System dynamics control simulation for sustainability of Indonesia's cocoa supply chain

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ABSTRACT

Indonesia's cocoa sector faces challenges in greenhouse gas emissions and smallholder income volatility. This study develops a system dynamics model to simulate the interrelationship between carbon emissions and economic performance across the cocoa value chain, identify leverage points, and evaluate alternative policy scenarios. The model integrates environmental and economic variables into dynamic feedback structures, enabling scenario-based assessment of intervention strategies. Five scenarios were simulated: composting cocoa waste increased farmer income by 2% and reduced farm-level emissions from 0.43 to 0.303 kg CO_2-eq/kg (29.79% total reduction); biogas conversion raised income by 13.56% and reduced emissions by 11%; converting cocoa waste into animal feed slightly increased income by 0.23% while cutting emissions by 58.6%; combining composting with improved transport efficiency reduced emissions by 14%; and integrating composting, logistics optimization, and government-supported input subsidies yielded the highest performance, with a 13.50% income increase and a 70% emission reduction. These results demonstrate that integrated, system-based interventions can enhance both economic resilience and environmental sustainability. The system dynamics model provides policymakers and supply chain actors with actionable insights for designing effective, climate-aligned strategies in Indonesia's cocoa industry.

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1. INTRODUCTION

Indonesia is one of the world's top cocoa bean producers, behind Côte d'Ivoire and Ghana, with an annual output of around 550 tons [1]-[3]. Cocoa, like other vital commodities like as palm oil, coffee, tea, and tobacco, makes a considerable contribution to the country's foreign exchange revenues [4]. However, Indonesia's cocoa supply chain is encountering increasingly complex and interconnected issues, notably at the upstream level with smallholder farmers [5], [6]. These concerns stem from long-standing environmental, social, and economic issues, including deforestation, child labor, and land degradation, as well as persistent farmer poverty and unequal value allocation [6].

Furthermore, global concerns about climate change and biodiversity loss have increased the need for sustainable practices in all economic sectors, including the cocoa industry [7]. While the expansion of cocoa planting provides economic opportunity for many tropical countries, it has resulted in significant environmental externalities [8]. Thus, with rising worldwide demand for chocolate, the cocoa sector must achieve a delicate balance between environmental stewardship and economic viability [7].

The environmental consequences of cocoa cultivation are widely established, with unsustainable farming practices contributing to soil deterioration, water contamination, and greenhouse gas emissions [8]. In response, long-term measures to minimize carbon emissions and sustainably manage the cocoa agro-industrial supply chain are increasingly recognized as critical, not only for ecological integrity but also for the long-term profitability of cocoa production systems [9], [10]. On the side of the economy, the vulnerability of agricultural incomes remains a major concern. This has resulted in the establishment of programs like the decent income community of practice, which aims to close structural income inequalities and ensure equitable pay for smallholder farmers [6]. Economic empowerment along the cocoa supply chain is critical to achieving overall sustainability goals.

To address these interconnected concerns, there is a growing interest in system-based techniques that can model and evaluate the dynamic interaction of environmental and economic elements. Green supply chain management (GSCM) has gained popularity as a conceptual framework for incorporating environmental issues into all stages of the supply chain, including reverse logistics. In parallel, system dynamics modeling provides a powerful methodological tool for simulating complex systems, allowing policy options to be developed and tested in the face of uncertainty and feedback [11]. System dynamics has also been positioned in engineering and computer science research as a control-oriented simulation environment that aids decision-making and optimization in complicated networks.

The integration of system dynamics modeling with the GSCM framework is a potential approach to understanding and managing trade-offs in sustainable cocoa production. This approach enables academics and decision-makers to investigate systemic interconnections, identify leverage points, and evaluate the impact of various interventions on supply chain players [12], [13]. Such integration is consistent with computational approaches to system optimization and control strategy design, both of which are becoming increasingly important for the development of sustainable industrial systems. Nonetheless, the existing body of research in this field is minimal. Most previous research either focuses exclusively on diagnostic assessments of sustainability challenges [14] or investigates actor-specific roles in GSCM implementation [15], without integrating these findings into a comprehensive, dynamic systems-based policy model.

This study fills that gap by creating a dynamic systems model based on the GSCM viewpoint that assesses both environmental and economic sustainability in the cocoa supply chain. The methodological innovation is the integrative application of system dynamics modeling to operationalize GSCM ideas in a comprehensive and adaptive policy simulation framework. This approach highlights how system-based simulation can be used in engineering and computer science to build successful intervention methods by acting as a computational decision-support and control-oriented modeling tool. Employing this approach, the study aims to provide concrete recommendations that will assist stakeholders in planning and implementing strategies for a low-carbon and economically resilient cocoa supply chain in Indonesia. As a result, the goal of this research is to develop a system dynamics model that simulates the interrelationship between carbon emissions and economic performance in the cocoa value chain, identifies leverage points, and evaluates alternative policy scenarios to support the long-term transformation of Indonesia's cocoa industry.

2. METHOD

2.1. Data collection

This study employs system dynamics to model the cocoa supply chain by integrating key environmental variables (e.g., carbon emissions) and economic metrics (e.g., prices and farmer income). Data were synthesized from diverse primary and secondary sources, spanning 2017 to 2023, to capture recent market and environmental trends. To ensure methodological rigor, the study utilized purposive sampling for stakeholder interviews and cross-validated data to minimize bias. Furthermore, sensitivity analysis was conducted to assess model robustness against parameter uncertainties, establishing a valid foundation for policymakers and researchers to design effective sustainability interventions.

2.2. Model development process

2.2.1. Conceptual model development (causal loop diagram)

The development of a system dynamics model seeks to reflect the intricate interrelationships between environmental and economic aspects in the cocoa supply chain. The model combines crucial variables, mathematical relationships, and feedback loops to describe the system's structure and behavior. Scenario-based simulations are used to investigate prospective interventions, such as sustainable farming methods, market volatility, and policy implementation, and to assess their environmental and economic consequences. This approach allows for the discovery of leverage points that can boost the overall sustainability of the cocoa supply chain [4].

Carbon emissions from the cocoa supply chain are not restricted to farming activities. They are also produced by waste collection, wood burning, chocolate processing, packaging, electricity and water consumption, and transportation. Farmers are notably associated with significant emission risks during land cultivation, and the processing step contributes through machinery use [16]. Collectors often oversee distribution and transportation activities, which lead to additional carbon emissions [17]. These problems highlight the importance of emission reduction methods throughout the cocoa agro-industry, with a focus on production efficiency and ecologically responsible practices.

This study uses a system dynamics modeling approach to assess the connections between carbon emissions, supply chain activities, and overall system performance. The model incorporates a number of critical characteristics to simulate real-world behavior. Figure 1 depicts way a causal loop diagram (CLD) is used to display and evaluate the cocoa supply chain's dynamic feedback structures.

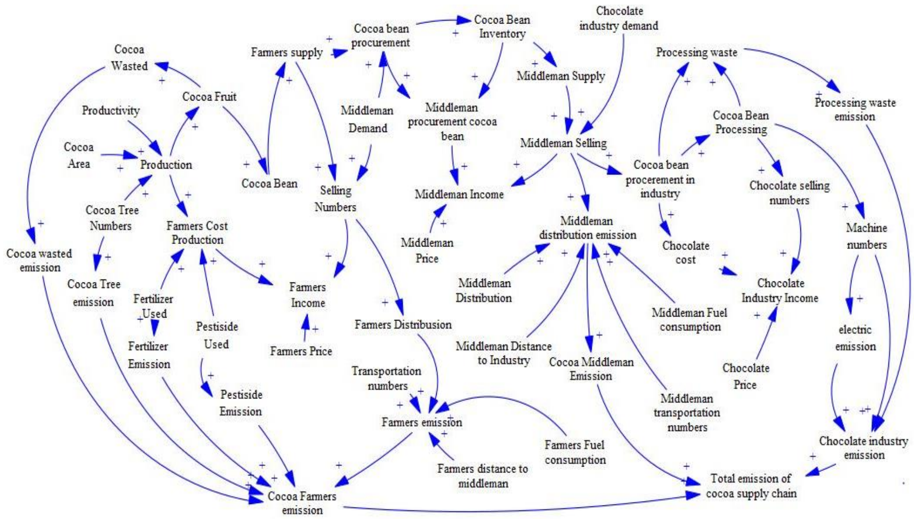


Figure 1. CLD of the Indonesian cocoa supply chain

The CLD, which depicts the key players and relationships in Indonesia's sustainable cocoa supply chain. The production system, economy, and environment are the three interconnected domains.
- Production system: this component explains how materials move via each supply chain participant's procedures. The flow of supplies from farmers to collectors and ultimately to the chocolate business is highlighted [4].
- Economy: this component describes the flow of expenses and income related to each actor's actions. It offers information about the supply chain's financial stability and economic transactions [18].
- Environment: this component focuses on the byproducts that each actor's supply chain operations produce. It takes into account the effects on the environment, including emissions and trash generated during the stages of cocoa production and processing [4].

