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Optimization of Aviation Biofuel Development as Sustainable Energy Through Simulation of System Dynamics Modeling

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ABSTRACT

This study aims to optimize the development of aviation biofuel as a sustainable energy source by simulating system dynamics modeling. This study is based on the System Dynamics modeling approach, which is a set of conceptual tools designed to understand the structure and dynamics of complex systems. This study used the system dynamics method specifically designed to analyze complex systems. It has been applied to various sustainability-related issues, including urban area sustainable development modeling, sustainability of water resources, environmental management, and sustainable urbanization. The result obtained using the quantitative modeling showed that the contribution of aviation biofuel to flight intensity in Indonesia is still insignificant. The practical implications of this study are that palm oil has the potential to be a viable raw material for aviation biofuel production in Indonesia, and implementing policies to mitigate negative consequences and optimize land use for aviation biofuel fuel production can contribute to sustainable urban development. The originality of this study lies in its use of System Dynamics modeling to analyze the potential of palm oil as a raw material for aviation biofuel production and identify the various social, economic, environmental, and technological factors that impact it.

INTRODUCTION

The System Dynamics method is a valuable tool for analyzing and predicting the behavior of complex physical, social, and economic systems. This method involves the formulation, simulation, and validation of future developments, making it possible to design and implement effective policy plans that have been applied to a wide range of sustainability issues, including urban area sustainable development modeling (Ab Rasid et al. 2021, Tan et al. 2018, Xing et al. 2019) sustainability of water resources, environmental management (Xiang et al. 2021), and sustainable urbanization (Mishra et al. 2017).

The System Dynamics method was utilized to model and simulate a sustainable management strategy for aviation biofuel development. Historical data from 2014 to 2019 was used to simulate and forecast future developments, and data processing was conducted using the Vensim PLE Software. The dynamic connection between the social, economic, and environmental spheres is intricate. The nature of the relationship is nonlinear, with a feedback loop. Hence, it is very meaningful to simulate the state and scenario of its development. The results of this study can contribute to guiding a more coordinated and sustainable development.

In this study, a custom model was developed specifically to reflect the unique conditions and characteristics of aviation biofuel development. The construction of this model is based on the mental model of the researchers and respondents, as well as relevant literature and previous studies. Thus, remarkable results were produced, unlike similar studies in other locations. System dynamics modeling depends on the ability of those conducting the study and close sources involved in the model production.

Previous studies showed the operational research methods used in biofuel supply chain planning (Gonzalez et al. 2018). Then, a case study analyzed a method for designing sustainable WEEE management system policies using optimization-based simulation (OBS) (Llerena-Riascos et al. 2021). A study also examined Indonesia's system dynamics approach to biodiesel fund management (Tupa R. Silalahi et al. 2020). The last was about dynamic system modeling of renewable energy diversification as a sustainability university (Arishinta & Suryani 2021). Thus, there was no yet study about aviation biofuel development as sustainable energy through simulation of system dynamics modeling,

System Dynamics modeling is a set of conceptual tools designed to help understand the structure and dynamics of complex systems. This method involves studying real-world situations to learn about the behavior and structure of a system and then examining the individual components to gain a deeper understanding. The approach is particularly well-suited for studying complex issues such as sustainable development. System dynamics modeling is carried out through four stages: observation of reality, preparation of models (conceptual), interpretation, and utilization of modeling results.

MATERIALS AND METHODS

The System Dynamics method is a valuable tool for analyzing and predicting the behavior of complex physical, social, and economic systems. This approach involves formulating, simulating, and validating future developments by observing the system's behavior, allowing for the design of effective policy plans. The System Dynamics method has been specifically designed for the analysis of complex systems. It has been applied to various sustainability-related issues, including urban area sustainable development modeling (Rusiawan et al. 2015, Strulak-Wójcikiewicz & Lemke 2019, Xing et al. 2019), sustainability of water resources (Kotir et al. 2016), environmental management (Van Oijstaeijen et al. 2020) and sustainable urbanization (Lu & Ke 2018).

