through diversification and integration, rather than simply pursuing economies of scale in developing sustainable agriculture in Indonesia.

The positive contribution of the integrated system to the environment, including increasing soil organic matter content, reducing greenhouse gas emissions by 2.4-3.7 tons CO_2-eq/ha/year, and increasing soil flora and fauna biodiversity, demonstrate its potential as a low-carbon agricultural strategy that can support national commitments in climate change adaptation and mitigation. The integrated system also contributes to strengthening social capital, as indicated by the increase in social network density which is positively correlated with the level of technology adoption.

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