Life Cycle Greenhouse Gases (GHG) Analysis of Oil Palm Empty Fruit Bunch-Based Dimethyl Ether: A case study in Indonesia

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Abstract— **The abundant residue of palm oil processing in Indonesia, such as oil palm empty fruit bunch (OPEFB), has the potential to be converted into dimethyl ether (DME) that can be used as an LPG substitute. Therefore, this study assesses the reduction of greenhouse gas (GHG) emissions when DME is utilised as a substitute for LPG in Indonesia. The reduction in GHG emissions was calculated using a life cycle analysis of GHG emissions for OPEFB-based DME, and the results were compared with those of LPG and coal-based DME. The results show that the life cycle GHG emission of OPEFB-based DME is 1.47 kg-CO_2eq kg-DME^{-1}. The GHG emission that can be reduced when LPG is substituted with OPEFB-based DME is 30%. Compared with coal-based DME projected to substitute LPG in Indonesia, the GHG emission reduction is 73%. The environmental burden of OPEFB-based DME is lower than that of LPG and coal-based DME, which shows that OPEFB-based DME is a more sustainable alternative. This study demonstrates that OPEFB-based DME produced in Kalimantan, Indonesia, has excellent development potential, particularly when it meets the GHG emissions reduction criteria.**

Keywords— DME, GHG, emission, life cycle analysis, LPG, OPEFB

I. Introduction

The potential of palm oil production waste as a feedstock for biofuel production, which can replace fossil fuels and supplement first-generation biofuels, has gained attention [1]–[3]. One of the most notable palm oil production wastes is the oil palm empty fruit bunch (OPEFB), particularly in Indonesia and Malaysia, as well as in Thailand, where palm plantations are cultivated [2], [4], [5]. Indonesia is the world's largest producer and exporter of palm oil, accounting for approximately 57% of global production [5], [6]. So far, this OPEFB has only been used for mulching and composting, which requires extreme caution because biomass is a potential source of pests and hazardous illnesses [7], [8].

Similar to other agricultural waste, OPEFB has the potential to be converted into energy through several processes, including direct combustion for heat and power, biochemical conversion to biogas or ethanol, and thermochemical conversion to synthesis gas and its derivative products, such as dimethyl ether (DME) [9]. DME is a clean biofuel that may be utilised for various purposes [10].

DME is similar to liquefied petroleum gas (LPG) and can be mixed with LPG for domestic and commercial applications [11], [12]. Utilising OPEFB to produce DME could be an appealing route for Indonesia, given the benefit of DME as a multipurpose fuel. OPEFB-based DME can serve as a substitute for LPG, significantly reducing LPG importation, which accounts for approximately 74% of national demand [2], [13], [14]. The government has initiated a project to develop DME from coal, aiming to reduce dependence on LPG imports.

Because OPEFB-based DME has the potential to replace fossil fuels such as LPG, it is essential to consider environmental burden in term of greenhouse gas (GHG) emission, where GHG emission is used as primary criteria in selecting sustainable biofuel according to the Renewable Fuel Standard (RFS) from the United States and the Renewable Energy Directive (RED) from the European Union [15], [16].

The life cycle GHG analysis research has been widely conducted on various biofuels, such as biodiesel and bioethanol [17]–[19]. The application of life cycle GHG analysis to assess the environmental impact of DME from agricultural waste or biomass appears to be limited compared to other biofuels. Some of the research conducted related to the life cycle GHG analysis of DME from biomass, including analysis of the impact on the environment and exergy analysis, comparison between CO_2 emissions produced in DME production using wood waste-based biomass, calculation of the life cycle GHG analysis of rice straw-based DME and the calculation of the life cycle GHG analysis of rice straw-based DME [18], [20]–[22].

Parvez et al. [20] conducted a study to analyse DME production in terms of exergy analysis and environmental impact through LCA studies. The study demonstrates that utilising CO_2 as a gasification agent, which was previously released into the atmosphere, resulted in a significant increase in exergy efficiency and was also more environmentally friendly, particularly in terms of its impact on human health, ecosystems, and resources.