The system dynamics in this study were used to model and simulate a sustainable aviation biofuel management strategy. The historical data used were from 2014 to 2019 for simulating and forecasting future developments. Data processing was carried out using Vensim PLE Software. In real terms, the dynamic interaction between social, economic, and environmental is complex. The nature of the relationship is nonlinear, with a feedback loop. Therefore, it is very meaningful to simulate the state and scenario of its development. The results of this study can contribute to guiding a more coordinated and sustainable development.

The model used in this study was built specifically according to the actual conditions in aviation biofuel development. The construction was based on the mental model of those who carried out the study, the respondent, and numerous previous studies. Therefore, the results are unique, and the outputs differ from similar studies in other locations. System dynamics modeling is highly dependent on the ability of those conducting the study and sources involved to produce models as closely as possible to the existing system.

RESULTS AND DISCUSSION

The Potential of Palm Oil in Aviation Biofuel Production

Developing bio-hydrocarbon fuels from vegetable oils is a key national priority in Indonesia. This program aims to achieve a renewable energy mix that includes biofuels, with a target of 23% by 2025. This goal aligns with the National Energy Policy, as the Indonesia National Energy Council (BPDPKS) outlined in 2021.

Indonesia is blessed with a diverse range of natural resources that have the potential to be utilized as sources of biofuels. However, in selecting raw materials for the production of biofuels, particularly aviation biofuels, various considerations must be taken into account, including the technical aspects of the production process, commercial viability, cultivation feasibility, and government policies. Previous research has shown that palm oil is the most promising raw material for the production of aviation biofuel (Siswahyu & Hendarwati 2014). It highlights the importance of considering the technical and commercial viability of potential biofuel sources and the need for further research and development in this area.

The selection of palm oil as the primary raw material for aviation biofuels in Indonesia is due to its technical superiority and suitability for the production process, making it a preferred choice over other potential feedstocks such as biomass, palm kernel, and coconut oil. It is supported by the growing trend of using palm oil as a feedstock for biodiesel in West Africa and Southeast Asia, with Indonesia and Malaysia being major players in the global production of palm oil (Nongbe et al. 2017). As a tropical country, Indonesia has the largest palm oil production potential, as reported in 2015. Indonesia and Malaysia accounted for 83% of global production, with 51% and 34%, respectively (Shigetomi et al. 2020).

Palm oil is a versatile raw material with a high content of medium-chain saturated and monounsaturated fatty acids, making it an ideal choice for producing aviation biofuels (Rutz & Janssen 2014). Palm oil is a perennial crop, unlike soybeans and rapeseed, meaning its oil production is continuous and uninterrupted (Wong et al. 2019). Additionally, palm oil has higher productivity, requiring less fertilizer, water, and pesticides than other crops (Mekhilef et al. 2011). The average world palm oil yield is 3.68 tons/ha/year, significantly higher than soybeans (0.36 tons/ha/year) and rapeseed (0.42 tons/ha/year) (Basiron 2007).

The processing of palm oil produces several derivative products, which include 21.5% Crude Palm Oil (CPO), 5%

Palm Kernel Oil (PKO), and Palm Kernel Cake (PKE), and the remaining waste products, such as fiber, empty fruit bunches, and Palm Oil Mill Effluent (POME) (Wicke et al. 2008). Crude Palm Oil (CPO) is the most commonly used raw material for biodiesel production. In tropical regions, oil palm plantations have the potential to yield 4.27-4.63 tons/ha/year (de Vries et al. 2010). The rapid growth of oil palm plantations in the country, particularly in Sumatra and Kalimantan, is driven by the vast forest areas and favorable climatic conditions (Wulandari et al. 2017). These conditions make Indonesia an important player in the global palm oil and biofuel industries.

Variables Impacting the Use of Palm Oil as Aviation Biofuel

The use of palm oil as a raw material for making aviation biofuels is related to various social, economic, environmental, and technological factors. The linkage can be backward or forward and comprises interrelationships capable of causing causal processes that form a feedback loop. The greater the variables related to the topic of study, the larger the potential loops formed. The variables involved in this study consisted of the following dimensions listed in Table 1.

