System Dynamics Simulation of Semi-Organic Fertilizer and Pest Management Scenarios to Enhance Sustainable Food Security in Bungur Village

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Abstract

This study investigates agricultural sustainability and food security in Bungur Village, Nganjuk Regency, East Java, by addressing critical challenges such as an aging farming population, heavy reliance on chemical fertilizers, and recurring pest infestations. To identify key determinants, Structural Equation Modelling–Partial Least Squares (SEM–PLS) was employed, while system dynamics modeling using STELLA software was applied to simulate three alternative intervention scenarios. The simulation results demonstrate that the adoption of semi-organic fertilizers increases profit by approximately 1% (Rp106.4 million), the use of environmentally friendly pest management enhances profit by 12% (Rp117.8 million), and the combined application of both strategies yields the highest improvement, with a 16% increase (Rp122.3 million) compared to the baseline condition (Rp105.6 million per hectare annually). Model reliability was confirmed through validation tests using mean comparison error (⩽5%) and variance explained (⩽30%). These findings highlight that integrated interventions are effective in improving productivity, profitability, and sustainability, while also providing incentives to encourage greater youth participation in agriculture. Nonetheless, the scope of this study is limited to Bungur Village and focuses exclusively on rice, shallots, and corn, without accounting for farmer-level heterogeneity. Future studies are recommended to extend the model to wider geographical contexts and incorporate factors such as climate variability and market fluctuations.

Keyword: *Food security, system dynamics, SmartPLS, triple bottom line.*

I. INTRODUCTION

Agriculture remains central to rural livelihoods and national food security, particularly in areas where economic activity relies heavily on farming. Bungur Village in Nganjuk Regency, East Java, exemplifies this condition with rice, shallots, and corn as its main commodities. Despite high production potential, the agricultural sector faces persistent challenges, including fluctuating prices, soil degradation due to chemical fertilizer overuse, aging farmer demographics, and recurring pest infestations. These issues threaten the sustainability of local food systems and require an integrated, evidence-based approach to intervention.

Previous studies have examined agricultural sustainability through system dynamics and socio-economic analyses (Mulyani et al., 2021; Bernadi, 2023; Salo & Kallio, 2023). However, research integrating fertilizer strategies and pest management within a comprehensive modeling framework remains limited, particularly at the village scale where food security outcomes are directly felt. Recent works highlight the importance of combining semi-organic fertilizer adoption with environmentally friendly pest control to improve productivity and reduce ecological impact (Anggraeni & Murnawan, 2024; Lestari & Rakhman, 2023; Wulandari & Hermawan, 2021). Yet, these studies often evaluate interventions separately, without a holistic framework linking social, environmental, and economic dimensions. This gap motivates the present study to provide a more integrated assessment.

The Triple Bottom Line (TBL) framework is adopted in this study because it explicitly captures the multidimensional nature of agricultural sustainability—economic (Profit), social (People), and environmental (Planet). This approach is particularly relevant for Bungur Village, where socio-demographic constraints (e.g., low youth involvement), environmental concerns (soil fertility loss), and economic pressures (profit margins) are deeply interconnected. By applying TBL, the study ensures that interventions are not assessed solely on financial gain but also on their ability to foster environmental resilience and social equity.

To address the identified challenges, this research integrates Structural Equation Modelling–Partial Least Squares (SEM–PLS) to identify key influencing factors, and a system dynamics model in STELLA to simulate intervention scenarios. Unlike prior studies, this work contributes a combined analytical framework that links farmer-level perceptions with long-term system behavior. The objective is to evaluate the impacts of semi-organic fertilizer use, pest control measures, and their integration on agricultural productivity, profitability, and sustainability, providing insights for local policy and practical strategies to strengthen rural food security.

II. INSTRUCTIONS

1) Food Security

Food security can be understood as a condition in which all individuals, at all times, have reliable physical, social, and economic accsess to sufficient, safe, and nutritious food that enables an active and healthy life (FAO, 2023). Within the framework of rural agliculture, food security is generally analyzed through four key dimensions:

a) Food availability – the extent of local agricultural production and overall food supply.

b) Food access – the capacity of households to obtain food through purchasing power and distribution mechanisms.

c) Food utilization – the effective use of food, including dietary quality and nutritional practices.

d) Food stability – the maintenance of adequate availability and access across different periods.

