Dynamic modelling of incentive policies on the upstream biodiesel supply chain: an Indonesian perspective

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Abstract. Palm oil is increasingly acknowledged as a valuable feedstock that provides a substantial and sustainable supply of renewable energy and is also utilized as a food source. In Indonesia, palm oil is utilized as a feedstock for the production of biofuel, specifically biodiesel. Government regulations strictly govern the biodiesel industry. The complexity and uncertainty of biodiesel's supply chain can greatly risk the long-term effectiveness of policies that promote the massive use of renewable energy. Extensive research has been conducted on renewable energy and its supply chain over the past decade. Nevertheless, the utilization of modelling and simulation techniques in this field has not been widely embraced. This model simulates the long-term dynamics of the upstream sector of the biodiesel supply chain, which encompasses oil palm plantations and the crude palm oil (CPO) industry. The main objective of this study is to investigate the impact of incentives on farmers and their role in improving the productivity of the upstream sector of the biodiesel supply chain. Further analysis shows that the incentive policy for farmers has an impact on increasing the productivity of fresh fruit bunch (FFB) harvests (tons/ha/year) and can support the sustainability of the long-term biodiesel industry without sacrificing the needs of the food industry, oleochemical industry, and others. Furthermore, it is anticipated that the export policy for CPO will also rise in tandem with the global increase in consumption, thereby affecting the revenue generated from export taxes.

1 Introduction

One of the biofuels developed in Indonesia is biodiesel. Biodiesel is recognized as a complement to traditional fuels. Compared to diesel fuel, biodiesel offers several advantages: it is safe, renewable, non-toxic, and biodegradable; it contains no sulfur; and it acts as a better lubricant. Socially and environmentally, biodiesel creates new jobs, revitalizes rural areas, and helps reduce global warming [1].

In Southeast Asia, palm oil plays an essential role in biofuel production. Indonesia is the primary producer, responsible for generating 45.5 million tons of crude palm oil (CPO) from 2022 to 2023. It produces an average of 5,000 liters of oil per hectare annually, markedly surpassing other oil crops [2]. This crop yields approximately ten times more oil than soybeans, sunflowers, or other oil-bearing crops. Palm oil remains an economical option among vegetable oils, since it can be easily transformed into biodiesel.

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At the 2015 21st United Nations Framework Convention on Climate Change (UNFCCC) in Paris, Indonesia committed to reducing greenhouse gas emissions by 29% by the year 2030. The current biodiesel policy is part of the plan to speed up the shift to clean energy and achieve net-zero emissions. Additionally, the commitment to use palm oil as a raw material for biofuel will help Indonesia meet its energy security and energy mix targets of 23% in 2025 and 31% in 2050. Accelerating the policy's implementation influences the macroeconomy, notably the trade balance and biodiesel incentives, which are heavily impacted by the CPO and diesel markets, along with environmental factors that drive forest land expansion for plantations [3]. Therefore, it is clear that policy can both hinder and promote successful bioenergy development [4].

Energy production in Indonesia is mainly managed by state-owned enterprises, with government policies playing a central role. Indonesia's mandatory biodiesel program has operated for 14 years and positively impacted the economy, society, and environment. It is also the largest, has the highest biodiesel blend, and is the longest-running among similar programs in other countries. The policy has encouraged progress in boosting biodiesel output in Indonesia.

The utilization of biodiesel as an energy resource commenced in 2006; however, its expansion notably accelerated following 2015. Before 2015, the proportion of biodiesel blended with diesel was merely 10%, subsequently increasing to 15% in 2015 and further rising to 30% in 2020 [5]. The government's initiatives to advance the biodiesel program are demonstrably reflected in its designation as a national strategic project within the 2020-2024 National Medium-Term Development Plan (RPJMN), as well as the establishment of the Palm Oil Plantation Fund Management Agency (BPDPKS) in 2015. BPDPKS serves as an institution overseeing palm oil plantation funds, mainly directing expenditures to support the growth of the biodiesel industry.

