Review article

Bio-Dimethyl Ether from Oil Palm Empty Fruit Bunch and Sustainability Assessment of Bio-Dimethyl Ether: A Case Study in Indonesia

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Abstract

Biomass from Oil Palm Empty Fruit Bunch (OPEFB) has the potential to be used as feedstock for bio-Dimethyl Ether (bio-DME) production through the gasification process. Bio-DME has the potential to replace liquified petroleum gas (LPG) and biodiesel as it has similar characteristics to both fuels. Therefore, this study was aimed to evaluate previous research on the OPEFB-based bio-DME and its sustainability, to identify existing gaps in the research and to formulate directions for valuable future research. The results showed that pertinent performances with simulation and technical analyses should be conducted with different process configurations and under different scenarios. Based on this review, a number of further topics should still be investigated, including the economic feasibility of OPEFB conversion into bio-DME at different locations and plant capacities; the simulation of OPEFB bio-DME plant using an indirect synthesis method and technical analysis of pilot plant; and the sustainability of OPEFB-based bio-DME in Indonesia on islands with a large concentration of oil palm plantations.

Keywords

assessment;

biomass;

bio-DME;

OPEFB;

sustainability

1. Introduction

Renewable energy is urgently needed as an alternative source to fossil fuel energy because fossil fuel reserves will diminish over time and because fossil fuels are sources of pollution. Among various available alternatives, renewable energy from biomass reportedly has great potential to be used as an energy source. This is due to it being a prospective source for the production of solid, liquid, and gaseous biofuels [1]. Also, it presently contributes to the world's energy need by 14% [2]. One abundantly available biomass type is Oil Palm Empty Fruit Bunch (OPEFB) waste which can be utilized as feedstock for biofuel production. OPEFB is available abundantly in Indonesia

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which is the world's number one producer of palm oil [3-5]. The waste value from average Crude Palm Oil (CPO) is 4 kg of dry biomass, one-third of which is OPEFB, and the remaining being leaves and stems [6]. According to the Director-General of New and Renewable Energy [7], the yearly potential of OPEFB waste in Indonesia was 14.24 million tons. Also, the utilization of this biomass has only been used for mulching and composting [8, 9], applications where a lot of caution is often required due to the biomass being a potential source of pests and harmful diseases. Meanwhile, composting is time-consuming, labor-intensive, and requires extensive land and heavy equipment [8].

OPEFB is often converted into biofuel through the gasification process, where the biomass undergoes several reaction steps until the end product is obtained. This thermochemical process converts biomass into a combustible gas (producer gas) or synthetic gas (syngas). Besides gasification, OPEFB is also converted into biodiesel and bioethanol [10-12]. Through the gasification process, the biofuels produced are dimethyl ether (DME), methanol, Fischer-Tropsch mixed alcohols, and hydrogen [13]. DME derived from biomass is referred to as bio-DME.

Bio-DME has the potential to replace diesel and liquefied petroleum gas (LPG). This product has a higher cetane number than ordinary diesel. It has suitable self-ignition characteristics for use as fuel in diesel engines, although several modifications are required for existing distribution systems [14-16]. Moreover, bio-DME has similar characteristics to LPG, making it a very suitable replacement [17-19]. The similarities between these fuels (bio-DME, diesel, and LPG) are shown in Table 1. As a substitute for LPG, bio-DME also became one of the Indonesian government's plans within the National Energy General Plan (RUEN) in 2017, which was to reduce the imports of liquified gas and save the state budget. In 2018 and 2019, the proportion of imported LPG was 74% of the domestic demand [20]. This was due to a 2% increase in the 72% import in 2017. A 78% increase in LPG importation was expected by 2050 [21]. An overview of LPG Balance in Indonesia is shown in Figure 1; the data were obtained from the Ministry of Energy and Mineral Resources (MEMR) [20]. Bio-DME is considered carbon-neutral and clean energy [22, 23], leading to the need to explore its sustainability, including life cycle analysis (LCA) of greenhouse gas (GHG) emissions and the net energy. These two indicators have been set as key factors in several sustainable biofuel policies, such as the Renewable Fuel Standard (RFS) and Energy Directive (RED) of the US and EU, respectively [24, 25]. According to these standards, sustainable biofuel must meet 60% or higher GHG saving compared to fossil fuel [26, 27].

