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Development of a System Dynamics Model to Optimize Productivity and Cost Efficiency in Sustainable Agricultural Systems

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Abstract

Sustainable agricultural systems require efficient input management to achieve optimal results in both productivity and profitability. This study aims to develop a system dynamics model to explore strategies for increasing productivity and cost efficiency in sustainable agriculture. The research was conducted in Singkalan Village, Balongbendo District, Sidoarjo Regency using STELLA software to build a simulation model. This model captures the relationship between key variables, including the use of superior crop varieties and semi-organic fertilizer, rice and corn yields, operational costs, and farmer profits. Three management scenarios were tested: (1) increasing productivity through superior varieties, (2) reducing operational costs by applying semi-organic fertilizer by 25%, and (3) combining the two approaches. The simulation results show that the combination of scenarios provides the best results, with an increase in rice productivity of 3.96%, a reduction in operational costs of 16.29%, and a profit for rice farmers of 1.27%. These results highlight the effectiveness of the system dynamics approach in assessing input-based policy interventions and supporting sustainable profit-oriented decision making in agriculture.

***Keywords**: cost efficiency, productivity, profitability, system dynamics*

I. INTRODUCTION

Rice farming underpins rural food security but faces critical challenges such as land conversion, yield fluctuations, and limited access to quality inputs. In Singkalan Village (±124.2 ha), field data collected between August and November 2024 revealed a sharp drop in rice-equivalent production from 1,281.33 tons (2022) to **820.66 tons** (2023), with minimal recovery to **826.10 tons** (2024), while annual consumption stayed steady at 239–251 tons. This decline in surplus from roughly fivefold to threefold signals growing vulnerability to climate stresses, input instability, and land-use changes. Which is represented in Figure 1 below.

Figure 1 Graph of Rice Consumption Level and Rice-Equivalent Harvest Yield in Singkalan Village 2019-2024

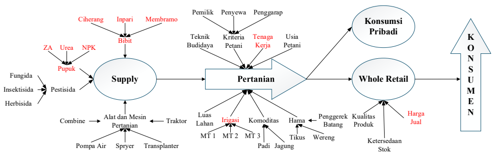

Figure 2 Mapping the Agricultural Supply Chain in Singkalan Village

The complexity of Singkalan's farming system is illustrated in Figure 2, showing interconnections between input supply (seeds, fertilizer, labor), production processes, and distribution channels to household and whole retail consumption. This diagram highlights how disturbance in one componentsuch as input delay or land conversion can trigger cascading effects across the system, underscoring the need for a comprehensive systems analysis.

Several studies have applied system dynamics in agriculture from cassava supply chains to organic farming simulations but typically lack focus on specific villages, use scant primary local data, and do not fully model the input-production-consumption-land-use interplay via policy scenarios. This gap is precisely what this study aims to address.

This study proposes optimizing inputs by combining improved seed varieties with rice straw–based semi-organic fertilizer, supported through training and pilot plots, modeled via system dynamics. Literature supports straw compost effectiveness: 16 t/ha produced 4,241.78 kg/ha yield (Kadir & Harsani, 2022). The model will test three management scenarios as outlined in the abstract: productivity boost, cost-efficiency, and combined approach.

This study aims to: (1) develop and validate a system dynamics model using Singkalan Village data (2019–2024); (2) simulate three input scenarios improved seed, straw compost, and their combination and evaluate impacts on productivity, costs, and profits; and (3) offer adaptive, sustainable policy recommendations (People, Planet, Profit). Its novelty lies in integrating primary village data into a comprehensive simulation of input-production-consumption-land dynamics under realistic policy scenarios. The model is expected to serve as a practical tool for local policymakers to design evidence-based interventions.