Farmers, middlemen, and the chocolate industry are the three primary supply chain actors that make up the CLD, and they all contribute to the system's dynamic behavior. By examining these variables and their interrelationships, the CLD reveals the feedback loops that govern the system's behavior. The reinforcing loops (e.g., higher production → higher income → increased input use → higher productivity) illustrate growth dynamics, while balancing loops (e.g., increased emissions → environmental costs → reduced sustainability) capture trade-offs between economic performance and environmental sustainability. The descriptions and definitions of key variables used in the CLD are presented in Table 1 to provide detailed clarity and facilitate model interpretation.

2.2.2. Quantitative model formulation (stock-flow diagram)

Building on the previously described CLD, a system dynamics model of the cocoa supply chain was created utilizing a stock-flow diagram (SFD) to capture the flow of materials, emissions, and economic activity within the system. The SFD model was built on several key assumptions. First, the model takes into account only three major actors in the cocoa supply chain: farmers, middlemen, and the chocolate processing sector. At the farmer level, the model focuses entirely on the conversion of cocoa pods into dry cocoa beans, leaving out deforestation-related activities. At the intermediary level, only distribution and transportation activities are evaluated. At the chocolate industry level, the model accounts for cocoa bean processing activities but does not include the transportation of additional raw ingredients or downstream sales distribution.

The model has three interconnected dimensions: production process, economic flow, and environmental impact. In the economic aspect, only raw material costs and selling prices are taken into account, while other operational expenditures such as labor and maintenance are excluded for simplicity. Field observations, statistical data from Indonesian statistic (*Badan Pusat Statistik* / BPS), industry reports, and relevant literature were used to determine parameter values and input data for the SFD, whereas emission coefficients were taken from the intergovernmental panel on climate change (IPCC) [19] database. Figure 2 shows the SFD, which was created using Vensim decision support system (DSS) software. This Figure 2 depicts the dynamic interactions of critical factors, allowing quantitative simulation and scenario analysis. Table 2 shows the mathematical equations, parameter definitions, and functional relationships employed in the model.

Table 1. Definition of key variables in the CLD

No.	Variable	Description	Domain	Actor
1	Cocoa area	Total land area used for cocoa cultivation	Production	Farmer
2	Cocoa tree numbers	Number of productive cocoa trees	Production	Farmer
3	Productivity	Yield of cocoa fruit per tree	Production	Farmer
4	Cocoa production	Total volume of cocoa fruit harvested	Production	Farmer
5	Cocoa bean	Dried cocoa bean output after post-harvest processing	Production	Farmer
6	Farmers price	Selling price per kilogram of cocoa beans	Economy	Farmer
7	Farmers income	Net income obtained from cocoa sales	Economy	Farmer
8	Fertilizer used	Amount of fertilizer applied per production cycle	Environment	Farmer
9	Pesticide used	Amount of pesticide applied	Environment	Farmer
10	Fertilizer/pesticide emission	Emissions generated from chemical input usage	Environment	Farmer
11	Cocoa wasted emission	Emission from unharvested or spoiled cocoa fruit	Environment	Farmer
12	Farmers fuel consumption	Fuel used for transport and farming activities	Environment	Farmer
13	Middleman procurement	Volume of cocoa beans purchased from farmers	Production/economy	Middleman
14	Middleman income	Revenue obtained from reselling cocoa beans	Economy	Middleman
15	Middleman fuel consumption	Fuel used for transportation and distribution	Environment	Middleman
16	Middleman distribution emission	Emissions from transportation and logistics	Environment	Middleman
17	Cocoa bean inventory	Stock of cocoa beans available for processing	Production	Industry
18	Cocoa bean processing	Conversion of dried beans into chocolate	Production	Industry
19	Processing waste	Waste generated during production	Environment	Industry
20	Chocolate price	Selling price of chocolate products	Economy	Industry
21	Chocolate income	Total revenue from chocolate sales	Economy	Industry
22	Electric emission	Emission from electricity used in production	Environment	Industry
23	Total emission of cocoa supply chain	Aggregated emission from all actors	Environment	System-wide

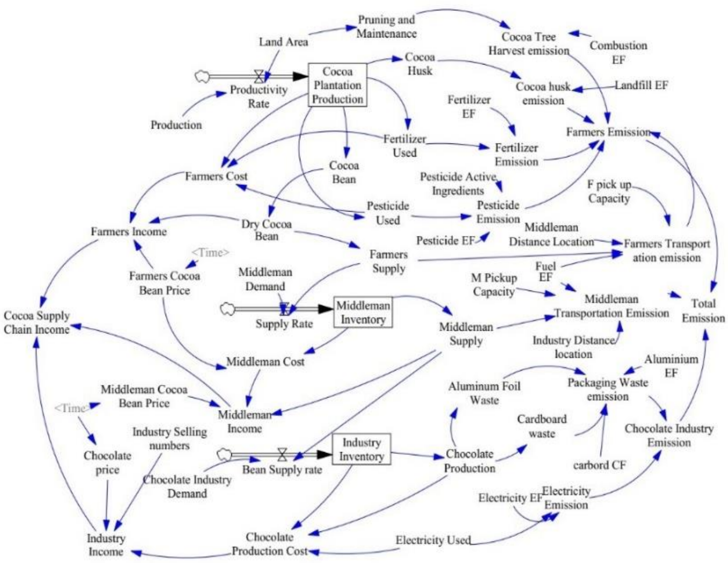


Figure 2. SFD of the Indonesian cocoa supply chain

Table 2. Variables, parameters, and functional relationships in the cocoa supply chain system dynamics model

Variable name	Function of time	Variable name	Function of time
Land area	5.04 Ha	Chocolate price	IDR 50000 * time
Production	800 Tons	Industry selling numbers	RANDOM NORMAL (1000, 3000, 1750, 2, 5)
Productivity rate	Production/land area	Industry income	(Industry selling numbers * chocolate price) - Chocolate production cost
Cocoa plantation production	INTEG (productiviy rate) Initial value = 4750 Tons	Cocoa supply chain income	(Farmers income + Industry income + middleman income)
Cocoa bean	Cocoa plantation production * 0.27 (0.27 → fraction of total cocoa fruit converted into dried cocoa)	Pruning and maintenance	0.13 * land area (0.13 → 13% of total plantation area requires maintenance annually)
Fertilizer used	Cocoa plantation production * 1.13 (1.13 → average fertilizer uses per ton of production (1.13 kg/kg product))	Factor emissions (EF)#	– Combustion EF = 58 kg CO_2e/L – Fertilizer EF = 0.2 kg CO_2e/kg – Landfill EF = 46 kg CO_2e/kg – Pesticide EF = 0.262 kg CO_2e/kg – Fuel EF = 21.2 kg CO_2e/L – Aluminum EF = 1.721 kg CO_2e/kg – Carboard EF = 0.46 kg CO_2e/kg – Electricity EF = 0.774 kg CO2e/kWh
Pesticide used	Cocoa plantation production * 0.0004 (0.0004 → average pesticide use per ton of production (0.0004 kg/kg))	Cocoa tree harvest emission	Pruning and maintenance * EF combustion
Farmers cost	(Cocoa plantation production * IDR 5073) + (fertilizer used*IDR 3118) + (pesticide used * IDR 17)	Cocoa husk	Cocoa plantation production * 0.73 (0.73 → cocoa fruit waste fraction (husk portion))
Dry cocoa bean	Cocoa bean * 0.29 (0.29 → share of cocoa beans that become dried, marketable product)	Cocoa husk emission	Cocoa husk * landfill EF
Farmers cocoa bean price	IDR 35000 * time	Fertilizer emission	Fertilizer used * fertilizer EF
Farmers income	(Dry cocoa bean * farmers cocoa bean price) - farmers cost	Pesticide active ingredients	0.189 (Fraction of active chemical in total pesticide mass)
Middleman demand	RANDOM NORMAL (1300, 1700, 1400, 20, 30)	Pesticide emission	Pesticide used * pesticide active ingredients*pesticide EF
Farmers supply	Dry cocoa bean	Middleman distance location	28.2 Km
Supply rate	Farmers supply/middleman demand	Farmer pick up capacity	907 Tons
Middleman inventory	INTEG (supply rate) Initial value = 1000	Farmers transportation emission	IF THEN ELSE (farmers supply / pick up capacity ≥ 1, Farmers supply / pick up capacity, 1) *(middleman distance location * 2/12.3) * fuel EF
Middleman cost	Farmers cocoa bean price + (middleman inventory * 1000)	Farmers emission	Cocoa husk emission + cocoa tree harvest emission + farmers transportation emission + fertilizer emission + pesticide emission
Middleman supply	Middleman inventory * 0.9 (0.9 → fraction of inventory that can be sold to industry)	Middleman pick up capacity	2 unit
Middleman cocoa bean price	IDR 37000 * time	Industry distance location	1 Km
Middleman income	(Middleman cocoa bean price * middleman supply) - middleman cost	Middleman transportation emission	IF THEN ELSE (middleman supply / pick up capacity ≥ 1, middleman supply / pick up capacity, 1) * (industry distance location * 2/12.3) * fuel EF
Chocolate industry demand	RANDOM NORMAL (100, 500, 250, 2, 30)	Aluminum foil waste	0.2*chocolate production (20% of total packaging weight made of aluminum foil)
Bean supply rate	Middleman supply/chocolate industry demand	Carboard waste	0.0001 * chocolate production (0.01% of total packaging weight in cardboard form)
Industry inventory	INTEG (bean supply rate) Initial value = 700	Packaging waste emission	(Aluminum foil waste * aluminum EF) + (cardboard waste * carbord EF * 0.9* 0.01 * 0.58 * (44/12))
Chocolate production	(Industry inventory + (industry inventory * 0.2)) * 45	Electricity emission	Electricity used * electricity EF
Electricity used	RANDOM NORMAL (200, 500, 250, 5, 201	Chocolate industry emission	Electricity emission + packaging waste emission
Chocolate production cost	(Chocolate production * IDR 10000) + (Electricity used * IDR 2200) + (Industry inventory * IDR 18889)	Total emission	Farmers emission + middleman transportation emission + chocolate industry emission

Notes:
– Data without the symbol (#) were obtained from field observations and interviews with actors in the cocoa supply chain.
– Data marked with the symbol (#) were sourced from the IPCC [19] and Zakcy [20].

