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System dynamics scenarios for sustainable oil palm management toward Indonesia's 2060 net zero target

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Abstract. *Hernawan E, Rosmiati M, Lastini T, Mustari E, Kandar M. 2025. System dynamics scenarios for sustainable oil palm management toward Indonesia's 2060 net zero target. Asian J Agric 9: 402-414.* Indonesia's palm oil sector plays a crucial role in national economic growth. However, it faces complex and interconnected challenges, including maintaining its significant contribution to GDP, supporting the expansion of biodiesel production, complying with the European Union's deforestation regulations, and fulfilling commitments under the Nationally Determined Contribution (NDC) by 2030, as well as the national target of achieving net-zero emissions by 2060. This study aims to identify an ambitious yet realistic pathway for sustainable palm oil plantation management through the development and application of a system dynamics model. The research uses secondary data sources, including national palm oil production statistics, demographic trends, economic indicators, and policy documents related to palm oil governance and climate change mitigation. The Indonesia Sustainability of Oil Palm Plantations Management (ISOPPM) model was designed to simulate the impacts of policy interventions focused on promoting the use of organic fertilizers, distributing superior oil palm seedlings, and expanding B40 biodiesel production. The model's accuracy and reliability were tested by comparing simulated results with historical data from national statistics. The results indicate that under the ambitious scenario, crude palm oil production could increase by 81.3% compared to the business-as-usual scenario. In comparison, plantation area expansion could be limited to 6.27%, enabling the sector to achieve net-zero greenhouse gas emissions as early as 2048. Furthermore, this scenario demonstrates the potential to mitigate forest biodiversity loss through more efficient land use and improved agricultural practices. Overall, the validated ISOPPM model indicates that with appropriate policy support and technological improvements, Indonesia's palm oil sector can significantly enhance productivity, minimise deforestation risks and biodiversity loss, and contribute meaningfully to national climate goals, ensuring a balance between economic development, environmental protection, and long-term sustainability.

Keywords: Biodiversity conservation, greenhouse gas emissions mitigation, Indonesia, land use change, sustainable palm oil

INTRODUCTION

Despite being among the world's top three most competitive countries in the palm oil sector—namely Indonesia, Malaysia, and Honduras (Lugo-Arias et al. 2024)—Indonesia's crude palm oil (CPO) exports face challenges from competing vegetable oils such as soybean and sunflower oil (Amiruddin et al. 2021). While rising global demand for vegetable oils, driven by population growth, income increases, and the shift towards biofuels and cleaner energy, supports continued production growth (Nugrahapsari et al. 2024), Indonesia's export volumes have fluctuated due to volatile prices and market competition. These conditions create uncertainty in export performance despite steady growth in domestic production and generally increasing export values. According to BPS (2024), CPO production increased by 3.67% from 2021, reaching 46.82 million tons in 2022 and rising slightly to 47.08 million tons in 2023. In contrast, export volumes declined from 2019 to 2022, with the sharpest drop in 2020 to 27.63 million tons, an 8.55% decrease from 2019, before recovering in 2023. Despite fluctuations in volume, the export value generally increased in line with global price trends. World Bank data show palm oil averaged USD 751/mt in 2017, raising export value by 2.32% from 2016. Prices fell to USD 639/mt in 2018 and USD 601/mt in 2019 but rebounded to USD 752/mt in 2020, lifting export value by 16.94% despite lower volume. Higher prices in 2021-2022 pushed export values to USD 29.5 billion in 2022, and although volumes rose in 2023, export value fell by 19.29% to USD 24.01 billion.

Producers of fresh fruit bunches (FFBs) in key exporting countries capture only a small share of final export prices—about 14% in Malaysia and 20% in Indonesia during 2010-2020 (Voora et al. 2023). The shift from fossil fuels to renewable energy drives palm oil demand, raising concerns about large-scale plantation expansion and biodiversity loss (Yasinta and Karuniasa 2021). Plantation area in 2018 increased sharply but grew slowly from 2019 to 2023, reaching 15.93 million ha (BPS 2024). Nevertheless, expansion into forests remains a major driver of biodiversity decline and carbon emissions (Rahmani et al. 2024). Applying adaptive management and conserving high-value areas—as in Central Kalimantan—can enhance sustainability while providing socio-economic benefits (Nasution et al. 2024). Long-term sustainability depends on institutional adaptability and governance, including regulations, certifications, and local alignment (Cifuentes-Espinosa et al. 2023). External drivers for sustainability include NGO pressure, competition, multinational buyer demands, regulatory compliance, standards adherence, and securing government and investor support, while internal drivers include reputational risks, labour constraints, strategic business cases, and philanthropic values (Nor-Ahmad et al. 2022). In Bengkalis District's palm oil processing industry, the sustainability status is moderate, and to achieve high sustainability, improvements are required in key variables across economic, social, technological, and institutional dimensions. Thus, targeted policies are essential to elevate the industry's sustainability (Hariyanti et al. 2022).

A causal loop links global prices, global demand, rising CPO production, forest conversion, and declining environmental quality in Indonesia, particularly the loss of forest functions such as flood control and carbon regulation. Addressing this necessitates scenario-based management grounded in dynamic systems to optimize sustainable plantation management, with a comprehensive understanding of the system ensuring models accurately represent real-world conditions (Li and Fang 2025). In the palm oil supply chain, input indicators include land area, productivity, and CPO prices; output indicators include production volume, derivatives (Astria et al. 2021), the sectoral SFD (Rahmayanti et al. 2025), and simulation-based strategies for value addition (Permatasari and Suryani 2022).

Accordingly, this study models a causal loop connecting prices, demand, production, forest conversion, and environmental decline—especially forest ecosystem service loss—and introduces a system dynamics framework integrating policy scenarios to optimize sustainable plantation management. By simulating the use of organic fertilizer, superior seedling distribution, and B40 biodiesel expansion, the model guides decision-makers toward balancing economic competitiveness and environmental sustainability. The study's input indicators include land area, productivity, and CPO prices, while output indicators include production volume, downstream products (Astria et al. 2021), sectoral SFD (Rahmayanti et al. 2025), and policy-driven supply chain value impacts (Permatasari and Suryani 2022). Ultimately, the contribution lies in an integrated scenario-based policy model for sustainable oil palm management in Indonesia using robust system dynamics (Li and Fang 2025), with the main objective being to determine optimal management scenarios for sustainability through dynamic systems modeling.

MATERIALS AND METHODS

Study area

The research was conducted from 2022 to 2024. The study area for this research is on the Scenario of Indonesian Sustainability Oil Palm Plantation Management in Indonesia across key regions known for their extensive oil palm plantations. Indonesia, located in Southeast Asia between latitudes 6°N to 11°S and longitudes 95°E to 141°E, is the world's largest producer of Crude Palm Oil (CPO). The research focuses on all CPO-producing regions, including Sumatra, Kalimantan, Sulawesi, and Papua, which mainly play a crucial role in national palm oil production. These areas have undergo rapid land-use changes, leading to resulting in both economic growth and environmental challenges such as , including deforestation, biodiversity loss, and increased carbon emissions.

