International Journal of Sustainable Energy Planning and Management Vol. 48 2026 5–19

International Journal of
Sustainable Energy Planning and Management

A preliminary assessment of sustainable aviation fuel potentials from municipal, agricultural, and plantation wastes in Indonesia

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ABSTRACT

Decarbonising the aviation sector demands innovative strategies, with Sustainable Aviation Fuel (SAF) emerging as a promising solution. Although Indonesia has pledged to adopt SAF, empirical assessments of its production potential remain scarce. This study addresses the gap by estimating SAF output using secondary data on municipal solid waste (MSW), rice residues, and palm residues. These inputs are geospatially mapped across Indonesia's provinces to identify spatial distribution and feasibility. Importantly, the estimation method is designed to be straightforward and readily replicable, allowing for rapid preliminary SAF assessments in other national contexts. Our analysis indicates a national production potential of approximately 37.06 M m^3/yr, with palm residues contributing 76.76%, rice residues 17.68%, and MSW 5.56%. Sumatra exhibits the greatest potential, attributable to its extensive palm oil infrastructure. Critically, Sumatra's renewable power capacity in the future could substantially offset the energy-related emissions from SAF production. These findings underscore the value of aligning waste feedstock availability with renewable energy capacity, while recognising competing resource demands. This study offers foundational data to guide supply chain and techno-economic analyses, as well as supports strategic planning for SAF deployment across Indonesia's regions.

Keywords

Renewable jet fuel;
Bio-jet fuel;
Renewable energy;
Feedstock mapping;
Circular bioeconomy

http://doi.org/10.54337/ijsepm.10615

1. Introduction

Decarbonising the energy sector requires a transition to renewable energy across all areas, including transport [1]. In this context, the aviation sector can use Sustainable Aviation Fuels (SAF) [2] that can be produced through various conversion pathways, using biomass [3] and hydrogen [4]. At present, biobased SAF is more economical than hydrogenbased SAF; however, the challenge in producing biobased SAF lies in the availability of feedstock [5]. Based on their types, feedstocks can be categorized into lipid-based and carbohydrate-based forms, each following a distinct production pathway. These feedstocks may come from dedicated energy crop plantations that supply materials for SAF. The advantage of using such plantations lies in their ability to guarantee a homogenous supply in terms of volume, price, and quality. However, establishing new plantations would require additional land and higher capital investments. Alternatively, SAF production can utilize municipal solid waste (MSW), along with agricultural, forestry, and plantation residues. The utilizations of these waste streams may cause a minimum investment costs and emissions [6].

Oil-based fuels remain necessary for the transition to net-zero emissions, including in Indonesia [7, 8]. Indeed,

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Received 08.08.2025 | Accepted 06.01.2026 | Published 23.03.2026

List of Abbreviations

EFB	*Empty Fruit Bunches*
FT	*Fitcher-Tropsch*
HTL	*Hydrothermal Liquefaction*
MSW	*Municipal Solid Waste*
POME	*Palm Oil Mill Effluent*
SAF	*Sustainable Aviation Fuel*

the development of SAF is a key element of Indonesia's net-zero emission agenda. As outlined in two Indonesian SAF development roadmap studies [9, 10], crude palm oil has been proposed as the main feedstock. Indonesia has already initiated production and testing of SAF derived from palm oil [11]. However, SAF production using palm oil is associated with the highest land emissions when compared to other feedstocks and similar production practices in other countries. Other feedstocks featured in Indonesia's SAF roadmap include used cooking oil, palm fatty acid distillate, and agricultural waste. Nevertheless, these roadmap studies do not provide a detailed mapping or assessment of Indonesia's overall SAF production potential.

Indeed, studies estimating the SAF production volume in Indonesia remain limited. Nguyen and Vuong [12] estimated the potential for SAF production in Indonesia, Malaysia, the Philippines, Thailand, and Vietnam using agricultural residues, food waste, and forestry wastes. In addition, they reviewed commitments from Southeast Asian airlines regarding SAF usage and projected the region's SAF demand through 2050. Other SAF studies in Indonesia have focused on identifying competitive SAF pricing [13], assessing the feasibility of cooking oil and sugarcane as SAF feedstocks [11], analysing the interconnections among the social, economic, technological, and environmental aspects of SAF production systems [14], and reviewing relevant policies and incentives [15].

Considering these gaps, our study aims to estimate the potential production of SAF from agricultural waste, palm oil plantation residues, and MSW across Indonesia. Our contributions are threefold. First, our estimations are carried out at the provincial level, offering a higher resolution than previous studies. Second, we match the SAF production potential in each province with the existing renewable energy power infrastructure and planned developments until 2030, thereby providing initial information on the potential emission level of the produced SAF. Third, we evaluate the risk to feedstock supply continuity by discussing the competing demands for MSW, rice straw, and palm plantation residues in other sectors.

The rest of the paper is organized as follows. Section 2 reviews the relevant literature; Section 3 presents the analytical methods; Section 4 details the potential for SAF production; and Section 5 discusses the analysis results in terms of renewable energy supply, competing feedstock uses in other sectors, waste quantity trends, and policy implications.

2. Literature Review

According to the International Civil Aviation Organization [16], SAF can be produced through 11 conversion processes that have been recognized by ASTM International. Additionally, 11 other conversion processes are currently under evaluation, while various studies are developing further methods. Feedstocks for SAF production include agricultural waste, plantation waste, and MSW. One type of agricultural waste is rice husk and rice straw. These residues are best processed using Fischer–Tropsch (FT) synthesis to produce SAF [6]. The FT process begins by drying the rice residues until their moisture content meets the requirement. The dried material is then gasified using steam and oxygen to produce syngas (a mixture of H_2 and CO). Methane and other hydrocarbons present are reformed into H_2 and CO, which are subsequently used in FT synthesis. Finally, the process continues with FT synthesis, followed by distillation and hydrocracking, to produce hydrocarbons that meet SAF specifications [17]. EFB, fibre, and palm shell represent appreciable portions of the fresh fruit bunch weight [18]. Although some of these residues are used as boiler fuel, the majority remains underutilized, thereby offering significant potential as SAF feedstock. MSW contains a significant fraction of carbohydrate-rich organic matter, making it suitable for gasification-to-FT processes [6]. MSW generally comprises a mixture of various waste types, each of which can be converted into SAF using different processes.

Feasibility analyses and supply chain assessments for these three feedstocks generally begin with estimating the availability of raw materials. Carvalho et al. [17] estimated the quantity of rice waste and four other agricultural byproducts across municipalities in Brazil. This estimation employed data on agricultural land area, crop productivity, the waste-to-main product ratio, the environmentally sustainable removal rate of residues, waste availability, and the

Table 1: Assumptions of parameter values.

Parameter	Value	Source
Dry MSW ratio (%)	49.26	[24]
MSW to SAF factor (L of SAF/ ton of MSW)	109.6	[27]
Straw to paddy ratio (%)	70.0	[28]
Husk to paddy ratio (%)	20.0	[29]
Paddy to SAF factor (L of SAF/ ton of rice husk and straw)	155.8	[30]
Palm to POME ratio (%)	50.0	[31]
Palm to EFB ratio (%)	23.0	[32]
Conversion factor from EFB to SAF (L of SAF/ton of EFB)	400	[33]
Conversion factor from POME to SAF (L of SAF/ton of POME)	1,080	[34]

low heating value of the waste. Similarly, the estimation of SAF production potential from palm plantation residues involves comparable steps by considering factors such as the extent of palm plantation areas, plantation productivity, waste availability, and process technologies [18].

The abundance of these three types of waste in Indonesia is considerable. As an agrarian country, Indonesia had a cropland area exceeding 50 Mha in 2021, making it the sixth-largest in the world [19]. One of its primary agricultural products is rice, with a production of 53.97 Mt in 2023, ranking as the fourth-largest globally [20]. Another major crop is palm oil, with Indonesia possessing the world's largest palm plantation area (14.95 Mha in 2022) and achieving the highest global production, reaching 46.5 M m^3 in 2024 [21]. Utilising palm oil waste for bioenergy could provide an exit strategy for provinces whose economies have traditionally depended on coal revenues [22]. Regarding MSW production, Indonesia ranked as the fourth-largest waste-generating country in the world, producing 62.7 Mt of waste in 2014 [23].

While data on MSW, agricultural waste, and plantation waste are available in various studies and reports, studies estimating the potential SAF yield from these waste sources were still limited. Therefore, our study aims to address this gap by estimating the SAF production potentials, analysing the emissions cleanliness of SAF based on the energy mix within power generation systems in each province, as well as assessing the sustainability of feedstock supply while considering potential conflicts with other feedstock uses.