Indonesia is the pioneering country worldwide to adopt B30 biodiesel [6]. The growth of the mandatory biodiesel program has resulted in higher incentive costs. Data from BPDPKS shows that incentives for mandatory biodiesel vary over time but generally increase, from approximately IDR 0.6 trillion in 2015 to around IDR 34.6 trillion in 2022 and IDR 18.3 trillion in 2023. The upcoming B35 program is projected to require incentives of IDR 37.34 trillion to support a B35 allocation of 13.75 million KL. These incentives are financed through the export levy levied on palm oil industry players.

The biodiesel supply chain commences with the upstream network, predominantly comprising oil palm plantations that cultivate fresh fruit bunches (FFB), subsequently processed into crude palm oil (CPO). In Indonesia, oil palm plantations are categorized into three ownership types: community-owned, private, and government-owned establishments. Over time, community-owned oil palm plantations have experienced more rapid expansion, constituting 40%. Conversely, private plantations represent 56%, with the remaining 4% owned by governmental entities. FFB will subsequently be dispatched to the palm oil mill (PKS) for the production of CPO feedstock, which serves as biodiesel feedstock.

Despite the implementation of the mandatory biodiesel program, many issues and challenges remain in managing the biodiesel supply chain. [7] emphasized the uncertainties within the biodiesel supply chain, acknowledging that palm oil an agricultural product is influenced by climatic conditions, insect populations, plant diseases, and cultivation decisions. Furthermore, land scarcity can escalate biomass prices. Seasonal fluctuations also contribute to elevated logistics costs, including inventory costs, while large and dispersed volumes augment transportation costs. Therefore, using dynamic system modelling in the biodiesel sector can improve understanding of system behavior, offering valuable insights for policymaking and the investigation of alternative strategies [8].

2 Method

The modeling process is iterative and requires feedback, often not following a straight sequence of steps. The stages in dynamic system modeling are as follows [9] and see in Fig.1:

1. Defining the problem boundaries
   In this section, the problem is initially identified by reviewing literature, analyzing secondary data, and conducting interviews with relevant parties. To effectively address the issue, it is also crucial to determine key variables. Identifying these variables involves analyzing various research models, primarily related to uncertainty in biodiesel supply chain management, and consulting with experts.
2. Problem hypothesis
   The problem hypothesis determines whether existing theories display dynamic behavioral characteristics. These initial hypotheses are developed via literature reviews and focus group discussions (FGDs), which emphasize the key variables that shape the feedback's dynamics and structure. Focus Group Discussion (FGD) is a qualitative data collection method where a group discusses a specific topic in depth, guided by a moderator. Main elements of FGDs include the participants, procedures, scope, focus, and level of participation [10]. At this stage, a mapping is developed to create a logical framework that precisely reflects real conditions and highlights the key variables in the mandated biodiesel policy system. The causal structure map is built using initial ideas, critical variables, reference patterns, and other data, utilizing tools such as model boundary diagrams, subsystem diagrams, causal loop diagrams, stock and flow maps, and policy structure diagrams.
3. Model formulation
   The conceptual model will be translated into a formal model, which clarifies any ambiguous concepts and identifies possible contradictions overlooked earlier. This formal representation includes comprehensive equations and parameters at the initial conditions.
4. Model testing
   Model testing involves structural, parameter, extreme condition, unit consistency, and scope feasibility tests. Its goal is to verify if the model accurately represents the real system's operation. If not, researchers need to revisit the initial phase to improve their understanding of the system and modify their methods as needed.
5. Policy formulation and evaluation
   Policy design and evaluation focus on enhancing outcomes. Policy design involves creating strategies, frameworks, and decision rules. It also requires testing policies for reliability, adaptability to changing key factors, and assessing the model setup, including performance across various scenarios. The process examines how policies might interact, potentially weakening or strengthening each other.