Each variable is represented as a time-dependent function, connected by algebraic and integral equations that embody the cumulative and feedback-based aspects of system dynamics modeling. Each emission component is approximated as the product of activity levels (e.g., fertilizer use, fuel consumption, and trash generation) and the corresponding emission factors shown in Table 2. The "IF THEN ELSE" logic was used to express conditional relationships like transit capacity and distance thresholds.

To determine broader applicability, this modeling approach can be used to other agricultural commodities with similar production-to-processing flows, such as coffee, palm oil, or rubber, by modifying parameters. However, its current structure assumes homogeneous agent behavior and static price elasticity, which may restrict its ability to capture regional diversity and market volatility. Future improvements may include stochastic demand modules or regional land-use change dynamics to improve robustness and generalizability.

2.2.3. Model validity test

To ensure the reliability of the developed model, a series of validation tests were conducted. The validation process includes structural validation and behavioral–statistical validation, as described below.

a. Structural model test

The structural validation process seeks to ensure that the model's structure and causal links correspond to the actual system. The test involved comparing the logical consistency of feedback loops, variable interactions, and causal directions to recognized theories and field practices. This verification was conducted using; 1) literature research on system dynamics modeling, cocoa production systems, and supply chain economics, and 2) consultations with cocoa cultivation, industry operations, and sustainable supply chain experts. Expert assessors analyzed and confirmed the sub-models for cocoa farming, intermediary activities, and chocolate production, verifying the model's conceptual soundness and realism.

b. Behavioral and statistical validation

Behavioral validation was carried out by comparing simulation results to historical data from 2017 to 2023 for important variables, specifically cocoa production volume. Historical data were sourced from the BPS and industry reports, and simulated results were generated using the established model under baseline conditions. Table 3 summarizes the comparative results, demonstrating the tight alignment of simulated and actual production trends. Model correctness was evaluated quantitatively using the mean absolute percentage error (MAPE) approach. A model is considered valid if the MAPE is less than 10%. As shown in Table 3, the calculated MAPE value of 2% demonstrates an outstanding match between simulated and historical data, validating the model's capacity to replicate real-world behavior.

Table 3. Model validation results

Time (year)	Cocoa production		MAPE (%)
	Data (Kg)	Simulation (Kg)	
2017	4,750	4,750	0
2018	4,900	4,908.73	0
2019	5,040	5,067.46	1
2020	5,040	5,226.19	4
2021	5,238	5,384.92	3
2022	5,338	5,543.65	4
2023	5,567	5,702.38	2
MAPE (%) (E1)			2
STDEV (%) (E2)			1.7

Cross-validation was performed by comparing the generated model's environmental performance findings to existing life cycle assessment (LCA) studies. Because one of the modeling features of this study is environmental effect estimation, LCA was employed as a baseline for emission levels. According to Miharza *et al.* [21], cocoa cultivation without deforestation generates approximately 2.18 kg CO_2-eq per kg of cocoa beans, while Neira [22] reported that chocolate production produces around 2.82 kg CO_2-eq per kg. The emission findings produced by the system dynamics model are within this range, indicating good agreement and validating the model's external validity. Table 4 presents a detailed comparison of the system dynamics simulation and LCA-based emission values using annual data.

The MAPE result for comparing the simulation and LCA models at the farmer level is 6.18% (<10%), with a standard deviation of 0.01% (<30%). For the chocolate production stage, the MAPE value is 1.57%, with a standard deviation of 0.06%. All results fall well under acceptable error thresholds, indicating that the model has a high level of accuracy and can be deemed valid and dependable for simulation and policy analysis.

Table 4. Model validation based on simulation compared to LCA method

Time (year)	Dry cocoa bean simulation model (Kg)	Farmer emission simulation model (Kg CO_2)	Emission according to LCA method (Kg CO_2)	MAPE (%)	Chocolate production: existing (Kg)	Industry emission simulation model (Kg CO_2)	Emission according to LCA method (Kg CO_2)	MAPE (%)
2017	371925	160713	170607.8	6.16	13207.9	37800	37246.3	1.46
2018	384354	166079	176309.2	6.16	13270.2	37995.1	37422.0	1.51
2019	396782	171445	182010.1	6.16	13329.5	38188.7	37589.2	1.57
2020	409211	176811	187711.5	6.17	13408.5	38383.9	37812.0	1.49
2021	421639	182177	193412.4	6.17	13471.7	38580.2	37990.2	1.53
2022	434068	187544	199113.8	6.17	13541	38774.4	38185.6	1.52
2023	446496	192910	204814.7	6.17	13611.9	38968.6	38385.6	1.50
2024	458925	198276	210516.1	6.17	13676.9	39164.4	38568.9	1.52
2025	471354	203642	216217.4	6.18	13737.9	39360.2	38740.9	1.57
2026	483782	209008	221918.3	6.18	13810.4	39554.5	38945.3	1.54
2027	496211	214374	227619.7	6.18	13881.3	39750.8	39145.3	1.52
2028	508639	219740	233320.6	6.18	13945.2	39949.1	39325.5	1.56
2029	521068	225106	239022	6.18	14012.4	40143.9	39515.0	1.57
2030	533496	230472	244722.9	6.18	14078	40341.5	39700.0	1.59
2031	545925	235838	250424.3	6.18	14147.1	40536.3	39894.8	1.58
2032	558354	241204	256125.7	6.19	14214.9	40732.7	40086.0	1.59
2033	570782	246570	261826.6	6.19	14282.6	40927	40276.9	1.59
2034	583211	251936	267528	6.19	14342.5	41121.6	40445.9	1.64
2035	595639	257302	273228.9	6.19	14406.2	41315.4	40625.5	1.67
2036	608068	262668	278930.3	6.19	14479	41509.4	40830.8	1.63
2037	620496	268034	284631.2	6.19	14545.9	41706.1	41019.4	1.65
2038	632925	273400	290332.6	6.19	14615.2	41899.8	41214.9	1.63
2039	645354	278766	296033.9	6.19	14687.2	42097.1	41417.9	1.61
2040	657782	284132	301734.9	6.20	14755.7	42292.8	41611.1	1.61
MAPE (%)				6.18	MAPE (%)			1.57
STDEV (%)				0.01	STDEV (%)			0.06

2.2.4. Sensitivity model

In dynamic modeling, sensitivity analysis entails determining how minor adjustments to the model's parameters may affect the model's output. In dynamic modeling, which frequently deals with complex systems and time-based interactions, this is especially crucial. Sensitivity testing aids in determining how resilient the model is to parameter changes and uncertainty [23]. Since farmer emissions are the most dynamic element of the environmental subsystem and are immediately impacted by production inputs including fertilizer, pesticides, and transportation fuel, they were chosen as the primary variable for sensitivity analysis in this study. Secondary data was used to validate the emission factor parameter values [19], [20]. To evaluate how the model might react to different emission situations, three simulated scenarios were created.

The sensitivity analysis supports the model's structural robustness and logical consistency under different input intensities. Figure 3 shows that the 'extreme high' scenario, which involves intense use of fertilizers, pesticides, and fuel, leads to much higher emission trajectories than the baseline, exceeding 400,000 Kg CO_2 by 2040. Figure 4 confirms baseline stability under normal field conditions. Figure 5 shows that 'extreme low' conditions, which reflect improved farming practices and lower input intensity, effectively kept emissions below the existing baseline. In all scenarios, the model demonstrates monotonic behavior with no chaotic oscillations, indicating that the simulation accurately depicts the causal links within Indonesia's cocoa supply chain and remains stable even under boundary circumstances.