Higo and Dowaki [21] researched the CO_2 life cycle of nine types of woody biomass in Japan and Papua New Guinea. This LCA study compared the production of DME using biomass waste from various plant/wood species in Papua New Guinea with that in Japan. The results show that DME produced from raw materials sourced in Papua New Guinea emitted lower CO_2 than DME produced from raw materials sourced in Japan, because biomass is concentrated in a single area. In Japan, it was scattered in various places.

Silalertruksa et al. [18] described the GHG life cycle in the production of DME made from rice straw in Thailand. DME from rice straw was previously considered waste without accounting for the emissions produced during the rice cultivation cycle; however, its contribution to reducing GHG emissions was quite significant when used as a substitute for diesel oil and LPG. Suppose GHG emissions in the rice cultivation cycle are considered. In that case, the contribution of GHG reduction was insignificant due to the extensive use of fossil energy and fertilisers in the rice cultivation cycle.

Lecksiwilai et al. [22] researched to analyse the net energy ratio (NER) and GHG life cycle emission of DME from agricultural wastes in Thailand, one of which is OPEFB. Based on the study's results, sugarcane leaves and shoots had the lowest contribution to GHG and the highest NER, indicating that the energy value produced was significantly higher than the energy required during the production process. The lowest NER with the highest contribution to GHG emissions was cassava stems. OPEFB has the second-lowest NER value and the second-highest GHG emissions. A deeper study of the OPEFB production process is needed, particularly in the production stage, to optimise the utilisation of waste heat in OPEFB-based DME production. GHG emissions reduction was calculated by comparing the DME produced with diesel, coal-based DME, and conventional DME from natural gas.

Although some life cycle GHG analysis studies related to biomass-based DME have been conducted, the specific research on the life cycle GHG analysis of DME from OPEFB as a substitute for LPG still seems lacking. To date, there is only one study by Lecksiwilai et al. [22] on the life cycle GHG analysis of DME from agricultural wastes in the Thai context, with one of the waste types being OPEFB. The study compared the DME from various agricultural residues with fossil fuels, including diesel, coal-derived DME, and natural gas-derived DME, but no comparison was made with LPG. Therefore, this study aims to assess the life cycle GHG analysis of OPEFB-based DME production in Indonesia as an LPG substitute. The context of Indonesia is quite different with Thailand especially in energy supply for the production of OPEFB-based DME, since the electricity supply for industry in Thailand is dominated by natural gas fueled power generation and in Indonesia is dominated by coal fired power plant [23], [24] This study also aims to compare the life cycle GHG emission of OPEFB-based DME with coal-based DME, which projected to be used as LPG substitute in Indonesia. This coal-based DME will substitute around 1×10^6 t (tonnes) of imported LPG [13].

II. Methods

Life cycle GHG emission analysis was calculated based on 1 kg of DME as the functional unit, with a heating value of 28.43 MJ kg^{-1} [18]. Since the actual DME factory is not yet available in Indonesia, the DME plant was assumed to be located in Tamiang Layang, East Barito Regency, Central Kalimantan, Indonesia. East Barito Regency was planned as a special economic zone in Central Kalimantan [25]. The East Barito regency is also the main crossing route from Central and West Kalimantan to the new capital of Indonesia.

Aspen HYSYS process simulation software was utilised to simulate the single-stage DME synthesis via syngas derived from the gasification process, which was fed into the DME synthesis reactor and subsequently into the purification process. This process simulation helps determine the material and energy flows used and applied in life cycle GHG analysis. It was assumed that the GHG emissions associated with manufacturing or machinery, or any modified infrastructure to support the use of DME, such as fuel injection systems and engine parts, are insignificant when distributed over the machine's lifetime [18].

OpenLCA software with an Agrybalise V.301 database was used to build the inventory and calculate the life cycle of GHG emissions. The environmental impact, in the form of GHG, is assessed using the method provided by openLCA, employing ReCiPe 2016 with midpoint impact category levels. In this study, OPEFB is considered waste; therefore, it should have zero life cycle emissions until the point of collection [26], [27]. As shown in Fig. 1, the system boundary encompasses the collection and transportation of OPEFB, gasification, DME production, transportation to a blending facility, and use as a biofuel, substituting for LPG and diesel. The following are the descriptions and assumptions for each stage used in this study.