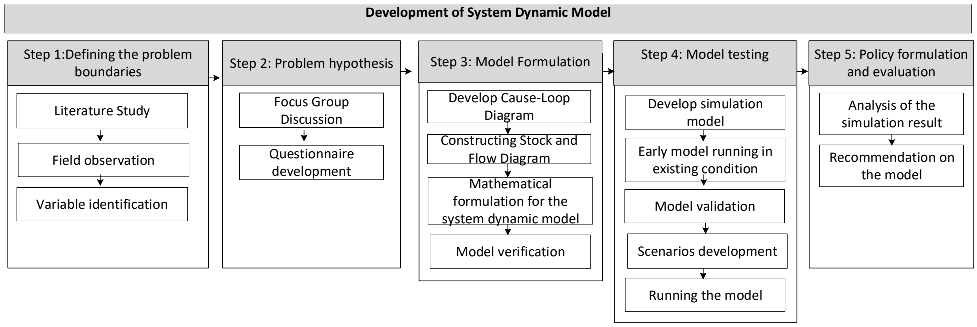


Fig.1. Research flowchart

3 Results and Discussion

3.1 Defining the problem boundaries

A primary aim of the mandatory biodiesel program is to cut diesel subsidies from the government budget, thereby saving energy subsidies. However, during implementation, the biodiesel sector also gains from incentives akin to subsidies. These include two parts: a diesel subsidy financed by the government and a FAME subsidy supplied by BPDPKS. The amount of this subsidy varies based on two indices: the fuel oil market index price for diesel and the biofuel market index price for biodiesel. Furthermore, if the per-liter Fatty Acid Methyl Ester (FAME) subsidy surpasses that of diesel, the overall biodiesel subsidy expenditure will increase, especially as the blending rate goes up, and the opposite is true [3].

The demand for palm oil (CPO) as a biodiesel feedstock is expected to grow due to current conditions. Besides biodiesel, CPO is used in various downstream products, making it important to monitor their availability and distribution. Infrastructure and technology enhancements are necessary to meet biodiesel distribution standards. Furthermore, the government should set up factories, fuel terminals, and transport vessels that meet FAME standards to support efficient distribution and boost market acceptance of biodiesel.

However, biodiesel development in Indonesia still falls short of its goals. Policy inconsistencies between the central and regional governments, such as issues with sustainable plantation certification and disagreements among different government ministries, along with a lack of new biofuel usage policies, have slowed the growth of the biodiesel industry [11]. Additionally, other risks like the Covid-19 pandemic have caused a drop in the value of CPO exports, leading to a decrease in export levies on government revenue. This reduces incentives for biodiesel industry stakeholders, farmers, and the public, which could threaten the sustainability of the biodiesel program. Therefore, it is crucial to review biodiesel policies, especially subsidy and incentive schemes, with various factors in mind to avoid overburdening the state budget.

3.2 Problem hypothesis

The overall system depiction uses big-picture mapping, which contains process mapping at the highest level, which covers the process broadly but with a low level of detail. The biodiesel supply chain begins with the upstream network, namely oil palm plantations, which produce FFB for CPO production. Oil palm plantations in Indonesia are divided into three types of ownership: smallholder oil palm plantations, private plantations, and government plantations. Over time, smallholder plantations that grow oil palm have grown relatively rapidly, accounting for 40% of the total. Meanwhile, private plantations account for 56%, and the remaining 4% are state-owned plantations. FFB are then sent to palm oil mills (PKS) to produce CPO feedstock, the raw material for biodiesel. Fig. 2 provides an overview of this study, focusing on the upstream biodiesel supply chain with processes, networks, and relationships between participants.