Food security is closely associated with agricultural productivity, climate resilience, and the sustainable management of land resources. Recent literature highlights that demographic shifts and escalating environmental pressures pose significant threats to food security, thereby underscoring the need for integrated modeling approaches to address these challenges (Mulyani et al., 2021; Saleh & Suherman, 2021).

2) Agricultural Sustainability

Sustainable agriculture is commonly defined as a system of farming that addresses contemporary demands for food and resources while safeguarding the ability of future generations to satisfy their own needs (Pretty, 2008). Within the broader discourse of sustainable development, agricultural practices are required to integrate productivity with environmental stewardship and the promotion of social equity.

As emphasized by the World Bank (2019), the sustainability of agriculture is contingent upon farmers' adaptive capacities, the integration of technological innovation, and the presence of supportive institutional and policy frameworks. Hence, agricultural sustainability extends beyond technical considerations, encompassing interrelated social and economic dimensions. Prior works have modeled fertilizer use, pest control, and land management separately (Lestari & Rakhman, 2023; Wulandari & Hermawan, 2021), but few have combined these aspects within an integrated sustainability framework. This gap motivates the present study.

3) Triple Bottom Line (TBL) Approach in Agriculture

The Triple Bottom Line (TBL) framework, introduced by Elkington in 1997, provides a multidimensional perspective for evaluating organizational performance by integrating economic, social, and environmental considerations. Within the agricultural context, these dimensions are often articulated as:

a) People (Social) – encompassing farmer welfare, youth participation in agricultural activities, and broader public health outcomes.

b) Planet (Environmental) – addressing the consequences of farming practices on soil quality, water resources, and ecological systems.

c) Profit (Economic) – relating to cost efficiency, household income from farming, and the market value of agricultural products.

This framework underscores the importance of assessing agriculture through a holistic lens, ensuring that economic achievements are pursued in harmony with environmental sustainability and social justice (Molla et al., 2021; Anggraeni & Murnawan, 2024). In this study, TBL is used to structure the evaluation of fertilizer and pest management strategies, ensuring that interventions are assessed beyond short-term profit

4) System Dynamics

System dynamics represents a quantitative modeling approach developed to analyze complex systems characterized by feedback structures and behaviors that evolve over time (Sterman, 2000). In the context of agriculture, such systems are shaped by internal drivers—such as resource inputs, labor availability, and technological adoption—as well as external influences, including climate variability, policy frameworks, and market conditions. The central components of system dynamics comprise:

a) Stocks – the accumulation of resources or outputs (e.g., cultivated land, total production).

b) Flows – the rates at which resources or outputs change (e.g., planting, harvesting).

c) Feedback loops – causal interactions that shape future system behavior.

d) Delays – temporal gaps between actions and their observable consequences.

Through these elements, system dynamics enables the simulation of long-term policy outcomes and alternative strategies in agricultural systems (Salo & Kallio, 2023). Nonetheless, much of the existing research remains dependent on assumptions derived from literature rather than being substantiated with empirical data.

5) System Dynamics Model Validation

Validation plays a critical role in establishing the credibility of system dynamics models. Two evaluation metrics that are frequently employed include:

a) Mean Comparison Error

This indicator quantifies the average difference between simulated outcomes and observed data, expressed as:

$$E_1 = \frac{|\bar{S} - \bar{A}|}{\bar{A}}$$

Where:
$\bar{S}$ = mean value of the simulation results
$\bar{A}$ = mean value of the actual data
A model is generally regarded as valid when the error value does not exceed 5%.

b) Percentage of Variance Explained (%Variance)

This metric evaluates how effectively the model captures the variability present in the observed data, thereby indicating its explanatory strength. The calculation is expressed as:

$$E_2 = \frac{|Ss - Sa|}{Sa}$$

Ss = the standard deviation derived from the simulation outcomes.

Sa = the standard deviation obtained from the observed (actual) data.

A model is generally considered valid when the error value (E2) is less than or equal to 30%.