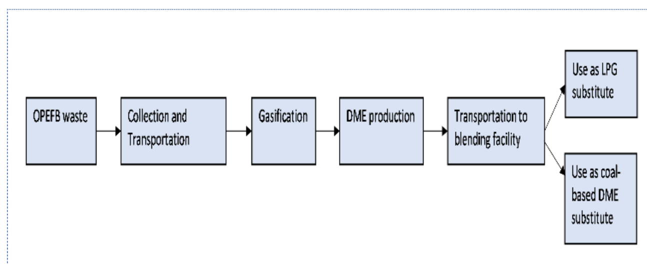

Fig. 1. The system boundary of OPEFB-based DME life cycle GHG analysis

A. *Collection and transportation of feedstock*

In this subsection, the OPEFB was assumed to be collected from palm oil mills surrounding Tamiang Layang, East Barito, Central Kalimantan. The collection area of OPEFB was set at a 100 km radius of the proposed DME plant location in Tamiang Layang, and the OPEFB waste was assumed to be already stacked in a stockpile.

From the stockpile, the OPEFB was transported to the DME factory, which was located at an average distance of 60 km from the palm oil mills to the DME plant. The OPEFB from the palm oil mills to the DME plant was delivered by a truck with a capacity of 8 t. This study considers OPEFB as waste; therefore, it should have zero life cycle emissions until the point of collection. Energy consumption during Fresh Fruit Bunch (FFB) cultivation and production was based on the work of Harsono et al. [17], which reported that 1.3% of the total energy consumed was used for farming and production in palm oil mills. The energy consumption during farming and production in palm oil mills was based on the work of Harsono et al. [28], which reported an energy consumption of 1.57 GJ t^{-1} for farming and production in palm oil mills.

B. DME Production

The DME plant, with a capacity of 41 t h^{-1} of OPEFB, was modelled in this study. OPEFB collected and transported to the DME plant were assumed to have 60 wt% moisture content and 1.46 wt% ash [29]. The OPEFB feedstock rate for simulation was converted to a dry ash-free (daf) basis; therefore, the feedstock rate becomes 16 t h^{-1}. The process configuration used for simulation purposes in DME production is adopted from several previous studies [30]–[33]. The DME synthesis simplified process flow diagram (PFD) is shown in Fig. 2.

The simulation was conducted using Aspen HYSYS. Several studies have used Aspen Hysys to simulate biomass gasification [32], [34] and DME production [4]. Because the OPEFB raw material is not a standard component in Aspen Hysys, it must be entered manually as a hypothetical solid component. The OPEFB was entered as a hypothetical solid component based on the ultimate analysis. The basis for the simulation is dry ash-free (daf), and the chemical formula of OPEFB as an input in Aspen Hysys was $C_{4.306}H_{6.176}O_{2.587}N_{0.048}S_{0.003}$ [35], [36]. The DME plant design was conducted per the following steps.

Biomass Pre-treatment. Raw biomass in any form must go through a pre-treatment process. This pre-treatment process consists of several parts, such as milling and drying [37], [38]. The electrical energy required for the milling and drying processes for every ton of OPEFB is 15 kW and 20 kW, respectively. The excess steam generated, along with the off-gas boiler's hot flue gas, fulfilled the thermal energy required for drying. The milling process could reduce the moisture content of OPEFB from 60 wt% up to 48 wt% [37]. Further drying of the OPEFB was conducted in the dryer section.

Gasification. The gasification process occurs in a fluidised bed gasifier, and the process flow, assumptions, and parameters are used as described in a previous study by Heryadi et al. [35]. As an oxidant, the gasifier uses steam and oxygen. The cryogenic air separation process provided oxygen. The oxygen purity was assumed to be 100%. The air separation unit's electricity consumption was calculated based on the electricity consumption reported in a previous study at 1.0 MWe kg-$O_2^{-1}s^{-1}$ [39]. The syngas composition from gasification was calculated using an equilibrium reaction at 900 $^{\circ}C$. During the gasification reaction, the process was assumed to be isothermal [40]. The waste heat from the gasifier was used to generate steam (steam generator I). Steam is generated and intended to be supplied to the distillation columns.