Study design

This study employed a system dynamics simulation model to analyze scenarios for sustainable palm oil plantation management. The model does not use a Life Cycle Assessment (LCA) or spatial approach, but focuses on policy simulations and feedback loops within the palm oil production system. Key data sources included national oil palm statistics in 2023 (Central Bureau of Statistics/ BPS), and relevant government policy documents related to palm oil development, biodiesel blending mandates, and climate change mitigation targets. Greenhouse gas (GHG) emissions were estimated using emission factors for land-use change and fossil fuel substitution potential, based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The calculation steps involved: estimating emissions from land expansion using default carbon stock loss factors, quantifying emission reductions from increased biodiesel production (B40) that displaces fossil diesel consumption, and aggregating net emissions under each policy scenario. Schematically, the framework of thinking-concept-framework of this research is shown in Figure 1.

Problem definition and formulation

Understanding the system should be analyzed first, before defining and formulating the problems (Muzayanah et al. 2018). The problem with sustainable palm oil management in Indonesia is the fact that the increasing demand for CPO is caused by domestic CPO demand and global CPO demand, with global CPO demand dependent on national biodiesel policies. However, the demand for CPO will drive the expansion of oil palm plantations and CPO production, resulting in environmental degradation, especially an increase in greenhouse gases (GHG).

Conceptual system formation

The conceptual system formation involves identifying the subjects involved in the system (system variables), and the relationships among these variables serve as a basis to form a causal loop and analyze the system's limitations. The limitation is to simplify the evaluation of the analyzed system. The next step is the formulation of a causal loop diagram, as illustrated in Figure 2. The formulation of this causal loop diagram is based on the results of the study in the KLHS RPJPN 2024-2045.

Model formulation

Model formulation is a step for converting inter-element relations or inter-variable relations in the system to computer language. In this study, the system is divided into four subsystems, including (i) CPO supply policy sub-model; (ii) CPO productivity sub-model; (iii) social sub-model; and (iv) environment sub-model (Figure 3).

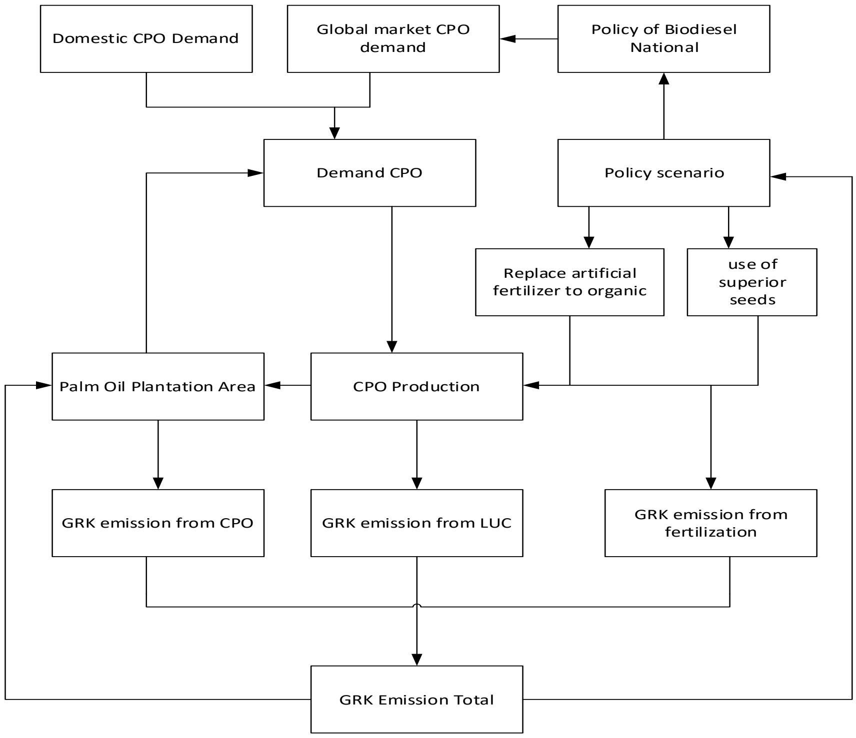

Figure 1. Methodological research framework for assessing total greenhouse gas (GRK) emissions related to Crude Palm Oil (CPO) production

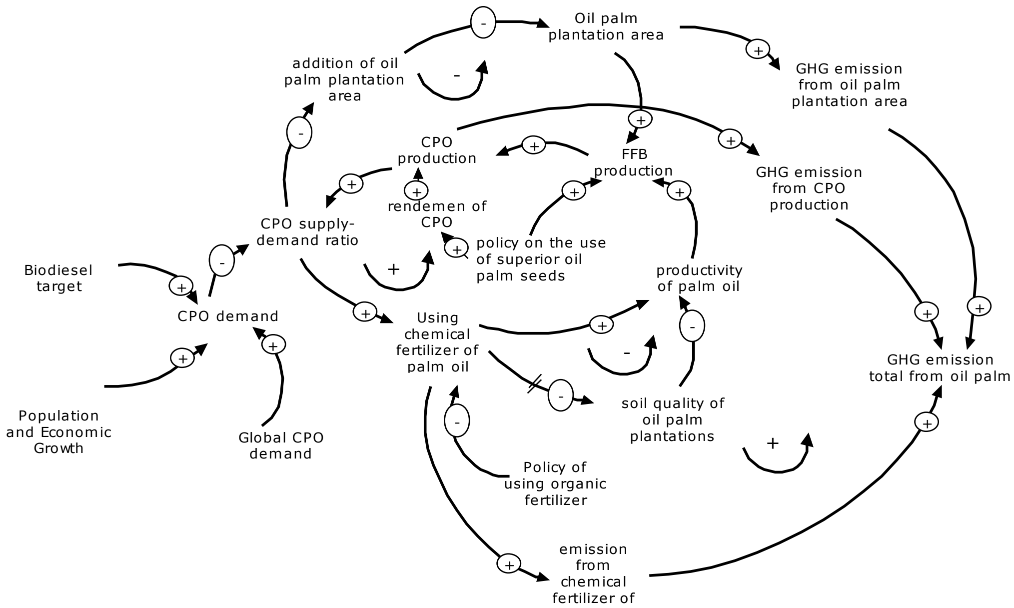

Figure 2. Causal-loop of optimizing the sustainability of oil palm plantations scenarios (Kusumadewi et al. 2024; Okarda et al. 2024)

Model simulation

After designing the causal loop diagram and the stock and flow diagram, simulations were conducted to understand the policy (Lin et al. 2020). The model can test various scenarios and explore future results with past conditions with simulations (Yuana et al. 2021). The model is simulated to observe the model's behavior, which is a description of the real system's behavior (Tram 2022). The main assumptions underpinning this study include steady demographic and economic growth, consistent land suitability, gradual adoption of sustainable farming practices, adherence to zero-deforestation commitments, and full implementation of the B40 biodiesel policy. Emission estimates rely on default IPCC emission factors and standard fossil fuel substitution coefficients. The model simulation was carried out in three scenarios in Table 1.

