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Evaluating the effectiveness of palm oil as bio-aviation fuel on Indonesia aviation industry: Reducing emissions and opportunity of having carbon allowances

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ABSTRACT

This study investigates the economic feasibility and environmental benefits of integrating Palm Kernel Oil (PKO)-based bio-aviation fuel (BAF) into Indonesia's domestic aviation sector. Drawing on data from major flight routes and applying a Hydroprocessed Esters and Fatty Acids (HEFA)-based emissions model, the analysis calculates CO_2 emission reductions of 74%–84% compared to conventional fossil jet fuel, providing strong evidence of its environmental potential. The cost-revenue model, combined with ARIMA-based price forecasting, reveals that despite isolated instances of positive profitability, such as on the Jakarta–Medan route in 2023, PKO-based BAF remains economically unviable under current market conditions, largely due to the persistent cost gap with fossil jet fuel. Price forecasts indicate sustained PKO price levels between USD 1170–1193 per metric ton and carbon credit prices averaging USD 77 per metric ton through 2026, suggesting limited opportunity for natural market correction. Sensitivity analysis identifies that carbon prices would need to rise by up to 182% to achieve breakeven, emphasizing the urgent need for robust policy measures, including minimum carbon pricing, fiscal incentives, and investment in supply chain efficiencies to make BAF adoption viable. This research advances the sustainable aviation fuels (SAF) literature by integrating emissions modeling, economic analysis, and market forecasting in the context of an emerging economy, providing a novel contribution to discussions on aviation decarbonization. The findings offer actionable insights for policymakers, industry stakeholders, and researchers aiming to design effective interventions and shape the future of sustainable aviation in Indonesia and similar emerging markets.

Contribution/Originality: This study contributes to the existing literature by integrating emissions modeling, ARIMA forecasting, and cost–revenue sensitivity analysis to evaluate palm kernel oil (PKO) as a bio-aviation fuel in Indonesia. It is among the few studies assessing whether carbon market mechanisms can offset PKO's higher production costs, thereby providing policy insights for emerging economies.

1. INTRODUCTION

Global climate commitments have increasingly prioritized decarbonization across industries, with the aviation sector emerging as a central focus due to its substantial contribution to anthropogenic greenhouse gas (GHG) emissions (Bräuer, Eckerle, & Köhler, 2021; Jing, Wang, & Liu, 2022). Although representing approximately 2–4% of total global emissions, aviation's environmental footprint is projected to escalate sharply if current operational and fuel use patterns persist (Bräuer et al., 2021; Jing et al., 2022). While the Paris Agreement does not explicitly regulate international aviation, the sector has voluntarily committed to ambitious targets: improving fuel efficiency by 1.5% annually, achieving carbon-neutral growth from 2020, and halving 2005 emissions by 2050 (Decios, Papadopoulos, & Vourdoubas, 2023; Jing et al., 2022). These international ambitions have spurred regional policy responses, such as the European Union's ReFuelEU Aviation regulation, mandating the progressive integration of sustainable aviation fuels (SAFs) into aviation fuel supplies (Dischl, Mayer, & Kraus, 2025; Shehab, Al-Maadeed, & Khatib, 2023). In parallel, the United States has implemented fiscal incentives, including tax credits for SAF production, to accelerate the industry's transition to lower-carbon fuels (Grimme, 2023). Together, these policy frameworks reflect a broad global commitment to decarbonize aviation and align industry practices with climate goals (Cabrera & Sousa, 2022; Shehab et al., 2023).

Indonesia's aviation sector, though comparatively modest in scale relative to global heavyweights, occupies a crucial position in the country's sustainability trajectory (Nugroho, Wijaya, & Hidayat, 2024). With a vast archipelagic geography and a rapidly expanding aviation market, Indonesia's aviation sector accounted for approximately 26.4% of total GHG emissions from the national transportation sector, equating to about 157,325 gigagrams of CO2 equivalent in 2018 (Nugroho et al., 2024). While international markets like the United States and China contribute more significantly to global aviation emissions, Indonesia's aviation growth trajectory signals a pressing need for preemptive decarbonization efforts (Noor, Pramono, & Sari, 2021; She, Li, & Chen, 2023). The International Air Transport Association (IATA) warns that, absent intervention, aviation emissions could surge to represent 15% of global CO2 emissions by 2050 (Singh, Gupta, & Kumar, 2018). Accordingly, adopting SAFs represents not only an environmental imperative but also an opportunity for Indonesia to secure its competitive position and honor international climate commitments.

The primary research problem addressed by this study centers on the economic feasibility of deploying Palm Kernel Oil (PKO)-based bio-aviation fuel (BAF) in Indonesia's domestic aviation sector (Hasibuan, Ramadhan, & Putra, 2025). While SAFs, including those derived from PKO, promise substantial emission reductions, their adoption is hindered by high production costs compared to conventional fossil-derived jet fuels (Hasibuan et al., 2025). This price gap poses challenges for airlines already operating under tight financial margins. Addressing this economic gap is essential, particularly in emerging markets where infrastructure investments are costly and consumer price sensitivity is high. As such, understanding whether carbon market mechanisms, such as carbon credits and allowances, can bridge this economic divide is of critical importance (Schlipf, Wagner, & Klein, 2024).

Globally, carbon markets have emerged as key instruments for driving decarbonization by creating financial incentives to reduce GHG emissions (Schlipf et al., 2024). Mechanisms such as carbon credits, emissions trading systems (ETS), and carbon border taxes enable industries to monetize emission reductions (Schlipf et al., 2024). In aviation, initiatives like the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) offer airlines the opportunity to offset emissions through market-based measures (Ramos–Fernández, Castillo, & Gómez, 2025). While promising, critics highlight that carbon credits alone may be insufficient to counterbalance growing demand and consumption patterns (Gössling & Humpe, 2020). Therefore, combining carbon market incentives with technological solutions such as SAFs becomes essential to achieving meaningful emissions reductions (Carlson, Peters, & Smith, 2023).

Within Indonesia's context, PKO emerges as a particularly viable SAF feedstock (Habibiasr, Nuryadin, & Yusuf, 2022; Hasibuan et al., 2025). Extensive palm oil production provides abundant raw material, and PKO's favorable chemical profile, notably its high lauric acid content, offers superior carbon yield and reduced emissions during combustion (Habibiasr et al., 2022). Compared to alternative feedstocks like waste oils or algae, which face supply chain or scalability challenges, or synthetic fuels, which entail high energy inputs and costs, PKO presents both an environmental and economic advantage for near-term implementation (Hasibuan et al., 2025). Recent Indonesian initiatives blending PKO-derived biofuels with conventional jet fuels have demonstrated emission reductions of approximately 2.83% to 2.95%, providing a tangible pathway toward decarbonizing aviation operations (Pitanova, Ivanov, & Popov, 2023; Sekartadji, Wibowo, & Hartanto, 2024).

Several international studies underscore the importance of carbon markets in facilitating SAF adoption (Champeecharoensuk, Suksri, & Nitisoravut, 2023; Schlipf et al., 2024; Speizer, Frank, & Larsen, 2024). For instance, Schlipf et al. (2024) argue that robust carbon pricing frameworks can accelerate technological innovation, while Speizer et al. (2024) emphasize that policy-driven market interventions are crucial to overcoming the upfront cost barriers of SAF deployment.