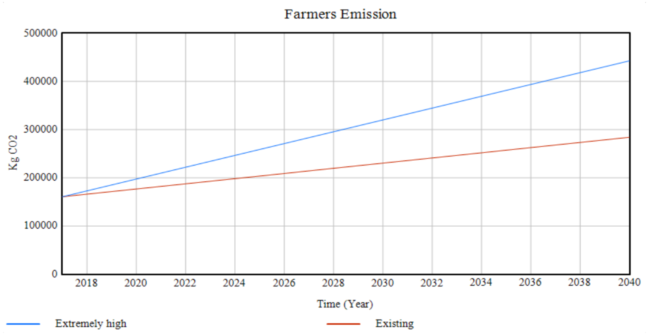


Figure 3. Farmers emission on high extreme sensitivity test

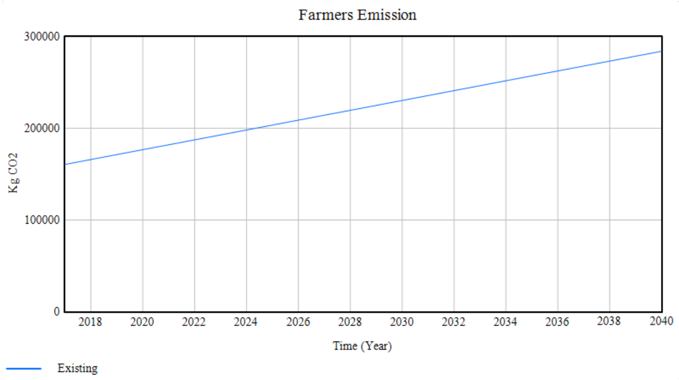


Figure 4. Farmers emission on normal condition sensitivity test

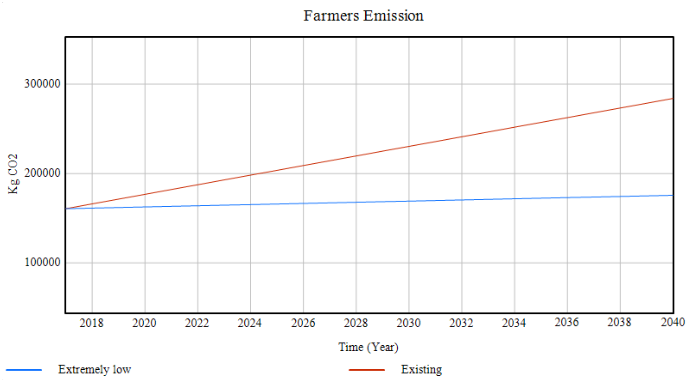


Figure 5. Farmers emission on low extreme sensitivity test

3. RESULTS AND DISCUSSION

3.1. Baseline simulation under existing conditions

Before adopting scenario-based interventions, a baseline simulation was run to determine the existing trend of carbon emissions in Indonesia's coco a supply chain. Figure 6 depicts expected emissions over the next 16 years, exhibiting a steady increase trend that leads to a growing carbon footprint. Consistent with Gao *et al.* [24], the carbon footprint of chocolate products includes all stages of the life cycle, from agriculture to processing, distribution, consumption, and end-of-life management, such as reuse or disposal. As a result, emission reduction at all stages is critical to achieving sustainable production and meeting national climate targets.

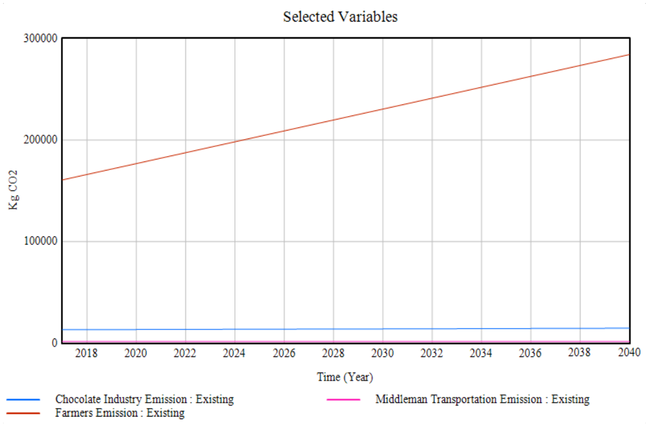


Figure 6. Baseline simulation under existing conditions

According to the current system, the model calculates carbon emissions at each supply chain level as follows: Cocoa farmers emit 0.43 kg CO_2-eq per kg, whereas middlemen emit 0.0017 kg CO_2-eq per kg. The chocolate processing sector emits 2.86 kg CO_2-eq per kg. These findings show that the processing stage accounts for the majority of emissions, emphasizing the importance of industrial processes in determining the overall carbon footprint. For supply chain participants, this means that interventions focused exclusively on cultivation or distribution may have little impact unless paired with efficiency improvements and emission reduction initiatives at the processing stage.

Unchecked emissions in the cocoa supply chain may result in four critical consequences. First, climate-induced variations in rainfall and temperature can reduce cocoa productivity and quality. Second, the overuse of inorganic fertilizers can accelerate soil degradation, affecting long-term land fertility. Third, biodiversity loss may occur due to deforestation and widespread agrochemical application [25], [26]. Fourth, socio-economic impacts, including reduced farmer income and potential exposure to carbon taxation in jurisdictions with regulatory frameworks, may arise [27], [28].

In Indonesia, the cocoa sustainability partnership (CSP) serves as a key multi-stakeholder mechanism to promote sustainability across the cocoa value chain. The CSP framework emphasizes six strategic blocks: agro-inputs, planting materials, knowledge dissemination, delivery mechanisms, financing, and government participation. Aligned with these objectives, this study formulates scenario-based interventions targeting three CSP blocks: 1) agro-input optimization through the application of compost derived from cocoa cultivation waste, aimed at increasing land productivity and farmer income; 2) knowledge enhancement to improve farmer skills, technical capacity, and professionalism; and 3) organizational efficiency via upgraded logistics and transportation practices. These interventions provide a system-oriented and evidence-based pathway for reducing emissions while strengthening farmer livelihoods, ensuring alignment with sustainability goals and supporting the long-term resilience of Indonesia's cocoa industry.

3.2. Scenario development and simulation result

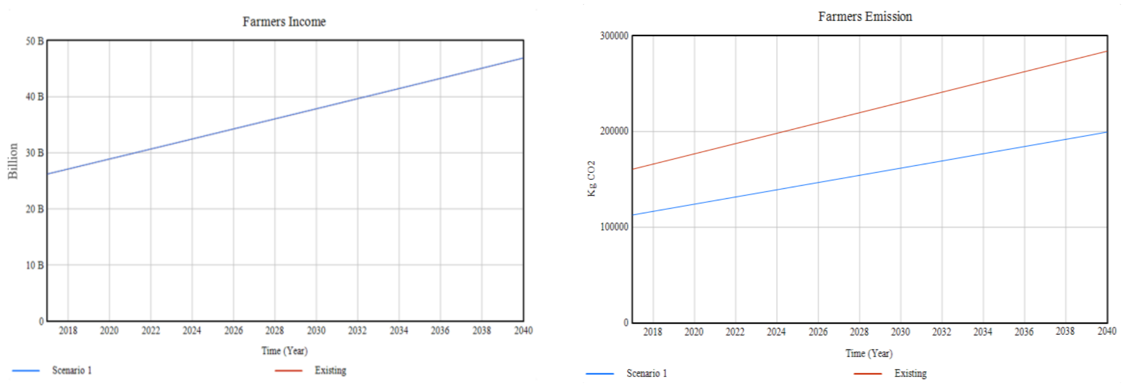
Based on the validated system dynamics model, five intervention scenarios were simulated to evaluate their impact on carbon emissions and farmer income in the cocoa supply chain. The scenarios were designed to integrate circular economy principles and policy interventions, thereby aligning environmental sustainability with socio-economic benefits. The simulated strategies include: 1) utilization of cocoa farming waste as organic compost, 2) conversion of cocoa waste into biogas, 3) use of cocoa waste as animal feed, 4) emission reduction in logistics and processing, and 5) reduction of input costs through financial support for fertilizers and pesticides, combined with profitable waste utilization practices.

Scenarios 1-3 emphasize waste valorisation throughout the production stage. Cocoa pod husk, cocoa mucilage, and cacao bean shell. The cocoa pod husk, which accounts for 70-80% of fruit weight, is made up of four separate layers (epicarp, mesocarp, sclerotic layer, and endocarp) that are rich in bioactive chemicals. Cocoa mucilage, a sticky white layer around the beans, contains fermentable sugars and vital minerals, whereas cacao bean shell, which accounts for 10-20% of bean weight, creates the cocoa bean's protective outer covering and includes antioxidant chemicals [29], [30]. Valorizing waste by-products as compost, biogas, or animal feed can lessen environmental impact while diversifying revenue streams. The simulation results investigate the potential for these measures to improve both ecological resilience and farmer welfare.

3.2.1. Scenario 1: utilization of cocoa farming waste as organic compost

The simulation results indicate that scenario 1 increases farmer income by 2% while reducing farm-level emissions from 0.43 to 0.303 kg CO_2-eq per kg, contributing to a 29.79% (~30%) decline in total supply chain emissions (see Figure 7). Figure 7(a) illustrates the projected increase in farmer income, whereas Figure 7(b) shows the corresponding reduction in carbon emissions across the farm level. These findings demonstrate that composting cocoa by-products into organic fertilizers is both economically and environmentally advantageous. Economically, the practice reduces reliance on costly synthetic fertilizers, lowering production expenses and strengthening household resilience [31]. Environmentally, the valorization of cocoa pod husks and cocoa bean shells diverts substantial biomass from uncontrolled decomposition or open burning-major sources of carbon emissions, while simultaneously improving soil fertility [32], [33]. Detailed simulation data supporting this analysis are provided in Table 5.

Although organic fertilizers may require larger volumes to achieve nutrient balance, their effectiveness has been enhanced through forage-based additives [31], [34]. They also improve soil microbial activity, cation exchange capacity, and moisture retention, supporting long-term yield improvements [35]. For farmers, these benefits translate into more sustainable production practices, reduced input costs, and stabilized yields, which collectively improve income security and resilience to market or environmental fluctuations [36], [37].