6) Linking SEM–PLS with System Dynamics

To strengthen methodological justification, this study combines SEM–PLS and system dynamics. SEM–PLS is first applied to farmer survey data to identify statistically significant constructs within the TBL dimensions. These constructs are then used to build the causal structure of the system dynamics model in STELLA. This integration ensures that the simulation reflects not only theoretical assumptions but also empirical evidence, addressing the gap in prior research where either statistical modeling or system dynamics was applied in isolation.

III. METHODOLOGY

This study applies a hybrid approach combining SEM–PLS and system dynamics modeling. SEM–PLS was used to identify significant sustainability constructs from farmer perceptions, while system dynamics captured feedback loops and long-term effects—offering advantages over static models. Data were collected through questionnaires from 120 farmers in Bungur Village (stratified by age, education, and crop type: rice 65%, shallots 22%, corn 13%). Reliability tests confirmed acceptable measurement quality (Cronbach's $\alpha > 0.70$; CR > 0.70; AVE > 0.50).

SEM–PLS results were then translated into STELLA stock–flow structures, for example: youth participation → *Active Farmer Population*, fertilizer practices → *Soil Fertility*, pest incidence → *Pest Population*. Three scenarios—semi-organic fertilizer, pest control, and combined intervention—were simulated for five years against a baseline. Model accuracy was assessed using mean comparison error ($E1 \leq 5\%$) and percentage of variance explained ($E2 \leq 30\%$), ensuring the reliability of the simulation before scenario testing.

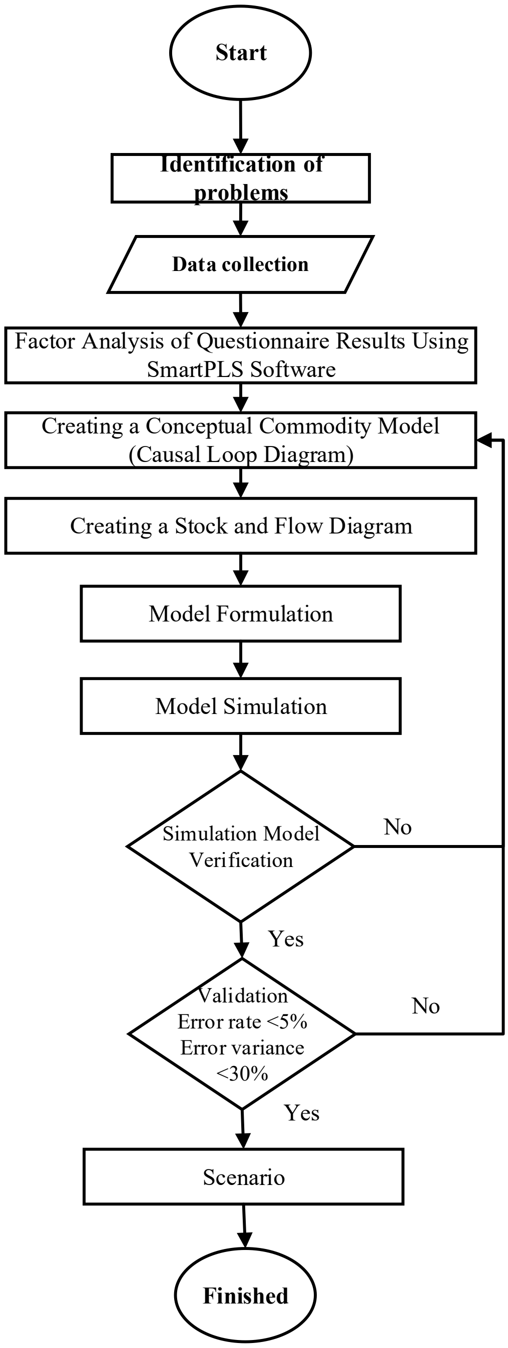

Figure 1 Flowchart Penelitian
(Source: Amanda, 2025)

IV. RESULTS AND DISCUSSION

1) SmartPLS Results and SEM Model

The application of Structural Equation Modeling (SEM) using SmartPLS with a formative model approach demonstrates that the sustainability and resilience of agriculture in Bungur Village are significantly shaped by three core constructs of the Triple Bottom Line (TBL) framework.

a) People (Social Dimension): Agricultural activities are largely carried out by elderly farmers, with minimal participation from younger generations. Moreover, access to updated agricultural knowledge and training remains limited.

b) Planet (Environmental Dimension): Intensive reliance on chemical fertilizers combined with the absence of standardized pest management practices has contributed to declining soil fertility and decreasing levels of agricultural productivity.