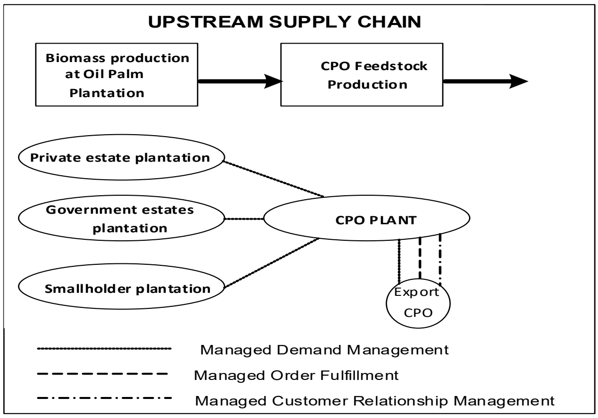


Fig.2. Upstream biodiesel supply chain and its activities

3.3 Model formulation

Making a stock and flow diagram (SFD) is meant to show how different variables are related and to create a system that can be measured by changing a cause-and-effect diagram into stocks and flows with clear mathematical definitions [12]. A stock represents the total amount of a variable that accumulates over time, while a rate indicates how quickly the system changes. A flow signifies the transfer of increases or decreases to the stock per unit time, either adding to or subtracting from the level. A converter, also known as an auxiliary, displays the value of the flow, and a connector functions as a link that shows the movement of material between different flows (aux-flow, aux-aux, stock-flow). Figure 3 shows the stock and flow diagram for the oil palm plantations sub-model.

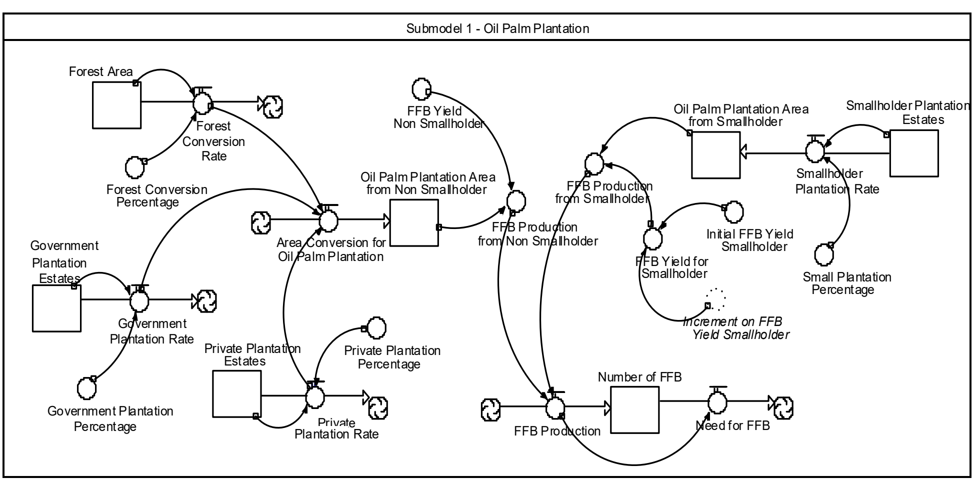


Fig.3. SFD for the oil palm plantation sub-model

Fig.3. illustrates that the oil palm plantation sub model was developed to identify key factors influencing the size of oil palm plantations and FFB productivity, which in turn affect CPO output. Land is a limited resource, managed and allocated by the government. Once land availability is exhausted, growth of oil palm plantations will cease. Land is accumulated across private, government (non-smallholder), and smallholder plantations, each with different productivity levels. Non-smallholder plantations generally outperform smallholders due to the use of better seeds and appropriate fertilizers. These land stocks are influenced by the rate of accumulation and other related variables (auxiliary).

The SFD for CPO production depicts the production amount and consumption, as shown in Fig. 4. CPO production is upstream in the biodiesel supply chain, serving as feedstock for biodiesel production. Aside from biodiesel, CPO is also utilized within the food and oleochemical industries, with demand influenced by population size. In addition to fulfilling domestic demands, some CPOs are exported. Domestic consumption is dependent on population size and per capita consumption levels. There are three leading stocks: population, which is affected by birth and death rates; CPO stocks, influenced by CPO production and exports; and CPO export taxes, impacted by the export tax rate, farmer incentives, and biodiesel incentives.