3. Methods and Data

The first step is to estimate SAF production from MSW. The average moisture content of MSW in Indonesian landfills is 50.74% [24]. Therefore, the total waste volume for each province in 2024, as reported by the National Waste Management Information System [25], was multiplied by 49.26% to obtain the dry waste weight. This dry waste was then multiplied by the conversion factor for dry waste into SAF. The conversion factor in Table 1 is based on Hydrothermal Liquefaction (HTL) technology.

$$SAF\ from\ MSW_i = MSW\ volume_i \times dry\ MSW\ ratio \times MSW\ to\ SAF\ Factor$$

The second step is to estimate SAF production from agricultural waste. The calculation begins with the rice production data for province in 2024 from the Ministry of Agriculture [26]. The volume of rice production is multiplied by the straw-to-paddy ratio to estimate the amount of rice straw waste, and similarly, it is multiplied by the husk-to-paddy ratio to determine the rice husk volume. These two waste volumes are then summed, and the total is multiplied by the conversion factor for paddy residue to SAF factor (see Table 1).

$$\begin{aligned} SAF\ from\ rice\ residues_i &= Rice\ production_i \\ &\times (straw\ to\ paddy\ ratio + husk\ to\ paddy\ ratio) \\ &\times paddy\ to\ SAF\ ratio \end{aligned}$$

The last step is to estimate SAF production from palm oil residues, specifically from palm oil mill effluent (POME) and EFB. First, the palm oil production data for province in 2022, obtained from the Central Statistics Agency [35], is multiplied by the conversion factors that translate palm oil output into POME and EFB waste. Next, each palm waste stream is individually multiplied by its corresponding conversion factor from waste to SAF. Finally, the estimated SAF values from both waste types are summed up to determine the total potential SAF production.

$$\begin{aligned} \textit{SAF from palm residues}_i &= (\textit{Palm productioni} \times \textit{palm to POME ratio}) \\ &\times (\textit{conversion factor of POME to SAF}) + (\textit{Palm production}_i \\ &\times \textit{palm to EFB ratio} \times \textit{conversion factor of EFB to SAF}) \end{aligned}$$

The next step involves creating maps that visualize the estimated potential SAF production from the three feedstock types. All the data is entered into a Google Sheet connected to Looker Studio (https://lookerstudio.google.com/), which converts the numerical data into statistical geo-maps. First, a national-scale map is generated for all provinces, and then a detailed provincial map is created for the areas with the highest potential SAF production.

Additionally, we developed a map showing both the total power plant capacity and the percentage of new renewable energy capacity projected for 2030. The data on existing and future power plant capacity was obtained from the State-owned Electricity Company [36]. This map is designed to analyse the feasibility of SAF production in province from the perspective of the emissions associated with the province's power generation system. Moreover, we obtained the projected emission factors for 2030 as follows: Sumatra (0.695 t of CO_2/MWh), Java and Bali (0.788 t of CO_2/MWh), Kalimantan (0.841 t of CO_2/MWh), and other islands (0.572 t of CO_2/MWh) [36]. These emission factors were then multiplied by electricity consumption required for SAF production, assumed to be 1.76 kWh/L of SAF [37], to estimate the emissions associated with producing a m^3 of SAF.

4. Analysis Results

The total potential SAF production from these three types of waste amounts to 37.06 M m^3/yr, comprising 28.45 M m^3 from palm plantation residues, 6.55 M m^3 from agricultural residues, and 2.06 M m^3 from MSW. The following subsections provide a detailed breakdown of this SAF potential across each province and district.

4.1. Potential SAF Production from MSW

In 2024, Indonesia generated approximately 38.17 Mt of MSW [25] that could be converted to about 2.06 M m^3 of SAF. The provinces with the highest SAF production potential from MSW are East Java (345,230 m^3), West Java (342,855 m^3), and Central Java (319,773 m^3), as shown in Figure 1. The East Java province has the highest MSW generation in 2024 for 6.39 Mt [25]. Figure 2 illustrates that within East Java, area with the largest amount of MSW are Surabaya city (10% of total MSW), Malang district (6%), and Sidoarjo district (5%).

Other provinces with high SAF production potential include West Java and Central Java, which generated MSW for 6.35 Mt and 5.92 Mt, respectively, in 2024 [25]. In West Java, areas with the highest SAF potential

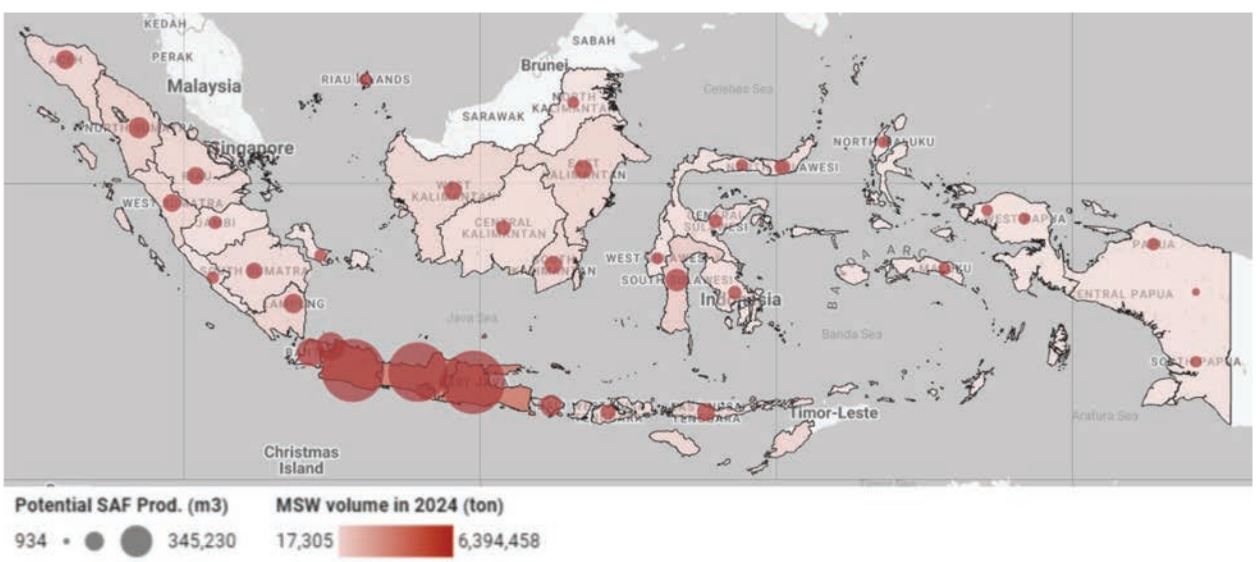


Figure 1: Map of SAF potential from MSW in Indonesia.

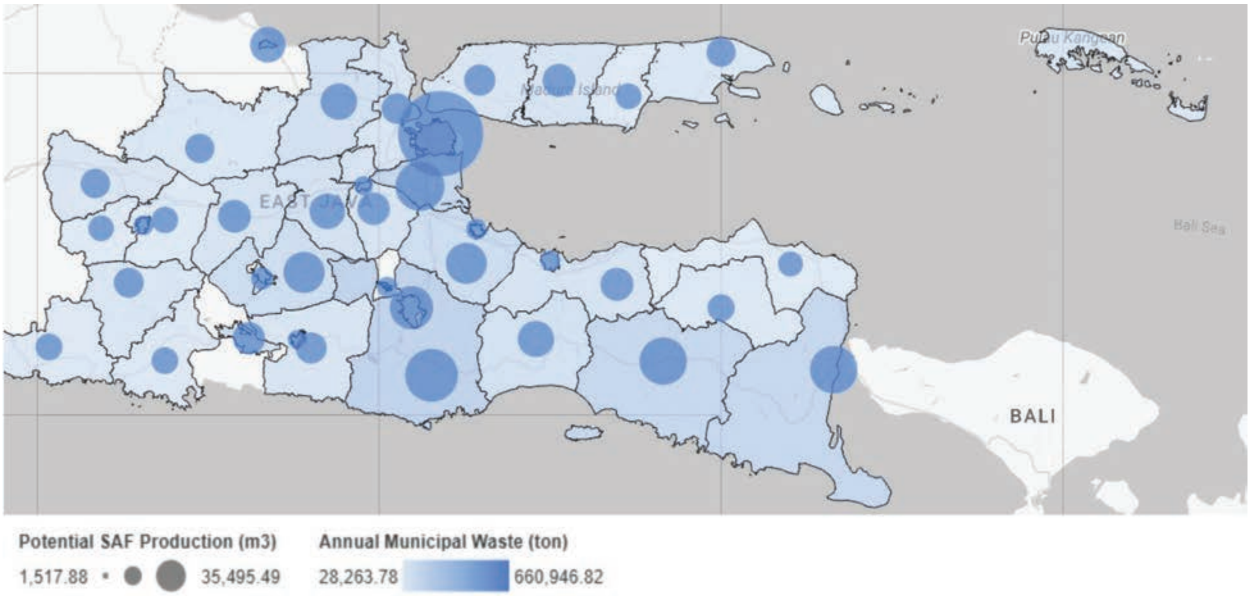


Figure 2: Map of SAF potential from MSW in East Java.

are Bekasi city, Bekasi district, and Bandung city. Meanwhile, the leading areas in Central Java are Semarang city, Brebes district, and Cilacap district. In contrast, the South Papua province records the lowest MSW generation (i.e., 17,305 t in 2024), yielding approximately 934 m^3 of SAF.