Water gas shifts. The water-gas shift (WGS) process ensures an H2/CO ratio of 1 [20]. The reaction temperature is 400 °C, and the pressure is 1000 kPa [34]. Before the acid gas removal operation, the syngas is cooled to 250°C [32]. The WGS employed is high-temperature WGS, which prefers a faster reaction rate [34].

Water removal and syngas cleanup. Water removal was modelled using a separator as a dryer, while acid gas removal was modelled using a Monoethanolamine (MEA) scrubber. The removal process was simulated using a water separator, which removes water at an acceptable concentration of less than 1% mol [34]. After the water is removed, the syngas is routed through an acid removal system modelled as a component splitter. The removal rates of CO_2 and H_2S were estimated to be 90% and 100%, respectively [34], [41].

DME synthesis. Water-purified syngas is compressed to 5 000 kPa, which corresponds to the operating pressure of the JFK process. The Gibbs reactor replicates the synthesis of DME, with an equilibrium reaction [42]. The reactor's working temperature is 2 600 ºC, as per the JFK process [43]. The temperature was maintained at 260°C throughout the reaction. (1) and (2) show reactions for single-stage DME synthesis [44].

$$2CO + 4H_2 <-> CH_3OCH_3 + H_2O \quad (1)$$

$$3CO + 3H_2 <-> CH_3OCH_3 + CO_2 \quad (2)$$

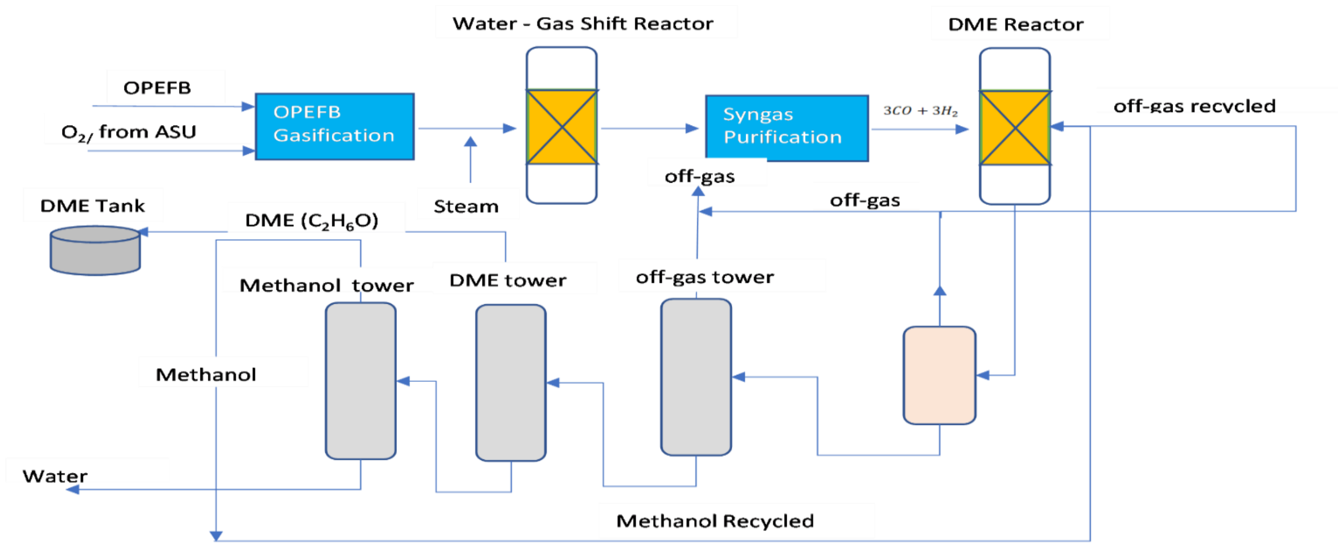

Fig. 2. Simplified process flow diagram of OPEFB-based DME production

Distillation. The first tower's distillation operation mainly separated CO_2 and other light gases from DME, methanol, and water (off-gas tower). The tower contains eleven stages, with the feed stage located on stage three, positioned below the condenser at the top. The gas, as a top product, is combined with the outlet gas from the Gas-Liquid separator and used as fuel for the steam boiler. The product enters the DME Tower with DME, methanol, and water at the bottom. The distillation process in the DME tower separates DME as the top product from methanol and water at the bottom. The DME tower comprises six stages, with the feed stage placed on stage two from the top.

The bottom products of the DME Tower, methanol and water, were separated further in the methanol tower. The top product of the distillation in the methanol tower was methanol, and the bottom was water.