In emerging markets, Champeecharoensuk et al. (2023) highlight the necessity of tailored decarbonization strategies, combining both fiscal incentives and technological investments, to achieve long-term climate goals. Lau (2022) further points to the economic and logistical potential of palm oil-derived SAFs in Southeast Asia, though cautioning against sustainability concerns inherent in first-generation biofuels.

Despite these promising insights, notable research gaps persist, particularly concerning the application of PKO-based BAF in Indonesia's unique economic, regulatory, and infrastructural landscape (Champeecharoensuk et al., 2023). While the environmental benefits of SAFs are well documented, less is known about the precise cost-benefit dynamics within Indonesia, where carbon markets are nascent and regulatory support is evolving. Furthermore, empirical studies quantifying the potential of carbon allowances to offset BAF production costs in Indonesia's aviation sector are scarce. Addressing these gaps is critical for informing both industry practice and policy design.

The present study aims to assess the economic viability of PKO-based BAF adoption in Indonesia's domestic aviation industry by integrating emissions reduction estimates, cost modeling, and carbon credit valuation (Hasibuan et al., 2025).

The novelty of this research lies in its empirical examination of whether carbon market mechanisms can realistically bridge the cost gap between PKO-based BAF and fossil-derived jet fuel in the Indonesian context. By focusing on one of the world's largest palm oil producers and a rapidly growing aviation market, this study contributes to the broader understanding of SAF feasibility in emerging economies and offers actionable insights for policymakers seeking to advance sustainable aviation strategies.

2. LITERATURE REVIEW

2.1. Carbon Emissions and Bio-Avtur Fuel (BAF)

Aviation fuel is derived from fossil fuels and comprises hundreds of hydrocarbons, primarily ranging from C8 to C16 molecules. Despite being a high-quality fuel, aviation fuel also contains various additives introduced during production to mitigate risks associated with temperature fluctuations (Han et al., 2021). The most commonly used fuel in the current aviation industry is gasoline-based aviation fuel, which offers several advantages, including its non-corrosive nature to aircraft components, stability, and low crystallization point (Heyne, Rauch, Le Clercq, & Colket, 2021). In 2010, global aviation fuel consumption was approximately 142 million metric tonnes, with projections indicating an increase of 2.8 to 3.9 times by 2040 (ICAO, 2022).

However, gasoline-based fuel consumption contributes to increased emissions. According to the International Civil Aviation Organization (ICAO), the combustion of 1 kg of jet fuel generates 3.16 kg of CO_2 emissions (ICAO, 2022). Figure 1 indicates that global energy-related emissions reached a record high of 37.4 billion tonnes (Gt) in 2023. Furthermore, Figure 2 shows that international aviation accounted for 1.77% of total CO_2 emissions in 2021 (Ritchie, 2024). As per the International Energy Agency (IEA), international aviation contributes around 2% of global energy-related CO_2 emissions, or approximately 800 million tonnes of CO_2.

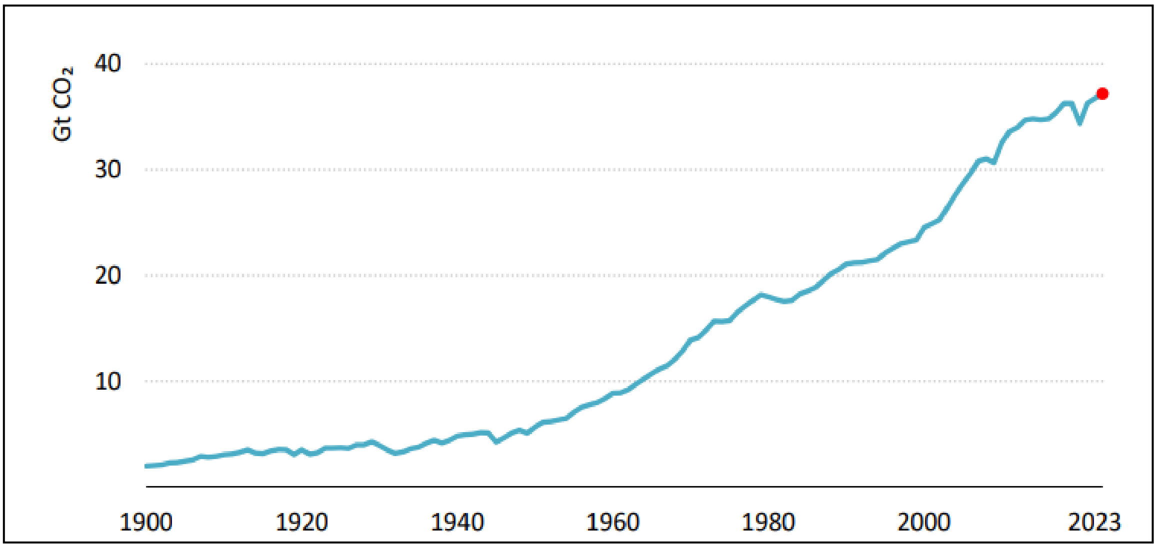

Figure 1. Global energy-related CO2 emissions and their annual change, 1990 – 2023.

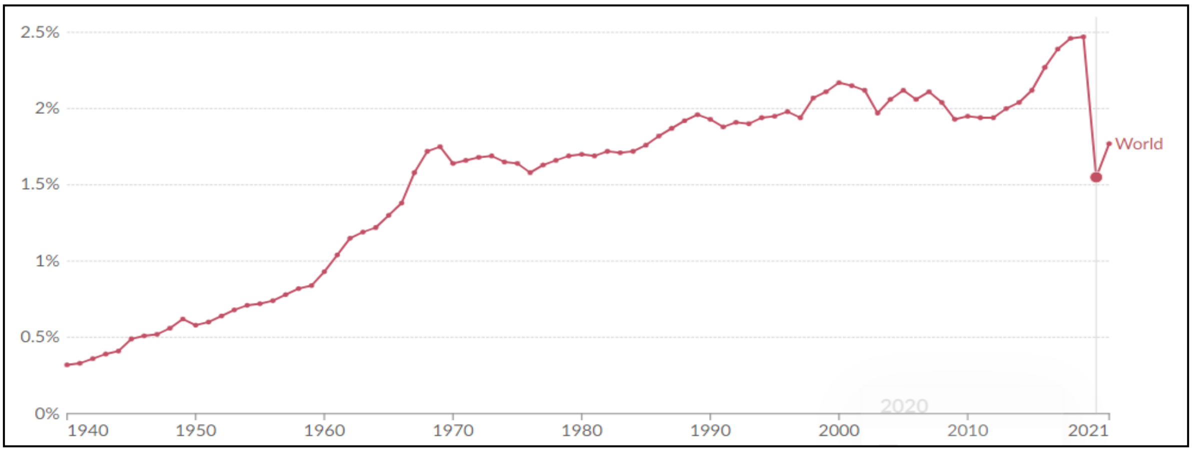

Figure 2. Aviation's share of global CO2 emissions, 1940 to 2021.

Global gasoline consumption is projected to reach approximately 2,500 million tonnes (Mt) by 2050 (ICAO, 2022). To meet emissions reduction targets, the International Civil Aviation Organization (ICAO) introduced the concept of Sustainable Aviation Fuels (SAF), with sustainability criteria developed as part of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). CORSIA classifies eligible fuels into two categories: CORSIA lower-carbon aviation fuel and CORSIA sustainable aviation fuel, the latter referring to renewable or waste-derived aviation fuels that meet CORSIA sustainability criteria (ICAO, 2022).