II. THEORY

A. Agriculture and Food Security

Agriculture is a form of utilizing biological resources by humans, particularly through crop cultivation, to meet food and economic needs. In Indonesia, the agricultural sector serves as a key foundation in the national economic structure due to its direct role in supplying basic necessities. This activity encompasses various subsectors, such as food crops, horticulture, plantations, livestock, and fisheries. The development of this sector is now focused on improving product quality, ensuring safety, and applying innovation and technology to meet the challenges of rising consumption. In the context of sustainability, agriculture must be managed efficiently with attention to ecological and social aspects. The principles of sustainable agriculture emphasize energy optimization, minimizing environmental impacts, and strengthening local food security through approaches such as community gardens and home yard utilization. (Arifien, et al., 2022)

Food self-sufficiency refers to a nation's ability to independently meet its population’s food needs by optimizing natural resources, human capital, socio-economic factors, and local wisdom. Meanwhile, food safety involves ensuring that food is free from contamination and aligns with societal norms. Law No. 18 of 2012 expands on the definition of food security found in Law No. 7 of 1996, incorporating elements of individual access, religious beliefs, and cultural values. This definition aligns with the FAO, which describes food security as a condition where everyone, at all times, has physical and economic access to sufficient, safe, and nutritious food that meets their dietary needs and preferences. Instability in food supply can trigger social and political unrest, threatening national stability. In response, the government pursues food security policies focused on boosting domestic production and implementing prudent import strategies. Considering Indonesia’s climatic vulnerability and limited agricultural infrastructure, a comprehensive food policy is crucial to protect vulnerable groups, particularly smallholder farmers and low-income communities. (BULOG, 2025)

B. Sustainability Approach in Agriculture (Triple Bottom Line)

The Triple Bottom Line (TBL) is an evaluative framework that assesses the overall success of a system through three core dimensions: economic (profit), social (people), and environmental (planet). Introduced by John Elkington (1994) and further discussed by (Fuadah, Yuliani, & Safitri, 2018),TBL critiques development models that prioritize financial gain alone. In the agricultural context, TBL emphasizes that sustainability cannot be achieved by productivity alone, but must also consider social welfare and environmental preservation.

The social dimension in sustainable agriculture emphasizes the protection of farmers and rural communities, ensuring they have access to appropriate technologies, and maintaining decent working conditions. The environmental **dimension** advocates for eco-conscious practices, including efficient water use, minimizing chemical inputs, and employing agroecological strategies such as crop rotation and agroforestry. The economic dimension underscores improving farmer livelihoods, strengthening local economies, and fostering agriculture-based enterprises. The integration of these three pillars under the TBL framework promotes equitable, adaptive, and enduring agricultural systems. For instance, the decision support framework (Singh & Srivastava, 2021). (Vukovic, Spitsin, Akerman, & Gammershmidt, 2025) (Rosario & Traverso, 2023).

C. Dynamic Systems

System thinking is a foundational approach for understanding the dynamics and complexities of systems, including those in the agricultural sector. It enables a comprehensive analysis of interactions among elements, thereby supporting policymakers in formulating systemic and sustainable solutions. Meadows (2008), as cited by (Sarasi, Yulianti, & Farras, 2021), defines a system as a set of interconnected components organized coherently to achieve a specific purpose. Similarly, Avianto (2018), referenced by the same authors, emphasizes that system thinking encourages a holistic and nonlinear understanding of cause-and-effect relationships within an interrelated structure.

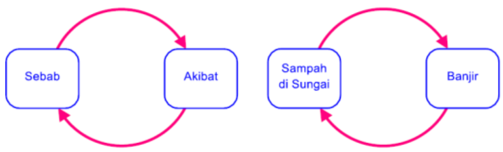

Figure 3. Casual Loop Diagram Example

In system dynamics modeling, the process begins with the development of a *Causal Loop Diagram* (CLD), which illustrates the interrelations among variables through feedback loops—either reinforcing (R) or balancing (B). This diagram serves as a conceptual basis for understanding the system structure. The next step is constructing a *Stock and Flow Diagram* (SFD), which quantitatively models the interactions using components such as stocks, flows, converters, and connectors. SFDs enable numerical simulation via tools like STELLA or Vensim, allowing analysis of system behavior over time under various intervention scenarios.

Model validation is conducted through both structural and behavioral tests. Structural validation includes *direct structure tests*, which compare the model to existing theories, and *structure-oriented behavior tests*, which assess how well the model's structure reflects real-world system behavior. Behavioral validity is then examined by comparing simulation results with actual data using statistical metrics such as mean error and standard deviation.

$$E1 = \sum_{t=1}^{n} \left|\frac{A_t - S_t}{A_t}\right| \times 100\% \quad (1)$$

$$E2 = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\left(\frac{A_t - S_t}{A_t} \times 100\%\right)^2} \quad (2)$$

These validation stages ensure that the model is not only logically and mathematically sound but also empirically reliable. Thus, system dynamics provides a robust analytical framework for developing agricultural policy strategies that are adaptive, integrated, and sustainable.