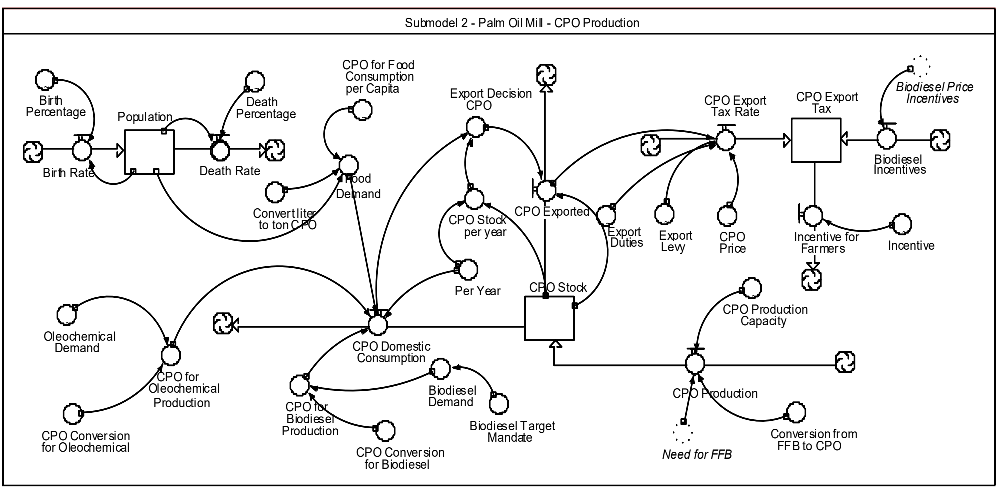
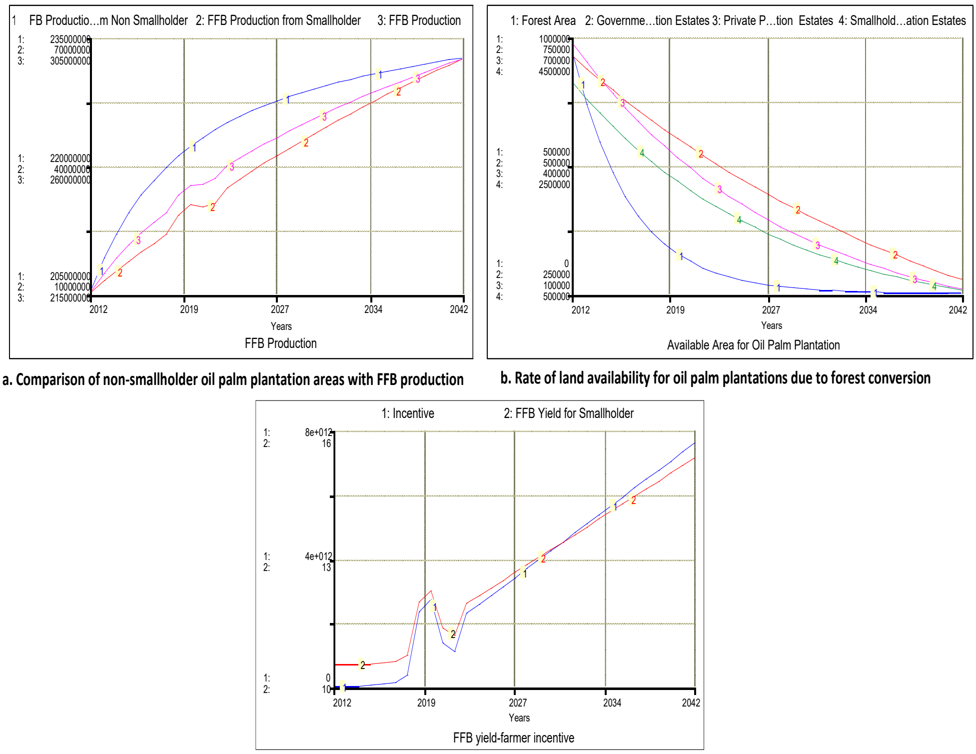


Fig. 4. SFD for the palm oil mill-CPO production

3.4 Model testing

In this section is to verify the model, ensuring it functions according to the SFD flowchart. Verification involves confirming that the conceptual model has been accurately translated into code, primarily by checking for errors in the simulation program [13]. This process also reviews the units and formulation of the model's variables to assess its credibility. In Stella 9.1.3, the Run tool provides the Check Units and Verify/Repair commands to aid in this verification.