Based on the potential of the OPEFB to be used as raw material and the exploration of bio-DME sustainability, questions were raised concerning the production of bio-DME and sustainability of bio-DME, using indicators such as GHG emission LCA and net energy. To address these questions, several previous studies need to be reviewed. Therefore, this study aims to evaluate previous studies, and to identify the gaps and shortcomings concerned with bio-DME from OPEFB. It also aims to provide an understanding of the research status of bio-DME made from OPEFB and the sustainability of bio-DME made from OPEFB. The results obtained are expected to aid researchers in conducting further future studies.

2. Bio-DME Synthesis Process

DME is a chemical compound derived from syngas. Syngas mainly consists of CO and H_2, and it is used as raw material for the production of DME [30, 31]. Syngas is obtained from natural gas and as the result of the gasification of coal and biomass. Syngas can be used for various purposes, such as raw materials for the production of ammonia, fertilizers, methanol, ethanol, production of DME, and so on [32-35].

Table 1. Physical and chemical properties of DME, diesel fuel, and LPG [28, 29]

Property	DME	Diesel	LPG	
			Butane	Propane
Chemical formula	CH_3OCH_3	C_8 to C_{25}	C_4H_{10}	C_3H_8
Molecular weight	46.07	96 and greater	58.13	44.11
Vapor pressure at 20°C (bar)	5.1	<0.01	8.4	2.1
Boiling point (°C)	-25	150-380	-0,5	-42.1
Liquid density at 20°C (kg/m^3)	660	800-840	610	501
Liquid viscosity at 25°C (kg/ms)	0.12-0.15	2-4	0.2	0.2
Gas specific gravity (vs air)	1.59	-	2.01	1.52
LHV (MJ/kg)	28.43	42.5	45.74	46.36
Cetane number	55-60	40-55	-	5
Air to fuel stoichiometric ratio (kg/kg)	9	14.6	14.8	15.7
Enthalpy of vaporization at normal temperature and pressure	460 (-20°C)	250	390	460 (-20°C)

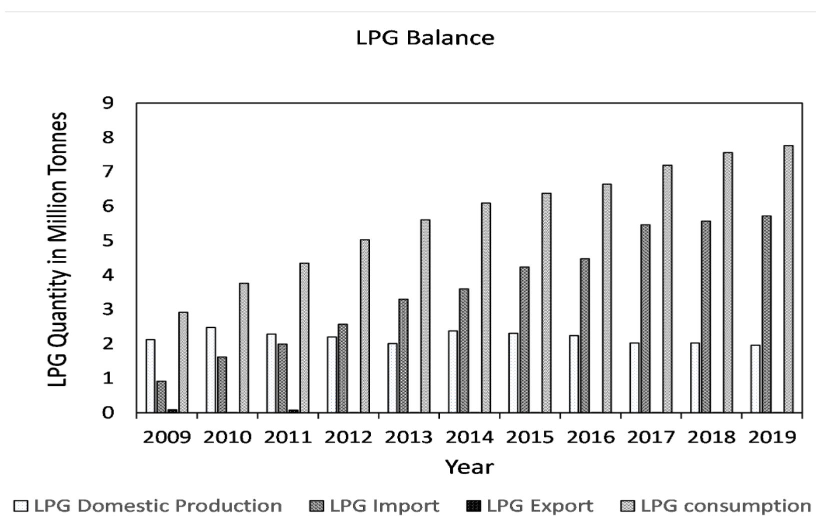

Figure 1. LPG Balance

There are four types of processes used in the production of bio-DME from biomass, namely gasification, water-gas shift reaction, gas purification, and biofuel synthesis [3, 36]. The typical reactions of the gasification, water-gas shift, and syngas purification processes are shown in Table 2. After the syngas purification, the bio-DME synthesis process indirectly or directly begins either through the indirect synthetic pathway or the direct synthetic pathway [37]. The indirect synthesis is a two-step process, where methanol is synthesized first before undergoing a dehydration reaction to produce bio-DME. Meanwhile, the direct synthesis is a single-step process, where bio-DME is produced directly from the syngas [38]. These synthetic reactions are shown in Table 3, and a typical process flow diagram (PFD) of the single-step synthesis is presented in Figure 2.