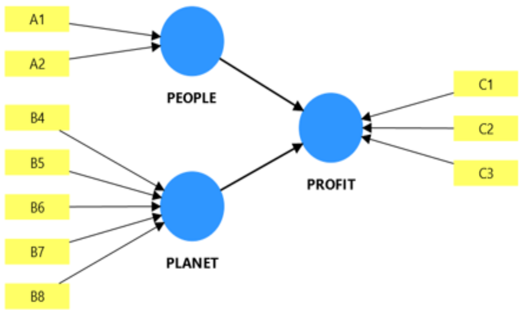

Figure 2 Model SmartPLS
(Source: Amanda, 2025)

Table 1 VIF Test Results
(Source: Amanda, 2025)

Construct	*Indicator*	*VIF*	*Criteria*
PEOPLE	A1	1.041	≤5
	A2	1.022	≤5
PLANET	B4	1.692	≤5
	B5	1.091	≤5
	B6	1.792	≤5
	B7	1.226	≤5
	B8	1.143	≤5
PROFIT	C1	3.138	≤5
	C2	3.250	≤5
	C3	4.195	≤5

The outer weights and VIF values from SmartPLS output indicate no significant multicollinearity among indicators. The adjusted R^2 value of the agricultural sustainability construct is adequately high, indicating strong model predictive power.

2) Causal Loop Diagram (CLD)

The Causal Loop Diagram (CLD) depicts the network of causal interrelationships among the key variables influencing the agricultural system in Bungur Village. It identifies two major types of feedback loops that define the dynamic behavior of the system.

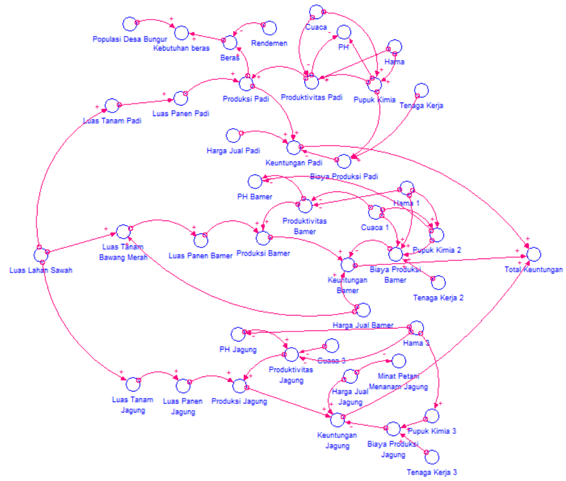

Figure 3 Causal Loop Diagram
(Source: Amanda, 2025)

3) Stock and Flow Diagram (SFD)

The Stock and Flow Diagram was designed with the support of STELLA software, applying the Triple Bottom Line (TBL) framework by dividing the model into three interconnected subsystems.

a) People

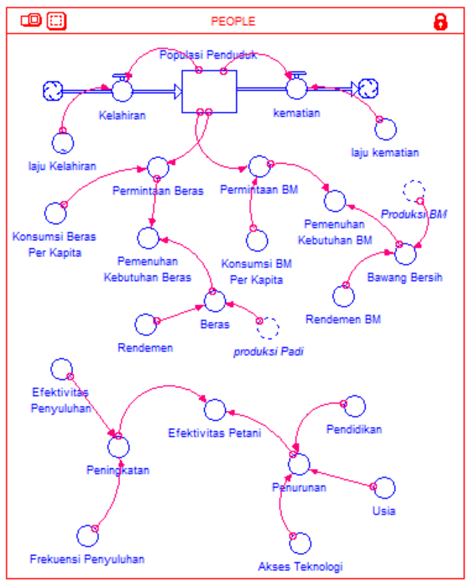

Figure 4 People Stock and Flow Diagram

(Source: Amanda, 2025)