(a) (b)

Figure7. Simulation results of scenario 1: (a) farmer income model and (b) carbon emission model

Table 5. Comparison simulation of farmer income and emission in existing condition and scenario 1

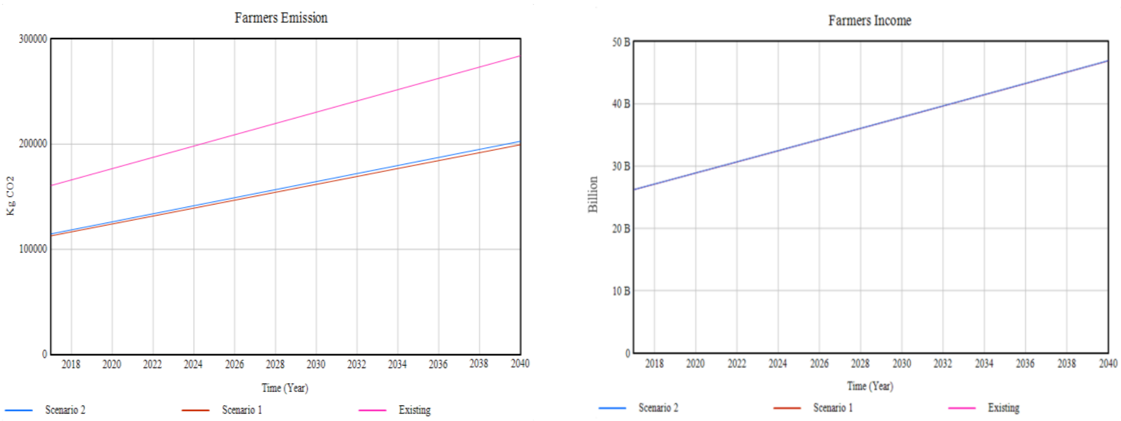
Time (year)	Farmers income: existing (IDR)	Farmers income: scenario 1 (IDR)	Farmers emission: existing (Kg CO_2)	Farmers emission: scenario 1 (Kg CO_2)
2017	2,62E+15	2,62E+14	160713	112845
2018	2,71E+15	2,71E+15	166079	116612
2019	2,80E+14	2,80E+15	171445	120379
2020	2,89E+15	2,89E+15	176811	124146
2021	2,98E+15	2,98E+15	182177	127913
2022	3,07E+15	3,07E+15	187544	131680
2023	3,16E+15	3,16E+15	192910	135447
2024	3,25E+15	3,25E+15	198276	139214
2025	3,34E+15	3,34E+15	203642	142981
2026	3,43E+15	3,43E+14	209008	146748
2027	3,51E+15	3,52E+15	214374	150515
2028	3,60E+15	3,61E+14	219740	154282
2029	3,69E+15	3,70E+15	225106	158049
2030	3,78E+15	3,79E+15	230472	161816
2031	3,87E+15	3,88E+15	235838	165583
2032	3,96E+15	3,97E+15	241204	169350
2033	4,06E+15	4,06E+15	246570	173117
2034	4,15E+15	4,15E+15	251936	176884
2035	4,24E+14	4,24E+15	257302	180651
2036	4,33E+15	4,33E+15	262668	184418
2037	4,42E+15	4,42E+15	268034	188185
2038	4,51E+14	4,51E+15	273400	191952
2039	4,60E+15	4,60E+15	278766	195719
2040	4,69E+15	4,69E+15	284132	199486
Average	3,22E+15	3,29E+15	2,22E+05	1,56E+05
	Difference	7,19E+13	Difference	6,63E+04
	Percentage	2.23%	Percentage	29.79%

From a supply chain perspective, this intervention indirectly benefits middlemen and processors by ensuring a more consistent quality and quantity of cocoa beans, which reduces supply volatility and enhances the predictability of downstream operations. To support the wider adoption of this practice, scaling the intervention would benefit from farmer training programs, community-level composting facilities, and sustainable certification schemes that reward environmentally friendly practices.

Although composting requires additional labor, representing a minor trade-off in operational efficiency, the long-term benefits clearly outweigh these costs [38]. These benefits include reduced carbon emissions, improved soil health, and more stable farmer incomes. Overall, scenario 1 demonstrates that composting as a waste-focused intervention can effectively support the economic, environmental, and social dimensions of sustainability, making it a practical and impactful strategy for promoting sustainable cocoa production in Indonesia.

3.2.2. Scenario 2: conversion of cocoa waste into biogas

The simulation results indicate that scenario 2 increases farmer income by approximately 13.56% and reduces farm-level emissions from an average of 222,000 kg CO_2-eq/year (existing) to 159,000 kg CO_2-eq/year, contributing to an 11% decline in total supply chain emissions (see Figure 8). Figure 8(a) illustrates the projected increase in farmer income, whereas Figure 8(b) shows the corresponding reduction in carbon emissions across the farm level. These findings demonstrate that anaerobic digestion of cocoa by-products is highly effective in simultaneously mitigating emissions and providing renewable energy for rural communities. Economically, the significant increase in farmer income highlights the attractiveness of this intervention at the community level, while the substantial emission reduction underscores its strong climate mitigation potential. Detailed simulation data supporting this analysis are provided in Table 6.



(a) (b)

Figure 8. Simulation results of scenario 2: (a) farmer income model and (b) carbon emission model

Table 6. Comparison simulation of farmer income and emission in existing condition and scenario 2

Time (year)	Farmers emission: existing (Kg CO_2)	Farmers emission: scenario 1 (Kg CO_2)	Farmers emission: scenario 2 (Kg CO_2)	Farmers income: existing (IDR)	Farmers income: scenario 1 (IDR)	Farmers income: scenario 2 (IDR)
2017	160713	112845	114689	2,62E+15	2,62E+14	2,62E+15
2018	166079	116612	118517	2,71E+15	2,71E+15	2,71E+15
2019	171445	120379	122346	2,80E+14	2,80E+15	2,80E+15
2020	176811	124146	126174	2,89E+15	2,89E+15	2,89E+15
2021	182177	127913	130003	2,98E+15	2,98E+15	2,98E+15
2022	187544	131680	133832	3,07E+15	3,07E+15	3,07E+15
2023	192910	135447	137660	3,16E+15	3,16E+15	3,16E+15
2024	198276	139214	141489	3,25E+15	3,25E+15	3,25E+15
2025	203642	142981	145317	3,34E+15	3,34E+15	3,34E+15
2026	209008	146748	149146	3,43E+15	3,43E+14	3,43E+15
2027	214374	150515	152975	3,51E+15	3,52E+15	3,52E+15
2028	219740	154282	156803	3,60E+15	3,61E+14	3,61E+15
2029	225106	158049	160632	3,69E+15	3,70E+15	3,70E+15
2030	230472	161816	164460	3,78E+15	3,79E+15	3,79E+15
2031	235838	165583	168289	3,87E+15	3,88E+15	3,88E+15
2032	241204	169350	172118	3,96E+15	3,97E+15	3,97E+15
2033	246570	173117	175946	4,06E+15	4,06E+15	4,06E+15
2034	251936	176884	179775	4,15E+15	4,15E+15	4,15E+15
2035	257302	180651	183603	4,24E+14	4,24E+15	4,24E+15
2036	262668	184418	187432	4,33E+15	4,33E+15	4,33E+15
2037	268034	188185	191260	4,42E+15	4,42E+15	4,42E+15
2038	273400	191952	195089	4,51E+14	4,51E+15	4,51E+15
2039	278766	195719	198918	4,60E+15	4,60E+15	4,60E+15
2040	284132	199486	202746	4,69E+15	4,69E+15	4,69E+15
Average	2,22E+05	1,56E+05	1,59E+05	3,22E+15	3,29E+15	3,66E+15
Difference		6,63E+04	6,37E+04	Difference	7,19E+13	4,37E+14
Percentage		-29.79%	-28.64%	Percentage	2.23%	13.56%

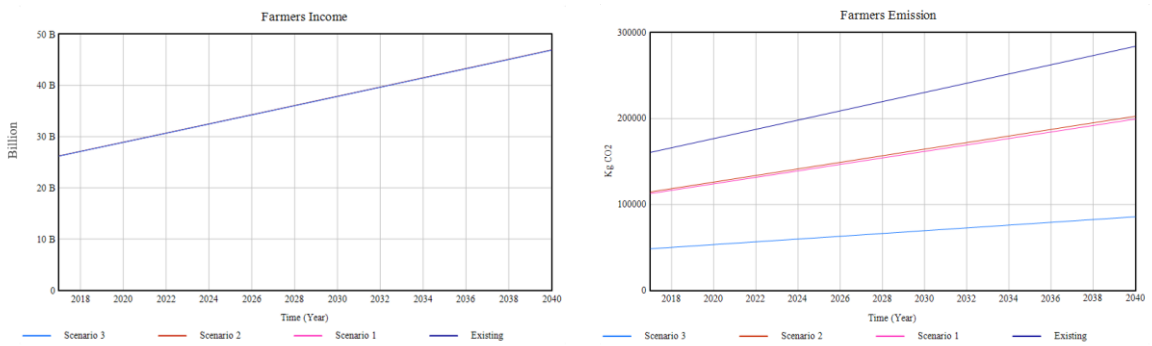
From a supply chain perspective, the valorization of cocoa pod husk and cacao bean shell through anaerobic digestion ensures efficient use of residues, indirectly benefiting middlemen and processors by stabilizing the quantity and quality of cocoa beans. The digestate by-product can be applied as a nutrient-rich fertilizer, reducing dependence on synthetic inputs and improving soil fertility [39]. Policy-wise, adoption is constrained by the high initial capital costs of anaerobic digestion systems, which may limit individual farmer participation. Therefore, cooperative ownership models or collective schemes are recommended to ensure accessibility and scalability across cocoa-producing regions.