Table 2. Typical gasification reaction [3, 39]

Reaction	Reaction Scheme
Partial Oxidation	$C_{3.4}H_{4.1}O_{3.3} + 2.775O_2 \rightarrow 3.4CO_2 + 2.05H_2O$
Gasification	$C_{3.4}H_{4.1}O_{3.3} + 0.1H_2O \leftrightarrow 2.15H_2 + 3.4CO$
Boudouard	$C_{3.4}H_{4.1}O_{3.3} + CO_2 \leftrightarrow 4.4CO + 0.9H_2O + 1.15H_2$
Methanation	$C_{3.4}H_{4.1}O_{3.3} + 8.05H_2 \leftrightarrow 3.4CH_4 + 3.3H_2O$
Methane Reforming	$CH_4 + H_2O \leftrightarrow CO + 3H_2$
Water Gas Shift	$CO + H_2O \leftrightarrow H_2 + CO_2$
CO2 removal (gas purification)	$CaO + CO_2 \leftrightarrow CaCO_3$

Table 3. DME synthesis reactions [40, 41]

Reaction	Reaction Scheme
Two steps DME synthesis	$CO + 2H_2 \leftrightarrow CH_3OH$
	$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O$
	$2CH_3OH \leftrightarrow CH_3OCH_3 + H_2O$
One Step DME synthesis	$2CO + 4H_2 \leftrightarrow CH_3OCH_3 + H_2O$
	$3CO + 3H_2 \leftrightarrow CH_3OCH_3 + CO_2$

The process of gasification is often at temperatures above 500°C [42-46], with pressure ranging from atmospheric [43, 45, 47] to 45 bar [36, 48]. The selection of the gasification reactor (gasifier) also depends on the syngas capacity to be produced. There are generally three types of gasifiers, namely fixed, fluidized, and entrained bed gasifiers for low, medium, and high capacities, respectively [49-51]. Also, two types of gasifying agents are often used for the gasification process, pure oxygen and air [33, 36, 52]. The gasification process that does not require high purity syngas uses air as the gasifying agent. This low purity syngas is often directly used for electricity generation, through an internal combustion engine (ICE) [4, 53]. To produce high purity syngas, pure oxygen