Crude Palm Kernel Oil (CPKO) has several advantages as a feedstock for bio-aviation fuel (BAF), including availability, cost-effectiveness, and abundance compared to medium-chain oils like coconut oil (Moonsrikaew et al., 2023). The study by Moonsrikaew et al. (2023) also highlights that the majority of carbon atoms in CPKO (approximately 74.74%) are found within the C8 to C16 carbon chain range, demonstrating its potential as a green feedstock. However, research specifically examining the emissions produced by PKO-based fuel during various phases of flight (e.g., takeoff, cruising, and landing) remains limited. The Indonesian government's 2021 test of BAF with a 2.4% blend of PKO focused solely on flight performance and safety.

According to Julio, Batlle, Rodriguez, and Palacio (2021), emissions generated from the production of bio-jet fuel are significantly lower than those from fossil-based jet fuel, with reductions of up to 84.7% for Hydroprocessing of Esters and Fatty Acids (HEFA) and 72.8% for Alcohol-to-Jet (ATJ) conversion. The cultivation phase of HEFA bio-jet fuel production contributes significantly to overall emissions, with total emissions slightly exceeding 600 kg CO_2eq/t, while ATJ-derived bio-jet fuel results in more than 1,000 kg CO_2eq/t. Similarly, Klein et al. (2018) assert that HEFA biorefineries produce the largest volume of Renewable Jet Fuel (RJF) and reduce climate change impacts by 70% compared to fossil-based jet fuel. Figure 3 illustrates the global-warming potential of the main HEFA and ATJ products.

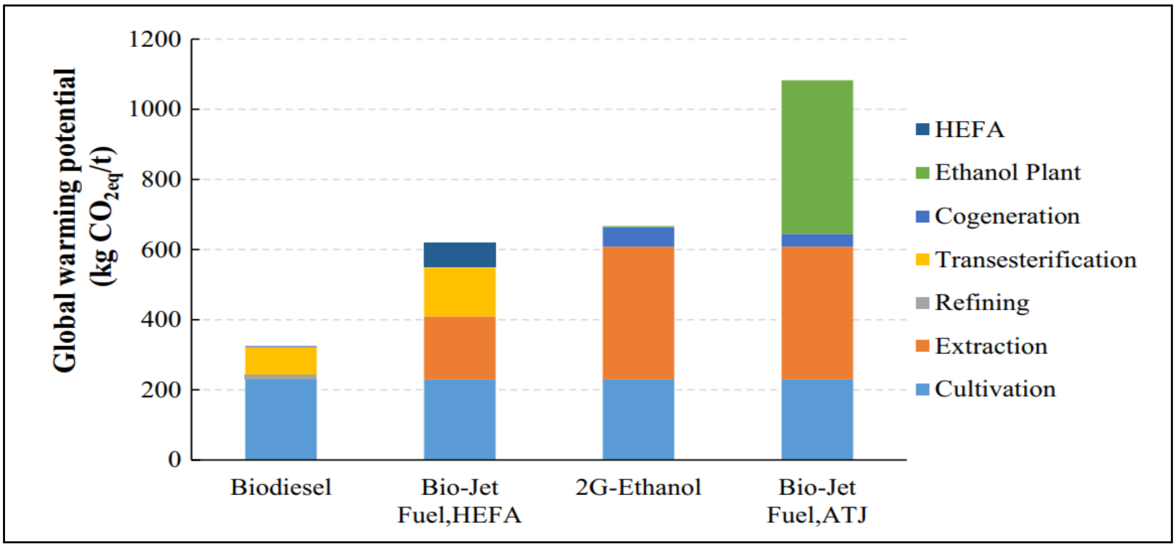

Figure 3. Global warming potential of the main products in the case study.

2.2. Forecasting

Forecasting carbon prices is currently a focus as many countries worldwide attempt to reduce total emissions produced from industrial activities. Research from (Ning, Pei, & Li, 2021) constructs an ARIMA model to forecast carbon emissions in four different areas in China: Beijing, Henan, Guangdong, and Zhejiang. The research shows that total emissions in Beijing and Henan will decline in the future. On the other hand, the total emissions in Guangdong and Zhejiang seem to be rising in the future. The decline in total emissions is attributed to the application of policies such as circular economy, green economy, and resources-saving & environmental-friendly city/society initiatives. Conversely, the increase in emissions in Guangdong and Zhejiang is due to rapid industrialization and urbanization, which still depend on fossil fuels.

Another research from Jiang and Wu (2015) attempts to forecast carbon prices using Support Vector Regression (SVR). The SVR model is constructed from ARIMA, BP neural network, Grey Model, and Genetic Programming. The research shows that the SVR model outperforms the other models in terms of Root Mean Square Error (RMSE) and Mean Absolute Percent Error (MAPE). Similarly, research from Zhao, Zhang, Gong, and Liu (2024) employs a decomposition-ensemble strategy and Markov process to analyze carbon futures returns. This model effectively captures the nonlinear, nonstationary, and volatile features of carbon prices and provides accurate point and interval forecasts. The results indicate that the combination of Moth-Flame Optimization and Variational Mode Decomposition (MFO-VMD), SVR, and Markov processes constitutes a favorable modeling approach.

Yahşi, Çanakoğlu, and Ağralı (2019) construct a different model to forecast future carbon prices. The first model is built from three methods: artificial neural network, decision tree algorithm, and random forest, using real data from the European Union's Emission Trading System (EU-ETS). The results show that the S&P Clean Energy Index is the most influential variable for carbon price, followed by the DAX Index and coal price.

2.3. Sensitivity Analysis

Sensitivity analysis is a mathematical model that can be seen as a machine capable of mapping from a set of assumptions (data, parameters, scenarios) into an inference (model output) (Saltelli & Annoni, 2010). Sensitivity analysis is used to determine the minimum price of a carbon allowance. Hence, the airlines will obtain the profit of using PKO as BAF. Carbon allowance is a tradable permit or certificate issued by the government under an Emission Trading System (ETS). It provides the holder with the right to emit one ton of CO_2 or an equivalent amount of another GHG (ISDA, 2021).

Research from Williams, Peterson, and Mooney (2005) studied supply and demand aspects that form the price of carbon credits. The study found that energy policy, energy prices, and technology are the main factors influencing the supply and demand of carbon allowances. Research from Hendrawati, Yuliasih, and Sulastri (2017) shows that the investment in building a production plant for Bioavtur using the Hydroprocessed Esters and Fatty Acids (HEFA) process in Indonesia is highly sensitive to raw material prices. Even a 1 percent increase in raw material prices renders the project infeasible.

3. METHODOLOGY

This study employs a multi-layered methodological framework to evaluate the economic feasibility and environmental impact of Palm Kernel Oil (PKO)-based bio-aviation fuel (BAF) adoption in Indonesia's domestic aviation sector. The approach integrates empirical data collection, emission reduction modeling, economic analysis, forecasting using the ARIMA model, and sensitivity analysis, ensuring a robust and data-driven assessment.