4.2. Potential SAF Production from Rice Residues

With a rice harvest area of approximately 2.27 Mha in 2024, Indonesia produced 46.74 Mt of rice and generated 42.07 Mt of rice straw and husk. This waste can be converted into roughly 6.55 M m^3 of SAF. The distribution of rice waste and the potential for SAF production are shown in Figure 3. East Java is the province with the largest volume of rice waste, generating around 7.47 million tons that can be utilized to produce 1.16 M m^3 of SAF. Figure 4 displays the distribution of rice waste and SAF production potential within the province. The main rice-producing districts are in the western region of East Java, i.e., Lamongan, Bojonegoro, and Ngawi. In addition, the region of Jember, together with these three districts, contributes about 31% of East Java's total rice output.

The potential to produce SAF from agricultural waste is also significant in Central Java and West Java. In 2024, Central Java produced 4.68 Mt of rice and generated 7.32 Mt of rice waste, which can be converted into 1.14 M m^3 of SAF. West Java's production figures are approximately 4.17 Mt of rice and 6.5 Mt of rice waste. This waste can be used as feedstock to produce about 1.01 M m^3 of SAF. Other provinces with significant SAF production potentials from rice waste include South Sulawesi, South Sumatra, Lampung, North Sumatra, Banten, and Aceh. Conversely, the provinces with the lowest SAF production potential are the Riau Islands and Highland Papua.

4.3. Potential SAF Production from Palm Residues

Indonesia's primary palm oil plantations are concentrated on the islands of Sumatra and Kalimantan, covering approximately 8.04 Mha and 5.86 Mha, respectively. Consequently, these islands have significant potentials for SAF production from palm oil residues (see Figure 5). Palm plantations in the Sumatra island may produce 15.79 Mt of waste, consisting of POME and EFB, which can be converted into 13.48 M m^3 and 2.3 M m^3 of SAF, respectively. Provinces with significant potentials are Riau (5.65 M m^3), North Sumatra (3.32 M m^3), South Sumatra (2.33 M m^3), and Jambi (1.53 M m^3).

In Kalimantan, the combined SAF production potential reaches 11.44 M m^3 from 13.24 Mt of palm waste. The three provinces with the greatest potential are Central Kalimantan (4.59 M m^3), West Kalimantan (3.36 M m^3), and East Kalimantan (2.36 M m^3). In contrast, palm oil plantations on other islands are relatively limited: Sulawesi has 428.87 kha, Papua has 242.33 kha, and Java has 33.48

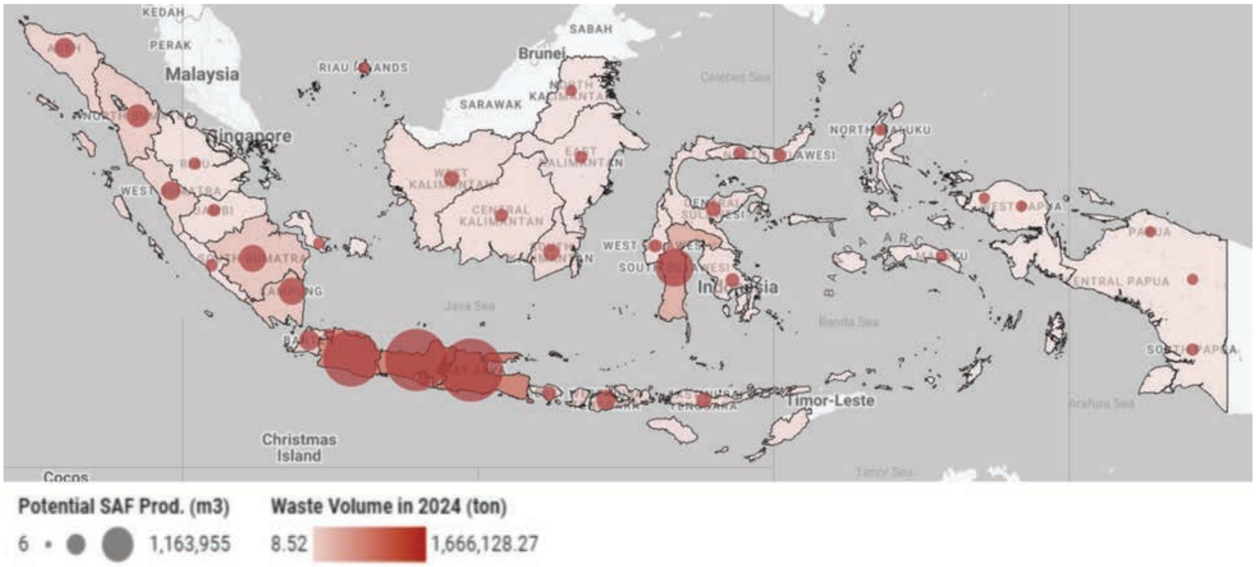


Figure 3: Map of SAF potential from rice residue in Indonesia.

kha. As a result, the SAF production potential from palm residues in these regions is only 638.69 MCM, 534.14 MCM, and 37.48 MCM, respectively.

5. Discussions

The SAF production potential estimated in Section 4 represents the maximum theoretical output, without accounting for actual availability due to the use of waste in other sectors. Therefore, we conducted a sensitivity analysis on waste availability for SAF production and examined its impact on the potential to meet domestic SAF demand. In addition, SAF production must also take into consideration the location of SAF demand, the availability of renewable energy, and the challenges involved.

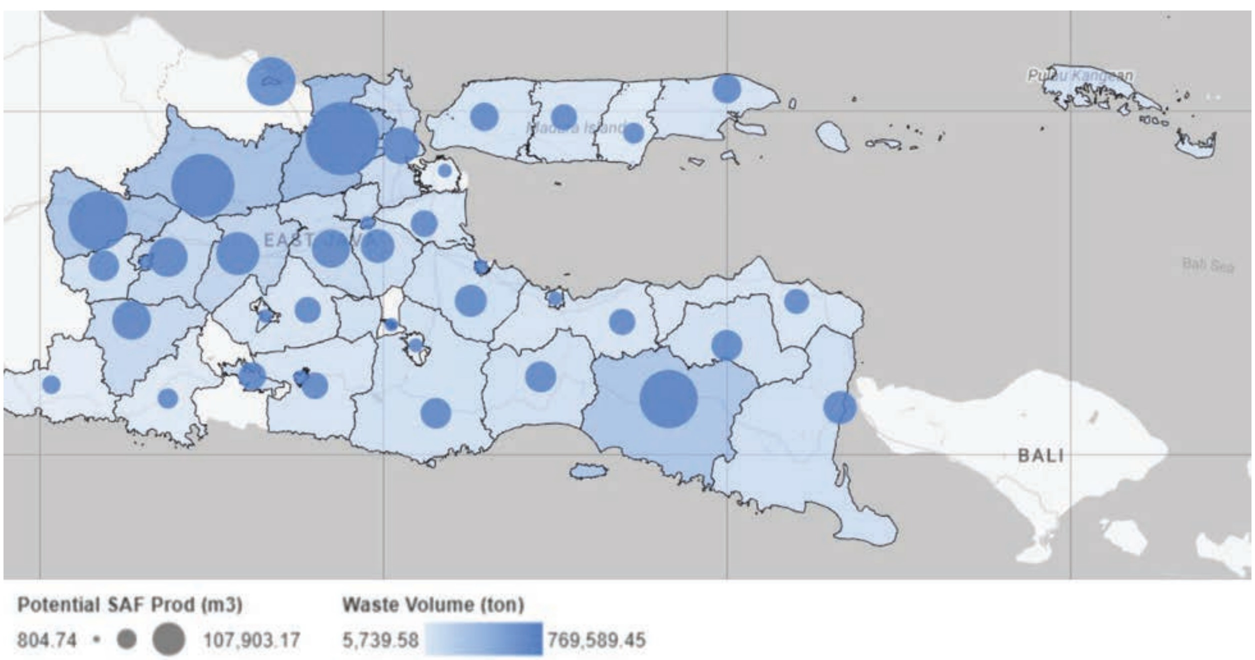


Figure 4**:** Map of SAF potential from rice residue in East Java.