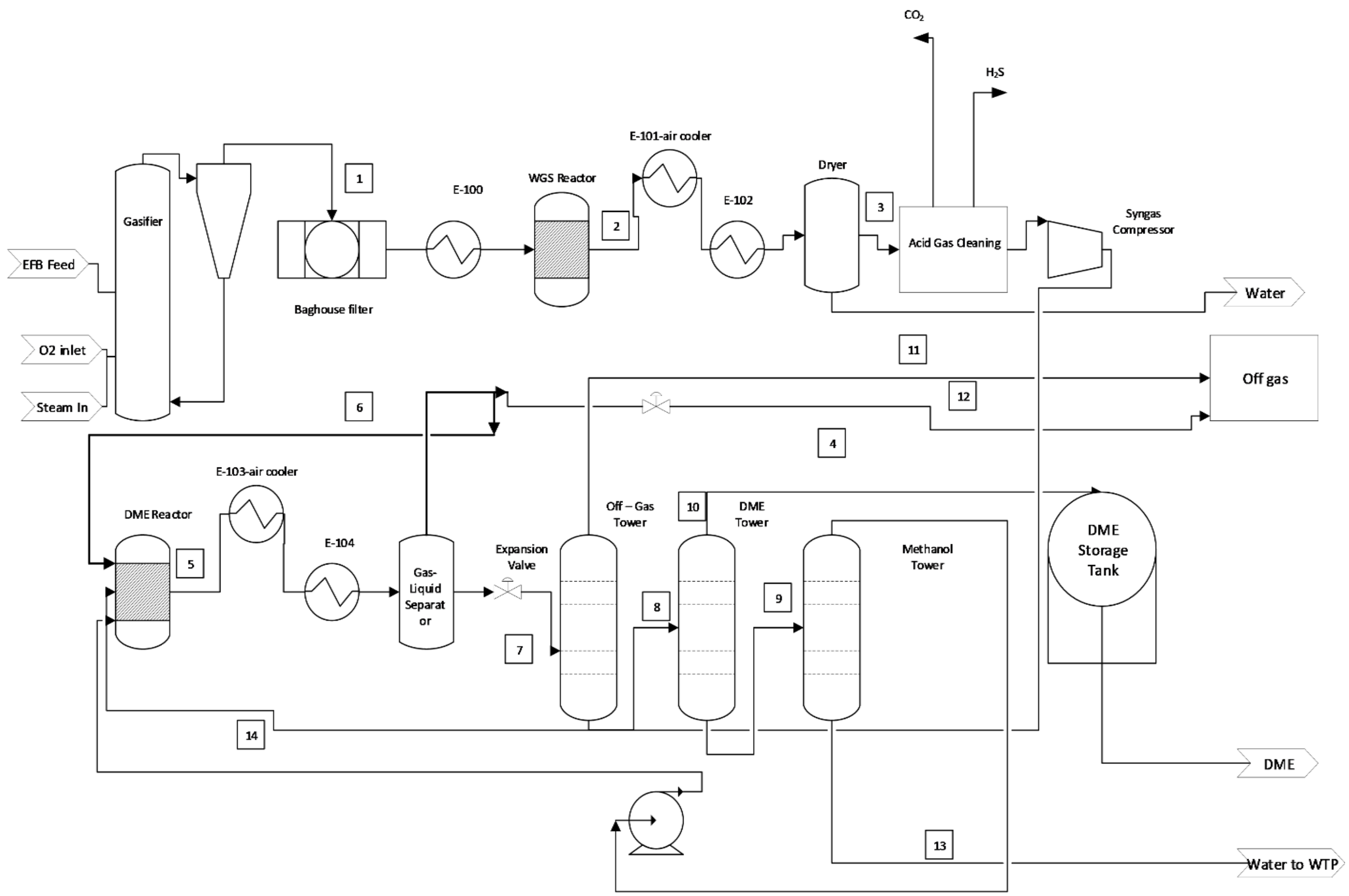

Figure 2. PFD of bio-DME synthesis

is needed as the gasifying agent in the gasification process, specifically when purified product is to be used as the feedstock of fuel and chemical production. High purity syngas is needed in the production of DME.

In the single-step synthesis, the syngas product was compressed to 50 bar, due to the operating pressure of the DME process [36, 53-56]. Meanwhile, the temperature was maintained at 240-280°C, through the continuous cooling in the reactor [36, 53, 54, 57]. In the two-step synthesis process, methanol was produced as an intermediate product before the final DME product. This methanol product subsequently underwent a dehydration reaction to form DME, where the operating pressure and temperature ranged between 8-10 bar and 180-270°C, respectively [56, 58]. In addition, the dehydration reaction was observed between 1-2 bar and 300-340°C [54].

3. Bio-DME from OPEFB

Several previous studies on the conversion of OPEFB into bio-DME have reportedly been carried out since 2017. These were often related to parametric studies, which used simulation software and techno-economic analysis [3, 41, 55]. However, studies concerning the direct experiments on the pilot and actual plants were not found during the selection of related literature.

According to Parbowo *et al*. [55], the economic potential of the conversion of OPEFB to bio-DME was determined. A quantitative approach was used in the study, and the simulation for gasification and synthetic reactions was conducted through Aspen Plus. The utilized OPEFB data were obtained from plantation parameters within the Kampar region, Riau, Indonesia. The capacity of this bio-DME plant was also 2.74 MW_{th}. In addition, the gasification process was initially conducted, accompanied by the biofuel synthesis. The technical feasibility factors were the result of mass and energy balance, as well as power efficiency. However, the economic feasibility was calculated using the IRR (Internal Rate of Return) indicator. A business plan was added to this study, which was for the transportation of Fresh Fruit Bunches (FFB) and OPEFB. The price of the utilized LPG was also IDR 145,000 per 12 kg. To aid competition, the minimum economic selling price for DME was set at IDR 11,371 per kg of LPG. This was the first study related to the techno-economic analysis of OPEFB-based bio-DME, and no environmental aspects or further assessments were subsequently carried out.

Heryadi *et al*. [41] described the simulation process of bio-DME conversion. This was conducted using the Aspen Hysys simulator software and the operating condition data obtained from previous literature, and examined the process of DME synthesis. This study was carried out using a DAF-based OPEFB (Dry Ash Free) as input. Also, the gasification process on a circulating fluidized bed gasifier was conducted and a direct synthetic process was carried out, where the energy efficiency was 73% and in line with several previous reports. The waste heat was also mostly used for electricity and heat generation, where the conversion of CO was 64% and in line with various related studies. However, the simulation process did not involve any environmental aspect assessment.