3.1. Data Collection

The foundation of the study's dataset is drawn from operational flight data on Indonesia's three busiest domestic routes: Jakarta–Denpasar (CGK–DPS), Jakarta–Medan (CGK–KNO), and Jakarta–Surabaya (CGK–SUB). These routes were selected due to their high passenger volume and flight frequency, representing critical corridors in the national aviation network (Nugroho et al., 2024). To ensure consistency in modeling, the Boeing 737-800 aircraft was chosen as the reference, given its widespread use across these routes and its representative fuel consumption profile, averaging 2.5–3 tons of jet fuel per hour (She et al., 2023). Flight duration data, including approximately 2 hours for Jakarta–Denpasar, 2.5 hours for Jakarta–Medan, and 1.5 hours for Jakarta–Surabaya, were integrated into the analysis to accurately estimate route-specific fuel consumption and subsequent emissions.

3.2. Emission Reduction Modeling

The estimation of emission reductions relies on the Hydroprocessed Esters and Fatty Acids (HEFA) method, recognized as one of the most efficient pathways for producing SAFs (Hasibuan et al., 2025; Julio et al., 2021). Based on literature values, it is assumed that the use of PKO-derived BAF achieves a 74–84% reduction in CO_2 emissions compared to fossil-derived jet fuel (Habibiasr et al., 2022). To quantify emissions, the International Civil Aviation Organization (ICAO) standard emission factor of 3.16 kg CO_2 per kilogram of jet fuel combusted was applied (ICAO, 2022). The resulting model multiplies estimated fuel consumption per flight by the CO_2 factor and applies the percentage reduction (k) to calculate the total emission abatement attributable to BAF adoption.

3.3. Economic Analysis

The economic analysis is anchored in a cost-revenue framework that evaluates the financial implications of integrating PKO-based BAF. The total cost calculation encompasses both operational costs, assumed at USD 0.18 per liter (adjusted annually for inflation, sourced from Bank Indonesia (2024)), and the cost of raw PKO, using a 1.9 conversion factor to account for the palm oil-to-jet fuel processing ratio (Hendrawati et al., 2017). These costs are combined to determine the total expenditure associated with BAF use per time period.

Revenue generation is derived from carbon allowances, calculated using the volume of emissions avoided and the prevailing carbon futures price (Schlipf et al., 2024). Profitability is defined as the difference between total revenue from carbon allowances and total costs, offering a snapshot of the economic viability of BAF use. Importantly, this model assumes adherence to emerging carbon market standards in Indonesia, aligning with mechanisms like the

Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which facilitate emissions trading and credit generation (Ramos–Fernández, Castillo, & Gómez, 2025).

The assumption of emissions reduction from BAF based on PKO using the HEFA method is derived from (Braun, Grimme, & Oesingmann, 2024), which states that emissions will decrease by approximately 74–84 percent compared to fossil jet fuel. Therefore, the formula for calculating the amount of carbon allowances is as follows.

$$TR_t = 3.16FC\ x\ k\ x\ CP_t \quad (1)$$

TR_t is total revenue at time t. *FC* stands for fuel consumption during flight activity based on the stated route. The number 3.16 is derived from an ICAO report stating that every 1 kg of jet fuel produces 3.16 kg of CO_2. *k* is the percentage emission reduction. The value of *k* varies from 74 to 84 percent. CP_t represents the carbon futures price at time t. However, the formula obtained for calculating the total cost of producing BAF is as follows.

$$TC_t = OC\ x\ (1 + I_t) + 1.9\ x\ RMP_t \quad (2)$$

TC_t is the total cost at time *t*. OC stands for operational cost, which is $0.18/liter, while I_t indicates inflation at time *t*. The assumption of operating cost for manufacturing BAF using the HEFA method in Indonesia is obtained from Hendrawati et al. (2017). However, this research was conducted in 2017; hence, it is necessary to make adjustments for operating costs as inflation in Indonesia has been increasing annually. Data related to inflation is obtained from Bank Indonesia (2024). The figure 1.9 represents the conversion factor of palm oil to jet fuel. RMP_t stands for PKO price as raw material at time *t*.

3.4. Forecasting (ARIMA Model)

To predict future trends in PKO prices and carbon futures prices, the study employs the Autoregressive Integrated Moving Average (ARIMA) model, a widely used time-series forecasting technique (Ning, Xu, & Wang, 2021). The analysis utilizes 180 months of historical data (September 2009–August 2024), sourced from commodity price databases (IndexMundim, 2024) and carbon market reports (Schlipf et al., 2024). Model construction follows standard ARIMA procedures, involving the determination of autoregressive order (p), differencing order (d), and moving average order (q), ensuring stationarity of the time series. Parameter significance is assessed using p-values, with variables retained only if they meet the 5% significance threshold (Montgomery, 2013). The time series forecasting method used to predict the carbon price is the Autoregressive Integrated Moving Average (ARIMA). The formula for the ARIMA (p, d, q) model is.

$$\Phi(B)\nabla^d x_t = \Theta(B)\varepsilon_t \quad (3)$$

Where $\nabla^d = (1 - B)^d$, $\Phi(B) = 1 - \varphi_1 B - .... - \varphi_p B_p$ is an autoregressive coefficient polynomial of the smooth reversible ARMA (p, q) model, and $\Phi(B) = 1 - \Theta_1 B - .... - \Theta_p B_p$ is the moving smoothing coefficient polynomial of the smooth reversible ARMA (p, q) model (Ning et al., 2021). Tables 1 and 2 in the study illustrate the model's parameter estimates and corresponding p-values, confirming the model's statistical robustness.

3.5. Sensitivity Analysis

Recognizing the variability in commodity markets, the study conducts sensitivity analysis to identify the carbon futures price thresholds necessary for airlines to achieve breakeven when adopting PKO-based BAF. Using forecasted data from the ARIMA model, the analysis simulates multiple scenarios combining key variables: median emission reduction (79%), fuel consumption per hour (2.75 tons), and average inflation rate (4.15%, based on Indonesian historical data). The minimum carbon futures prices are calculated for each route USD 132/MT for Jakarta–Medan, USD 164/MT for Jakarta–Denpasar, and USD 219/MT for Jakarta–Surabaya, representing the breakeven points where carbon credit revenue offsets additional BAF costs (Schlipf et al., 2024).

Table 3 summarizes the forecasted PKO and carbon futures prices over the 28-month projection period, while Tables 4–6 provide detailed breakdowns of income, total costs, proposed carbon prices, and profit margins for each analyzed route. These tables are integral to illustrating the nuanced interactions between commodity prices, fuel consumption, and emissions abatement, offering a comprehensive view of the economic conditions under which BAF adoption becomes financially sustainable.

In summary, the methodological approach of this study integrates rigorous data collection, robust emission and economic modeling, advanced forecasting techniques, and targeted sensitivity analyses. This design enables a holistic evaluation of whether PKO-based BAF can serve as a viable pathway for Indonesia's aviation sector to meet its sustainability targets and align with global climate commitments.

4. ANALYSIS

The analysis was conducted using 180 monthly observation data from September 2009 to August 2024. The analysis focused on the three busiest flight routes in Indonesia: Jakarta – Bali (CGK – DPS), Jakarta – Medan (CGK – KNO), and Jakarta – Surabaya (JKT – SBY), utilizing the Boeing 737–800 as the object of study. The analysis employed a range of 74–84 percent for the *k* value. The fuel consumption of the Boeing 737–800 is approximately 2.5 to 3 tons per hour. Using the median value of *k* (79 percent) and fuel consumption (2.75 tons/hour), the detailed calculations of income, total cost, and total revenue are shown below. Figures 4 – 6 compare total costs and revenues on the Jakarta–Denpasar, Jakarta–Medan, and Jakarta–Surabaya routes.