Table 1. Key differences between the BAU, moderate, and ambitious scenarios

Aspect	BAU	Moderate scenario	Ambitious scenario	Sources
Initial level of total oil palm plantation area in 2023	15,928,712 hectares	15,928,712 hectares	15,928,712 hectares	(BPS-Statistics Indonesia 2024)
Initial level of total CPO production in 2023	47,084,299 tons	47,084,299 tons	47,084,299 tons	(BPS-Statistics Indonesia 2024)
The average CPO productivity	3.264 tons per hectare	3.264 tons per hectare	3.264 tons per hectare	(BPS-Statistics Indonesia 2024)
The average of fresh fruit bunch	20.1 ton per hectare	20.1 ton per hectare	20.1 ton per hectare	(Suhartono et al. 2023)
The average urea requirement	0.225 tons per hectare	0.225 tons per hectare	0.225 tons per hectare	(Suhartono et al. 2023)
Supported by productivity from urea	57.219%	57.219%	57.219%	(Suhartono et al. 2023)
Emissions from urea fertilizer application	1,920 kgCO_2e per ton of urea applied	1,920 kgCO_2e per ton of urea applied	1,920 kgCO_2e per ton of urea applied	IPCC 2006
GHG emissions from oil palm plantation land use	233.7102 MtCO_2e	233.7102 MtCO_2e	233.7102 MtCO_2e	(N2thFREL)
The average GHG emissions from processing one ton of crude palm oil (CPO)	1,600 kgCO_2e	1,600 kgCO_2e	1,600 kgCO_2e	(Acobta et al. 2023)
The Indonesian population in 2023	278,696,200 people	278,696,200 people	278,696,200 people	(BPS-Statistics Indonesia 2024)
Fertilizer	100% urea	50% urea, 50% organic	100% organic	Established
Seedlings	Conventional seedlings	Superior seedlings on 50% of area	Superior seedlings on entire area	Established
Biodiesel policy	No B40 policy	B40 at 50% of BAU target	Full B40 implementation	Established
Expected production	47.08 million tons	~50% higher than BAU	~100% higher than BAU	Established
Synthetic fertilizer use	Full use	Reduced by 50%	Eliminated	Established

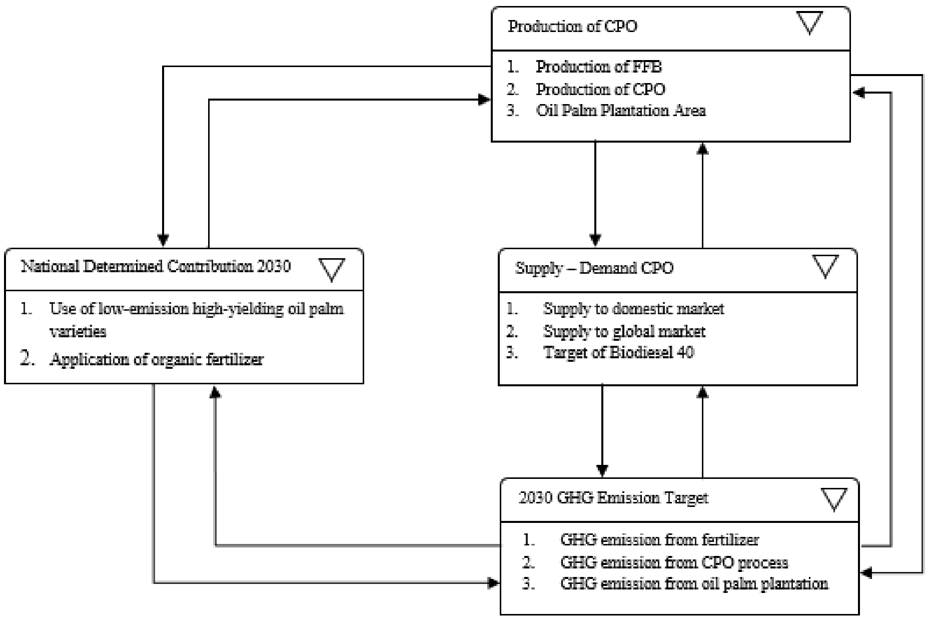

Figure 3. Research model of optimizing the sustainability of oil palm plantations scenarios (Kusumadewi et al. 2024; Okarda et al. 2024)

Policy/decision analysis and improvement

The reliability of the model was tested, and the results will be used to observe or test the condition being analyzed. By using this model, system conditions, system behavior, and system response to the policy regarding the system can be observed. Therefore, adjustments to policy and system structure can be made immediately if needed. This model is called Dynamic Model of Indonesia's Sustainability of Oil Palm Plantations Management (ISOPPM). The research model in ISOPPM was divided into four sub-models as follows:

Policies to support the achievement of agriculture sector NDC in 2030 sub-model

The Policies to support the achievement of consistent low-emission high yielding oil palm varieties and application of organic fertilizer. In this sub-model, the model will represent efforts to support climate change mitigation in achieving the 2030 NDC target (Twidyawati et al. 2021).

Production of CPO sub-model

The sub-model is divided into the production of FFB, production of CPO, and the oil palm plantation area, based on BPS data with a baseline in 2023. In this sub-model, CPO production from year to year will be observed with driving-variables from using organic fertilizer to replace artificial fertilizer policy, low-emission high-yielding oil palm varieties policy, and policy of biodiesel with contain 40% of biofuel (B40) production (Mokhtar et al. 2023). The policy will affect FFB production, and CPO production and restrain the expansion of oil palm plantations.

Supply - demand CPO sub-model

This sub-model describes the ratio of demand to supply of CPO. CPO demand comes from the domestic market, the global market, and the need for CPO for the development of B40 biodiesel. Meanwhile, CPO comes from the CPO production sub-model. The ratio of demand to supply will affect the addition of oil palm plantation areas.

2030 GHG emission target sub-model

This sub-model describes the impact of policy on supporting the mitigation of climate change to meet the GHG emission target in 2030. Total GHG emissions are the sum of emissions from oil palm expansion from forest land, artificial fertilizer use, and CPO processing. Based on the development of these four sub-models, a dynamic model is formed dynamic model of Indonesia's Sustainability of Oil Palm Plantations Management (ISOPPM) (Figure 4).

Model use

The goal of this step is to answer the research question that was identified at the beginning of the modelling research. This involves designing and simulating for search the scenario of optimizing the sustainability of oil palm plantation management with analysis, interpretation, and communication of simulation results using the same general procedure as using real-world results.

Validation and sensitivity analysis

Statistical analysis in dynamical systems focuses more on error measurement, model validation, and parameter sensitivity, rather than hypothesis testing as in inferential statistics. The dynamic model is required for the verification process to identify any potential error that emerges after running the modelling scenario from SFD. The validation process is carried out to ensure the model behavior output is accurate and in line with expectations and realities in the field. The authors employ AME (Absolute Mean Error) to validate the process (Wehantouw et al. 2021). In this study, the average error between model results and actual data was used.