Steam and power generation. The steam boiler is fueled by waste heat from the plant and utilises off-gas to generate steam for both process requirements and power generation. Two steam generators were available. The first is waste heat from the gasifier, WGS, and DME reactor, which generates saturated steam and is designated Steam Generator I. The steam generator generated saturated steam at 3900 kPa, which was used to generate electricity using a saturated steam turbine. The steam pressure outlet of the turbine is 900 kPa, and this steam is used as a heating medium in the reboiler of the distillation columns (from the off-gas tower to the methanol tower). The second, an off-gas boiler, was used as fuel for a superheated steam boiler designated as steam generator II. Superheated steam was used as turbine feed, generating electricity through a superheated steam turbine. The outlet pressure of the steam turbine is 1000 kPa, and this superheat steam turbine was used as a gasifying agent in the gasifier and as a reactant in the WGS reactor.

DME Transportation. The OPEFB-based DME produced is compressed and transported to the blending facility in Balikpapan, which is 320 km from the DME plant in Tamiang Layang, East Barito. The road tanker is a conventional 10-wheel LPG truck with a total load capacity of 16 t. The losses of DME and other fuels during transportation, uploading, and storage were not factored into the calculations.

DME Application. The DME is considered a substitute for LPG as the primary cooking fuel in Indonesia. GHG emissions from the usage of DME are compared to the GHG emissions from the use of LPG. However, this assumed that DME would only be utilised as a partial substitute for LPG for home cooking and heating applications at 20 vol.% levels. It is confirmed that at 20 vol.%, modification to the current cooking appliances is not required [11]. Apart from LPG, OPEFB-based DME is also considered an alternative to coal-based DME, which is expected to be used commercially in 2026 to substitute around 1 x 10^6 t of imported LPG. LPG life cycle GHG emission data are 0.34 kg-CO_2eq kg-DMEeq^{-1} for the production stage and 1.76 kg-CO_2eq kg-DMEeq^{-1}, respectively [18]. Coal-based DME life cycle GHG emission data are 3.9 kg-CO_2eq kg-DME^{-1} for the production stage and 1.6 kg-CO_2eq kg-DME^{-1} for the use stage, respectively [22].

III. Result and Discussion

A. Simulation Results

The process flow diagram (PFD) of the process is displayed in Fig. 3. The material balance resulting from the simulation is shown in Table 1.