Causal Loop Diagram of the Development of Biofuels as Sustainable Aviation Biofuels

Causal Loop Diagrams (CLD) are created based on the mental model and related references. Meanwhile, the causality relationships between variables are marked with arrows. The CLD analysis results carried out based on the collection of primary and secondary data are shown in Fig. 1.

The development of aircraft fuel in aviation biofuel significantly affects society's economic, social, environmental, technological, and political/regulatory aspects. CLD's Development of Aviation Biofuel as Sustainable Biofuel shows that applying a mixture of aviation biofuels in pure aviation fuel (avtur) affects the decrease in the resulting pollution. It also can reduce the process of global warming in the long run.

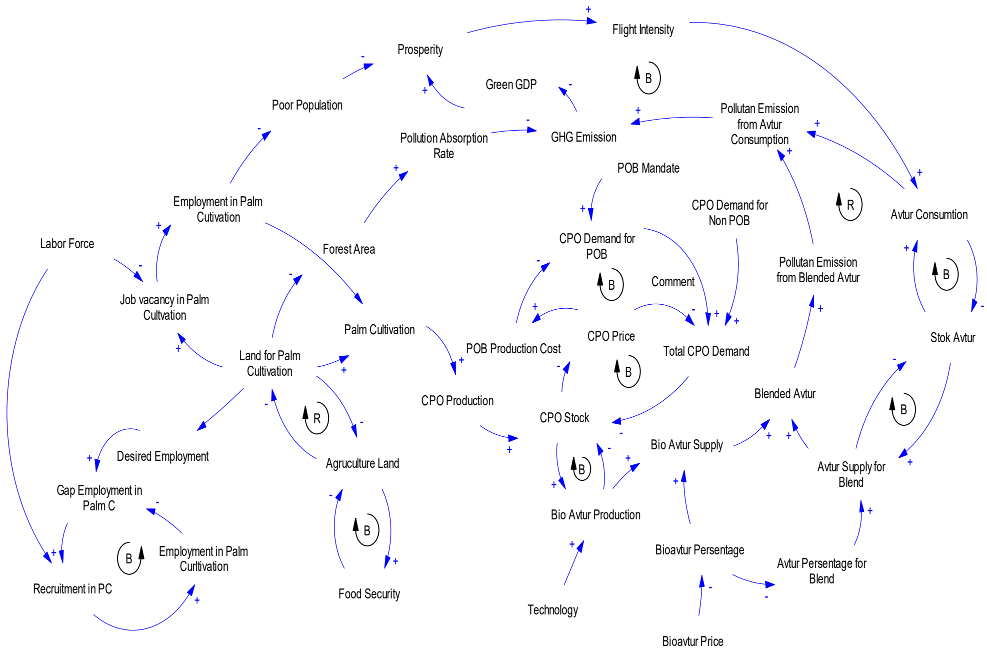
The use of aviation biofuels also affects increasing socioeconomic activity macroeconomically, especially in aspects of physical development and sustainable digitization of various industries. This process also increases various community activities, including mobility, by utilizing public transportation in the form of airplanes. Others include a rise in flight intensity not accompanied by increased aviation biofuel production, which reduces the ratio of aviation biofuel mixtures and avtur due to a lack of aviation biofuel stocks. This process potentially increases the production of pollutants from aircraft transportation. In the long run, these conditions hinder the socio-economic activities of the community.

In the environment, producing aviation biofuels

Table 1: Aviation biofuel Modeling Variables as Sustainable Biofuels.

Dimension	Principle	Criteria
Social	P1: Respect property and land tenure	C1-Rights of land access
	P2: Social acceptability	C2-National energy security
		C3-Local prosperity
	P3: Promote responsible work conditions	C4-Health & safety-employees
		C5-Labor laws
	P4: Prevent alteration to the food supply	C6-Food supply
Political	P5: Relationship between national and international aviation biofuel promotion policies	C7-Agreement national/international aviation biofuel blend-avtur, Subsidy scheme, Advanced aviation biofuel promotion
	P6: National aviation biofuel production consistent with international environmental policies	C8-Biomass is not edible for aviation biofuel production.
		C9-National amount of land suitable for biomass
	P7: Promote commitment to ethics and transparency	C10-Emision condition GHE
Economic	P8: Economic viability	C11-Influence oil market/aviation biofuel
		C12-Influence diesel market/aviation biofuel
		C13-Production aviation biofuel, Ethical commitment, Land conflicts
		C14-Compliance with local laws
		C15-Influence vegetable oil market/aviation biofuel
		C16-Influence glycerol market/aviation biofuel

Source: own elaboration



Source: own elaboration.