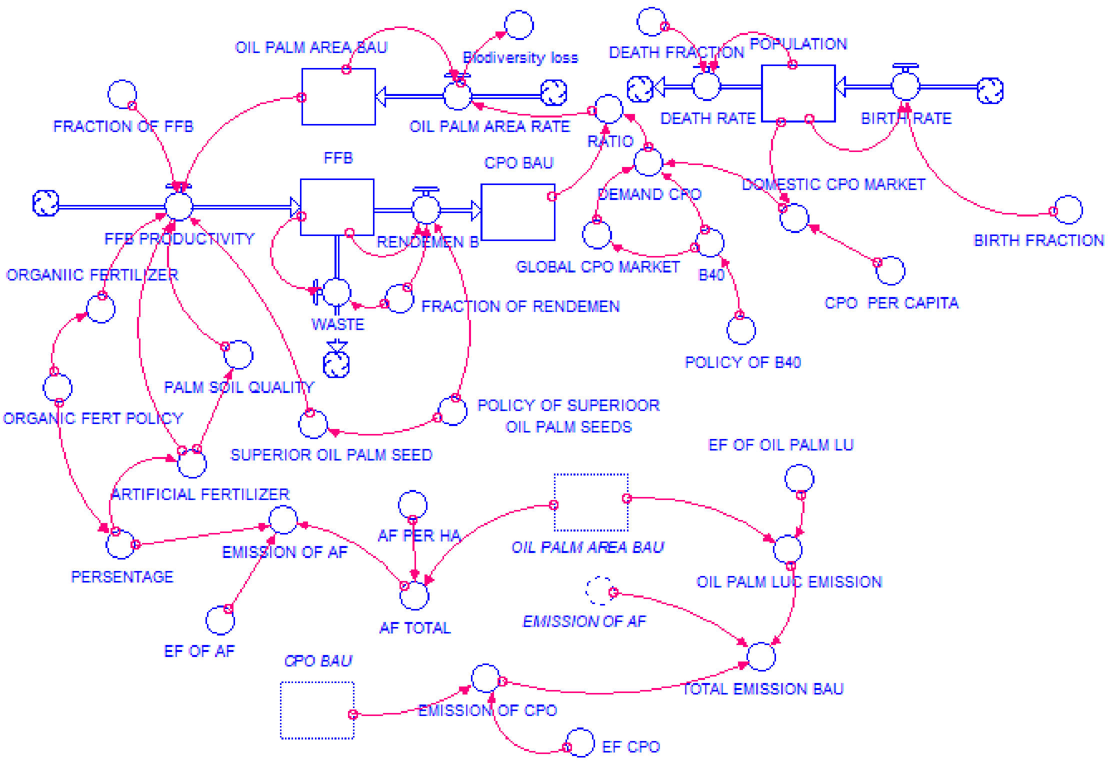

Figure 4. Dynamic model of Indonesia's Sustainability of Oil Palm Plantations Management (ISOPPM) (Kusumadewi et al. 2024; Okarda et al. 2024)

$$MAPE = \frac{1}{N}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{At}\right|$$

Where:
MAPE: Mean Absolute Percentage Error
At: Actual data at time t
Ft: Simulation/model results at time t
N: Data number
The smaller the MAPE, the more accurate the model.

Sensitivity analysis evaluates the responsiveness of a dynamic system model to changes in key parameters. It helps determine the robustness of the model and the reliability of its policy insights. In a system dynamics framework, sensitivity analysis is typically conducted by varying parameters within a defined range and quantifying the effect on selected output variables. The most common approach is to calculate a sensitivity coefficient (SC), expressed as:

$$SC = \frac{\Delta Y / Y}{\Delta X / X}$$

Where:
Y: Output variable (e.g., plantation area, CPO production),
X: Input parameter (e.g., policy of use organic fertilizer, and high yield varieties),
ΔY: Change in output caused by a change in X
ΔX: Change in the parameter value.
SC>1 indicates that the output is highly sensitive to the parameter, while SC<1 suggests low

RESULTS AND DISCUSSION

The simulation results from the three scenarios obtained from the study showed that the policies support the achievement of an inclusive approach, which involves using low-emission, high-yielding oil palm varieties and applying organic fertilizers. The three scenarios include the business-as-usual scenario (BAU scenario), the moderate scenario, and the ambitious scenario. The three scenarios will show differences in the sustainability indicators of Indonesia's oil palm plantations, namely the controlled development of oil palm plantation areas, increased CPO production, low GHG emissions that support GHG emission targets, and the reduction of biodiversity loss.

Projected palm oil plantation

The scenario policies incorporate the adoption of low-emission of high-yielding oil palm varieties and the application of organic fertilizers. For the 2025-2060 period, simulations assess oil palm plantation area, crude palm oil (CPO) production, biodiversity loss, and greenhouse gas (GHG) emissions. The historical baseline expansion rate from 2015 to 2023 averaged 13,590 ha yr^{-1} (BPS 2023), with a total plantation area of 15.33 Mha in 2023. Projections indicate that annual expansion under the business-as-usual (BAU) scenario reaches 95,384.78 ha yr^{-1}, exceeding that of the Moderate (87,076.22 ha yr^{-1}) and Ambitious (81,607.08 ha yr^{-1}) policy scenarios. By 2060, plantation area is estimated at 19.11 Mha for BAU, compared to 18.78 Mha and 18.65 Mha under the Moderate and Ambitious scenarios, respectively. These results suggest that targeted policy measures could substantially limit plantation expansion relative to the baseline trajectory.

Projected CPO

In contrast, the projected annual CPO production (Figure 6A) is 52,890,689.47 t yr^{-1} under BAU, 77,559,421.04 t yr^{-1} under the moderate scenario, and 98,149,720.84 t yr^{-1} under the ambitious scenario. Consequently, cumulative production by 2060 is estimated at 2,332,362,742.59 t for BAU, compared with 3,220,437,079.01 t for moderate and 3,961,687,871.67 t for ambitious scenarios (Figure 6.B).

Impact on biodiversity loss and GHG emissions

Assuming continued conversion of forest to oil palm, projected annual biodiversity loss (Figure 7.A) is highest under BAU (95,384.78 ha yr^{-1}), followed by moderate (87,076.22 ha yr^{-1}) and ambitious (81,607.08 ha yr^{-1}) scenarios. GHG emissions decline across all scenarios (Figure 7.B), with net removal occurring from 2041 in BAU (−1.03 $MtCO_2e$), 2039 in moderate (−0.83 $MtCO_2e$), and 2038 in ambitious (−1.71 $MtCO_2e$), reaching −18.28, −31.98, and −32.69 $MtCO_2e$, respectively, by 2060. Emission reductions and increased sequestration arise from both reduced plantation expansion and carbon uptake by maturing palms, with only minor differences between moderate and ambitious outcomes.

A summary of these comparisons, covering the average annual expansion of oil palm plantation area, CPO production, biodiversity loss, and GHG emissions, is presented in Table 2.

Simulation outcomes revealed clear differences among scenarios and time periods. In 2025-2030, all scenarios substantially reduced oil palm expansion and biodiversity loss relative to the 2014-2023 baseline (over 65% reduction), while increasing CPO production. GHG emissions also fell sharply (over 80% in BAU), with the Ambitious scenario achieving the greatest production gains (+6.8% above BAU) alongside marginally lower emissions and biodiversity loss, indicating that policy interventions can enhance yields while maintaining environmental benefits.

In the long term (2031-2060), plantation expansion and biodiversity loss remained more than 80% below baseline, reflecting reduced extensive growth. However, production pathways diverged markedly: BAU achieved only modest gains, whereas moderate and ambitious scenarios yielded 45% and 83% higher CPO production than BAU, respectively. These gains came with significant trade-offs, as GHG emissions rose more than twofold under moderate and nearly threefold under ambitious, underscoring the tension between production targets and climate commitments.