Inayat *et al*. [3] conducted a simulation process on bio-DME production, although the purity of the product obtained was ignored. The Aspen Hysys simulator was used to simulate various parameters that affected the production of bio-DME through the gasification process. These analyzed parameters were the steam and oxygen to biomass ratio (S/B and O/B), as well as temperature and pressure. To obtain optimum results, the ratio of hydrogen to carbon monoxide (H_2/CO), O/B, and S/B were 1, 0.37, and 0.27, respectively. Also, the optimum temperature and pressure were 140°C and 1000 kPa, respectively. These results were in line with several previous studies, which used various types of biomass in many laboratory experiments. Therefore, this study was useful for several simulation processes, to specifically obtain inventory on the LCA and net energy calculations.

Based on Table 4, the studies were mostly conducted with OPEFB conversion into bio-DME through simulation, and were based on technology and economic analysis. However, there were no specific studies related to the environmental analysis.

Table 4. OPEFB conversion into bio-DME studies

Author (s)	Main Topic	Main Results
Parbowo *et al*. [55]	A study to determine the feasibility of bio-DME-integrated mill and a proposed business plan	Engineering economics method was used to find feasibility of bio-DME plant. For DME to be competitive, the minimum economic selling price was set at IDR 11,371 per kg. To make transport costs more efficient, the use of FFB and OPEFB carriers to the plant was proposed for utilization.
Heryadi *et al*. [41]	A study of a single-stage process configuration, to obtain a bio-DME yield, energy efficiency, and biomass conversion ratio	The simulation of the OPEFB to bio-DME had an energy efficiency of 73%, as the conversion of CO was 64% at a pressure and temperature of 5000 KPa and 260°C.
Inayat *et al*. [3]	A study on the simulation of biofuel production from EFB, based on the parameters affecting the yield of bio-DME	The analyzed parameters were steam and oxygen to biomass ratio (S/B and O/B), as well as temperature and pressure. The results showed that H_2/CO, O/B, and S/B = 1, 0.37, and 0.27, respectively. In addition, the optimum temperature and pressure were 140°C and 1000 kPa, respectively.

4. Sustainability Assessment of Bio-DME

Several studies conducted used net energy and LCA of GHG emission to assess the sustainability of bio-DME, where these two indicators were set as key criteria with the RFS and RED standards of renewable biofuel [26, 27]. Despite the performance of a few related studies, only one showed that the OPEFB was used as biomass feed among other agricultural wastes [56].

According to Silalertruksa *et al*. [24], the LCA of GHG emissions was described in the production of rice straw bio-DME in Thailand. This study showed that LCA was carried out on bio-DME plant. In this study, the total LCA of GHG emissions was the value to be obtained. The study suggests that the bio-DME plant had been built in the central part of Thailand where rice straw was collected at a 30 km radius (collection area 703 km^2). Furthermore, the feed of rice straw was 1,661 kg h^{-1}, with the production process of bio-DME simulated using the Aspen Plus software. Also, the gasifier used for gasification was a bubbling fluidized bed gasifier with a combustor. The LCA of GHG emissions was subsequently carried out with two calculation scenarios. The first stage considered rice cultivation in the life cycle analysis. Meanwhile, the second scenario assumed that the rice cultivation stage was excluded from the analysis. The analysis to determine the reduction of GHG emissions was also conducted through comparisons with conventional fuels, such as LPG and diesel. While considering the cultivation scenario and vice versa, the GHG emissions substituted for diesel were 72 and 25 g CO_2e MJ^{-1}, with reductions found at 14% and 70%, respectively. When bio-DME was substituted for LPG, the potential for GHG emission reduction varied from 2-66%, with mixture variations between 15-20%. In addition, the reduction was only 2% when the life cycle of rice cultivation was considered.