Fig. 1: CLD of aviation biofuel development as sustainable biofuel.

from sorghum requires special land, which competes with agricultural land and industry needs. The decline in agricultural land can potentially reduce the level of food security and the existence of sorghum land. Therefore, adequate attention must be paid to the regulations and strategies for optimizing sorghum land to ensure sorghum stock is one of the aviation biofuel fuels. On the other hand, the existence of sorghum plantations can absorb labor and contribute to increasing the welfare of the population.

CLD of the Development of Biofuels as Sustainable Aviation Biofuels

Stock and Flow Diagrams (SFD) are built on preconstructed qualitative models and used as a projection tool for the future aviation biofuel management system. SFD also allows for the conduction of simulations on created models. SFD in this study is shown in Fig. 2.

SFD is used to estimate the system's behavior. The development of the number of flights is the main variable observed in this study because it is the main indicator in designing an alternative fuel system. This process is characterized by the increasing availability of fuel and the intensity of flights. The simulation results carried out are shown in Fig. 3.

This research yields simulation results that depict a concerning trend: a decrease in the extent of agricultural and forested land from 2015 to 2030, accompanied by an expansion of oil palm plantations. The surge in oil palm production is closely linked to the potential expansion of oil palm plantation acreage, which incentivizes the conversion of agricultural and forested land. The implications of this land conversion have been extensively discussed in the scientific literature.

The papers collectively provide evidence that the conversion of forested land into oil palm plantations leads to a loss of biodiversity and contributes to regional climate change. (Koh et al. 2011) shows that the conversion of peat swamp forests to oil palm plantations in Southeast Asia resulted in biodiversity declines and carbon emissions. Vijay et al. (2016) further support this, demonstrating that oil palm expansion in various regions has led to deforestation and threatened biodiversity-rich ecosystems. Koh & Wilcove (2008) confirms that forests are indeed being cleared for oil palm cultivation, resulting in significant biodiversity losses. Finally, (Edwards et al. 2013) highlight the negative impact of forest conversion to oil palm on functional diversity, particularly in terms of dung beetles. These findings collectively emphasize the need for conservation efforts and sustainable land-use practices to mitigate the negative effects of oil palm expansion on biodiversity and climate change.

The context provided by the scientific literature underscores the urgency of this issue, as such land conversion can jeopardize invaluable ecosystems and carry significant ecological consequences. Hence, this research underscores the need for serious attention to the impacts of oil palm plantation growth on agricultural and forested land and emphasizes the importance of implementing the solutions proposed in the scientific literature to maintain a balance between industry needs and environmental sustainability.

Palm oil is one of the high-demand commodities used to produce vegetable oil. The use of palm fruit to produce oil started in the 1980s. The palm species used as the main source of palm oil are Elaeis guineensis from Africa and the American palm Elaeis oleifera, found in native South and Central America. According to (Affandi & Astuti 2018), ripe palm fruit has a high oil content of 35 to 45%. (Amiruddin 2022) stated that the average oil content of dried mesocarp palm fruit from nine commercial DxP palms in PPKS is 76.3%, while the oil content of dry kernels is between 47.1 to 54.1%. The main purpose of developing oil palm plantations is to produce oil for food. Furthermore, palm oil is also used as a raw material for biofuels in developing technology mixes of renewable fuel and diesel. The government implemented a policy to increase the percentage of biodiesel from palm oil.