III. METHOD

A. Type of Research

This study applies a quantitative-descriptive approach utilizing system dynamics modeling in STELLA software to explain inter-variable relationships within agricultural systems holistically and simulate system behavior over time. The methodology is explanatory, enabling not only the portrayal of current system dynamics but also the assessment of how various policy scenarios could impact sustainability—particularly in enhancing input efficiency and profitability. Similar implementations have proven effective in agricultural sustainability analysis. For instance, (Susanti, Priyanto, Muladno, Astuti, & Lucia, 2023) applied system dynamics to evaluate the sustainability and economic feasibility of smallholder beef production systems in South Sumatra.

Moreover, (Aprillya & Suryani, 2023) employed dynamic system simulation to analyze factors influencing the quality of paddy production and inform food security policy strategies. Additionally, a case study of indoor farming systems integrating IoT in 2023 demonstrated the capability of system dynamics to characterize complex crop production environments under varying nutrient inputs (Ryu, Subah, & Baek, 2023).

This study employs a quantitative-descriptive approach using system dynamics modeling with STELLA software to holistically explain the interrelationships among variables and simulate system behavior over time. The explanatory nature of this method not only describes the current conditions of the agricultural system but also analyzes the potential impacts of various policy scenarios on sustainability, particularly related to input efficiency and profitability improvement. System dynamics is widely recognized as an effective approach to model agricultural sustainability because it integrates ecological, social, and economic dimensions into a unified framework (Koksal & Strahle, 2021). Recent studies have shown that STELLA-based modeling enables researchers to visualize causal feedback loops and evaluate alternative policy scenarios in agriculture . Moreover, system dynamics facilitates the exploration of long-term consequences of decisions, supporting adaptive and sustainable agricultural strategies (Mao et al., 2023).

The system dynamics method applied in this research is explanatory in nature, as it not only describes the current condition of the system but also analyzes the potential impacts of various policy scenarios on the sustainability of the agricultural system, particularly in terms of input efficiency and profitability improvement. The modeling and simulation process is conducted using STELLA software, which facilitates visual representation of causal relationships and mathematical computations within the system structure.

B. Research Design

Figure 4. Flowchart

This research employs a quantitative approach using system dynamics to develop a sustainable agricultural model in Singkalan Village. The process begins with a literature review and field studies including interviews to identify the key problems in the local agricultural system. The data collected include both primary and secondary data. Primary data cover land area, crop yield, planting schedules, production costs, rice consumption, and commodity prices from 2019 to 2024. Secondary data include land area distribution, demographic data, main crops, RDKK documents, and official statistics from BPS.

Once the problems are identified, a questionnaire is developed based on the Triple Bottom Line (People, Planet, Profit). The collected responses serve as the foundation for building a Causal Loop Diagram (CLD), which illustrates the causal relationships among key system variables. The CLD is then translated into a Stock and Flow Diagram (SFD) to quantitatively model the system structure, followed by mathematical formulation for simulation purposes.

The model undergoes verification (to test logical consistency) and validation (to ensure simulation results match real-world data). Upon successful validation, policy scenarios are developed and followed by scenario result analysis to evaluate their long-term impacts on agricultural sustainability. The final stage involves drawing conclusions and policy recommendations based on model insights to support more adaptive and sustainable agriculture at the local level.

C. Data Analysis Techniques

The data analysis techniques in this study are conducted through several structured stages that support the development of a system dynamics model. First, both quantitative and qualitative data obtained from questionnaires, field studies, and secondary sources are analyzed using a quantitative descriptive approach to understand the characteristics of the agricultural system and the influencing factors. Questionnaire data based on the aspects of People, Planet, and Profit are analyzed to identify key variables to be integrated into the system dynamics model.

Next, the classified data are used to develop the Causal Loop Diagram (CLD) to map the causal relationships between variables. Once the relationship structure is established, a Stock and Flow Diagram (SFD) and mathematical formulation are developed using simulation software such as STELLA. The analysis is conducted iteratively through the processes of model verification and validation, including comparison between simulation results and actual data using Behavior Pattern Testing and Structure-Oriented Behavior Testing.