From an environmental perspective, converting cocoa pod husk and cacao bean shell into biogas through anaerobic digestion presents a promising pathway for renewable energy generation. Indonesia's high cocoa production generates approximately 1680-2088 kilotons of cacao bean shell and cocoa pod husk annually, providing abundant biomass feedstock for this process [40]. The biochemical composition of these residues, rich in proteins, fats, and carbohydrates, makes them suitable substrates for methane-producing microbes, thereby facilitating efficient biogas yields [41]. The biogas produced can substitute up to 20% of household cooking gas demand [42], while the digestate by-product serves as a nutrient-rich fertilizer, reducing reliance on synthetic inputs.

Although the implementation of anaerobic digestion systems requires substantial initial investment, representing a trade-off between upfront cost and operational sustainability, the long-term benefits, including emission reduction, renewable energy generation, improved soil fertility, and increased farmer income, clearly outweigh these challenges [43]. Overall, scenario 2 demonstrates that cocoa waste valorization via biogas production can advance the economic, environmental, and social dimensions of sustainability, offering a practical and impactful strategy for promoting sustainable cocoa production in Indonesia.

3.2.3. Scenario 3: conversion of cocoa waste into feed-stock

The simulation results indicate that scenario 3 reduces farm-level emissions from an average of 222,000 kg CO_2-eq per year (existing) to 64,700 kg CO_2-eq per year, corresponding to a 58.6% reduction, while increasing farmer income marginally from 3.22×10^{15} to 3.23×10^{15}, or about 0.23% per production cycle (see Figure 9). Figure 9(a) illustrates the projected increase in farmer income, whereas Figure 9(b) shows the corresponding reduction in carbon emissions across the farm level. These results suggest that, although scenario 3 does not provide large-scale income gains, it is highly effective in reducing emissions and supporting integrated farming systems through feed substitution. Detailed simulation data supporting this analysis are provided in Table 7.



(a) (b)

Figure 9. Simulation results of scenario 3: (a) farmer income model and (b) carbon emission model

Strategically, this scenario focuses on converting cocoa pod husk and cacao bean shell into livestock feed, which complements other waste valorization strategies, such as biogas production [44]-[46]. From a supply chain perspective, the feed-stock pathway diversifies the outlets for cocoa residues, indirectly enhancing resilience and circularity of the cocoa supply chain. By substituting conventional feed, it also reduces costs for livestock farmers and mitigates the environmental burden associated with waste disposal.

From an environmental perspective, scenario 3 achieves substantial emission reduction at the farm level, although the impact on farmer income is modest. The implementation requires affordable detoxification techniques to ensure feed safety and nutritional quality [46]. While this represents a trade-off between economic gain and environmental benefit, the scenario contributes to sustainability by promoting circular use of cocoa waste and integrating crop-livestock systems. Overall, scenario 3 demonstrates that cocoa waste valorization through feed-stock production provides a complementary pathway alongside composting and biogas production, advancing environmental and social sustainability, even if the direct economic benefit is limited. Detailed simulation data supporting this analysis are provided in Table 6.

Table 7. Comparison simulation of farmer income and emission in existing condition and scenario 3

Time (year)	Farmers emission: existing (Kg CO_2)	Farmers emission: scenario 1 (Kg CO_2)	Farmers emission: scenario 2 (Kg CO_2)	Farmers emission: scenario 3 (Kg CO_2)	Farmers income: existing (IDR)	Farmers income: scenario 1 (IDR)	Farmers income: scenario 2 (IDR)	Farmers income: scenario 3 (IDR)
2017	160713	112845	114689	48543.7	2,62E+15	2,62E+14	2,62E+15	2,62E+15
2018	166079	116612	118517	50162.6	2,71E+15	2,71E+15	2,71E+15	2,71E+15
2019	171445	120379	122346	51781.5	2,80E+14	2,80E+15	2,80E+15	2,80E+15
2020	176811	124146	126174	53400.5	2,89E+15	2,89E+15	2,89E+15	2,89E+15
2021	182177	127913	130003	55019.4	2,98E+15	2,98E+15	2,98E+15	2,98E+15
2022	187544	131680	133832	56638.3	3,07E+15	3,07E+15	3,07E+15	3,07E+15
2023	192910	135447	137660	58257.3	3,16E+15	3,16E+15	3,16E+15	3,16E+15
2024	198276	139214	141489	59876.2	3,25E+15	3,25E+15	3,25E+15	3,25E+15
2025	203642	142981	145317	61495.1	3,34E+15	3,34E+15	3,34E+15	3,34E+15
2026	209008	146748	149146	63114.1	3,43E+15	3,43E+14	3,43E+15	3,43E+15
2027	214374	150515	152975	64733	3,51E+15	3,52E+15	3,52E+15	3,52E+15
2028	219740	154282	156803	66351.9	3,60E+15	3,61E+14	3,61E+15	3,61E+15
2029	225106	158049	160632	67970.9	3,69E+15	3,70E+15	3,70E+15	3,70E+14
2030	230472	161816	164460	69589.8	3,78E+15	3,79E+15	3,79E+15	3,79E+14
2031	235838	165583	168289	71208.8	3,87E+15	3,88E+15	3,88E+15	3,88E+14
2032	241204	169350	172118	72827.7	3,96E+15	3,97E+15	3,97E+15	3,97E+15
2033	246570	173117	175946	74446.6	4,06E+15	4,06E+15	4,06E+15	4,06E+15
2034	251936	176884	179775	76065.5	4,15E+15	4,15E+15	4,15E+15	4,15E+15
2035	257302	180651	183603	77684.5	4,24E+14	4,24E+15	4,24E+15	4,24E+15
2036	262668	184418	187432	79303.4	4,33E+15	4,33E+15	4,33E+15	4,33E+15
2037	268034	188185	191260	80922.4	4,42E+15	4,42E+15	4,42E+15	4,42E+15
2038	273400	191952	195089	82541.3	4,51E+14	4,51E+15	4,51E+15	4,51E+15
2039	278766	195719	198918	84160.2	4,60E+15	4,60E+15	4,60E+15	4,60E+15
2040	284132	199486	202746	85779.1	4,69E+15	4,69E+15	4,69E+15	4,69E+15
Average	2,22E+05	1,56E+05	1,59E+05	6,47E+04	3,22E+15	3,29E+15	3,66E+15	3,23E+15
Difference		6,63E+04	6,37E+04	-9,14E+04	Difference	7,19E+13	4,37E+14	7,49E+12
Percentage		-29.79%	-28.64%	-58.55%	Percentage	2.23%	13.56%	0.23%

3.2.4. Scenario 4: emission reduction at the collector and processing stages, particularly in logistics and distribution

The simulation results indicate that scenario 4 delivers substantial environmental gains by combining the waste valorization measures introduced in scenario 3 with targeted logistics improvements at the collector level. Specifically, replacing transportation fleets older than ten years with fuel-efficient alternatives enhances fuel efficiency by 61% and achieves a 65.26% reduction in total supply chain emissions compared to the baseline (see Figure 10). While the magnitude of emission reduction is similar to scenario 3, the inclusion of logistics optimization improves operational efficiency, reduces fuel costs, and strengthens midstream sustainability performance within the cocoa supply chain. Detailed simulation data supporting this analysis are provided in Table 8.

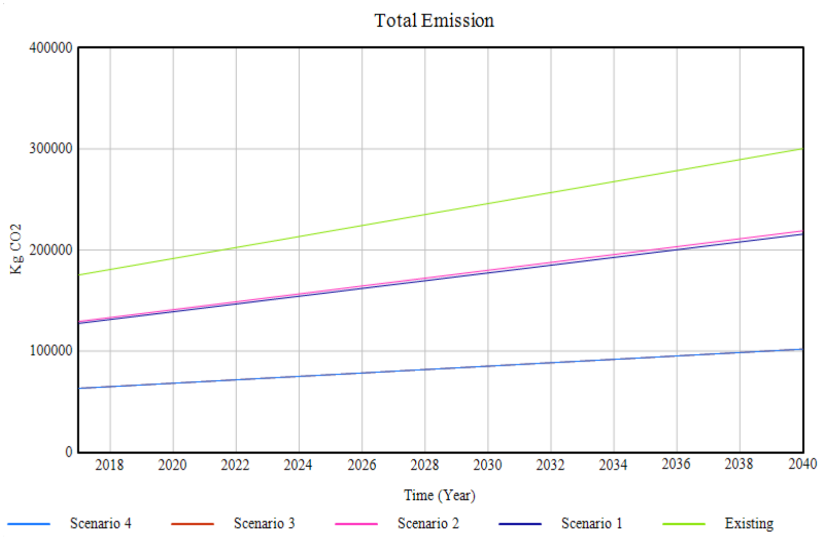


Figure 10. Simulation of scenario 4 for the carbon emission model

From a technical perspective, logistics inefficiencies have long been a persistent emission hotspot. Collectors and processors often rely on vehicles over a decade old, with degraded combustion performance caused by worn injectors, piston rings, and catalytic converters. These mechanical inefficiencies result in excessive CO_2 emissions, incomplete combustion, and higher operating costs [47]. By transitioning to newer vehicle models compliant with stricter emission standards, environmental performance is enhanced while reducing total transportation expenses. The simulation outcomes thus confirm that technological modernization within logistics can create dual benefits, improving both climate performance and economic viability.