Additionally, model validation is carried out to verify the relationships between variables through precise analysis of each system's behavior. Multiple validation tests are performed to ensure the model reliably represents real-world problem systems. Model validation aims to verify that the results produced by the model accurately represent reality, even when employing alternative data sources. One validation procedure involves performing a parameter test. Parameter testing aims to evaluate the appropriateness of the relationships between simulation sub-models, particularly the constants or variables within the model, to determine whether they are reasonable and accurately represent real-world conditions. The process for assessing model parameters includes analyzing two related data sets for the variables and comparing the actual logic with the simulation results. The model is considered accurate if the simulation outputs match the logic.



a. Comparison of non-smallholder oil palm plantation areas with FFB production

b. Rate of land availability for oil palm plantations due to forest conversion

c. Farmer incentives and FFB productivity

Fig 5. Results of dynamic system simulation

Fig. 5.a illustrates the relationship between non-smallholder oil palm plantation area and FFB production. The primary concept is that an increase in plantation area correlates with higher FFB production, and vice versa. This concept is compared to the simulation results, depicted in a graph demonstrating a positive correlation between FFB production and plantation area. Model simulations are conducted to observe the behavior of the system that accurately represents real-world conditions within the biodiesel supply chain. The model was executed utilizing Stella 9.1.3 software and simulated until the year 2042, in accordance with the government policy program outlined in the 2050 National Energy General Plan (RUEN).

The simulations on the oil palm plantation sub-model aim to forecast land use by smallholder, private, and government oil palm plantations, while also projecting productivity levels and FFB output and assessing the impact of government incentives for farmers. The recent increase in palm oil prices has stimulated heightened public interest in the ownership of oil palm plantations, resulting in an expected expansion of oil palm cultivation areas through 2042. Notably, the growth in smallholder plantations surpasses that of non-smallholder plantations. This expansion has chiefly entailed forest conversion, particularly between 2012 and 2030, although projections indicate a decline until 2042; see Fig. 5b. As plantation expanses broaden, the production of Fresh Fruit Bunches (FFB) is projected to increase. The continual augmentation of FFB production until 2042 will escalate the demand for FFB processing capacity, considering both volume and processing capabilities. Similarly, based on the current plantation area, production is anticipated to rise owing to the substantial number of immature plants. It requires up to four years for oil palms to yield their initial fruit and attain full productivity by the age of 30 years.

To achieve the target FFB production, the government supports farmers through the People's Oil Palm Rejuvenation (PSR) program. This program offers incentives such as infrastructure support (fertilizers, pesticides, machinery, transportation, etc.), training for human resources, and outreach on sustainable and environmentally friendly plantation practices. These incentives are provided annually by BPDPKS, which allocates funds from CPO export levies. Since 2017, the PSR program has been active in 21 provinces and 123 districts within key oil palm areas, covering about 180,000 hectares annually. The program aims to boost productivity by replacing old, unproductive plants (over 25 years) with quality seedlings. Farmer incentives are expected to increase yields, reaching a peak of 15 tons/hectare in 2042, as shown in Fig. 5c.

3.5 Policy formulation and evaluation

This section will discuss policy scenario models, which are derived from the development of existing models. Dynamic systems models can function as practical tools for decision-making, enabling the testing of various policy formulation scenarios. The development of policy scenarios was carried out through expert interviews and an analysis of pertinent regulations and policies.

3.5.1. Scenario 1: Escalating intensification of oil palm plantations

The palm oil plantation intensification program has been carried out through an incentive scheme for palm oil farmers since 2015. The plantation intensification initiative enhances oil palm productivity through the optimal utilization of existing land resources or by refraining from expanding planting areas. Such efforts encompass the application of fertilizers, high-quality seeds, irrigation systems, maintenance, and extension services [13]. Implemented by the BPDPKS, the program includes PSR initiative as well as support for facilities and infrastructure. Government incentives are incrementally increased annually in proportion to the land area possessed by farmers. However, incentives for oil palm intensification have not been evenly distributed across all smallholders' lands, with smallholders accounting for 43% of Indonesia's total oil palm plantation area. The current incentive offered to farmers is IDR 25 million per hectare. However, this amount is still seen as insufficient for agricultural intensification activities. As a result, the farmer incentive parameter will be increased by 10% each year.