The final step of the analysis is the development of policy scenarios and scenario result analysis to evaluate their impacts on the sustainability of the agricultural system. This process enables adaptive, evidence-based decision-making in response to the complex dynamics of local agricultural systems.

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IV. RESULTS AND DISCUSSION

A. Casual Loop Diagram

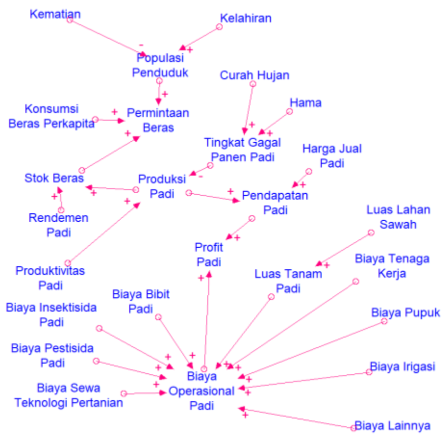


Figure 5. Casual Loop Diagram

The Causal Loop Diagram (CLD) in Figure 5 illustrates the dynamic interrelationships among key variables within the rice farming system. Population growth increases rice demand, which drives the need to boost production. Production is influenced by factors such as productivity, yield rate, cultivated land area, rainfall, and crop failure rates. Farmers' profit is highly dependent on production outcomes and total operational costs, including fertilizers, labor, irrigation, seeds, pesticides, and technology. Increases in these costs can reduce profits and hinder the sustainability of agricultural practices. A similar pattern is observed in maize cultivation, where profitability is closely tied to cost efficiency, yield reliability, and the risk of harvest failure due to pests or climate variability. The CLD highlights that systemic imbalance occurs when production cannot keep pace with rising demand—primarily due to land constraints, high input costs, and climate-related risks. Thus, improving input efficiency and technological support are critical to sustaining agricultural systems in the long term.

B. Stock and Flow Diagram

1. Sub Model People

The population sub-model illustrates the relationship between population size, rice consumption, and total production. Consumption is calculated by multiplying population and per capita demand, while production sums yields across seasons. Comparing the two reveals surplus or deficit conditions, serving as a basis for food security assessment and sustainable management strategies.

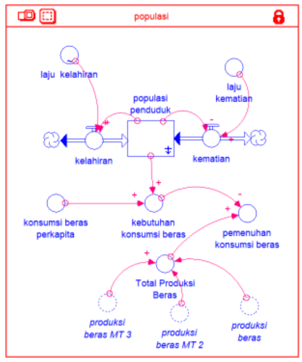


Figure 6. Sub Model People

2. Sub Model Planet

The submodel in Figure 7 presents the Stock and Flow Diagram (SFD) for the Planet dimension during the first planting season, exclusively allocated for rice cultivation. The model illustrates land area fluctuations due to land conversion, assuming 100% of the area is planted. Total rice production is influenced by productivity and crop failure rates during the season.

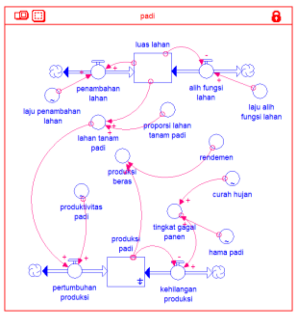


Figure 7. Sub Model Planet

3. Sub Model Profit

This submodel presents the simulation results of a Stock and Flow Diagram (SFD) to estimate rice farmers' profits. It illustrates how various cost components such as fertilizers (urea, NPK, ZA), labor, seeds, pesticides, insecticides, technology fees, and irrigation contribute to total operational costs. Profit is calculated as the difference between revenue (production × selling price) and total cost. Any changes in input costs or production output directly affect profitability within a single planting season.

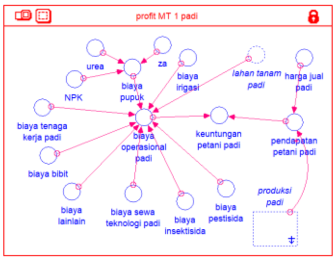


Figure 7. Sub Model Profit

C. Development of Policy Scenarios

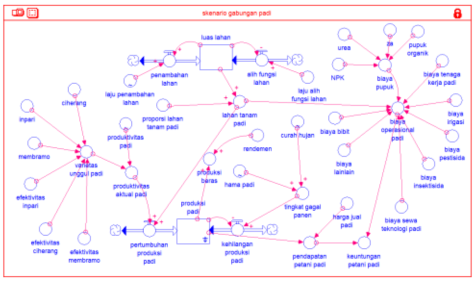


Figure 8. Stock and Flow Diagram for Rice Policy Scenarios

The figure 9 above illustrates the SFD structure of the combined scenario, showing the interconnection between yield improvement and input efficiency to achieve a sustainable agricultural system.