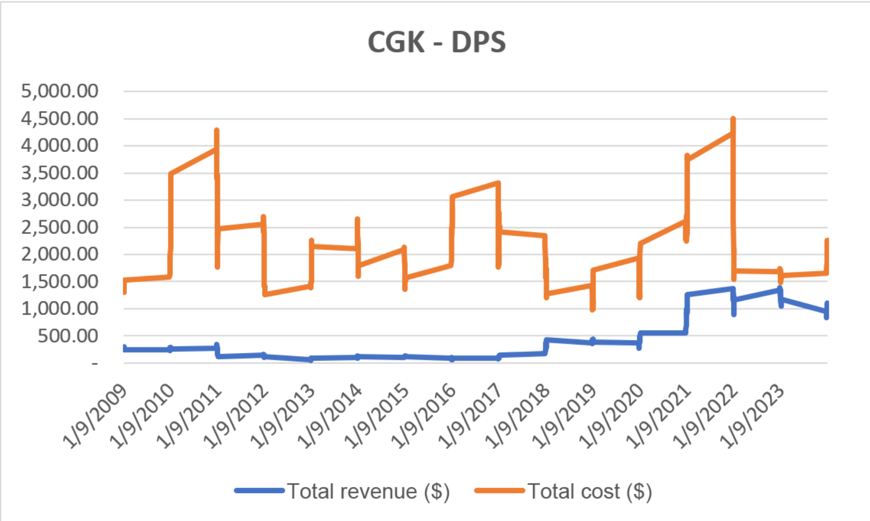

Figure 4. Comparison of Total Cost and Total Revenue of Jakarta - Denpasar (CGK - DPS) Route.

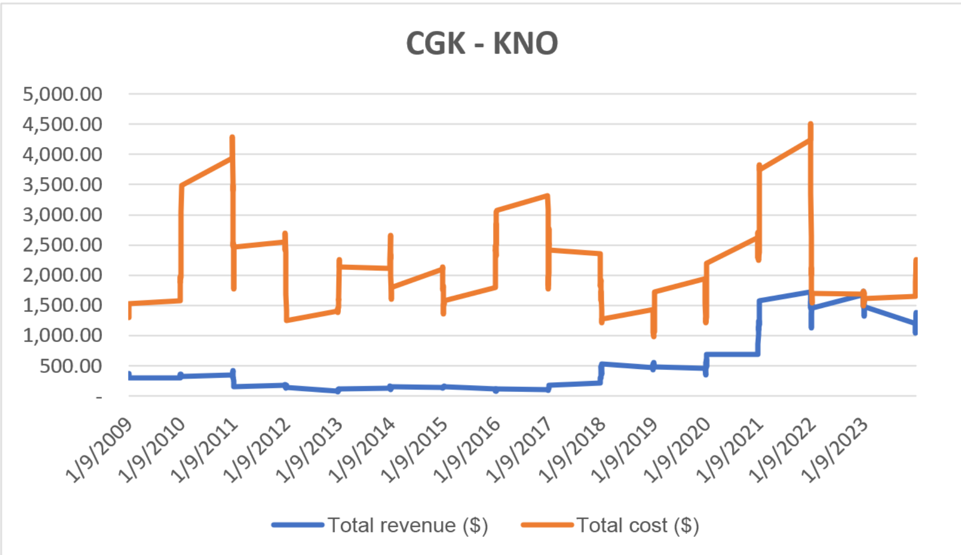

Figure 5. Comparison of total cost and total revenue of Jakarta - Medan (CGK - KNO) route.

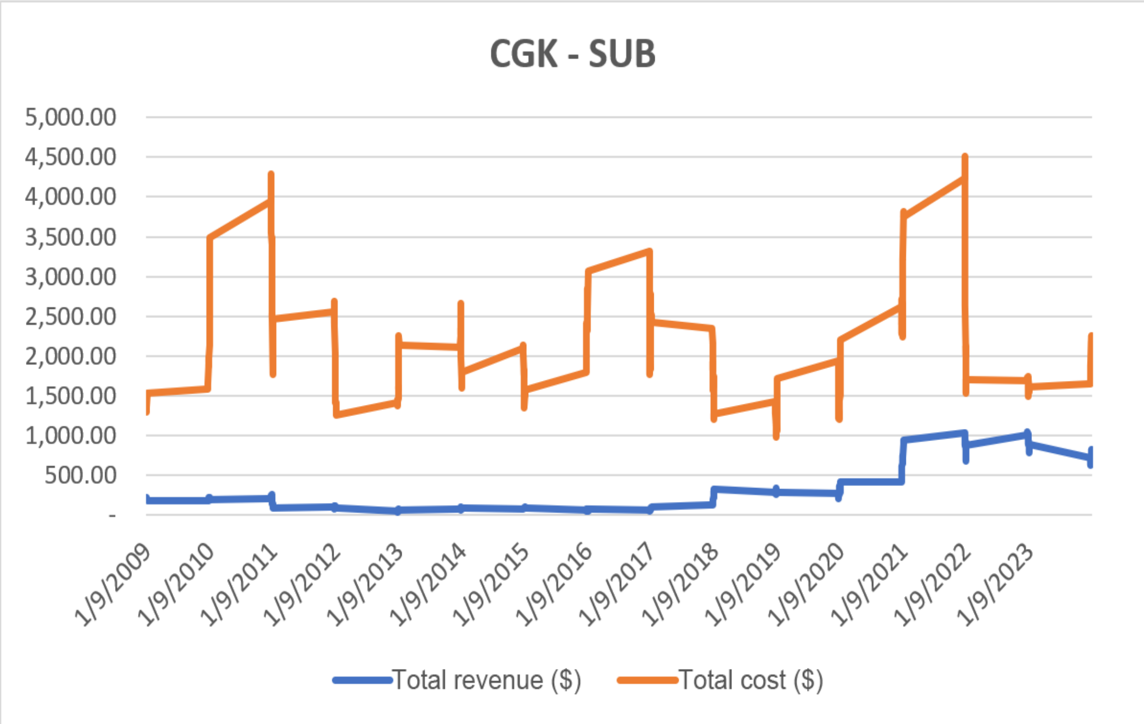

Figure 6. Comparison of total cost and total revenue of Jakarta - Surabaya (CGK - SBY) route.

Figures 7 – 9 display profit trends for each route.