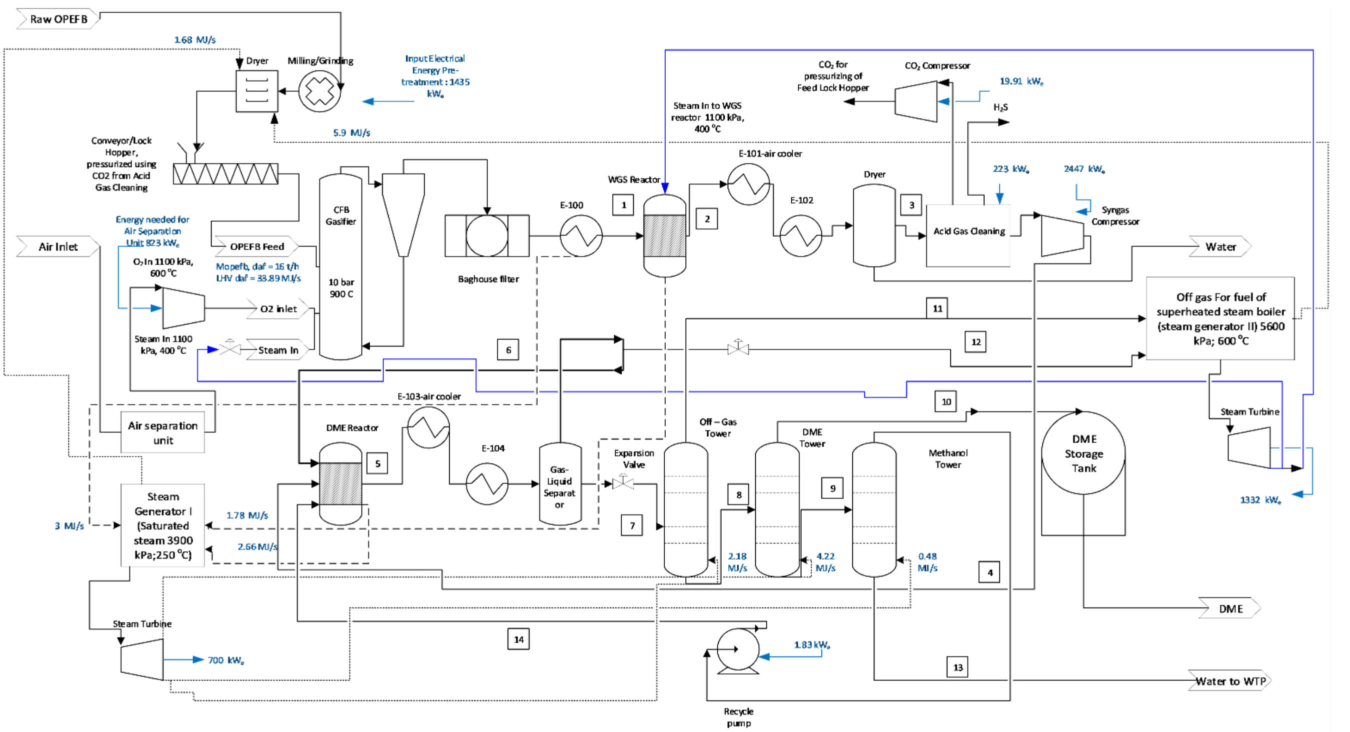

Fig. 3. Process flow diagram with electricity consumption/production and heat transfer

TABLE I
STREAM COMPOSITION OF THE OPEFB-BASED DME PRODUCTION SIMULATION RESULT

Stream Name	Gasifier outlet	WGS reactor outlet	Dryer outlet	DME reactor Inlet	Distillation Inlet	DME
Stream No.	1	2	3	4	7	10
Vapour Fraction	1	1	1	1	0.2113	0
Temperature (°C)	400	400	25	243	-30.73	42.75
Pressure (kPa)	998	997	997	5000	1000	950
Molar Flow (kgmole h^{-1})	1314	1486	1476	1307	393.8	170.4
Mass Flow (kg h^{-1})	24,740	27,839	27,666	20,230	15,700	7,834
Heat Flow (MJ h^{-1})	-85,420	-131,299	-147,414	-72,890	-105,400	-34,390
Mole Frac (%)						
H_2	30.16	38.27	38.52	43.52	0.31	0
CO	54.83	37.49	37.73	42.63	1.01	0
CO_2	1.2	12.46	12.54	1.41	34.97	0
H_2O	0.89	0.98	0.34	0.39	3.93	0.25
CH_4	11.58	10.32	10.39	11.73	10.69	0
H_2S	0.22	0.2	0.2	0	0	0
N_2	0.3	0.27	0.27	0.3	0.13	0
CH_3OH	0	0	0	0	5.83	0.1
CH_3OCH_3	0	0	0	0	43.12	99.64

The OPEFB-based DME produced is 7834 kg/h. The DME recovered from the DME tower has a purity of 99.6%, which is higher than 99%, within the range of a few previous study results [45]–[48]. The mass yield of OPEFB-based DME is in agreement with several other studies on the ratio of OPEFB to DME yield, where the feedstock as received to product ratio was around 5 to 1, and the feedstock daf basis to product ratio was 2 to 1 [3], [34]. In this study, the CO conversion is still within the range of other studies, where the CO conversion is 90% or higher [43], [45].