Model validation

Validation that was done in this model uses AME (Absolute Mean Error) model between the Indonesia oil palm statistics and the result of the model simulation. The data that were used in this validation were the total oil palm area data and CPO production from 2014 to 2023. Based on the AME test, the significance value that was obtained for total oil palm plantation was 0.044 (Table 3) and CPO production was 0.00194 (Table 3), smaller than the α value (0.05). Therefore, the conclusion is that there is no significant difference between actual data and simulation data.

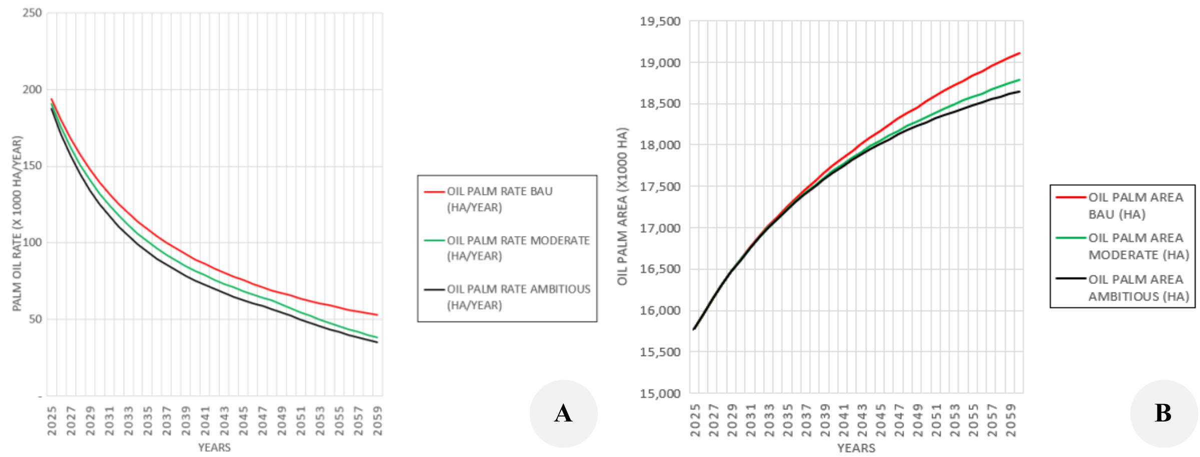

Figure 5. A. Projected oil palm plantation expansion rate and B. Cumulative plantation area under BAU, moderate, and ambitious scenarios for 2025-2060

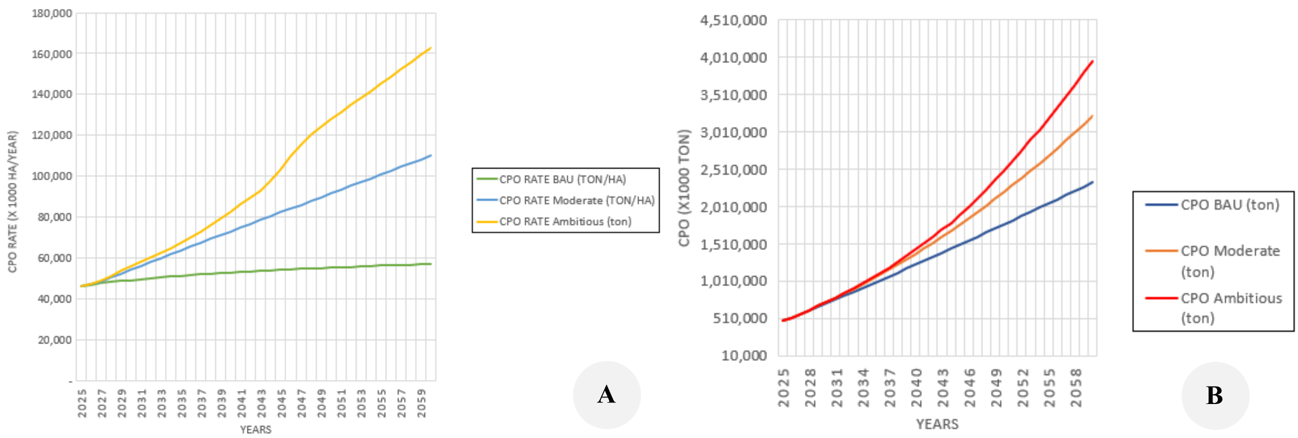

Figure 6. A. Projected annual and B. Cumulative CPO production under BAU, moderate, and ambitious scenarios for 2025-2060

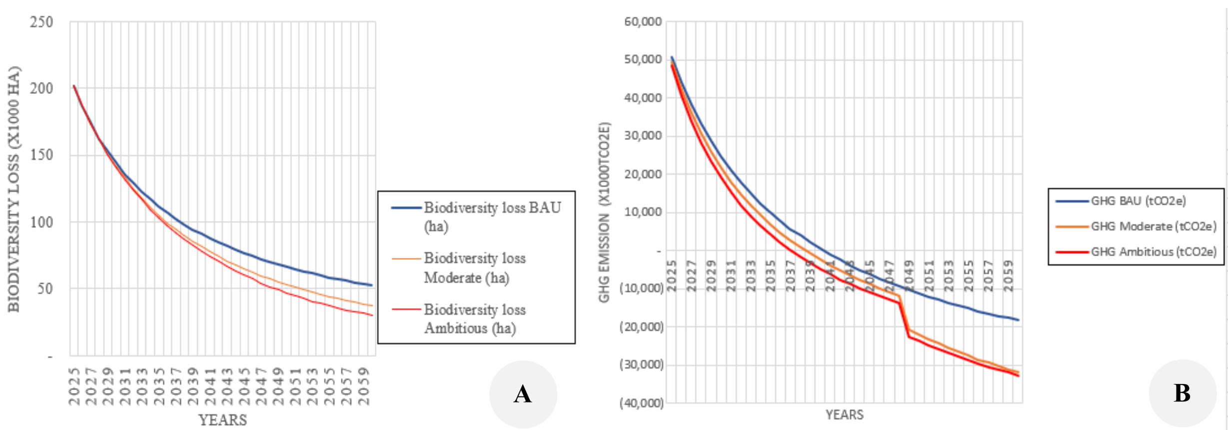

Figure 7. A. Projected impact of biodiversity loss and B. GHG emission under BAU, moderate, and ambitious scenarios for 2025-2060

Table 2. Comparison of projected moderate, and ambitious scenarios with BAU scenario period 2025 to 2030 and 2031 to 2060

Period	Scenario	Category			
		Palm oil plantation (ha $year^{-1}$)	CPO production (ton $year^{-1}$)	Biodiversity loss (ha $year^{-1}$)	GHG emission (tCO_2e $year^{-1}$)
2014-2023	Baseline level	508,383.58	39,275,827.33	572,084.08	208,728,466.19
2025-2030	BAU	176,394.62	48,068,090.01	170,224.25	36,577,200.20
	Moderate	175,746.43	50,439,837.07	169,373.95	35,974,610.23
	Ambitious	175,492.62	51,356,735.07	169,044.24	35,910,238.34
	% BAU to baseline	-65.30	22.39	-70.24	-82.48
	% Moderate to BAU	-0.37	4.93	-0.50	-1.65
	% Ambitious to BAU	-0.51	6.84	-0.69	-1.82
2031-2060	BAU	83,132.61	52,823,243.25	81,628.98	- 4,046,436.16
	Moderate	72,324.54	76,753,225.35	70,611.91	- 10,615,563.96
	Ambitious	67,873.35	96,451,590.65	66,056.70	- 14,037,796.54
	% BAU to baseline	-83.65	34.49	-85.73	-101.94
	% Moderate to BAU	-13.00	45.30	-13.50	162.34
	% Ambitious to BAU	-18.36	82.59	-19.08	246.92