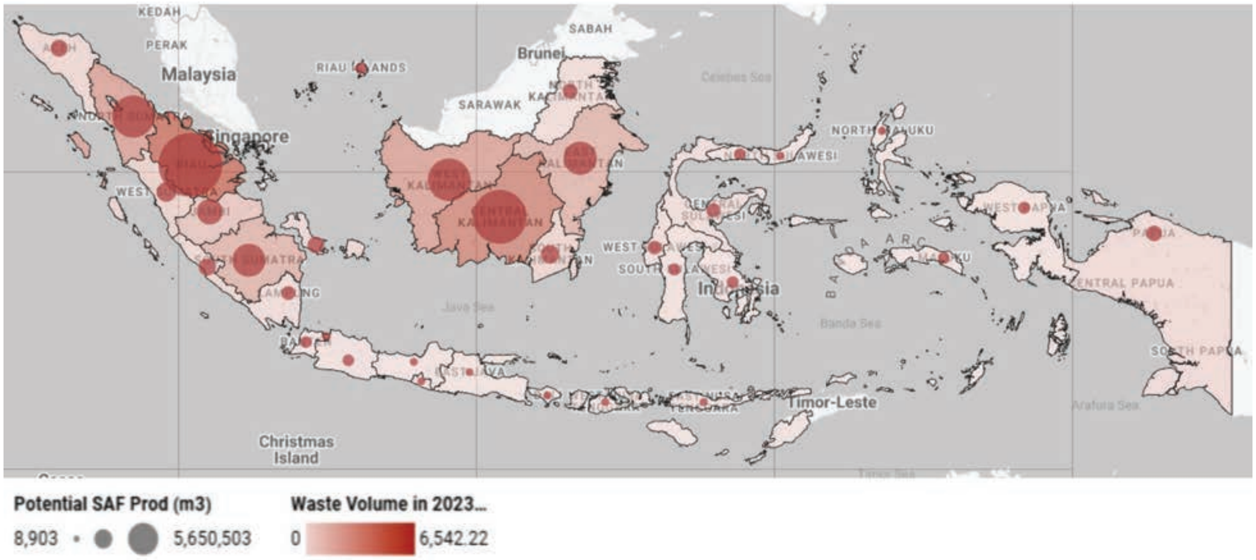


Figure 5: Map of SAF potential from palm residue in Indonesia.

5.1. Utilization of Feedstocks for Other Purposes

Figure 6 shows the existing jet fuel demand and its projection up to 2060 under the low, BaU, and high scenarios [10]. Indonesia's jet fuel consumption peaked at 5.7 M m^3 in 2018, then declined due to the COVID-19 pandemic, reaching 5.0 M m^3 in 2019 and 2.0 M m^3 in 2021 [38]. Recovery followed with consumption rising to 3.3 M m^3 in 2022 and 4.3 M m^3 in 2023. In 2018, this fuel supported 1.1 million flights, dropping to 541,300 by 2022 [39]. Aircraft movements in 2023 totalled 717,788 domestic and 98,637 international flights [40]. Java remained dominant, accounting for 40% of domestic and 52% of international flights. Soekarno-Hatta (Java) and Ngurah Rai (Bali) led international traffic, with 42% and 32%, respectively [40].

Figure 6 shows that jet fuel demand is projected to rise to 6.3 M m^3 in 2030 and continue increasing to 15.8 M m^3 in 2060 under the BaU scenario. GOI [10] targets a gradual increase in the share of SAF blended into jet fuel, from 2.5% in 2030 to 12.5% in 2040 and 50% in 2060, equivalent to 7.9 M m^3 of SAF in 2060. This total SAF demand in 2060 could be met by the overall SAF production potential from MSW, rice residues, and palm waste, amounting to 37.06 M m^3 of SAF. However, the prospective utilisation of these feedstocks for SAF requires rigorous assessment, given their current and diverse applications across multiple sectors, such as biomass fuels in power plants [41-44]. Furthermore, demand for MSW, agricultural, and plantation residues is expected to grow steadily in line with the circular bioeconomy agenda (please see Table 2).

Various alternative applications of the three waste streams listed in Table 2 indicate that not all of them can be utilised for SAF production. Therefore, a sensitivity analysis was conducted to assess the impact of waste availability on meeting SAF demand targets. Figure 7 presents the results of the sensitivity analysis on variations in the availability of a single feedstock for SAF production (ranging from 0% to 100% of total feedstock availability), as well as variations in the availability of all three feedstocks simultaneously. As a result, SAF production potential is strongly influenced by the availability of palm waste. Using 20% of palm waste for SAF production would reduce the potential output to 38.59% of the total SAF production, assuming all other waste streams could be fully utilised for SAF. However, if only 20% of all waste streams were available for SAF production, the potential output would fall to 7.41 M m^3 of SAF, making it insufficient to meet domestic SAF demand.

5.2. Electricity Supply for SAF Production Plants

Java's high demand of jet fuels presents an opportunity to scale SAF production, particularly using feedstocks such as MSW and rice residues. SAF productions in Java will be supported by increasing renewable generation capacity, reaching 13.5 GW by 2030 [36], with the largest shares in West Java (52.1%), Central Java

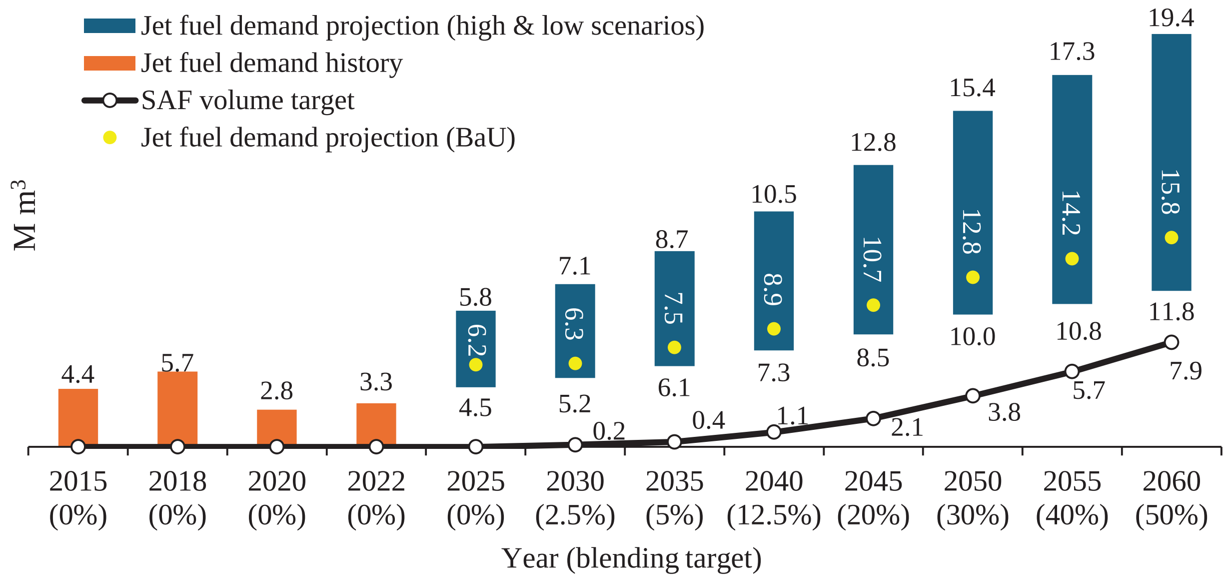


Figure 6: Demands of jet fuel and SAF (data source from [10]).

(21.5%), and East Java (19.4%) (see Figure 8). SAF produced in West and Central Java can supply airports in Java and support exports, while East Java may supply Bali's Ngurah Rai Airport.