The DME plant utilises the available waste heat to generate saturated steam. The generated saturated steam is mainly supplied to the distillation columns' reboiler. Excess heat from the Gasifier, WGS, and DME reactors generates saturated steam at 3 900 kPa. The saturated steam is generated mainly to supply the heat for the distillation column and acid gas cleaning system. The off-gas generates superheated steam at 5 600 kPa and 600 °C [32], and this superheated steam is utilised for gasification reactions and the water-gas shift reaction. Before entering the gasifier and water gas shift reactor, superheated steam is fed into the turbine to generate electricity. The superheated steam pressure is reduced to 1 000 kPa to match the operating pressure of the gasifier and WGS reactor. Fig. 3 illustrates the energy consumption/ production, as well as heat transfer, in this OPEFB-based DME plant.

Based on the simulation results, the input and output of the OPEFB-based DME plant were used as an inventory for the life cycle GHG emission. The inventory is tabulated in Table 2, using a functional unit of 1 kg DME.

B. *Simulation Life Cycle GHG Emission of OPEFB-based DME*

This study's total life cycle GHG emissions of OPEFB-based DME are 1.47 kg-CO_2eq kg-DME^{-1}. The result shows that an OPEFB-based DME can substitute for LPG and reduce GHG emissions by 30%. As shown in Table 3, the highest GHG emissions in this study are from the DME production stage, where the feedstock and DME transportation contribute to lesser GHG emissions. The life cycle GHG emission results in this calculation are lower than those in the previous study, where the life cycle GHG emission of OPEFB-based DME was 1.75 kg-CO_2eq kg-DME^{-1} [22]. When used as a fuel, the OPEFB-based DME's GHG emissions were not considered due to its carbon neutrality benefit when using biomass as a feedstock [18], [36]. The comparison of the life cycle GHG emissions of OPEFB-based DME with LPG is shown in Fig. 4.

TABLE III
INVENTORY DATA FOR OPEFB-DME LIFE CYCLE GHG EMISSION ANALYSIS

Inventory	Unit	Value
Inputs EFB	kg	5.20
Water	kg	2.60
Electricity	MJ	4.37
Feedstock transportation	kg km	624
DME transportation	kg km	320
Output DME	kg	1
Waste Water	kg	0.06

TABLE IV
LIFE CYCLE GHG EMISSION OF OPEFB-BASED DME PRODUCTION

Stage of life cycle GHG emission analysis	Value (kg-CO2-eq kg-DME^{-1})
Feedstock acquisition	0.00
Feedstock transportation	0.14
DME production	1.28
Transportation to the DME blending facility	0.05
Use	0
Total	1.47

In a previous study by Lecksiwilai et al. [22], the GHG emissions in the DME production stage were lower, but with higher electricity consumption. Meanwhile, this study's GHG emissions in the DME production stage are higher, despite lower electricity consumption. The lower electricity consumption and higher GHG emissions in this study are attributed to the power generated by coal-fired power plants, particularly in the Kalimantan region, where these plants dominate power generation [23]. Meanwhile, a previous study by Lecksiwilai et al. [22] was conducted in Thailand, where the electricity supply is dominated by natural gas, which is cleaner than coal. Natural gas accounts for 55.3% of Thailand's power generation mix, while coal-fired power plants contribute 17.9% to the country's energy mix [24].