Table 8. Comparison simulation of total emission in existing condition and scenario 4

Time (year)	Total emission: existing (Kg CO_2)	Total emission: scenario 1 (Kg CO_2)	Total emission: scenario 2 (Kg CO_2)	Total emission: scenario 3 (Kg CO_2)	Total emission: scenario 4 (Kg CO_2)
2017	175465	1,28E+05	1,29E+05	6,33E+04	63278.1
2018	180894	1.31E+05	1.33E+05	6,50E+04	64959.8
2019	186320	1,35E+05	1,37E+05	6,67E+04	66638.3
2020	191765	1,39E+05	1,41E+05	6,84E+04	68336.7
2021	197195	1,43E+05	1,45E+05	7,00E+04	70019.4
2022	202631	1,47E+05	1,49E+05	7,17E+04	71708
2023	208068	1,51E+05	1,53E+05	7,34E+04	73398.3
2024	213500	1,54E+05	1,57E+05	7,51E+04	75082.7
2025	218927	1,58E+05	1,61E+05	7,68E+04	76763.3
2026	224366	1,62E+05	1,65E+05	7,85E+04	78455.1
2027	229804	1,66E+05	1,68E+05	8,02E+04	80145.5
2028	235234	1,70E+05	1,72E+05	8,18E+04	81828.9
2029	240668	1,74E+05	1,76E+05	8,35E+04	83515.6
2030	246100	1,77E+05	1,80E+05	8,52E+04	85200.7
2031	251536	1,81E+05	1,84E+05	8,69E+04	86889.4
2032	256970	1,85E+05	1,88E+05	8,86E+04	88576.7
2033	262405	1,89E+05	1,92E+05	9,03E+04	90264
2034	267831	1,93E+05	1,96E+05	9,20E+04	91943.3
2035	273262	1,97E+05	2,00E+05	9,36E+04	93626.6
2036	278701	2,00E+05	2,03E+05	9,53E+04	95319.1
2037	284135	2,04E+05	2,07E+05	9,70E+04	97005.5
2038	289571	2,08E+05	2,11E+05	9,87E+04	98694.4
2039	295009	2,12E+05	2,15E+05	1,00E+05	100386
2040	300445	2,16E+05	2,19E+05	1,02E+05	102074
Average	237950.1	171692.5	174244.8	82688.65833	82671.23
Difference		-66257.6	-63705.3	-155261.425	-155279
Percentage		-27.85%	-26.77%	-65.25%	-65.26%

The combined strategy underscores the importance of addressing upstream waste valorization and downstream logistics modernization simultaneously. As noted by Savino *et al.* [27], transportation-related strategies play a pivotal role in emission reduction across agricultural supply chains, where optimizing vehicle operation and routing contributes directly to both sustainability and profitability. In this scenario, collector-level modernization not only reduces logistics-based emissions but also improves supply chain coordination and delivery reliability, indirectly supporting farmers through more predictable product flows.

From a sustainability perspective, scenario 4 exemplifies a systemic intervention that enhances both environmental and economic dimensions. Quantitatively, the 65.26% reduction in total emissions corresponds to a significant mitigation potential equivalent to over 155,000 kg CO_2-eq annually, while the 61% increase in fleet fuel efficiency lowers transportation energy intensity per unit of cocoa delivered. These improvements support the decarbonization targets of Indonesia's agro-industrial sector and contribute to green logistics transformation in rural commodity chains.

While this approach demonstrates strong technical and environmental performance, its adoption requires coordinated policy measures. The high upfront investment needed for fleet renewal and compliance with emission standards may deter small-scale collectors. Therefore, public-private partnership schemes, such as subsidized credit for new vehicles [48], logistics cooperatives, or carbon offset incentives, should be developed to enhance accessibility and ensure equitable participation.

Overall, scenario 4 reflects a pragmatic balance between economic efficiency and environmental responsibility, where integrated actions across the production and distribution stages generate synergistic sustainability gains. By pairing waste utilization with cleaner transportation systems, the cocoa sector can simultaneously enhance profit margins, reduce environmental footprints, and strengthen long-term supply chain resilience.

3.2.5. Scenario 5: reduction of input costs through financial support for fertilizers and pesticides, integrated with one of the most profitable waste utilization strategies

Simulation results indicate that scenario 5 generates the highest overall performance among all interventions tested. The combination of government-financed fertilizer and pesticide subsidies with profitable waste valorization strategies results in a 13.50% increase in farmer income, from an average of 3.22×10^{15} IDR under existing conditions to 3.65×10^{15} IDR under this scenario. Concurrently, total emissions along the cocoa supply chain decline from 0.43 kg CO_2-eq per kg of beans to 0.13 kg CO_2-eq per kg, representing a 70% reduction compared to baseline conditions (see Figure 11). These findings highlight that institutional financial support, when paired with sustainable practices, can effectively align economic resilience and environmental sustainability within the cocoa sector. Detailed simulation data supporting this analysis are provided in Tables 9 and 10.

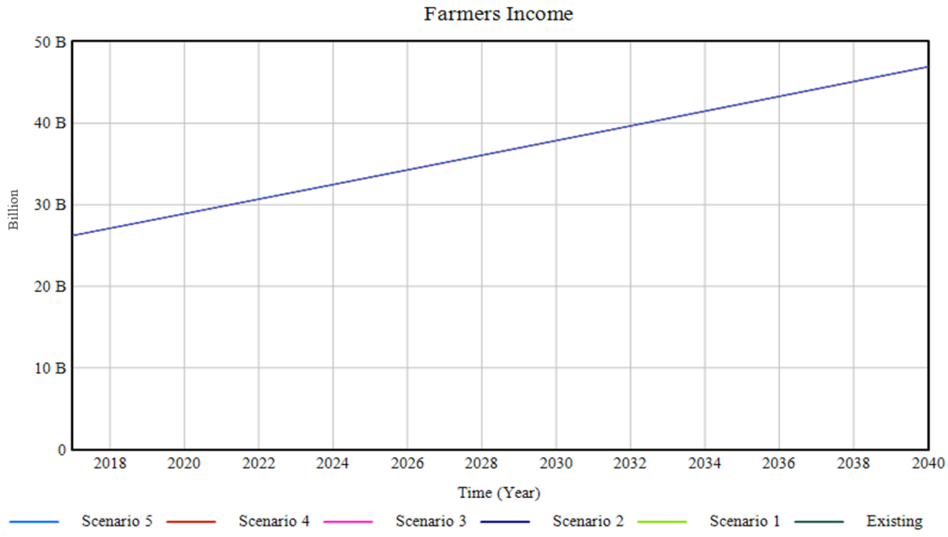


Figure 11. Simulation of scenario 5 for the farmer income model

Table 9. Comparison simulation of total income in existing condition and scenario 5

Time (year)	Farmers income: existing (IDR)	Farmers income: scenario 1(IDR)	Farmers income: scenario 2 (IDR)	Farmers income: scenario 3 (IDR)	Farmers income: scenario 4 (IDR)	Farmers income: scenario 5 (IDR)
2017	2,62E+15	2,62E+14	2,62E+15	2,62E+15	2,62E+15	2,62E+15
2018	2,71E+15	2,71E+15	2,71E+15	2,71E+15	2,71E+15	2,71E+15
2019	2,80E+14	2,80E+15	2,80E+15	2,80E+15	2,80E+15	2,80E+15
2020	2,89E+15	2,89E+15	2,89E+15	2,89E+15	2,89E+15	2,89E+15
2021	2,98E+15	2,98E+15	2,98E+15	2,98E+15	2,98E+15	2,98E+15
2022	3,07E+15	3,07E+15	3,07E+15	3,07E+15	3,07E+15	3,07E+15
2023	3,16E+15	3,16E+15	3,16E+15	3,16E+15	3,16E+15	3,16E+15
2024	3,25E+15	3,25E+15	3,25E+15	3,25E+15	3,25E+15	3,25E+15
2025	3,34E+15	3,34E+15	3,34E+15	3,34E+15	3,34E+15	3,34E+15
2026	3,43E+15	3,43E+14	3,43E+15	3,43E+15	3,43E+15	3,43E+15
2027	3,51E+15	3,52E+15	3,52E+15	3,52E+15	3,52E+15	3,52E+15
2028	3,60E+15	3,61E+14	3,61E+15	3,61E+15	3,61E+15	3,61E+15
2029	3,69E+15	3,70E+15	3,70E+15	3,70E+14	3,70E+14	3,70E+15
2030	3,78E+15	3,79E+15	3,79E+15	3,79E+14	3,79E+14	3,79E+15
2031	3,87E+15	3,88E+15	3,88E+15	3,88E+14	3,88E+14	3,88E+15
2032	3,96E+15	3,97E+15	3,97E+15	3,97E+15	3,97E+15	3,97E+15
2033	4,06E+15	4,06E+15	4,06E+15	4,06E+15	4,06E+15	4,06E+15
2034	4,15E+15	4,15E+15	4,15E+15	4,15E+15	4,15E+15	4,15E+15
2035	4,24E+14	4,24E+15	4,24E+15	4,24E+15	4,24E+15	4,24E+15
2036	4,33E+15	4,33E+15	4,33E+15	4,33E+15	4,33E+15	4,33E+15
2037	4,42E+15	4,42E+15	4,42E+15	4,42E+15	4,42E+15	4,42E+15
2038	4,51E+14	4,51E+15	4,51E+15	4,51E+15	4,51E+15	4,51E+15
2039	4,60E+15	4,60E+15	4,60E+15	4,60E+15	4,60E+15	4,60E+15
2040	4,69E+15	4,69E+15	4,69E+15	4,69E+15	4,69E+15	4,69E+15
Average	3,22E+15	3,29E+15	3,66E+15	3,23E+15	3,23E+15	3,65E+15
Difference		7,19E+13	4,37E+14	7,49E+12	7,49E+12	4,36E+14
Percentage		2.23%	13.56%	0.23%	0.21%	13.50%