Based on Higo and Dowaki [57], a study related to the LCA of CO_2 from nine types of woody biomass was conducted in Japan and Papua New Guinea (PNG). The results were used to confirm the correlation between bio-DME and CO_2 emissions. In this study, a gasification experiment was carried out to obtain mass and energy balances, as well as the DME yield. Moreover, the LCA was carried out according to the ISO 14040 method. The CO_2 intensity relied on the bulk density and bio-DME production, which was higher in Japan compared to PNG at 16.3-47.2 g CO_2 MJ^{-1} and 12.2-36.7 CO_2 MJ^{-1}, respectively. The results showed that the PNG bio-DME produced lower CO_2 emissions, indicating that the biomass concentrated in one area. However, it was scattered in various locations in Japan. In addition, this study did not consider any economic aspects, and the assessment of sustainability was done only using the LCA of GHG emission indicator.

Lecksiwilai *et al*. [56] analyzed the net energy ratio (NER) and LCA of GHG emissions, which were obtained from various types of biomass. Based on this study, the results were extreme compared to attain the most sustainable DME. The agricultural biomass wastes compared were obtained from sugarcane leaves and shoots, cassava stems, corn stalks, OPEFB, and rice straw. These wastes were compared to the DME production from coal, with the NER and LCA (kg CO_2e kg^{-1} DME) values observed at 4.83/0.89 (sugarcane leaves and shoots), 1.69/1.75 (OPEFB), 2.38/1.24 (rice straw), 1.07/2.11 (cassava stems), 4.52/0.93 (corn stalks), and 0.58/5.5 (coal), respectively. In this study, sugarcane leaves and shoots showed the most sustainable bio-DME fuel, due to being the lowest contributor to GHG emissions at the highest NER. This indicated that the energy value produced was much higher than the power required during the production process. The results also showed that cassava stems had the lowest NER value, which contributed to the highest GHG emissions. This was accompanied by the OPEFB, which had the second-lowest and highest NER value and GHG emissions, respectively. Therefore, a deeper study on the OPEFB production process should still be conducted, by utilizing the waste heat maximally generated. In addition, no economic feasibility analysis was included in the study. This was found to be valuable as a reference for further studies, based on the sustainability analysis through net energy ratio and GHG emission LCA.

Parvez *et al*. [23] also analyzed the influence of energy analysis on the environment through LCA studies. The utilized biomass feed was gumwood with a 50,000 kg h^{-1} flowrate. The study aimed to analyze a more concise process configuration, using CO_2 as a gasification agent, compared to the oxygen and steam used by bio-DME production reaction, and was subsequently simulated by the Aspen plus software. A search for energy and exergy efficiency was then conducted, as well as an analysis of environmental impacts, specifically the LCA of GHG emissions. From the simulations and calculations, the loss of exergy was smaller in the CO_2 process than in the conventional bio-DME production reaction, at an efficiency level of 57%. The impact analysis on the environment showed that the effects on human health, ecosystems, and resources were lower in the CO_2 process. This indicated that the use of CO_2 as a gasifying agent provided a significant increase in efficiency. It was more environmentally friendly, specifically in its impact on human health, ecosystems, and resources. In addition, no study on the economic feasibility analysis was incorporated into this study. The LCA analysis should be used as a reference for further related future studies, without involving the exergy test.

Based on Table 5, the study was mostly carried out on bio-DME sustainability assessment, using net energy and LCA of GHG emission. However, there were no specific studies related to the sustainability assessment of bio-DME from OPEFB.

Table 5. Sustainability assessment of Bio-DME studies

Author (s)	Main Topic	Main Results
Silalertruksa *et al*. [24]	The GHG life cycle analysis of bio-DME obtained from rice straw in Thailand	Life cycle analysis was carried out on bio-DME, where the total GHG generated was calculated. With and without rice cultivation, bio-DME GHG yields substituted for diesel were 72 and 25 g CO_2e MJ^{-1}, with a reduction at 14% and 70%, respectively. When substituted for LPG, GHG potentially reduced between 2 and 66%. However, this was only 2% when the life cycle of rice cultivation was taken into account.
Higo and Dowaki [57]	The determination of CO_2 intensity to produce Japan and PNG bio-DME	This study presented the implementation of LCA, to determine the CO_2 intensity of the DME process based on biomass gasification. For Japan, the CO_2 intensity range was higher than the case of PNG, with values observed at 16.3-47.2 and 12.2-36.7 CO_2 MJ^{-1}, respectively.
Lecksiwilai *et al*. [56]	The assessment of bio-DME sustainability through various waste biomass types in Thailand	The assessment was carried out using two indicators of sustainability (NER and the LCA of GHG emissions) on various types of biomass. Using NER and LCA, the sugarcane leaves and shoots were the most sustainable bio-DME raw materials.
Parvez *et al*. [23]	The study of bio-DME production analysis was reviewed from exergy analysis and environmental impact, through LCA studies. The two factors used involved qualitative and quantitative energy analysis indicators (Exergy), as well as the impact on the environment	The study aimed to analyse a more concise process configuration, using CO_2 as a gasification agent. The exergy loss was smaller in CO_2 processes than conventional reactions, at an exergy efficiency of 57%. In addition, the environmental impact on human health, ecosystems, and natural resources was lower.