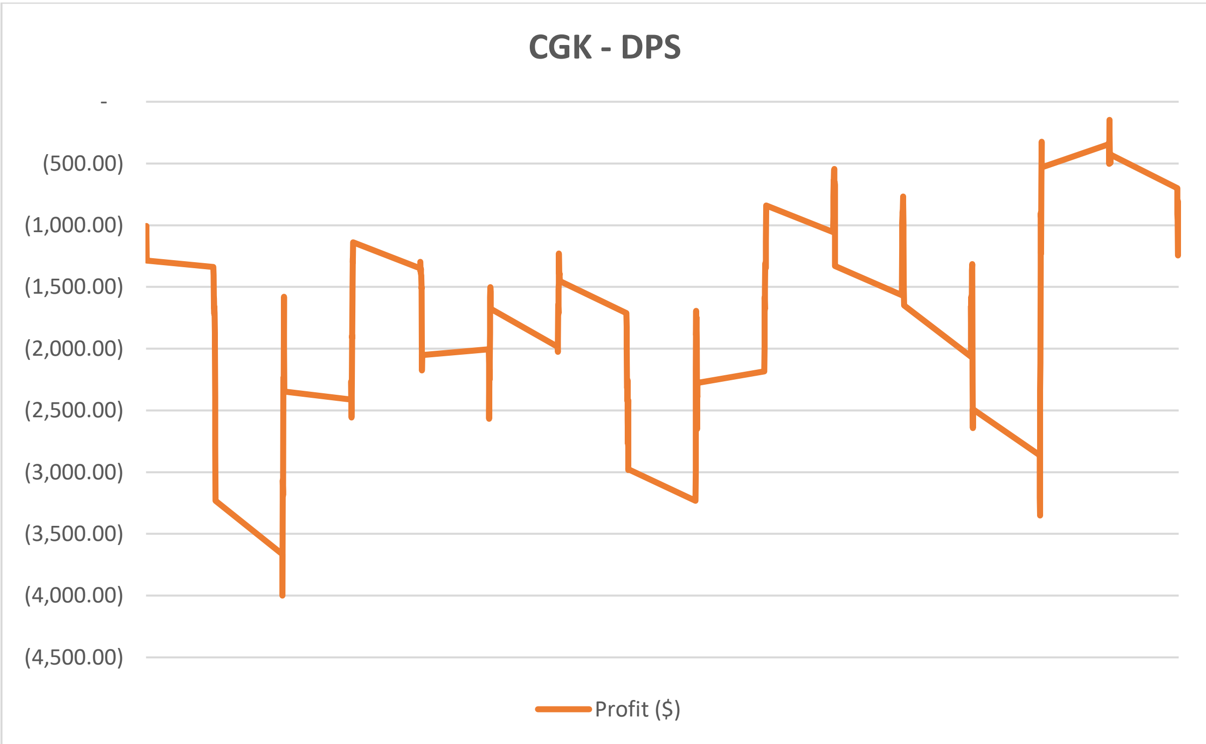

Figure 7. Profit Generates from Jakarta - Denpasar (CGK - DPS) Route.

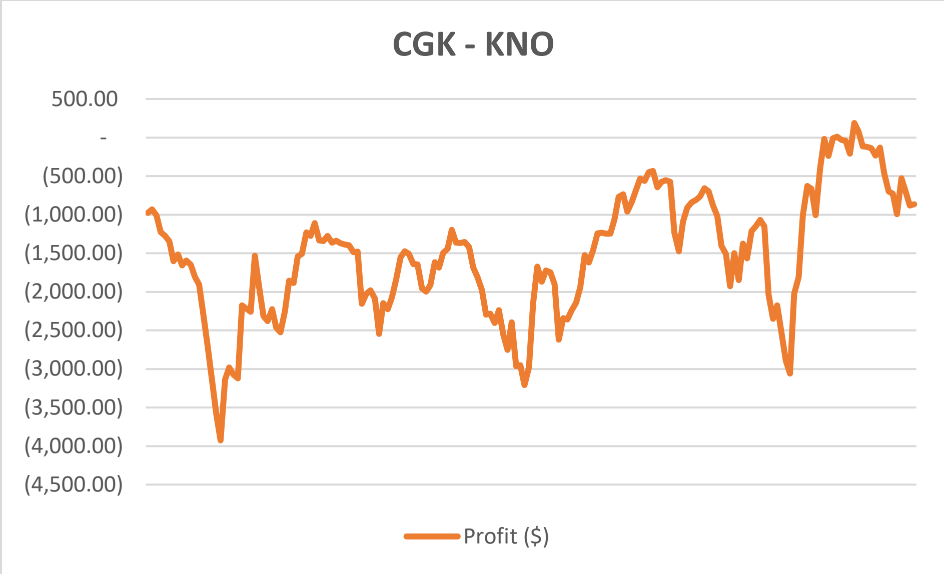

Figure 8. Profit Generates from Jakarta - Medan (CGK - KNO) Route.

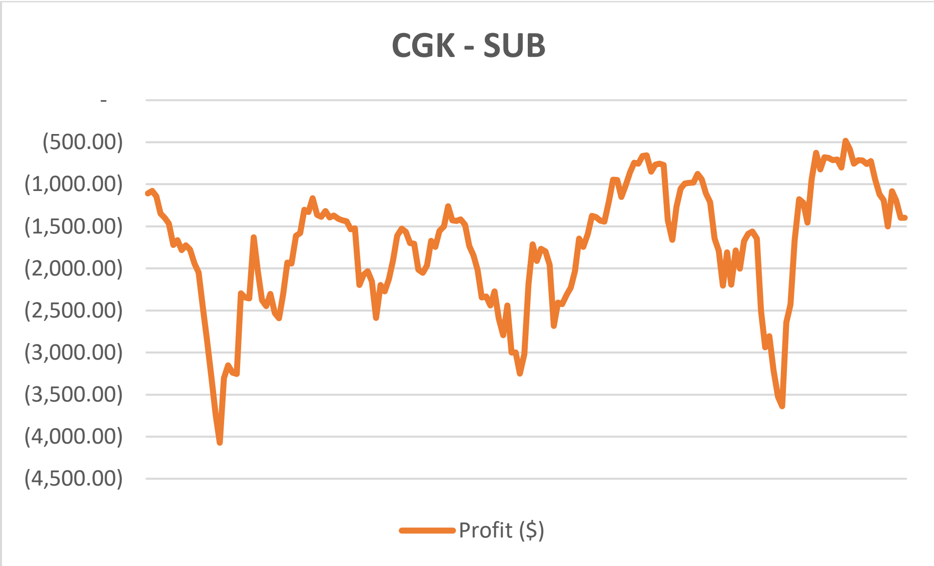

Figure 9. Profit Generates from Jakarta - Surabaya (CGK - SBY) Route.

4.1. Total Revenue, Total Cost, and Profit

The flight hours from Jakarta to Denpasar, Medan, and Surabaya, respectively, are 2 hours, 2.5 hours, and 1.5 hours. From the graph, it can be seen that during September 2009 – August 2024, although total revenue has shown an uptrend in recent months, it still cannot offset the total costs incurred from using BAF made from PKO. The total revenue generated from carbon allowances does not align with the total costs arising from using BAF produced from PKO. As a result, the profit remains negative during the analysis period. Only the route from Jakarta to Medan in July 2023 generated revenue of approximately $76.66. The total revenue from carbon allowances is affected not only by the value of k and fuel consumption per hour but also by the flight duration. We can conclude that the highest value of k and the longest flight duration will generate more carbon allowances, thus increasing the total revenue.

However, increasing k value to a maximum of 84 percent and consumption of fossil fuel to 3 tons/hour does not really make any changes. Based on 180 monthly observations data, the Jakarta – Denpasar (CGK – DPS) route only generates positive profit in June 2023. A better result is obtained from the Jakarta – Medan (CGK – KNO) route, where positive profit occurred once in November 2022 and during 2023. In contrast, the Jakarta – Surabaya (CGK – SUB) route generates the worst results with no positive profit.

This condition indicates that using PKO as BAF to replace fossil jet fuel is not feasible, as the BAF will increase the operational flight cost and burden the financial condition of airlines. As a result, the customer will be harmed due to the increase in ticket prices. Since Indonesia is the largest producer of Palm Oil and the program of mixing fossil diesel fuel with CPO continues until CPO can 100 percent replace fossil diesel fuel, it is difficult to expect that PKO prices will reduce at the same level as carbon futures prices. What can be done by the government is to stipulate the minimum price of carbon allowances and apply policies that support the increasing demand for carbon allowances, such as a carbon tax.