The scenario development in the *Stock and Flow Diagram* (SFD) is based on three main approaches: (1) increasing productivity through the use of superior rice varieties, (2) improving cost efficiency by reducing NPK and urea fertilizer usage by 25% each and replacing them with straw-based organic fertilizer and agricultural EM4, and (3) combining both strategies.

1. Scenarios for Using Superior Varieties of Rice

This scenario focuses on boosting rice productivity through the adoption of superior genetic seed varieties. In the Indonesian setting, trial data from 2012 to 2022 show that Inpari 46 can yield up to 6.78 t/ha approximately 1.4–2.0 t/ha above average farmer yields (~5.6 t/ha) (Sulaeman, et al., 2023). When coupled with site-specific technology packages, this variety approaches its full yield potential.

Field trials in West Java also revealed that salt-tolerant varieties like Inpari 34 and Inpari 35 yielded 93 % more than conventional farmer practices on saline soils, translating into a yield increase of about 1.3 t/ha and an additional benefit of USD 301/ha (Sembiring, et al., 2020).

In the Stock and Flow Diagram (SFD), this scenario is modeled via a *high-yield variety effectiveness* converter variable that tangibly boosts productivity thereby enhancing harvest output, farmer income, and overall food security.

Table 1. Results Scenarios for Using Superior Varieties of Rice

Productivity		
Tahun	**Base**	**Skenario**
2025	7,79	7,99
2026	7,79	7,99
2027	7,79	7,99
2028	7,79	7,99
2029	7,79	7,99
Mean	7,79	7,99
Persentase	2,567%	

Based on the results of the first scenario, a graph of differences in productivity can be seen as in Figure 10 below.

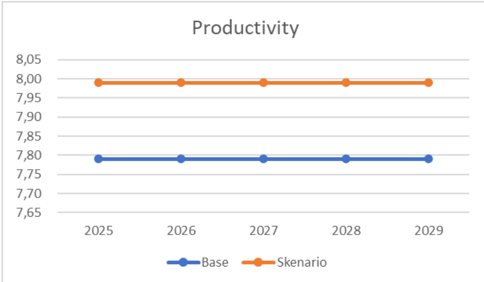


Figure 9. Scenario 1 Productivity Comparison Chart

The implementation of high-yield seed varieties has led to a 2.535% increase in rice productivity compared to the baseline condition. This improvement highlights the significant role of superior seeds in enhancing crop yields, improving production efficiency, and reinforcing food security. Thus, incorporating improved seed varieties into agricultural policy is a relevant strategy to achieve long-term sustainable productivity.

2. Scenario of Switching from Chemical Fertilizer to Semi-Organic Fertilizer

This scenario focuses on cost-efficiency and sustainability by reducing NPK/urea use by 25% and substituting the reduction with on-farm fermented rice straw compost activated by EM4. Practical steps include composting rice straw with EM4, mixing the compost into fertilizer applications, and adjusting annual fertilizer plans so that a 25% cut in chemical fertilizer is offset partly by organic nutrient inputs.

Indonesian field evidence from the last five years supports this approach. Substitution trials using straw compost showed that partial replacement of chemical fertilizer can maintain yields while improving soil fertility indicators (total N, soil organic C) findings reported in SRI and field substitution studies (Rantung, et al., 2023) (Nastiti & Asngad, 2024).

Studies on EM4-assisted straw processing report improved compost quality, enhanced soil water retention, and favorable N dynamics compared with non-EM4 treatments, confirming EM4's role in accelerating decomposition and improving organic nutrient availability. (Kusuma, Tika, & Arda, 2025)

My simulation results (operational cost reduction ≈ **1.629%** across 2025–2029) align with empirical indications that on-farm composting can reduce input expenditures when chemical fertilizer is partially substituted. (Suhendra, Ikhsan, & Yanti, 2024)

In short: a 25% substitution of chemical fertilizer with EM4-assisted rice straw compost yields a **positive cost–environment trade-off**—lower operational costs, improved soil health, and broadly stable yields—making it a viable, locally implementable policy for sustainable rice farming.