Table 10. Comparison simulation of total emission in existing condition and scenario 5

Time (year)	Dry cocoa bean existing (Kg CO_2)	Farmers emission: existing (Kg CO_2)	Farmers emission: scenario 1 (Kg CO_2)	Farmers emission: scenario 2 (Kg CO_2)	Farmers emission: scenario 3 (Kg CO_2)	Farmers emission: scenario 4 (Kg CO_2)	Farmers emission: scenario 5 (Kg CO_2)
2017	371925	160713	112845	114689	48543.7	48526.3	48526.3
2018	384354	166079	116612	118517	50162.6	50145.2	50145.2
2019	396782	171445	120379	122346	51781.5	51764.1	51764.1
2020	409211	176811	124146	126174	53400.5	53383.1	53383.1
2021	421639	182177	127913	130003	55019.4	55002	55002
2022	434068	187544	131680	133832	56638.3	56620.9	56620.9
2023	446496	192910	135447	137660	58257.3	58239.9	58239.9
2024	458925	198276	139214	141489	59876.2	59858.8	59858.8
2025	471354	203642	142981	145317	61495.1	61477.7	61477.7
2026	483782	209008	146748	149146	63114.1	63096.7	63096.7
2027	496211	214374	150515	152975	64733	64715.6	64715.6
2028	508639	219740	154282	156803	66351.9	66334.5	66334.5
2029	521068	225106	158049	160632	67970.9	67953.5	67953.5
2030	533496	230472	161816	164460	69589.8	69572.4	69572.4
2031	545925	235838	165583	168289	71208.8	71191.3	71191.3
2032	558354	241204	169350	172118	72827.7	72810.3	72810.3
2033	570782	246570	173117	175946	74446.6	74429.2	74429.2
2034	583211	251936	176884	179775	76065.5	76048.1	76048.1
2035	595639	257302	180651	183603	77684.5	77667.1	77667.1
2036	608068	262668	184418	187432	79303.4	79286	79286
2037	620496	268034	188185	191260	80922.4	80904.9	80904.9
2038	632925	273400	191952	195089	82541.3	82523.9	82523.9
2039	645354	278766	195719	198918	84160.2	84142.8	84142.8
2040	657782	284132	199486	202746	85779.1	85761.7	85761.7
Carbon Emission per kg	0.432012	0.30332	0.308277	0.130448	0.130414	0.130414	

Fertilizer subsidies are a well-established policy instrument to enhance productivity and improve smallholder welfare [49]. In smallholder cocoa systems, labor is primarily family-based and thus not a direct cash expenditure, making input costs (particularly fertilizers and pesticides) the dominant financial burden. By subsidizing these inputs, governments can directly reduce production costs, thereby improve household income stability and enable farmers to reinvest in productivity-enhancing and environmentally sustainable practices such as waste valorization. In turn, higher profitability encourages adoption of circular initiatives that transform cocoa pod husks or shells into useful by-products, further contributing to emission mitigation and nutrient cycling at the farm level.

From a supply chain perspective, this scenario creates a cascade of benefits. Increased farmer profitability strengthens upstream resilience, allowing farmers to maintain consistent supply volumes and quality standards demanded by processors and exporters. Simultaneously, the lower input costs stabilize farm-gate prices, reducing volatility across the midstream network of collectors and processors.

These findings are consistent with broader evidence showing that targeted subsidies and institutional incentives can significantly improve recycling rates, stakeholder engagement, and socioeconomic welfare, particularly when tailored to local conditions [50]. Studies also indicate that integrated policy packages that combine subsidies, penalties, and education are more effective than single instruments in overcoming adoption barriers and sustaining behavioral change [51]. For instance, combined measures in construction waste management have successfully increased contractor participation in recycling initiatives, while in agriculture, subsidies to support waste recovery and organic fertilizer production have accelerated circular economy transitions and reduced environmental pollution [50]. Nevertheless, while subsidies can catalyze adoption and short-term benefits, policy design must also consider long-term financial sustainability and the risk of dependency. Overall, scenario 5 demonstrates that environmental reform in agriculture is most effective when supported by robust government intervention and incentive-aligned policies that link waste valorization with improved farmer welfare.

However, scenario 5 also involves trade-offs. While subsidies stimulate short-term gains and accelerate adoption, they carry fiscal risks and potential dependency if not supported by a clear phase-out or cost-sharing mechanism. Hence, a sustainable policy design should include graduated subsidy structures, capacity-building programs, and institutional monitoring systems to maintain alignment between financial incentives and environmental performance. Integrating such measures into national cocoa sustainability frameworks ensures that farmer welfare improvements are not achieved at the expense of long-term fiscal stability.

Overall, scenario 5 demonstrates that combining financial policy intervention with technological waste utilization offers the most balanced and synergistic pathway toward a sustainable cocoa supply chain. The scenario effectively strengthens farmer welfare, improves circular resource use, and achieves substantial decarbonization across production and distribution segments, providing a model for integrated sustainability policy in Indonesia's agroindustrial sector.

3.3. Uncertainty analysis and comparison with target emission reductions

A sensitivity analysis was conducted on key input parameters, such as fertilizer use, cocoa pod husk generation, and transportation efficiency, to assess the robustness of the model outcomes. The results indicate that variations in farmer emissions and production parameters produce consistent and logical responses throughout the system without destabilizing other variables. This demonstrates that the model is stable and capable of accurately representing the causal relationships within Indonesia's cocoa supply chain. When compared with the sustainable cocoa production program (SCPP) targets in Indonesia, which aim to reduce cocoa plantation greenhouse gas emissions by 30% over five years while increasing carbon sequestration, the simulated interventions, such as waste valorization, input subsidies, and logistics optimization, show the potential to meet or even exceed these national targets under favorable implementation conditions.

These findings highlight that policy recommendations should consider both the expected impacts and the inherent uncertainties in the system. Interventions like cooperative biogas adoption, fertilizer subsidies, or transportation upgrades can be designed with phased implementation or buffer mechanisms to account for variability in outcomes. By framing the simulation results alongside national targets and uncertainty considerations, the model provides a practical and risk-informed guide for sustainable cocoa supply chain management in Indonesia.

3.4. Recommendation for stakeholders

The simulation identifies actionable strategies to optimize Indonesia's cocoa supply chain across economic and environmental dimensions. Key interventions include promoting waste-to-biogas conversion and organic fertilizers via cooperatives, alongside improved price transmission mechanisms to stabilize farmer income. To operationalize this, the study advocates integrating system dynamics with information and communication technology (ICT) platforms for real-time monitoring, using optimization models for efficient subsidy allocation, and adopting green logistics. However, success depends on addressing socio-economic barriers; therefore, incentive programs must prioritize smallholders to bridge capital and infrastructure gaps. Ultimately, this integrated decision-support framework aligns supply chain reforms with Indonesia's climate and development goals, offering a scalable pathway for sustainable agriculture.

4. CONCLUSION

This study employed a system dynamics model to evaluate the trade-offs between carbon emissions and economic performance in Indonesia's cocoa supply chain. Simulations of five scenarios revealed distinct impacts: scenario 1 (organic compost) increased income by 2% and reduced total emissions by 29.79% (farm-level decreasing from 0.43 to 0.303 kg CO_2-eq/kg); scenario 2 (biogas) boosted income by 13.56% with an 11% emission cut; scenario 3 (cocoa feed) achieved a 58.6% emission reduction but only marginal income growth (0.23%); and scenario 4 (logistics/processing) reduced emissions by 65.26%. Scenario 5, integrating subsidies with waste utilization, emerged as the optimal intervention, raising income by 13.50% and slashing total emissions by 70% (from 0.43 to 0.13 kg CO_2-eq/kg). These findings confirm that integrating institutional support with sustainable practices is the most effective strategy, validating system dynamics as a robust decision-support tool for balancing farmer welfare and environmental sustainability.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
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CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, Imam Santoso (IMS), upon reasonable request.

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