4.2. Forecasting

The ARIMA model is employed to forecast PKO and carbon futures prices for the next 28 months, extending to December 2026. The model construction process will be conducted using MINITAB software. During model development, adjustments are required if the p-value of any parameter exceeds 5 percent. As illustrated in Tables 1 and 2, a p-value below 5 percent indicates that all parameters are statistically significant, thus validating the model's suitability for forecasting. The optimal forecasting model for PKO prices is achieved with an autoregressive order (p) of 2, a differencing order (d) of 1, and a moving average order (q) of 2. Conversely, the optimal model for forecasting carbon futures prices uses autoregressive, differencing, and moving average orders of 3, 1, and 3, respectively. Table 1 presents the p-value results for ARIMA parameters used to forecast PKO prices. All parameters are statistically significant ($p < 0.05$), confirming the model's robustness for price prediction.

Table 1. P - Value result of all parameters for PKO price.

Type	Coef.	SE Coef.	T-Value	P-Value
AR 1	-0.4891	0.0689	-7.09	0
AR 2	0.5075	0.0698	7.27	0
MA 1	-0.62667	0.00893	-70.2	0
MA 2	0.3668	0.0462	7.93	0

Table 2 presents the p-value results for ARIMA parameters used to forecast carbon futures prices, all below 5%, verifying the statistical validity of the forecast model.

Table 2. P - Value result of all parameters for the carbon futures price.

Type	Coef.	SE Coef.	T-Value	P-Value
AR 1	-0.553	0.134	-4.14	0
AR 2	-0.517	0.132	-3.91	0
AR 3	0.2829	0.0914	3.1	0.002
MA 1	-0.498	0.104	-4.77	0
MA 2	-0.5773	0.0894	-6.46	0
MA 3	0.4113	0.0695	5.92	0

Next, the step involves constructing the forecasting model using the specified values of p, d, and q. The forecasting results for both PKO and carbon futures prices can be seen in Table 3.

Table 3. Forecasting PKO and carbon futures price.

Date	PKO price ($)	Carbon futures price ($)
01/09/2024	1183.30	77.54
01/10/2024	1170.90	77.50
01/11/2024	1190.75	77.49
01/12/2024	1174.75	77.48
01/01/2025	1192.65	77.48
01/02/2025	1175.77	77.48

Date	PKO price ($)	Carbon futures price ($)
01/03/2025	1193.11	77.48
01/04/2025	1176.06	77.48
01/05/2025	1193.20	77.48
01/06/2025	1176.17	77.48
01/07/2025	1193.20	77.48
01/08/2025	1176.22	77.48

Table 3. Forecasting PKO and carbon futures price (Continued).

Date	PKO price ($)	Carbon futures price ($)
01/09/2025	1193.17	77.48
01/10/2025	1176.27	77.48
01/11/2025	1193.13	77.48
01/12/2025	1176.30	77.48
01/01/2026	1193.10	77.48
01/02/2026	1176.34	77.48
01/03/2026	1193.06	77.48
01/04/2026	1176.38	77.48
01/05/2026	1193.02	77.48
01/06/2026	1176.42	77.48
01/07/2026	1192.98	77.48
01/08/2026	1176.45	77.48
01/09/2026	1192.95	77.48
01/10/2026	1176.49	77.48
01/11/2026	1192.91	77.48
01/12/2026	1176.53	77.48

4.3. Sensitivity Analysis

Sensitivity analysis is conducted to provide a suggestion regarding the price of carbon futures; thus, the airline company can still generate revenue while transitioning from fossil fuel to BAF made from PKO. The sensitivity analysis was performed using forecasting data with the following assumptions: median value of k (79 percent), fuel consumption (2.75 tons/hour), and an inflation rate of 4.15 percent, derived from the average inflation rate during the observation data period. The details of the calculation are shown in Table 4.

Table 4. Income, total cost, and total revenue of Jakarta - Denpasar (CGK - DPS) route.

Date	PKO price ($)	Inflation	Total cost ($)	Proposed carbon price ($)	Total revenue ($)	Profit ($)
01/09/2024	1183.30	0.04	2248.46	164.00	2.251.75	3.29
01/10/2024	1170.90	0.04	2224.90	164.00	2.251.75	26.86
01/11/2024	1190.75	0.04	2262.61	164.00	2.251.75	(10.86)
01/12/2024	1174.75	0.04	2232.21	164.00	2.251.75	19.55
01/01/2025	1192.65	0.04	2266.22	164.00	2.251.75	(14.47)
01/02/2025	1175.77	0.04	2234.15	164.00	2.251.75	17.60
01/03/2025	1193.11	0.04	2267.10	164.00	2.251.75	(15.34)
01/04/2025	1176.06	0.04	2234.71	164.00	2.251.75	17.04
01/05/2025	1193.20	0.04	2267.27	164.00	2.251.75	(15.52)
01/06/2025	1176.17	0.04	2234.91	164.00	2.251.75	16.85
01/07/2025	1193.20	0.04	2267.26	164.00	2.251.75	(15.51)

Table 4. Income, total cost, and total revenue of Jakarta - Denpasar (CGK - DPS) route (continued).

Date	PKO price ($)	Inflation	Total Cost ($)	Proposed carbon price ($)	Total revenue ($)	Profit ($)
01/08/2025	1176.22	0.04	2235.01	164.00	2.251.75	16.74
01/09/2025	1193.17	0.04	2267.21	164.00	2.251.75	(15.45)
01/10/2025	1176.27	0.04	2235.09	164.00	2.251.75	16.66
01/11/2025	1193.13	0.04	2267.14	164.00	2.251.75	(15.39)
01/12/2025	1176.30	0.04	2235.17	164.00	2.251.75	16.59
01/01/2026	1193.10	0.04	2267.07	164.00	2.251.75	(15.32)
01/02/2026	1176.34	0.04	2235.24	164.00	2.251.75	16.51
01/03/2026	1193.06	0.04	2267.00	164.00	2.251.75	(15.24)
01/04/2026	1176.38	0.04	2235.31	164.00	2.251.75	16.44
01/05/2026	1193.02	0.04	2266.93	164.00	2.251.75	(15.17)
01/06/2026	1176.42	0.04	2235.38	164.00	2.251.75	16.37
01/07/2026	1192.98	0.04	2266.86	164.00	2.251.75	(15.10)
01/08/2026	1176.45	0.04	2235.45	164.00	2.251.75	16.30
01/09/2026	1192.95	0.04	2266.79	164.00	2.251.75	(15.03)
01/10/2026	1176.49	0.04	2235.52	164.00	2.251.75	16.23
01/11/2026	1192.91	0.04	2266.72	164.00	2.251.75	(14.96)
01/12/2026	1176.53	0.04	2235.59	164.00	2.251.75	16.16
Total profit						**55.84**

Table 5. Income, total cost, and total revenue of Jakarta - Medan (CGK - KNO) Route.