Despite these plans, renewable sources account for only 22.73% of Java's total generation capacity, potentially increasing emissions from SAF production. Options include constructing dedicated renewable plants

Table 2: Potential alternative uses of feedstocks in Indonesia.

Type of Waste	Sector	Application
MSW	Energy	Refuse-derived fuels & solid recovered fuel as coal substitutes, incineration for power generation, green hydrogen
	Social/ Environmental Management	Community-based waste banks
	Construction	Aggregate substitution in lightweight ceramics
Rice Residues	Energy	Bioethanol production from straw, rice husk for biomass power generation, bio-oil, biochar
	Environment/ Agriculture	Biochar for GHG mitigation and soil enhancement
	Livestock	Dried broken rice as livestock feed
	Cosmetics Industry	Cosmetic ingredients from cellulose and hydrolysed proteins
	Construction	Construction materials
Oil Palm Residues	Energy	Biogas production from POME, bioethanol and xylitol from EFB, gasification of trunks/fronds for electricity, catalytic biochar from EFB
	Food/ Pharmaceutical/ Cosmetics Industry	Extraction of bioactive compounds (vitamin E, flavonoids)
	Environment	Wastewater bioremediation using microalgae
	Industrial	Industrial fuel from palm kernel shells
	Materials/ Construction	Composite panels from palm trunks/ fibres
	Tourism	Decorative elements

Sources: [45-54].

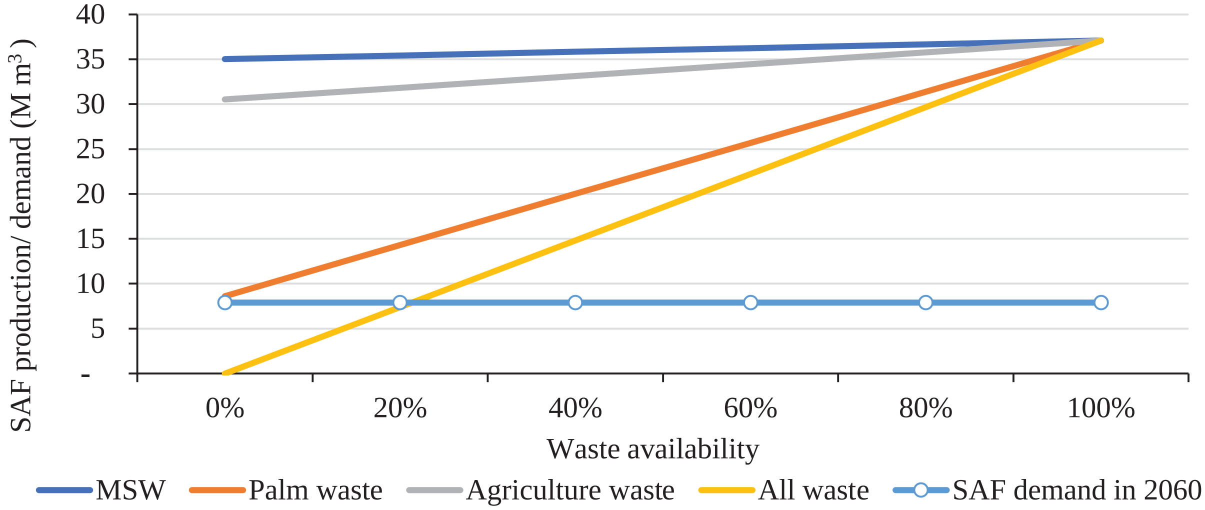


Figure 7: Sensitivity analysis on waste availability for SAF production.

or purchasing renewable energy certificates. Conversely, Sumatra's greener energy mix is projected to reach 11.3 GW (or 52.74% renewable) by 2030, led by North Sumatra (3.2 GW). SAF from Sumatra could serve regional airports and be exported to Malaysia and Singapore. Java and Sumatra should thus act as strategic hubs for scaling SAF deployment, informing future expansion.

Figure 9 illustrates emissions associated with SAF production. Sumatra, with the highest SAF potential, has an emission factor of 0.695 tCO_2/MWh, equating to approximately 122 kg of CO_2/m^3 of SAF. Emissions in Kalimantan and Java–Bali are higher due to greater reliance on coal-fired generation. Sulawesi, Papua, Nusa Tenggara, and Maluku show lower emissions, although their SAF production potential remains relatively limited.

5.3. Challenges

The development of SAF from agricultural residues and MSW faces a range of technical, economic, environmental, and social challenges. A primary technical barrier is the significant variability in feedstock volume and composition. Agricultural and plantation waste is

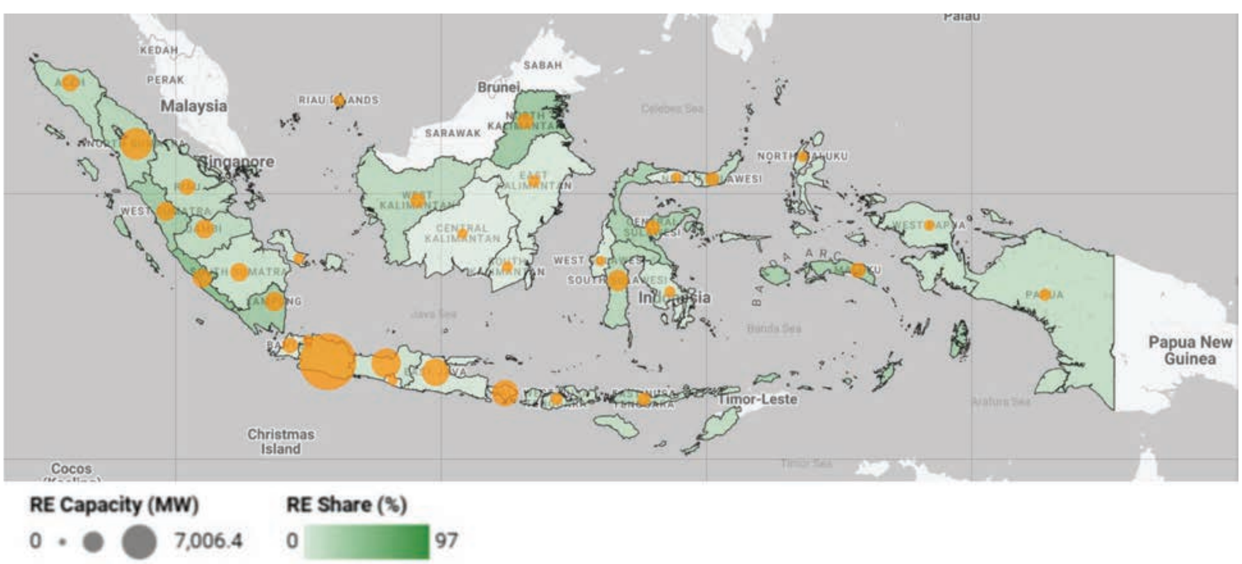
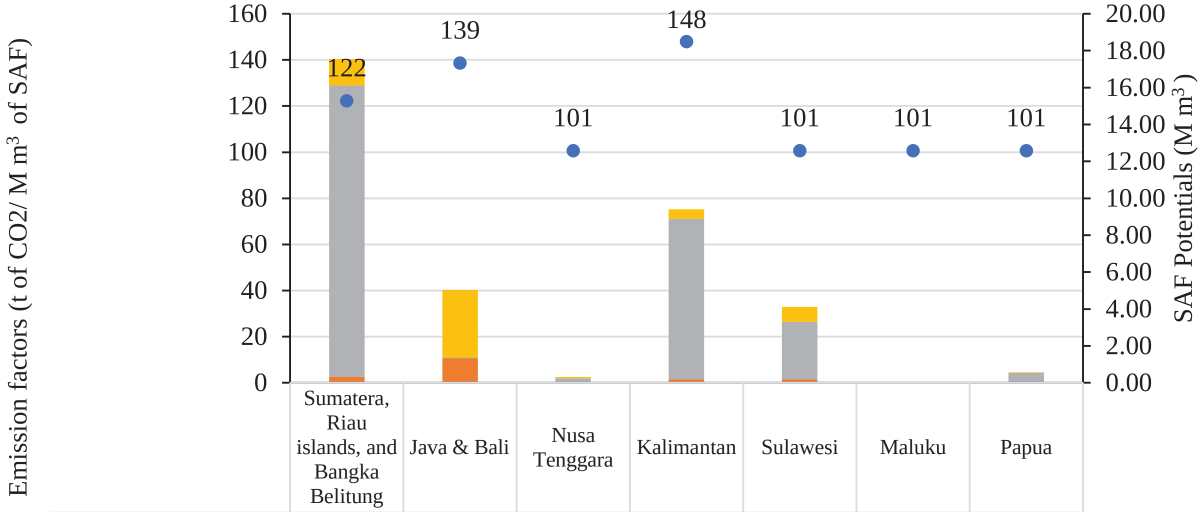


Figure 8: Map of renewable energy capacity and its share by 2030 (data source from [36]).