Although some of the electricity used in this study is still supplied by the national grid, which is generated from coal-fired power plants, the life cycle GHG emissions of OPEFB-based DME are still lower than those of LPG household applications. Furthermore, when comparing the DME from OPEFB with the DME from coal, the life cycle GHG emissions are significantly lower, resulting in a 73% reduction in GHG emissions. The comparison of OPEFB-based DME with LPG and coal-based DME is shown in Fig. 4. The feedstock acquisition stage and its usage as fuel are the most significant contributors to GHG emissions from coal-based DME. It is evident that coal mining is an energy-intensive activity, and the majority of energy consumption comes from fossil fuels; therefore, higher GHG emissions are inevitable. The GHG emissions of DME from coal usage must be accounted for, unlike DME from biomass, whose GHG emissions are not counted due to the carbon neutrality of biomass.

When OPEFB-based DME was compared to coal-based DME, the OPEFB-based DME had a milder impact on global warming. Using OPEFB biomass as a feedstock for producing DME has more advantages in reducing the environmental burden. This study shows that significant reductions in GHG emissions can be achieved by utilising biomass to substitute for fossil-based fuels.

Power generation from renewable sources should be chosen to reduce electricity usage from coal-fired power plants. The integration of biomass power plants that use OPEFB and other palm oil wastes as feedstock with OPEFB-based DME plants can also be considered. This integration can further reduce the life cycle GHG emissions and minimise GHG emissions from the production stage of OPEFB-based DME, as biomass-based fuel is not counted due to its carbon neutrality.

Moreover, utilising biomass, such as palm oil waste, can also benefit the local community and stimulate economic activity. Investment in biomass energy infrastructure and supply is expected to boost income and economic growth. Biomass energy offers substantial economic benefits to the local community by generating new jobs across multiple sectors of the biomass supply chain, fostering economic growth, and promoting a greener environment through reduced emissions.

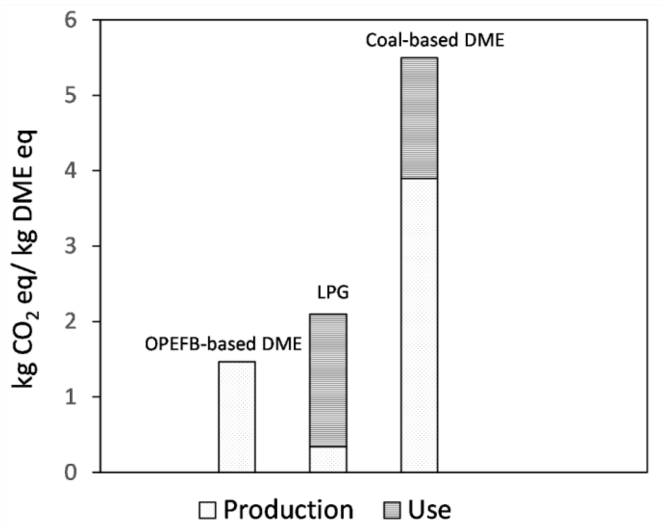

Fig. 4. Life cycle GHG emissions of OPEFB-based DME, LPG, and coal-based DME

IV. Conclusion

This research aims to determine the life cycle analysis of GHG emissions for producing DME from OPEFB. The entire DME production process was simulated using Aspen Hysys, resulting in a mass and energy balance for the inventory of the life cycle analysis. The software used to calculate the life cycle GHG emissions of OPEFB-based DME is openLCA with an Agrybalise V301 database.

The overall GHG emissions of the OPEFB-based DME were calculated to be 1.47 kg-CO_2eq kg-DME^{-1}. This study considers OPEFB as waste; therefore, it should have zero life-cycle emissions until the point of collection is complete. Comparing the OPEFB-based DME life cycle GHG emission with LPG life cycle GHG emission and coal-based DME life cycle GHG emission, reduced GHG emissions by 30% and 73%, respectively. OPEFB-based DME's environmental burden is lower than that of LPG and coal-based DME, contributing positively to GHG emission reduction.

This research demonstrates that OPEFB-based DME produced in Kalimantan, Indonesia, has excellent development potential, particularly when it meets the criteria for reducing GHG emissions. Moreover, utilising OPEFB in valuable biofuels, such as DME, would be beneficial for stimulating local development and economic activity.

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