Table 2. Result Scenario of Switching from Chemical Fertilizer to Semi-Organic Fertilizer

Operational costs		
Tahun	**Base**	**Skenario**
2025	1.167.246.763,25	1.148.238.122,32
2026	1.168.414.010,01	1.149.386.360,44
2027	1.169.582.424,02	1.150.535.746,80
2028	1.170.752.006,45	1.151.686.282,55
2029	1.171.922.758,45	1.152.837.968,83
Mean	1.169.583.592,44	1.150.536.896,19
Persentase	-1,629%	

Based on the results of the second scenario, a graph of the difference in operational costs can be seen as in Figure 11 below.

Figure 10. Comparison graph of operational costs for Scenario 2

The semi-organic fertilizer scenario, involving a 25% reduction in chemical fertilizer use replaced by organic inputs, has proven effective in enhancing rice farmers' profitability. This approach not only promotes environmentally sustainable agriculture but also reduces input costs without significantly compromising yields. Consequently, it offers farmers greater economic margins and serves as an efficient and eco-friendly policy alternative.

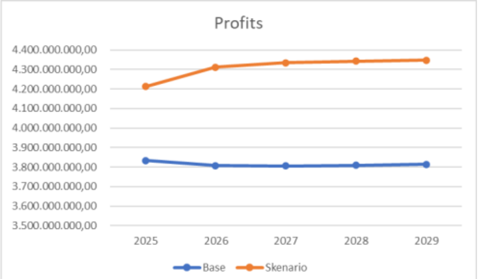
3. **Combined Scenario between Superior Varieties and Semi-Organic Fertilizer**

This combined scenario integrates two main interventions: the use of high-yield crop varieties and the application of semi-organic fertilizers made from fermented straw and EM4. The objective is to simultaneously enhance productivity and reduce operational costs. High-yield varieties contribute to increased crop output, while semi-organic fertilizers support cost efficiency and soil fertility. This synergy is expected to improve food security (Planet dimension) and enhance farmers' profitability (Profit dimension). In the Stock and Flow Diagram (SFD), the scenario is represented by two key converters high-yield variety effectiveness and semi-organic fertilizer composition which jointly influence productivity and operational costs.

Table 3. Result Combined Scenario between Superior

Profits		
Tahun	**Base**	**Skenario**
2025	3.833.584.012,10	4.211.921.862,21
2026	3.807.742.796,61	4.311.345.925,20
2027	3.806.959.847,92	4.334.699.699,35
2028	3.810.056.627,80	4.342.842.884,69
2029	3.813.756.819,58	4.347.947.424,70
Mean	3.814.420.020,80	4.309.751.559,23
Persentase	12,986%	

Based on the results of the second scenario, a graph shows the difference in profits from the results of the two scenarios as in Figure 12 below.



(Arifien, et al., 2022) (Kadir & Harsani, 2022)

Figure 11. Comparison graph of profits from the results of scenarios 1 and 2

The implementation of the high-yield seed scenario resulted in notable productivity improvements for both rice and maize. Rice productivity increased by 2.535% compared to baseline conditions, while maize showed a more substantial gain of 8.405% following the intervention. These outcomes confirm that the use of high-yield varieties contributes significantly to enhancing crop yields, improving production efficiency, and strengthening food security. Thus, this strategy is highly recommended as part of sustainable agricultural policy aimed at boosting output and long-term efficiency.

V. CONCLUSION

This study developed a system dynamics model to improve cost efficiency and profitability in sustainable agricultural systems in Singkalan Village. The simulation results demonstrate that a combined policy scenario using improved crop varieties and reducing chemical fertilizer by 25% significantly decreases operational costs while enhancing farmers' profits. Specifically, the scenario increases rice farmers' profit by **1.22%** and maize farmers' profit by **2.56%**, while reducing operational costs by **16.29%** for rice and **16.22%** for maize. These findings confirm that input efficiency and technological innovation are key strategies for optimizing long-term economic gains. Therefore, policy support that promotes the adoption of cost-effective agricultural technologies and access to financing is essential to sustain farm profitability.

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