	Sumatera, Riau islands, and Bangka Belitung	Java & Bali	Nusa Tenggara	Kalimantan	Sulawesi	Maluku	Papua
SAF from paddy residue	1.43	3.66	0.07	0.53	0.82	0.02	0.03
SAF from palm residue	15.79	0.04	0.25	8.70	3.13	0.01	0.53
SAF from MSW	0.33	1.34	0.01	0.18	0.18	0.01	0.02
Emission factors	122	139	101	148	101	101	101

Figure 9: Total SAF potential by island and associated emissions from SAF production.

seasonal (i.e., abundant during harvest periods and scarce during off seasons) and exhibits wide heterogeneity in both chemical and physical properties. Geographic dispersion further exacerbates these challenges. Agricultural residues are typically scattered across rural regions with limited transport infrastructure, complicating efficient collection and raising logistics costs. This spatial fragmentation, combined with inadequate connectivity, constrains the potential for scaling up SAF production. Moreover, only a handful of Indonesian cities have integrated waste management systems that link waste collection to energy recovery.

Similar challenges exist with MSW. Waste management continues to grapple with low source-separation rates and insufficient processing infrastructure. Consequently, urban waste generally comprises a mixed stream of organic and inorganic materials, often containing high moisture and contaminants such as metals and plastics. This variability hampers SAF production, particularly in pretreatment, conversion, and purification stages, by diminishing process efficiency and fuel quality.

Conversion technology selection also poses significant hurdles. Thermochemical pathways, including pyrolysis, gasification, HTL, and advanced catalytic upgrading systems. Pyrolysis bio-oil, for instance, is oxygen-rich and chemically unstable, requiring substantial upgrading to meet aviation fuel standards. Gasification hinges on consistent syngas quality, which is sensitive to feedstock type and moisture content. HTL is well-suited for wet biomass but entails high energy requirements and catalyst degradation concerns. Biochemical pathways such as fermentation and microbial gas conversion face limitations due to process inhibition, costly enzymes, and microbial inefficiencies. Catalyst deactivation, caused by sulphur, chlorine, and alkali metals, remains an underappreciated issue, resulting in coke formation, catalyst poisoning, and frequent maintenance, all of which lower efficiency and increase costs.

Substantial capital investment is required to establish dependable feedstock supply chains, pretreatment facilities, and conversion plants. The seasonal fluctuations in agricultural biomass also intensify economic uncertainty. As a result, SAF remains costlier than conventional jet fuel. For context, the average global price of Jet-A1 fuel between 2022 and 2024 ranged from 0.6 to 1 US$/L [55, 56]. In contrast, SAF derived from rice husk is priced at approximately 2.48 US$/L, from MSW at 1.50–1.73 US$/L, and from used cooking oil at 0.98–1.44 US$/L [6].

Environmental and social considerations present further obstacles. While SAF derived from waste has the potential to mitigate emissions and reduce landfilling, conversion processes may still produce pollutants if poorly managed. Life cycle emissions vary significantly depending on feedstock and conversion pathway. Additional environmental risks (e.g., thermal process emissions, residual waste, and water consumption) require rigorous monitoring. Social acceptance is another major constraint, particularly for waste-to-energy projects that often encounter public resistance due to perceived health risks and air pollution. These concerns are frequently fuelled by limited public awareness and minimal community engagement during planning phases. Strengthening public trust in SAF initiatives will require evidence-based communication strategies and participatory approaches.

5.4. Policy Implications

While the production of SAF from waste in Indonesia holds significant promise, its advancement demands a holistic policy framework supported by strategic recommendations. First, regional disparities in feedstock availability and infrastructure readiness must be addressed. Provinces such as those in Sumatra, characterised by abundant palm oil residues and relatively high shares of renewable energy, offer promising entry points for SAF development. In early-stage implementation, waste-based feedstock utilisation should be incentivised through schemes that recognise associated environmental benefits.

Robust cross-sector collaboration is imperative. Enhanced coordination among key ministries (e.g., Ministry of Energy and Mineral Resources, Ministry of Transportation, Ministry of Environment, and the Ministry of National Development Planning) is essential to align sectoral targets, harmonise regulations, and reduce administrative bottlenecks. The formation of a national task force or an inter-ministerial working group on SAF could facilitate these efforts. Engagement with private actors is equally vital. Public-private partnerships, underpinned by financial instruments such as green bonds, tax incentives, or risk-sharing mechanisms, can help mitigate investment risks and accelerate project roll-out in high-potential regions. Further priorities include collaborative research to strengthen SAF potential assessments, integrating techno-economic viability, environmental implications, and logistical constraints.

As competition for waste feedstock intensifies, allocation must be carefully optimised. Cross-sectoral demand may result in feedstock scarcity and price volatility, particularly where strategic priorities differ across energy, agricultural, and waste management sectors. In response, there is an urgent need for comprehensive waste utilisation policies that consider spatial-temporal variations in feedstock availability, economic valuation, emissions reduction potential, and socio-environmental impacts. Policy instruments such as waste-use hierarchies, environmentally weighted incentive schemes, and standardised quality assurance protocols for waste-derived feedstocks can help mitigate conflict and ensure equitable resource access. SAF development should also consider other wastes, such as waste cooking oils [57].

Evidence-based decision-making should be underpinned by comparative assessments, such as life cycle analysis, cost-benefit studies, and scenario modelling aligned with national targets. Employing airborne Light Detection and Ranging surveys can substantially improve the accuracy and consistency of feedstock data measurements [58]. To support strategic planning and robust modelling, it is critical to strengthen national data systems, particularly at the municipal level for waste inventories and at airport hubs for fuel demand forecasting.

6. Conclusion

Demand for SAF continues to rise as the aviation sector intensifies its decarbonisation efforts. The Indonesia government expects the SAF demand will reach 0.2 M m^3 in 2030 and 7.9 M m^3 in 2060. SAF can be produced from waste and viable waste streams for SAF production include MSW, rice residues, and palm residues. However, studies estimating SAF production potential from waste in Indonesia remain scarce. This study aims to address that gap by estimating the SAF production potential from MSW, rice residues, and palm residues across all provinces. It offers a preliminary assessment of the country's capacity for waste-derived SAF.

Our estimates suggest a total SAF production potential of 37.06 M m^3, predominantly sourced from palm residues (76.76%), with agricultural residues contributing 17.68% and MSW 5.56%. Therefore, the availability of palm residues is crucial to meeting SAF demand. If palm residues are not available, all other waste streams would need to be fully utilised for SAF production to meet domestic demand. The sensitivity analysis further indicates that more than 20% of all three waste streams must be used for SAF production if Indonesia is to meet its domestic SAF needs by 2060.

The study has several limitations. Chief among them is its full reliance on secondary data. Although rice waste and MSW datasets exist at the municipal level, their quality and resolution require improvement through targeted surveys. Palm residue data were only available at the provincial level, highlighting the need for higher-resolution inputs, such as municipal or sub-district datasets. Future studies should conduct field surveys to validate assumptions regarding feedstock availability. Additionally, data on jet fuel demand at individual airports could not be obtained. Addressing this gap will require collaboration with the Ministry of Transportation, the State-owned Oil and Gas Company, and the Ministry of Energy and Mineral Resources.

Another limitation lies in the simplicity of the estimation model, which was developed in-house using literature-sourced conversion factors. While this approach offers a baseline assessment, it omits more advanced evaluations such as supply chain optimisation, techno-economic analysis, and operational feasibility assessments. Accordingly, further research should refine the model and identify the most promising regions for SAF production. A case study of the SAF supply chain in the International Soekarno-Hatta Airport would help illustrate the analysis, including estimates of economic viability.