b) Planet

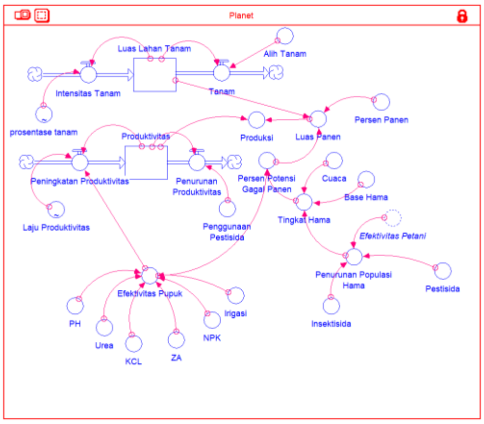

Figure 5 Planet Stock and Flow Diagram
(Source: Amanda, 2025)

c) Profit

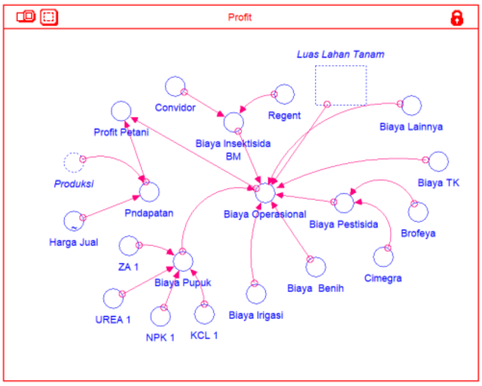

Figure 6 Profit Stock and Flow Diagram
(Source: Amanda, 2025)

4) Simulation Results: Baseline and Alternative Scenarios

The system was simulated over a five year period under four distinct conditions:

a) Baseline Model: Representation of the current situation without any intervention.
b) Scenario 1: Introduction of semi-organic fertilizer practices.
c) Scenario 2: Application of environmentally sustainable pest management methods.
d) Scenario 3: A combined strategy integrating the use of semi-organic fertilizers and eco-friendly pest control.

Simulation results are summarized below:

a) Productions (tons)

Figure 7 comparison of production results

The simulation results (Figure 8) show that production output increases most significantly under Scenario 3 (combined intervention), followed by pest control (Scenario 2), while semi-organic fertilizer alone (Scenario 1) gives a smaller improvement compared to the baseline. This indicates that pest management plays a stronger role in stabilizing yields.

b) Cost (million IDR)

Figure 8 comparison of operational costs

As presented in Figure 9, operational costs decrease most notably under Scenario 3. Pest control reduces crop losses and input waste, while the adoption of semi-organic fertilizers lowers dependence on expensive chemical inputs. The combined scenario demonstrates the most efficient cost reduction strategy compared to the baseline.

c) Profit per hectare (million IDR)

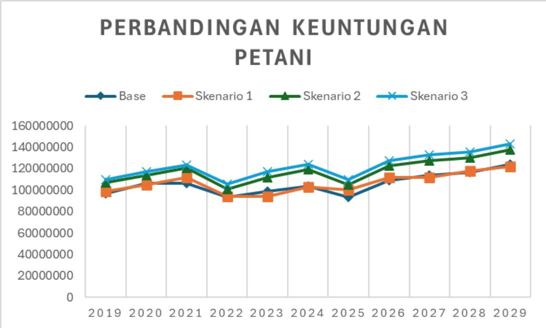

Figure 9 comparison of profits per hectare

Figure 10 highlights the effect of each intervention on farm profitability. Semi-organic fertilizer increases profit only marginally, pest control raises it more substantially, and the combined intervention yields the highest profit improvement. This confirms that integrated strategies are most effective for achieving economic sustainability.

The trend analysis indicates that Scenario 3 produces the most favorable outcomes, demonstrating notable improvements in both agricultural production and profitability, while simultaneously contributing to a reduction in operational expenses.

V. CONCLUSION

The findings of this study reveal that the sustainability of agriculture in Bungur Village is constrained by several key challenges, including the predominance of elderly farmers, heavy reliance on chemical fertilizers, and recurring pest infestations. Using a hybrid SEM–PLS and system dynamics approach within the Triple Bottom Line framework, the findings indicate that combining semi-organic fertilizer and pest control yields the most significant gains in productivity and profitability. Policy implications include the need for local governments and extension services to promote semi-organic fertilizer adoption through training and subsidies, institutionalize integrated pest management, and create incentives for youth participation in farming. The study is limited to a single village and self-reported data, suggesting that future research should expand to broader regions, incorporate climate and market uncertainties, and test policy scenarios to enhance generalizability.

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