Table 3. Analysis of AME (Absolute Mean Error) of plantation area actual and model

Year	Based on plantation area			Based on CPO production		
	Plantation area actual (ha)	Plantation area model (ha)	AME	CPO production actual (ton)	CPO production model (ton)	AME
2015	11,260,276	11,826,096.83	0.05025	31,070,015.00	31,300,445.08	0.0074
2016	11,201,465	12,603,645.52	0.12518	31,487,986.00	34,035,354.85	0.0809
2017	12,383,101	13,210,333.80	0.06680	34,940,289.00	36,486,608.57	0.0443
2018	14,326,350	13,705,411.65	0.04334	42,883,631.00	38,522,684.87	0.1017
2019	14,456,612	14,122,289.55	0.02313	47,120,247.00	40,199,859.48	0.1469
2020	14,586,597	14,481,596.54	0.00720	45,741,845.00	41,599,545.51	0.0906
2021	14,621,693	14,796,897.13	0.01198	45,121,480.00	42,789,696.47	0.0517
2022	15,338,556	15,077,547.74	0.01702	46,819,672.00	43,820,478.85	0.0641
2023	15,928,712	15,330,253.19	0.03757	47,084,299.00	44,727,772.27	0.0500
Average			0.038			0.07

Discussion

ISOPM model

The dynamic model of Indonesia's Sustainability of Oil Palm Plantations Management (ISOPPM) was developed to support the implementation of sustainable palm oil management in Indonesia. The model is complex and consists of four interlinked sub-models: (i) CPO production, (ii) CPO supply-demand, (iii) greenhouse gas (GHG) emissions, and (iv) policy interventions. Together, these components provide a decision-support framework to help achieve Indonesia's Nationally Determined Contribution (NDC) target for 2030 and the net-zero emission goal by 2060. The model assumes that oil palm plantations are not converted to other land uses, only legally established plantations are considered, and policy interventions become effective in 2048. The production sub-model includes plantation area, fresh fruit bunch (FFB) production, CPO production, expansion rate of plantations, FFB productivity, and oil extraction rate. The supply-demand sub-model incorporates Indonesia's population, domestic demand for CPO, and global demand. The GHG emission sub-model captures emissions from fertilizer use and land-use change, as well as sequestration from oil palm growth. The policy sub-model covers the use of organic fertilizers, adoption of high-yielding varieties, and biodiesel blending (B40) policies. Initial conditions were set in 2014, with a plantation area of 10,754,801 ha, FFB production of 35,210,472.25 t, and CPO production of 29,278,189 t. Indonesia's population in the base year was 252,164,790. Converter/fraction variables included average FFB yield of 3.67 t ha^{-1}, a birth rate of 1.4%, and a death rate of 0.6%.

The projection results using the ISOPPM model indicate that, even without policy interventions such as the adoption of organic fertilizers and superior seedlings, the BAU scenario still demonstrates improvements, including reduced oil palm plantation expansion, increased CPO production, and decreases in biodiversity loss and GHG emissions. The sensitivity value of replacing artificial fertilizer with organic fertilizer is 22.65 (very high sensitivity). This aligns with mitigation action plans in the AFOLU sector, particularly the implementation of the Indicative Moratorium Map (PIPIB), which restricts new investments in natural forests and protected peatland areas. In addition, pressure from the global market—especially from European consumers banning CPO imports from Indonesia due to concerns about peatland conversion—further limits expansion. According to Indriyadi (2022), the oil palm industry remains controversial and subject to increased scrutiny, resulting in stricter permitting requirements. These controversies are related to plantation expansion, price fluctuations, and the associated impacts on biodiversity loss, GHG emissions, and erosion. Therefore, as highlighted by (de Rosa et al. 2022), mitigation efforts that enhance industry performance can play a significant role in reducing the carbon footprint and biodiversity impacts of palm oil production. Therefore, the ISOPM model can be used as a generic model for decision-making in sustainable palm oil plantation management.

This requires a complex model that can consider a variety of variables, including economic, social, and environmental factors, such as system dynamics. At the oil palm plantation level, system dynamics applications can be used to generate simulations of CPO production, CPO supply and demand, and downstream refinery processes (Astria et al. 2021), the palm oil supply chain in SIPOS model with three main components: (i) the palm oil supply chain, (ii) the sustainability scenario development intervention, and (iii) the output indicators to evaluate the results of each scenario (Okarda et al. 2024), and JAPOS (Jurisdictional Approach Modelling for Palm Oil Sustainability) model with output indicators including CPO production, deforestation, emissions, and trade value (Kusumadewi et al. 2024). This study, conducted at the national level, demonstrates that the utilization of system dynamics, incorporating variables pertaining to policy, economic activity, population, and environment, has yielded interactions that can be employed to identify pertinent policies, thereby facilitating the realization of the zero-emission objective for the oil palm plantation sector. There are three scenarios applied in the simulation: scenario of BAU, scenario of moderate, and ambitious scenario. The results we want to see and analyze are the differences in the trends of the three scenarios in 2060, namely (i) the increase in oil palm plantation area, (ii) CPO production, and (iii) the achievement of the net zero emission target in 2060. The scenarios are differentiated by policies on the use of artificial fertilizers, the use of superior oil palm seedlings, and policies on the production of B40 biodiesel. The design of these scenarios is aligned with Indonesia's climate pledges, particularly the Nationally Determined Contribution (NDC) target of reducing greenhouse gas (GHG) emissions by 31.89% (unconditional) and up to 43.2% (conditional) by 2030 compared to the BAU projection (MoEF 2021). The ambitious scenario specifically supports the FOLU (Forestry and Other Land Use) Net Sink 2030 roadmap and the long-term goal of net-zero emissions by 2060 by minimizing land expansion, promoting organic inputs, and increasing biodiesel substitution for fossil diesel. However, each scenario entails specific risks and constraints. The BAU scenario poses the greatest risk of failing to meet the NDC targets due to continued reliance on conventional fertilizers, limited productivity gains, and ongoing land expansion, which could result in higher emissions and deforestation pressures. The moderate scenario reduces these risks by partially shifting to organic fertilizers, improved seedlings, and higher biodiesel blending, but its success depends on farmer adoption rates, market incentives, and policy enforcement. Inconsistent implementation could limit its effectiveness in delivering emission reductions. The ambitious scenario offers the highest potential to meet or exceed Indonesia's climate targets, yet it faces significant practical challenges. These include the technical feasibility of fully replacing synthetic fertilizers with organic alternatives, the availability and affordability of superior seedlings, and the infrastructure required to support nationwide B40 biodiesel production. Moreover, smallholders may lack capacity or resources to adopt all recommended practices without substantial government support, capacity building, and financial incentives (MoEF 2022; MEMR 2023).