CRediT Authorship Contribution Statement

Ika Inayah: Writing – original draft, review & editing, Validation, Supervision, Formal analysis. **Khansa Ghumaydha Dzikra**: Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Muhammad Indra al Irsyad**: Writing – review & editing, Validation, Supervision, Conceptualization. **Roni Kastaman**: Writing –review & editing, Validation, Supervision, Resources, Conceptualization. **Irawan**: Writing – review & editing, Validation, Formal analysis. **Anthony Halog**: Writing – review & editing, Validation, Formal analysis. All authors have the same role as the main contributor.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors would like to thank the editor and the two anonymous reviewers for their constructive comments, which have helped improve the analysis in this article.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work the authors used CoPilot for language review and editing purposes to enhance readability and clarity. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

[1] Osorio-Aravena J, Aghahosseini A, Bogdanov D, Caldera U, Muñoz-Cerón E, Breyer C, Transition toward a fully renewable-based energy system in Chile by 2050 across power, heat, transport and desalination sectors. Int J of Sust Energy Plan and Mgt 25 (2020) p 77-94. http://doi.org/10.5278/ijsepm.3385

[2] Bramstoft R, Skytte K, Decarbonizing Sweden’s energy and transportation system by 2050. Int J of Sust Energy Plan and Mgt 14 (2017) p 3-20. https://doi.org/10.5278/ijsepm.2017.14.2

[3] Mezzera F, Fattori F, Dénarié A, Motta M, Waste-heat utilization potential in a hydrogen-based energy system-An exploratory focus on Italy. Int J of Sust Energy Plan and Mgt 31 (2021) p 95-108. https://doi.org/10.5278/ijsepm.6292

[4] Hansen CB, Skov IR, PTX Project Implementation of two projects in Denmark: Takeaways and Insights. Int J of Sust Energy Plan and Mgt 40 (2024) p 96-114. https://doi.org/10.54337/ijsepm.8082

[5] Abid H, Skov IR, Mathiesen BV, Østergaard PA, Standalone and system-level perspectives on hydrogen-based sustainable aviation fuel pathways for Denmark. Energy 320 (2025) p 135450. https://doi.org/10.1016/j.energy.2025.135450

[6] Detsios N, Theodoraki S, Maragoudaki L, Atsonios K, Grammelis P, Orfanoudakis NG, Recent Advances on Alternative Aviation Fuels/Pathways: A Critical Review. Energies 16 (4) (2023) p 1904. https://doi.org/10.3390/en16041904

[7] Soemanto A, Mohi E, Santosa J, al Irsyad MI, Hesty NW, Strategies for Indonesia’s low carbon energy transition based on a participatory energy system dynamic model. Energy Research & Social Science 127 (2025) p 104231. https://doi.org/10.1016/j.erss.2025.104231

[8] Soemanto A, Mohi E, al Irsyad MI, Gunawan Y, The Role of Oil Fuels on the Energy Transition toward Net Zero Emissions in Indonesia: A Policy Review. EVERGREEN Joint Journal of

Novel Carbon Resource Sciences & Green Asia Strategy 10 (04) (2023) p 2074-83. https://doi.org/10.5109/7160867

[9] PSE UGM, Kajian Akademis Peta Jalan Implementasi Bioavtur. Yogyakarta, Indonesia: Pusat Studi Energi Universitas Gadjah Mada (PSE UGM); 2023. p. 172.

[10] GOI, Peta Jalan Pengembangan Industri Sustainable Aviation Fuel (SAF) Indonesia. Jakarta, Indonesia: Government of Indonesia (GOI); 2023. p. 74. https://maritim.go.id/uploads/magazine/20241015092900-2024-10-15magazine092716.pdf

[11] Nugroho DA, Sitompul MR, Widadi N, Sustainable aviation fuel development: case study in Indonesia. IOP Conference Series: Earth and Environmental Science 1294 (1) (2024) p 012032. https://doi.org/10.1088/1755-1315/1294/1/012032

[12] Nguyen KN, Vuong H, A case study on sustainable aviation fuel adaptation by South East Asian countries: Opportunities, reality, and the current gaps. Case Studies in Chemical and Environmental Engineering 10 (2024) p 100988. https://doi.org/10.1016/j.cscee.2024.100988

[13] Hendrawati TY, Siswahyu A, Ramadhan AI, Analysis of Technoeconomy of Bioavtur Production With Hydroprocessed Esters And Fatty Acids (Hefa) Process In Indonesia. International Journal of Scientific & Technology Research 7 (3) (2018) p 39-43.

[14] Nuryadin D, Nurcholis M, Rahmanda GA, Sustainable Bioavtur: A System Dynamics Approach to Addressing the Aviation Industry's Environmental Impact. ICARAF-2022: IOP Conference Series: Earth and Environmental Science; 2023. p. 012032. https://doi.org/10.1088/1755-1315/1242/1/012032. https://dx.doi.org/10.1088/1755-1315/1242/1/012032

[15] Atmowidjojo A, Rianawati E, Chin BLF, Yusup S, Quitain AT, Assabumrungrat S, et al., Supporting Clean Energy in the ASEAN: Policy Opportunities from Sustainable Aviation Fuels Initiatives in Indonesia and Malaysia. IOP Conference Series: Earth and Environmental Science 940 (1) (2021) p 012031. https://doi.org/10.1088/1755-1315/940/1/012031

[16] ICAO, Conversion processes Environment. Montreal, Canada: International Civil Aviation Organization (ICAO); 2024. https://www.icao.int/environmental-protection/GFAAF/Pages/conversion-processes.aspx

[17] Carvalho F, da Silva FTF, Szklo A, Portugal-Pereira J, Potential for biojet production from different biomass feedstocks and consolidated technological routes: a georeferencing and spatial analysis in Brazil. Biofuels, Bioproducts and Biorefining 13 (6) (2019) p 1454-75. https://doi.org/10.1002/bbb.2041

[18] Martinez-Valencia L, Valderrama-Rios C, Sustainable Aviation Fuel Production in Colombia: Opportunities and Challenges. Washington, US: Washington State University; 2024. p. 161. https://doi.org/10.7273/000006281.

[19] FAO, Land statistics and indicators 2000-2021:. Global, regional and country trends. FAOSTAT Analytical Brief 71. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO); 2023. p. 14. https://openknowledge.fao.org/server/api/core/bitstreams/5c8b2707-1bcf-4c29-90e2-3487e583f71e/content

[20] FAO, Rice production. With major processing by Our World in Data. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO); 2025. https://ourworldindata.org/grapher/rice-production

[21] Shahbandeh M, Leading producers of palm oil worldwide from 2024/2025. 7 February 2025 ed. Hamburg, Germany: Statista; 2025. https://www.statista.com/statistics/856231/palm-oil-top-global-producers/

[22] Al Irsyad MI, Quist J, Rahayu HP, Blok K, A Strategic Plan for Renewable Energy Transition in a Coal Dependent Region using Participatory Backcasting: The Case of South Kalimantan Province in Indonesia. Int J of Sust Energy Plan and Mgt (2025) p. http://doi.org/10.54337/ijsepm.9826

[23] Waste Atlas, Municipal Solid Waste generation. D-Waste; 2014. http://www.atlas.d-waste.com/

[24] Zhen Z, Zhang H, Yan M, Wu A, Lin X, Susanto H, et al., Experimental study on characteristics of municipal solid waste (MSW) in typical cites of Indonesia. Progress in Energy & Fuels 8 (1) (2020) p 13. https://doi.org/10.18282/pef.v8i1.716

[25] MEF, Sistem Informasi Pengelolaan Sampah Nasional: SIPSN. Jakarta, Indonesia: Ministry of Environment and Forestry (MEF); 2025. https://sipsn.menlhk.go.id/sipsn/public/data/timbulan

[26] MA, KSA BPS Padi - 2024 Jakarta, Indonesia: Ministry of Agriculture (MA); 2024. p. 10. https://app.powerbi.com/view?r=eyJrIjoiOGRmMTIwYTYtMWVmOS00YjAyLWFkOTEtMjQ0YjlhYWM3M2EwIiwidCI6IjhjYjJjMjI3LWFlZjYtNDRjNS04OWVkLTA0NTY2YzM2YzE1NyIsImMiOjEwfQ%3D%3D

[27] Seiple T, Jiang Y, Snowden-Swan LJ, Betzsold N, Ramasamy KK, Fuller C, Cost-Effective Opportunities to Produce Sustainable Aviation Fuel from Low-Cost Wastes in the U.S. ACS Sustainable Chemistry & Engineering 11 (33) (2023) p 12326-35. https://doi.org/10.1021/acssuschemeng.3c02147

[28] Bakker R, Elbersen H, Poppens R, Lesschen JP, Rice straw and wheat straw-potential feedstocks for the biobased economy. Wageningen, The Netherlands Wageningen UR; 2013. p. 31. https://research.wur.nl/en/publications/rice-straw-and-wheat-straw-potential-feedstocks-for-the-biobased-

[29] Abbas A, Ansumali S, Global Potential of Rice Husk as a Renewable Feedstock for Ethanol Biofuel Production. BioEnergy Research 3 (4) (2010) p 328-34. https://doi.org/10.1007/s12155-010-9088-0

[30] López M, Leon S, Rocha S, Saenz J, Rincon S, Silva V, et al., Analysis of the Potential for Sustainable Aviation Fuel (SAF) Production from Colombian Agro-Industrial Residues. Chemical

Engineering Transactions 109 (2024) p 31-6. https://doi.org/10.3303/CET24109006

[31] BPS, Statistik Kelapa Sawit Indonesia. 30 November 2021 ed. Jakarta, Indonesia: Badan Pusat Statistik, 2020. https://www.bps.go.id/id/publication/2021/11/30/5a3d0448122bc6753c953533/statistik-kelapa-sawit-indonesia-2020.html

[32] PNPM Mandiri, Manual Pelatihan Teknologi Energi Terbarukan. Jakarta, Indonesia: Danish International Development Agency (DANIDA); 2012.