It is anticipated that increasing plantation intensification will enhance palm oil productivity, thereby directly influencing crude palm oil (CPO) output. This serves as a raw material for downstream products and has the potential to improve the welfare of palm oil farmers. Table 1 presents a comparison between current Fresh Fruit Bunch (FFB) production and productivity levels and those under Scenario 1, which incorporates a 10% increase in farmer incentives. The data demonstrates that a 10% augmentation in incentives—implemented through programs such as PSR, fertilizer distribution, and infrastructure development results in higher FFB yields and enhanced harvest productivity.

Table 1. Comparison of FFB production, current productivity levels, and scenario 1

	Existing		Scenario 1	
Year	**FFB production (ton/year)**	**FFB yield (ton/ha)**	**FFB production (ton/year)**	**FFB yield (ton/ha)**
2025	260,118,450.7	11.4	262,559,301.5	12.3
2026	262,271,599.3	11.49	265,100,855	12.48
2027	264,327,071.1	11.59	267,538,054.5	12.66
2028	266,319,524.2	11.7	269,880,914	12.84
2029	268,240,225.9	11.82	272,159,822.5	13.02
2030	270,121,389.4	11.95	274,338,776.8	13.2
2031	271,950,073.2	12.1	276,445,352.8	13.38
2032	273,780,400.9	12.25	278,484,976.9	13.56
2033	275,597,584.1	12.43	280,462,399.2	13.73
2034	277,432,610.7	12.62	282,381,812	13.91
2035	279,267,937.4	12.84	284,246,945.1	14.1
2036	281,133,770.6	13.07	286,086,154.9	14.28
2037	283,061,103.8	13.33	287,852,778.5	14.46
2038	285,030,236.8	13.61	289,574,212.8	14.63
2039	287,071,547	13.92	291,252,973	14.81
2040	289,216,058.3	14.26	292,891,374.3	14.99
2041	291,468,808.2	14.64	294,491,558.5	15.17
2042	293,834,271.8	15.06	296,055,516.2	15.36

The designed alternative scenarios need testing to assess their reliability, sensitivity to parameter uncertainty, and model structure, including their performance [14]. Fig. 2 presents the simulation results that demonstrate the output performance of the dynamic system model, particularly regarding the biodiesel incentive. The scenario was executed in three stages: short term (2027), medium term (2032), and long term (2042). This stage aims to help policymakers assess targeted outcomes within a set timeframe. Then, they can review each policy and make improvements based on changing conditions. The incentives for biodiesel are set to increase from 2027 to 2032, subsequently declining in 2042.

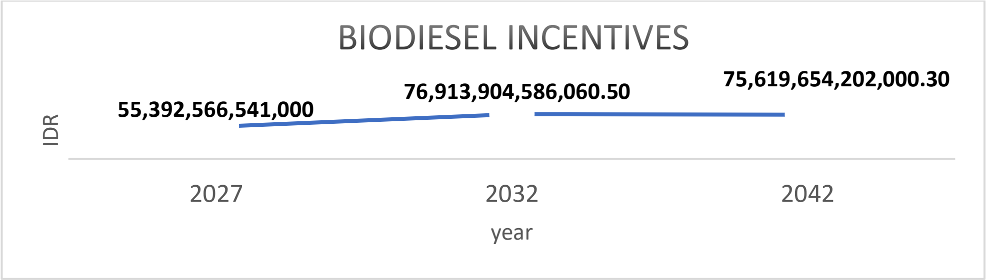


Fig.8. Results of the simulation of policy scenarios regarding incentive

3.5.2. Scenario 2: Increasing CPO exports

This scenario proposes a 20% rise in CPO export value to enhance domestic palm oil production. CPO exports also contribute to export levies and fees, overseen by BPDPKS, which includes incentives for farmers and the biodiesel sector, along with other programs supporting sustainable palm oil development. The initiative also seeks to keep FFB prices stable for farmers. CPO exports presume that domestic demand for cooking oil, oleochemicals, and biodiesel has already been met, while also considering the growing global demand. Improved productivity in palm oil plantations will augment CPO production, serving as feedstock for downstream products. Consequently, CPO will be allocated to satisfy domestic requirements, stabilize prices and supplies, and potentially increase exports. Table 2 presents the outcomes of elevated export levels in comparison to existing data.