Date	PKO price ($)	Inflation	Total cost ($)	Proposed carbon price ($)	Total revenue ($)	Profit ($)
01/09/2024	1183.30	0.04	2248.46	132.00	2.265.48	17.02
01/10/2024	1170.90	0.04	2224.90	132.00	2.265.48	40.59
01/11/2024	1190.75	0.04	2262.61	132.00	2.265.48	2.87
01/12/2024	1174.75	0.04	2232.21	132.00	2.265.48	33.28
01/01/2025	1192.65	0.04	2266.22	132.00	2.265.48	(0.74)
01/02/2025	1175.77	0.04	2234.15	132.00	2.265.48	31.33
01/03/2025	1193.11	0.04	2267.10	132.00	2.265.48	(1.61)
01/04/2025	1176.06	0.04	2234.71	132.00	2.265.48	30.77
01/05/2025	1193.20	0.04	2267.27	132.00	2.265.48	(1.79)
01/06/2025	1176.17	0.04	2234.91	132.00	2.265.48	30.58
01/07/2025	1193.20	0.04	2267.26	132.00	2.265.48	(1.78)
01/08/2025	1176.22	0.04	2235.01	132.00	2.265.48	30.47
01/09/2025	1193.17	0.04	2267.21	132.00	2.265.48	(1.72)
01/10/2025	1176.27	0.04	2235.09	132.00	2.265.48	30.39
01/11/2025	1193.13	0.04	2267.14	132.00	2.265.48	(1.66)

Table 5. Income, total cost, and total revenue of Jakarta - Medan (CGK - KNO) route (Continued).

Date	PKO price ($)	Inflation	Total cost ($)	Proposed carbon price ($)	Total revenue ($)	Profit ($)
01/12/2025	1176.30	0.04	2235.17	132.00	2.265.48	30.32
01/01/2026	1193.10	0.04	2267.07	132.00	2.265.48	(1.59)
01/02/2026	1176.34	0.04	2235.24	132.00	2.265.48	30.24
01/03/2026	1193.06	0.04	2267.00	132.00	2.265.48	(1.51)
01/04/2026	1176.38	0.04	2235.31	132.00	2.265.48	30.17
01/05/2026	1193.02	0.04	2266.93	132.00	2.265.48	(1.44)
01/06/2026	1176.42	0.04	2235.38	132.00	2.265.48	30.10
01/07/2026	1192.98	0.04	2266.86	132.00	2.265.48	(1.37)
01/08/2026	1176.45	0.04	2235.45	132.00	2.265.48	30.03
01/09/2026	1192.95	0.04	2266.79	132.00	2.265.48	(1.30)
01/10/2026	1176.49	0.04	2235.52	132.00	2.265.48	29.96
01/11/2026	1192.91	0.04	2266.72	132.00	2.265.48	(1.23)
01/12/2026	1176.53	0.04	2235.59	132.00	2.265.48	29.89
Total profit						**440.28**

Table 6. Income, total cost, and total revenue of Jakarta - Surabaya (CGK - SUB) Route.

Date	PKO price ($)	Inflation	Total cost ($)	Proposed carbon price ($)	Total revenue ($)	Profit ($)
01/09/2024	1183.30	0.04	2248.46	219.00	2.255.19	6.73
01/10/2024	1170.90	0.04	2224.90	219.00	2.255.19	30.29
01/11/2024	1190.75	0.04	2262.61	219.00	2.255.19	(7.43)
01/12/2024	1174.75	0.04	2232.21	219.00	2.255.19	22.98
01/01/2025	1192.65	0.04	2266.22	219.00	2.255.19	(11.03)
01/02/2025	1175.77	0.04	2234.15	219.00	2.255.19	21.03
01/03/2025	1193.11	0.04	2267.10	219.00	2.255.19	(11.91)
01/04/2025	1176.06	0.04	2234.71	219.00	2.255.19	20.48
01/05/2025	1193.20	0.04	2267.27	219.00	2.255.19	(12.09)
01/06/2025	1176.17	0.04	2234.91	219.00	2.255.19	20.28
01/07/2025	1193.20	0.04	2267.26	219.00	2.255.19	(12.08)
01/08/2025	1176.22	0.04	2235.01	219.00	2.255.19	20.17
01/09/2025	1193.17	0.04	2267.21	219.00	2.255.19	(12.02)
01/10/2025	1176.27	0.04	2235.09	219.00	2.255.19	20.09
01/11/2025	1193.13	0.04	2267.14	219.00	2.255.19	(11.95)
01/12/2025	1176.30	0.04	2235.17	219.00	2.255.19	20.02
01/01/2026	1193.10	0.04	2267.07	219.00	2.255.19	(11.88)
01/02/2026	1176.34	0.04	2235.24	219.00	2.255.19	19.95

Table 6. Income, total cost, and total revenue of Jakarta - Surabaya (CGK - SUB) Route (Continued).

Date	PKO price ($)	Inflation	Total cost ($)	Proposed carbon price ($)	Total revenue ($)	Profit ($)
01/03/2026	1193.06	0.04	2267.00	219.00	2.255.19	(11.81)
01/04/2026	1176.38	0.04	2235.31	219.00	2.255.19	19.88
01/05/2026	1193.02	0.04	2266.93	219.00	2.255.19	(11.74)
01/06/2026	1176.42	0.04	2235.38	219.00	2.255.19	19.80
01/07/2026	1192.98	0.04	2266.86	219.00	2.255.19	(11.67)
01/08/2026	1176.45	0.04	2235.45	219.00	2.255.19	19.73
01/09/2026	1192.95	0.04	2266.79	219.00	2.255.19	(11.60)
01/10/2026	1176.49	0.04	2235.52	219.00	2.255.19	19.66
01/11/2026	1192.91	0.04	2266.72	219.00	2.255.19	(11.53)
01/12/2026	1176.53	0.04	2235.59	219.00	2.255.19	19.59
Total profit						**151.95**

According to Tables 4 to 6, the minimum carbon futures prices for the routes Jakarta–Surabaya (CGK–SUB), Jakarta–Denpasar (CGK–DPS), and Jakarta–Medan (CGK–KNO) are USD 164/MT, USD 132/MT, and USD 219/MT, respectively. These values represent increases of 112 percent, 70 percent, and 182 percent over the forecasted prices. Setting the minimum carbon price based on the lowest observed value (the minimum carbon price for the CGK–KNO route) may impact airlines' incentives to operate on other routes, such as CGK–DPS and CGK–SUB. It would be preferable for the government to establish the minimum carbon price based on the highest price, as airlines generate positive total revenue across all flight routes. This approach would help ensure that the increase in operational costs due to the use of PKO as BAF is not passed on to customers through higher ticket prices.

5. CONCLUSIONS

This study provides a comprehensive assessment of the economic and environmental implications of adopting Palm Kernel Oil (PKO)-based bio-aviation fuel (BAF) in Indonesia's domestic aviation sector. While the environmental performance is promising, achieving 74–84% CO_2 emission reductions per kilogram of fuel, the economic evaluation reveals a persistent and substantial cost gap compared to fossil jet fuel. Price forecasts predict that PKO prices will remain elevated and carbon futures prices stable, making the current market landscape insufficient to support BAF profitability. Sensitivity analyses show that carbon credit prices would need to increase by 70–182% across key domestic routes to achieve breakeven, underscoring the critical need for strong policy interventions. These findings highlight the essential role of minimum carbon pricing, fiscal incentives, and regulatory support in bridging the economic gap and advancing aviation decarbonization. The study contributes to the global sustainable aviation fuels (SAF) literature by offering an integrated, data-driven perspective tailored to the challenges and opportunities in emerging economies like Indonesia. Further research should explore combining first-generation feedstocks like PKO with advanced biofuels and synthetic aviation fuels to enhance long-term sustainability and scalability.

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