This development is faced with the problem of limitations

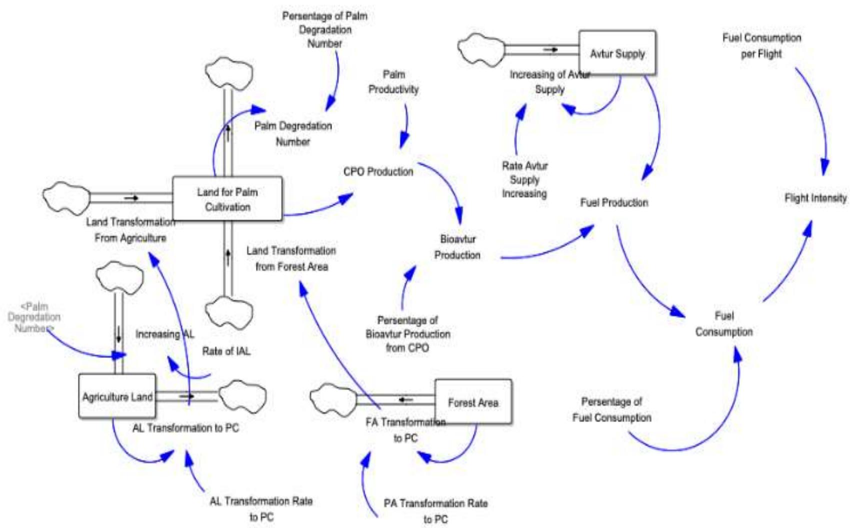


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Fig. 2: SFD of Aviation biofuel development as sustainable biofuel.

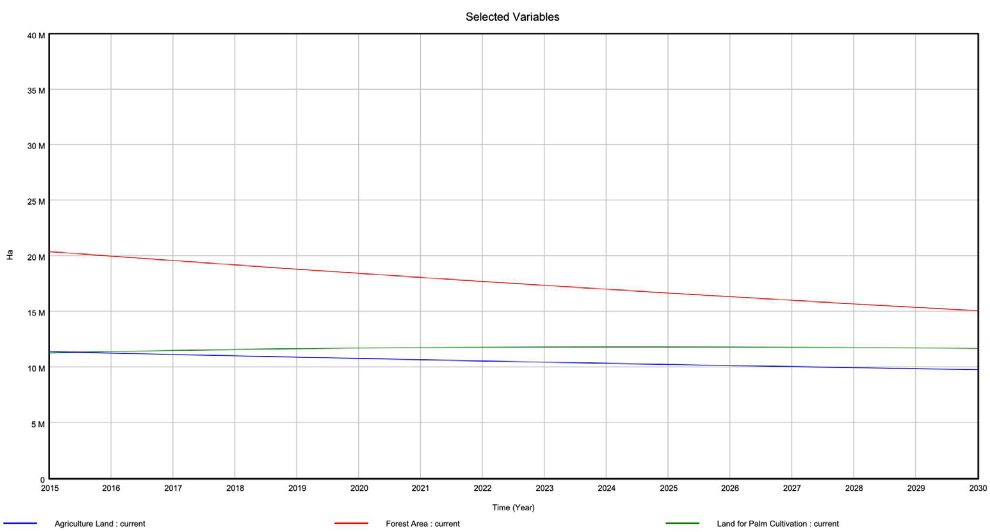

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Fig. 3: The Relationship between agricultural land area, forests, and oil palm plantations.