[33] Kurniawan TA, Ali M, Mohyuddin A, Haider A, Othman MHD, Anouzla A, et al., Innovative transformation of palm oil biomass waste into sustainable biofuel: Technological breakthroughs and future prospects. Process Safety and Environmental Protection 193 (2025) p 643-64. https://doi.org/10.1016/j.psep.2024.11.073

[34] Rahmanulloh A, Biofuels Annual Report. In: Osinski J, editor. Jakarta, Indonesia: US Department of Agriculture; 2024. p. 24. https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels%20Annual_Jakarta_Indonesia_ID2024-0018

[35] BPS, Statistik Kelapa Sawit Indonesia (Indonesian Oil Palm Statistics) 2022. Jakarta, Indonesia: Central Bureau of Statistics (BPS); 2023. p. 152. https://www.bps.go.id/id/publication/2023/11/30/160f211bfc4f91e1b77974e1/statistik-kelapa-sawit-indonesia-2022.html

[36] PLN, Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) PT PLN (Persero) 2021 - 2030. Jakarta, Indonesia: Perusahaan Listrik Negara (PLN); 2021. https://web.pln.co.id/stakeholder/ruptl

[37] Pipitone G, Zoppi G, Pirone R, Bensaid S, Sustainable aviation fuel production using in-situ hydrogen supply via aqueous phase reforming: A techno-economic and life-cycle greenhouse gas emissions assessment. J Clean Prod 418 (2023) p 138141. https://doi.org/10.1016/j.jclepro.2023.138141

[38] MEMR, Handbook of Energy & Economic Statistics of Indonesia 2023. In: (MEMR) MoEaMR, editor. Jakarta, Indonesia2024. https://www.esdm.go.id/en/publication/handbook-of-energy-economic-statistics-of-indonesia-heesi

[39] Romero L, Total number of flight departures in Indonesia from 2013 to 2022. 4 September 2023 ed. Hamburg, Germany: Statista; 2023. https://www.statista.com/statistics/977155/indonesia-total-flight/

[40] BPS, Air Transportation Statistics 2023. Jakarta, Indonesia: Central Bureau of Statistics (BPS); 2024. p. 282. https://www.bps.go.id/id/publication/2024/11/25/a8fac4f872ffc88d3f45d0d3/statistik-transportasi-udara-2023.html

[41] Hernandez-Escalante M, Martin-del-Campo C, A biomass waste evaluation for power energy generation in Mexico based on a SWOT & Fuzzy-logic analysis. Int J of Sust Energy Plan and Mgt 35 (2022) p 5-26. https://doi.org/10.54337/ijsepm.7073

[42] Siregar YI, Ranking of energy sources for sustainable electricity generation in Indonesia: A participatory multi-criteria analysis. Int J of Sust Energy Plan and Mgt 35 (2022) p 45-64. https://doi.org/10.54337/ijsepm.7241

[43] Fitriana I, Warsito B, Hilmawan E, Santosa J, The Optimization of Power Generation Mix to Achieve Net Zero Emission Pathway in Indonesia without Specific Time Target. International Journal of Sustainable Energy Planning & Management 41 (2024) p. https://doi.org/10.54337/ijsepm.8263

[44] Langer J, Lombardi F, Pfenninger S, Rahayu HP, Al Irsyad MI, Blok K, The role of inter-island transmission in full decarbonisation scenarios for Indonesia's power sector. Environmental Research: Energy (2024) p. https://doi.org/10.1088/2753-3751/ad53cb

[45] Aziz SA, Astrini N, Rianawati E, Halog A, Al Irsyad MI, Challenges in Adopting Successful Waste-to-Energy Policies in EU Countries: Indonesia study case. Conference Challenges in Adopting Successful Waste-to-Energy Policies in EU Countries: Indonesia study case. IEEE, p 278-83. https://doi.org/10.1109/EPEC56903.2022.10000255

[46] Huang J, Jin Y, Chu X, Shu Z, Ma X, Liu J, Development of a loose powder sintering method for the preparation of porous ceramic from municipal solid waste incineration fly ash. Waste Management 169 (2023) p 243-52. https://doi.org/10.1016/j.wasman.2023.06.010

[47] Rathour RK, Devi M, Dahiya P, Sharma N, Kaushik N, Kumari D, et al., Recent trends, opportunities and challenges in sustainable management of rice straw waste biomass for green biorefinery. Energies 16 (3) (2023) p 1429. https://doi.org/10.3390/en16031429

[48] Vargas-Escobar P, Flórez-Acosta O, Corrales-García LL, Renewing the potential of rice crop residues as value-added products in the cosmetics industry. Heliyon 10 (7) (2024) p. https://doi.org/10.1016/j.heliyon.2024.e28402

[49] Arabani M, Ebrahimi M, Shalchian MM, Majd Rahimabadi M, Influence of Biomass-Modified Asphalt Binder on Rutting Resistance. Advances in Civil Engineering 2024 (1) (2024) p 8249248. https://doi.org/10.1155/2024/8249248

[50] Sugiyono A, Kuncoro AH, Fitriana I, Wijaya PT, Ridlo R, Wibowo E, et al., Strategies Toward Energy Transition in Indonesia: An Assessment of Multi-Regional Biomass Supply for Coal Co-Firing Power Plants. Int J of Sust Energy Plan and Mgt 47 (2025) p 43-56. https://doi.org/10.54337/ijsepm.10514

[51] Cuan JEI, Garcia VF, Ensinas AV, Optimal biorefinery design and supply chain for the production of sugarcane bagasse pellets, electricity and bioethanol in Colombia. Int J of Sust Energy Plan and Mgt 45 (2025) p 5-22. https://doi.org/10.54337/ijsepm.9744

[52] Kurbatova T, Sidortsov R, Trash to Hryvnias: The economics of electricity generation from landfill gas in Ukraine. Int J of Sust

Energy Plan and Mgt 33 (2022) p. https://doi.org/10.54337/ijsepm.6707

[53] Fitriana I, Hadiyanto, Warsito B, Himawan E, Santosa J, The Optimization of Power Generation Mix To Achieve Net Zero Emission Pathway in Indonesia Without Specific Time Target. Int J of Sust Energy Plan and Mgt 41 (2024) p 5–19. https://doi.org/10.54337/ijsepm.8263

[54] Yaumidin UK, Priyanti A, Al Irsyad MI, Hasibuan AM, Pribadi DO, Daulay H, et al., Harnessing Indonesia's Circular Bioeconomy: Integrating Land, Marine, Forest, and Water Resources for Food System Sustainability. The Australian Journal of Agricultural and Resource Economics (2026) p. 1–16. https://doi.org/10.1111/1467-8489.70088

[55] EIA, Petroleum & Other Liquids. Washington, US: Energy Information Administration (EIA); 2025. https://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm

[56] IATA, Jet Fuel Price Monitor. Montreal, Canada: International Air Transport Association (IATA) 2025. https://www.iata.org/en/publications/economics/fuel-monitor

[57] Espinosa EAM, Rodríguez RP, Sierens R, Verhelst S, Emulsification of waste cooking oils and fatty acid distillates as diesel engine fuels: An attractive alternative. Int J of Sust Energy Plan and Mgt 9 (2016) p 3-16. https://doi.org/10.5278/ijsepm.2016.9.2

[58] Torre L, Biomass estimation using LiDAR data. Int J of Sust Energy Plan and Mgt 17 (2018) p 79-90. https://doi.org/10.5278/ijsepm.2018.17.7