Reduction in palm oil plantation expansion

The simulation results underscore the critical role of policy measures in curbing oil palm plantation expansion. Without intervention, the BAU scenario indicates a rapid acceleration of expansion, averaging 95,384.78 ha yr^{-1} and culminating in 19.11 Mha of total plantation area by 2060. In contrast, the Moderate and Ambitious policy scenarios—through the adoption of low-emission, high-yielding oil palm varieties and the application of organic fertilizers—are projected to prevent expansion of approximately 0.33 Mha and 0.46 Mha, respectively, compared to BAU. While these reductions may seem limited relative to the overall scale of development, they represent a significant restraint on land conversion pressures that would otherwise encroach on forest ecosystems. The three dimensions of biodiversity are currently being exhausted at a higher rate; as a result, there is a great concern regarding biodiversity loss, with rich and unique habitats increasingly degraded and fragmented (Kumari et al. 2021). Preventing further expansion is therefore essential for reducing biodiversity loss, safeguarding ecosystem services, and limiting additional GHG emissions. More importantly, the findings demonstrate that targeted policies can enhance productivity without requiring proportional land expansion, thereby supporting both economic and environmental objectives. This emphasizes the need for strong governance and sustained policy enforcement to ensure that oil palm development remains within sustainable land-use boundaries.

The simulation results for 2025-2060 reveal the critical role of policy interventions in shaping the trajectory of oil palm expansion. The policies to support this achievement of consistent low-emission high yielding oil palm varieties and application of organic fertilizer. In this sub-model, the model will represent efforts to support climate change mitigation in achieving the 2030 NDC target. Historically, from 2014 to 2023, plantation expansion proceeded at an average rate of 13,590 ha yr^{-1} (BPS 2023), reaching 15.33 Mha in 2023. Without policy intervention, the BAU scenario projects a rapid increase in expansion, reaching 95,384.78 ha yr^{-1} and a total of 19.11 Mha by 2060. By comparison, the Moderate and Ambitious scenarios constrain expansion to 87,076.22 ha yr^{-1} (18.78 Mha) and 81,607.08 ha yr^{-1} (18.65 Mha), respectively. These reductions highlight the potential of policy interventions to curb expansion and deliver important environmental benefits. Slower rates of deforestation under the moderate and ambitious scenarios mitigate biodiversity loss, particularly in primary and secondary forest habitats that host high concentrations of endemic and threatened species (Meijaard et al. 2020). In parallel, reduced forest-to-plantation conversion contributes to lower GHG emissions, while the maturation of existing plantations enhances carbon sequestration. As a result, both policy scenarios achieve net-negative emissions earlier than BAU, aligning with climate mitigation goals. Notably, while the absolute difference in plantation area between the moderate and ambitious scenarios is modest (0.13 Mha by 2060), the cumulative gains in GHG removal and biodiversity conservation are more pronounced under the Ambitious pathway, underscoring the value of incremental policy ambition. These findings carry strong relevance for Indonesia's commitments to the Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action) and SDG 15 (Life on Land).

Increased CPO production

The findings demonstrate that policy interventions promoting high-yielding oil palm varieties along with organic fertilizer application can effectively moderate plantation expansion while boosting productivity. The simulation results reveal significant differences in CPO production trajectories under the three policy scenarios. Under BAU, annual production is projected at 52.89 million t yr^{-1}, substantially lower than the 77.56 million t yr^{-1} and 98.15 million t yr^{-1} projected under the moderate and ambitious scenarios, respectively. These differences become even more pronounced when considering cumulative production by 2060, with BAU reaching 2.33 billion t, compared to 3.22 billion t and 3.96 billion t under the moderate and ambitious scenarios. Such findings highlight that policies promoting the adoption of high-yielding, low-emission oil palm varieties and organic fertilization can significantly enhance productivity while simultaneously restraining land expansion (Woittiez et al. 2017). The ambitious scenario's earlier achievement of net-negative emissions and greater biodiversity protection directly support these targets, while maintaining relatively stable CPO production levels. This aligns with the literature, which indicates that land-use governance reforms, yield intensification, and conservation set-asides can reduce environmental trade-offs in palm oil landscapes (Austin et al. 2019).

Since 2013, Indonesia has progressively implemented biodiesel blending to reduce its heavy reliance on fossil diesel. The current mandate, B35, requires a 35% biodiesel-to-diesel volume ratio, with plans to increase the blend to 40% (B40) in the near term. This policy is regarded as a strategic measure to curb oil imports and enhance the share of renewables in the national energy mix, supporting the target of achieving 23% renewable energy by 2025 (Mokhtar et al. 2023). Ecologically, this outcome reflects the capacity of improved varieties to produce higher fresh fruit bunch (FFB) yields per unit area, thereby reducing pressure for extensive plantation growth, while organic fertilizers enhance soil fertility, improve nutrient cycling, and sustain long-term productivity with lower environmental costs. Consequently, in support of sustainable biofuel production from a developing country, future development may need to incorporate the type of land use changes prior to plantation development of palm plantations (Ostfeld and Reiner 2024). The application of PKS waste can substantially improve plantation management efficiency by optimizing input–output dynamics. Its use as an organic fertilizer offers an environmentally friendly alternative that reduces reliance on synthetic fertilizers, thereby promoting sustainable agricultural practices. These findings have policy relevance, supporting the integration of PKS waste utilization into strategies for advancing sustainable palm oil production (Martial et al. 2024). The anticipated increase in palm oil demand resulting from this policy necessitates the implementation of complementary strategies that sustainably enhance yields while minimizing additional land conversion. Overall, while biodiesel blending policies are vital for renewable energy goals, the anticipated increase in palm oil demand underscores the need for complementary ecological strategies—such as sustainable intensification, degraded land utilization, and organic waste recycling—to enhance yields while minimizing biodiversity loss and GHG emissions from further land conversion.

Indonesia's 2060 net zero target from palm oil sector

In reference to the 2030 GHG emission reduction target by Government of Indonesia (GOI), the mitigation scenarios adopted in the agricultural sector include the cultivation of low-emission rice varieties on 902,000 hectares of paddy fields, the implementation of more efficient irrigation systems, the application of organic fertilizers, the utilization of livestock waste, and improvements in livestock feed supplements. In the FOLU sector, mitigation measures focus on reducing deforestation and forest degradation, land rehabilitation, peatland water management, and peatland restoration. By applying the ISOPPM model with two key measures in the agricultural sector—namely, the use of organic fertilizers and superior seedlings in oil palm plantations—positive impacts are also observed for mitigation outcomes in the FOLU sector, especially for mitigation to correlation with deforestation reduction. Reduced oil palm plantation expansion could lower the average expansion rate by up to 18.36% under the ambitious scenario and decrease average biodiversity loss by 19.08% by 2060 compared to the BAU scenario. This policy approach can also reduce emissions and even enhance GHG absorption from the atmosphere by up to 246.92% relative to BAU conditions. In addition to the social impacts, there are also negative ecological impacts, including increased carbon emissions due to reduced land cover. The conversion of tropical forests to oil palm plantations has resulted in a significant reduction in the number of species that can be supported to live in them (Dadi 2021). Expansion of oil palm plantation areas in Thailand, the world's third-largest oil palm producer, for food and fuel may sometimes encroach on forest areas, leading to biodiversity loss (Jaroenkietkajorn et al. 2021). This has resulted in customary land enclosures, violations of customary rights and the ecological, economic, and socio-cultural burdens that indigenous peoples are facing as a result of the loss of forest and land resources (Runtuboi et al. 2021).