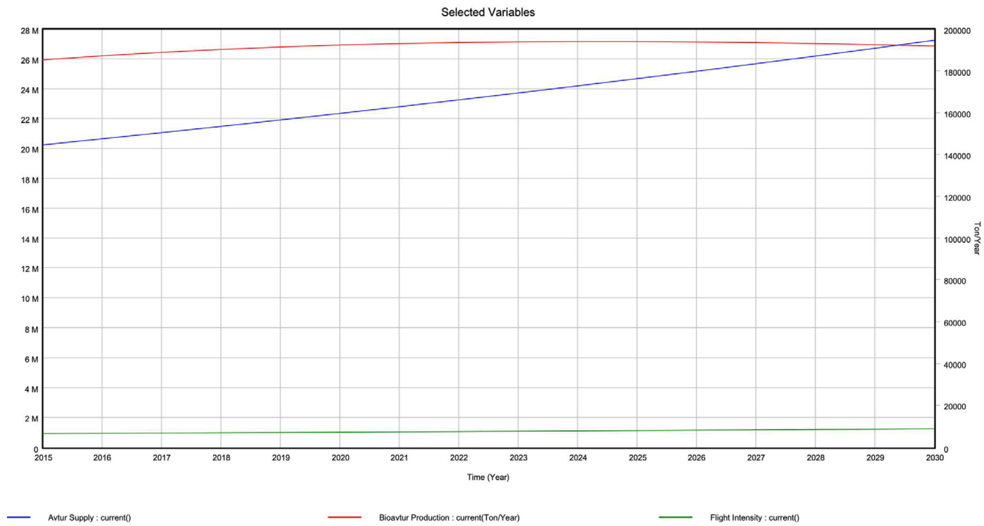

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Fig. 4: The Relationship between avtur production, aviation biofuel, and flight quantity.

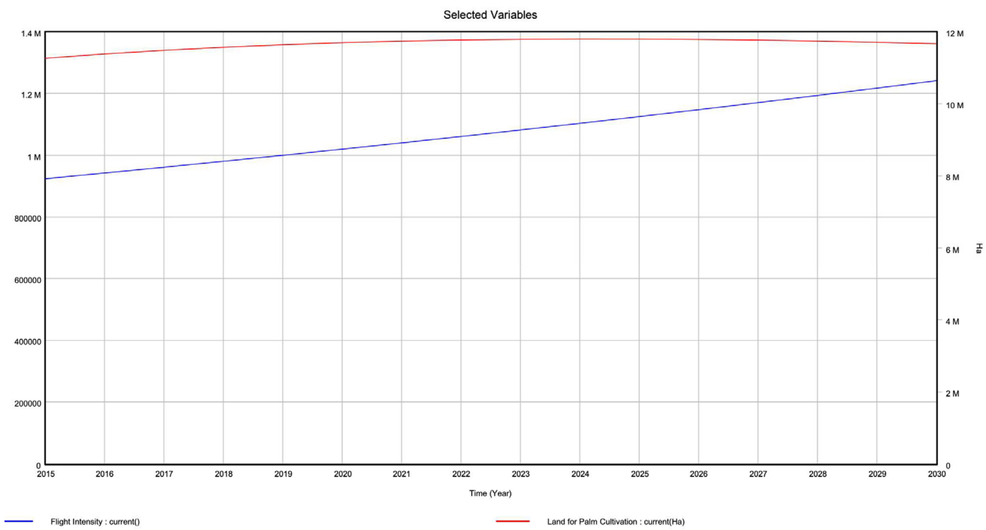

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Fig. 5: The Relationship between oil palm plantation area and flight intensity.

and land use change. Land on earth does not increase but decreases because it is mostly intended for development. The development of science led to a cultural change from the old to the modern era. It is in addition to an increase in the type and amount of infrastructure, which requires space. One of the consequences of land is its use to cultivate vegetables and build structures. Another example is the growth of the human population, thereby leading to an additional food supply.

The supply of avtur is projected to continue to increase in line with the development of the aviation industry (Fig. 4). Conversely, the aviation biofuel offering will form a curve with a maximum production value in 2023. The supply of avtur and the community's needs drove the increase in flight intensity. The production of aviation biofuels has little impact on flight intensity because the fuel needs of the aircraft are still largely met from conventional aviation fuel.

However, the impact of aviation biofuel production on flight intensity is considered to be minimal because the majority of aircraft fuel needs are still met by conventional aviation fuel. Rising jet fuel prices, potential future emissions legislation, and concerns about fuel security