Table 2. Comparison of CPO stocks and export volumes across the current situation and Scenario 2

	Existing		Scenario 2	
Year	**CPO stock (ton)**	**CPO exported (ton/year)**	**CPO stock (ton)**	**CPO exported (ton/year)**
2025	107,392,924.23	31,838,879.48	65,048,470.66	31,946,265.23
2026	108,558,769.89	32,217,877.27	65,907,958.26	32,524,235.33
2027	109,637,227.51	32,567,630.97	66,600,067.72	32,953,979.13
2028	110,646,960.54	32,891,168.25	67,200,935.14	33,300,033.86
2029	111,602,655.16	33,194,088.16	67,750,250.35	33,600,467.57
2030	112,511,683.39	33,480,796.55	68,264,949.95	33,875,125.18
2031	113,384,626.65	33,753,505.02	68,283,797.67	34,132,474.98
2032	114,217,266.95	34,015,387.99	67,192,694.40	34,141,898.84
2033	113,881,596.90	34,265,180.09	65,525,023.18	33,596,347.20
2034	112,685,864.71	34,164,479.07	63,542,874.53	32,762,511.59
2035	110,864,786.32	33,805,759.41	61,576,915.66	31,571,992.90
2036	108,600,286.29	33,259,435.90	61,792,456.71	28,202,466.67
2037	105,992,630.61	32,580,085.89	61,995,119.52	26,998,011.76
2038	103,118,526.54	31,797,789.18	62,185,787.81	25,764,606.76
2039	100,035,854.88	30,935,557.96	62,365,267.85	24,506,755.18
2040	96,791,799.54	30,010,756,47	62,534,297.94	23,231,409.74
2041	93,404,437.48	29,037,539.86	62,693,556.40	21,923,875.07
2042	89,901,218.34	28,021,331.24	62,843,668.27	20,599,177.36

Based on the findings in Table 2, although the export value increased by 20%, the export volume experienced fluctuations and declined between 2035 and 2042. CPO supply levels remain stable, ranging between 60 and 68 million tones. Concurrently, current market conditions exhibit a comparable pattern, with export volumes experiencing fluctuations and declining from 2025 to 2042. This decline is mainly due to increased domestic demand for CPO, fueled by population growth, rising needs for downstream sectors like biodiesel, cooking oil, and oleochemicals, and restrictions on forest conversion for plantation expansion. While increasing CPO exports can boost government income, too many exports might harm the local economy, especially by driving up prices of products like cooking oil that depend on CPO, because there wouldn't be enough available for local use. This danger intensifies when worldwide CPO prices are elevated but domestic prices remain low, prompting producers to export significant volumes. Without regulation, farmers may rapidly transform land into oil palm plantations due to high FFB prices, perhaps leading to oversupply and a subsequent long-term chain reaction. Additionally, long-term ecological consequences will encompass biodiversity loss and environmental deterioration due to land expansion [15].

4 Conclusion

This study presents a dynamic system model consisting of two sub-models: oil palm plantations and CPO production. Simulations projected outcomes from 2023 to 2042. The analysis focused on biodiesel incentives, aligned with government policies promoting biodiesel as an alternative energy source. Some alternative scenarios involve implementing policies to enhance the intensification of oil palm plantations by providing farmers with incentives of 10% annually and increasing CPO exports by 20%. FFB production is expected to reach 296,055.516.2 tons annually, with a yield of 15.36 tons per hectare in 2042. Meanwhile, CPO stocks are projected to reach 62,834,668.27 tons, with annual exports of 20,599,177.36 tons. It is expected that FFB production and productivity will rise, while CPO stocks and export volumes are likely to decline. The policy implications of this research can also assist governments and policymakers. It provides valuable insights to help palm oil farmers, the CPO industry, and the biodiesel sector strengthen their supply chains, supporting the sustainability of the mandatory biodiesel program.

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