The improving energy efficiency in the manufacturing sector could reduce emissions by 81.309% by 2048, supports Indonesia's target to reach zero emissions by 2060

(Husada and Jeosoef 2022). The term "net-zero emissions" signifies a condition where the amount of carbon emissions released into the atmosphere is balanced by the amount that can be absorbed by the Earth (Qalbie and Rahmaniah 2023). In the agricultural sector, net zero emissions refer to the elimination of all agricultural GHG emissions so that there is an overall balance between GHG emissions produced and GHG emissions taken up from the atmosphere (Khalil et al. 2024). On a global scale, agriculture has been identified as a significant contributor to climate change, and conversely, it is also significantly impacted by climate change. This underscores the necessity for the development and implementation of technologies and innovations designed to reduce greenhouse gas emissions within the agricultural sector. Among the potential solutions to this problem are the de-carbonization of on-farm energy use, the adoption of nitrogen fertilizer management technologies, alternative rice planting methods, and the integration of feeding and breeding technologies to reduce enteric methane emissions. The implementation of these measures, when combined, has the potential to reduce agricultural greenhouse gas emissions by 45% (Rosa and Gabrielli 2023). The elements to consider in balancing emissions reductions from different sectors require broader political, ethical, and social considerations, especially where there is the potential for temporal climate trade-offs to arise (Lynch et al. 2021). Mitigation measures may vary between countries, but ultimately, all farms will be required to reduce emissions and increase sequestration to reach environmental targets. In addition, it will be necessary for farms to increase production sustainably to ensure food security (McNicol et al. 2024).

As the world’s largest producer and consumer of palm oil, Indonesia is currently facing substantial challenges following the adoption of the European Union (EU) Parliament Resolution concerning the use of palm oil and its relation to deforestation. The regulation entails restrictions and a de facto rejection of palm oil and its derivative products, which is projected to result in a decline in the country's Gross Domestic Product (GDP) by approximately 155.28 million euros (Benyaich et al. 2023; Hamid and Paramitaningrum 2023). In response to trade barriers imposed on palm oil in the European Union market, Indonesia has undertaken several strategic measures. These include raising the issue at the World Trade Organization (WTO) forum and formulating the National Action Plan for Sustainable Palm Oil (*Rencana Aksi Nasional Kelapa Sawit Berkelanjutan*, RAN KSB) for the period 2019-2023, as mandated by Presidential Instruction No. 6 of 2019. Actional Action Plan (NAP) is a policy established to achieve oil palm plantations that support sustainable development in 18 cities in Indonesia, including (i) increasing plantation capacity, (ii) environmental management, (iii) conflict Management and management, and (iv) implementation of ISPO in Indonesia (Hamid and Paramitaningrum 2023). The results of this study show that if the policy of increasing the capacity of oil palm plantations with the use of organic fertilizers, and the use of superior seeds can increase the production of FFB, and CPO and contribute to reducing the rate of deforestation due to land expansion for oil palm plantations. This condition will also accelerate the achievement of the NZE target earlier than 2060.

Oil palm plantations are one of the mainstay industry sectors in Indonesia, attracting serious attention from the government, investors (private sector), and farmers (community) who are never devoid of the dynamics of the problem, and conflict between stakeholders (Saleh et al. 2020). Achieving sustainability management in oil palm plantations can be accomplished by implementing the principles and criteria outlined by the Indonesian Sustainable Palm Oil (ISPO). The institutional strengthening of independent smallholders requires sustained support and attention from the government as well as other business actors throughout the oil palm agriculture-industry supply chain. The proposed institutional strengthening model consists of three key stages: the establishment of smallholder corporations, the formation of independent cooperatives, and the revitalization of the Indonesian Independent Oil Palm Smallholders Association (Raharja et al. 2020). Based on the result, replanting based on the using organic fertilizer with the ambitious scenario (100% replacement artificial with organic fertilizer, and 100% using superior seed) can increase production CPO by 81.309% from the BAU scenario, while the expansion of oil palm plantation area can be reduced to 6.27% and GHG emissions can reach zero by 2048 compared to the BAU and moderate scenarios. Under these conditions, substantial improvements can be achieved by immediately implementing policies on the use of organic fertilizers and the use of improved palm seedlings by 2025.

Scientists, stakeholders, and communities must commit to supporting these policies to prove that Indonesian oil palm plantations can control deforestation for oil palm expansion, in addition to achieving the NZE target before 2060. The challenge for scientists and the seed industry in the palm oil industry to produce superior palm oil seeds must be accelerated by continuous research efforts. Meanwhile, producing organic fertilizers must be done on a mass manufacturing scale, rather than on a household scale, with a quality and completeness of nutrient content that is significantly higher than that of artificial fertilizers. Meanwhile, oil palm plantation companies, both large and small, must apply good plantation practices and be fully certified.

Management implication

The institutionalization of sustainable palm oil in Indonesia is shaped by both exogenous and endogenous factors. International pressure and the expansion of global sustainability networks have driven shifts in national institutional frameworks, while domestic political dynamics and commitments to reducing greenhouse gas emissions have supported gradual institutional reforms. The ISPO certification reflects these developments, synthesizing existing regulations and demonstrating the path-dependent nature of sustainability policy in Indonesia (Astari et al. 2025), alongside the implementation of the Indonesia Sustainable Palm Oil (ISPO) policy, which is considered the most effective policy alternative (Suratiningsih et al. 2023). Meanwhile, the introduction of the policy resulted in a substantial decline in large firms' profits, amounting to IDR 75 million (approximately USD 5,250), with the negative impact increasing in line with firm size. Moreover, firms that rapidly acquired land prior to the policy's prohibition on land expansion experienced a marked decrease in performance. These findings indicate that a punitive approach to sustainable production does not effectively support the palm oil sector. However, large companies that had already aligned with international sustainability standards prior to the implementation of the domestic policy were able to derive notable benefits (Kunene and Chung 2020). In terms of landscape management, regional authorities must also implement policies related to landscape-level conservation benefits, reduced deforestation pressure, and the need for biodiversity safeguards in policy implementation. Therefore, well-designed incentive mechanisms are essential to encourage both companies and smallholders to adopt policies that promote the substitution of synthetic fertilizers with organic alternatives and the use of high-quality oil palm seedlings. Beyond incentives for plantation companies, targeted support should also be provided to fertilizer producers to stimulate the production and distribution of organic fertilizers. Additionally, incentives for researchers are vital to accelerate the development of superior oil palm varieties, for example through dedicated research grants and improved access to state-of-the-art laboratory facilities.

In conclusion, the validated ISOPPM model demonstrates that ambitious mitigation policies can substantially increase CPO production while curbing plantation expansion and achieving net-zero GHG emissions by 2038. These outcomes highlight the need for Indonesia to adopt firm strategies from 2025, focusing on productivity gains through organic fertilizers, superior seedlings, with complemented by sustained research on high-yield oil palm varieties. Policy measures should integrate biodiversity safeguards and landscape conservation, supported by incentives for corporations and smallholders to adopt sustainable practices. Such an approach would address deforestation governance challenges, align with international sustainability commitments, and strengthen Indonesia's competitiveness in the global palm oil market.

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