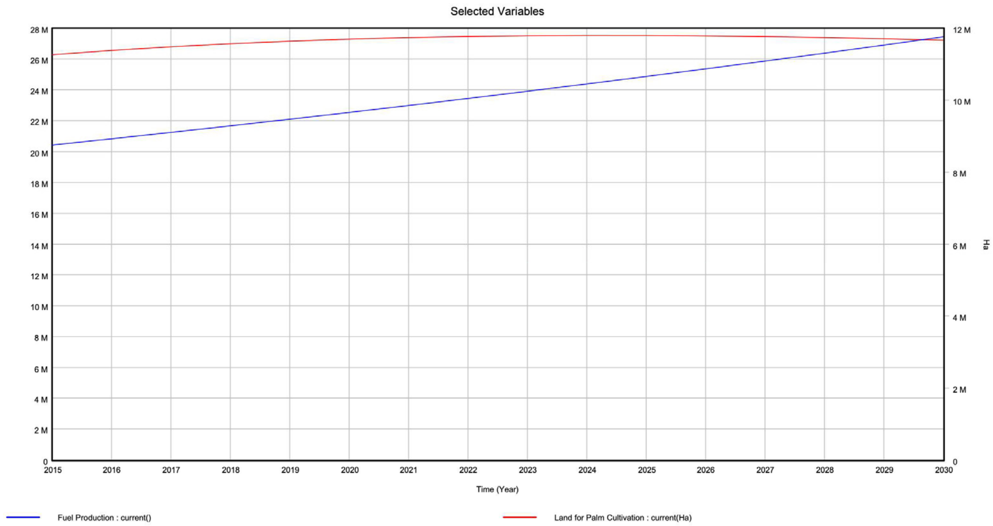

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Fig. 6: The Relationship between avtur fuel production and oil palm plantation land area.

drive the market development of aviation biofuel. However, the commercialization of aviation biofuels is constrained by high production costs, limited availability of suitable feedstocks, uncertainty surrounding sustainability criteria, and a perceived lack of political and policy support (Gegg et al. 2014). In the EU28, the market penetration of aviation biofuels is currently negligible, but there is potential for growth.

The intensity of aviation continues to rise (Fig. 5). However, on the other hand, the extent of agricultural land fluctuates and begins to decline from the year 2024. This phenomenon is attributed to the fact that aviation fuel is still predominantly derived from fossil energy sources. This indicates that the production of bio-aviation fuel, which is associated with the availability of oil palm plantations, does not exhibit a significant correlation with aviation intensity.

On the Other hand, Nygren et al. 2009) predict a substantial shortage of jet fuel by 2026 due to the decline in crude oil production, making it challenging for the aviation industry to replace it with fuel from other sources. The challenges and perspectives of biomass-derived aviation fuels, emphasizing the need for improved production technology and integration of biology, chemical engineering, and energy crops, are important things to increase the use of aviation biofuel (Wang et al. 2019). Environmental, economic, and social impacts associated with aviation biofuel production in Brazil, including the use of agricultural land and intensive water use (Cremonez et al. 2015).

Generally, the production of avtur fuel is constantly increasing, with a decrease in oil palm agriculture (Fig. 6). The decline can occur due to competition for the use of oil palm plantation land, food crops, and forest land. However, increasing the need for avtur and decreasing oil palm land shows that the production of both commodities is not significantly correlated.

The potential increase in agricultural land demand for oil palm expansion is due to rising demand for palm oil. Still, it does not directly address the correlation between avtur and oil palm land (Othman 2003). Singh & Bhagwat (2013) highlights the negative environmental impacts of agricultural expansion, including oil palm, but does not specifically address the correlation between avtur and oil palm land. On the other hand, Nasution et al. (2019) compare the income prospects of cocoa and oil palm farming, indicating that oil palm farmers have higher income prospects than cocoa farmers. Still, it does not directly address the correlation between avtur and oil palm land.

CONCLUSIONS

The aviation industry contributes to greenhouse gas emissions, although this contribution is relatively small compared to other sectors. The qualitative modeling results describe the direct and indirect relationships between social, economic, technological, and environmental dimensions in the development system of biofuels as sustainable aviation biofuels. This study used quantitative system dynamics modeling to assess the contribution of aviation biofuels to flight intensity in Indonesia, which was found to be insignificant. However, increasing aviation biofuel production has the potential to reduce the amount of land used for agriculture and forests, as it would reduce the need for land conversion for oil palm plantations. It would not have a direct impact on flight intensity in Indonesia. To mitigate negative consequences, several policies should be implemented, such as limiting land conversion, regulating palm oil trade schemes, and promoting the use of technology in aviation biofuel production.

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