5. Discussion

OPEFB is abundant and available in Indonesia and found to proportionally increase with the production of CPO. Approximately 14.24 million tons of OPEFB were found to be available yearly [7], with every 7 tons having the potential to produce 1 ton of bio-DME [58]. This indicated that 14.24 million tons of OPEFB produced 2.03 million tons year^{-1} bio-DME. The annual production of bio-DME also had the potential to substitute 23.5% of LPG demand in 2021, which was at 8.5 million tons per year [21]. As the raw material of bio-DME production, OPEFB showed the potential to be extensively utilized, and the Indonesian government (through RUEN in 2017) stated that DME should be used for LPG substitution in order to reduce dependency on imports. This has led to the current building of a DME plant with coal as raw material involving the collaboration of public and private companies [59]. Once construction is complete, an opportunity for the development of the technology should be widely opened, especially for bio-DME production. This should be a more cost-efficient way to use biomass waste compared to coal, considering the abundance of available OPEFB. In the development of a bio-DME from OPEFB production facility, the limitation is not similar to the product obtained from coal. Moreover, a more decentralized DME plant approach is required, considering the scattered palm oil mill locations within Indonesia, specifically on Kalimantan and Sumatera Islands. Bio-DME from the OPEFB facility should ideally be close to the palm oil mill, where CPO waste is always available. This indicates that the closeness of a bio-DME plant to the EFB source leads to lower transportation costs and GHG emissions.

The technical and economic analyses of bio-DME production were also evaluated in previous studies. According to the technical study, there was a possibility to implement the simulated production process into the actual reaction. This economically indicated that the substitution of OPEFB-based bio-DME for LPG was declared feasible, considering several limitations that needed further analysis. Also, further economic analysis with different locations and capacities of bio-DME plants should be carried out, to support the feasibility of previous studies. Although several technical studies related to OPEFB were available, further research should still be investigated to determine the configuration of the indirect bio-DME production process, where methanol is an intermediate product and is valuable and indispensable to the biodiesel industry. By considering methanol in the economic study, the profitability of the OPEFB-based bio-DME plant is expected to increase. In addition, other future technical analyses should be realistically based on laboratory and pilot plant studies in order to better validate the results of simulation reports.

Based on bio-DME sustainability studies reviewed, several previous studies used the LCA of GHG emissions and net energy indicators for their sustainability indicators. These studies showed different variations in the sustainability analysis, and also highlighted the utilization of various biomass as feedstock for plants. The results indicated that the sustainability of bio-DME as a biofuel relied on the biomass type, the location of collection, and the assumptions used in determining the system boundaries in the LCA study. These observations are quite important as no related study has ever been conducted in Indonesia. Therefore, the sustainability of OPEFB-based bio-DME should be further investigated based on the potential of the raw material and an island with large palm oil plantations.

Based on the increase in the studies related to the manufacture of OPEFB-based bio-DME, the implementation of the government's goals as stated in the 2017 RUEN is expected to be promoted. This should be carried out through the implementation and construction of a bio-DME plant, to reduce the LPG import burden. Moreover, the government can significantly contribute towards the reduction of greenhouse gas emissions by substituting fossil fuels (LPG and diesel) with bio-DME. More studies on sustainability are subsequently needed to support the Indonesian government program, which is based on substituting LPG with bio-DME and utilizing the abundant

OPEFB waste in Indonesia. In addition, future studies should also simultaneously address the sustainability of OPEFB-based bio-DME and its economic feasibility.

6. Conclusions

The studies related to bio-DME were found to be generally new and specifically on the use of OPEFB. Only a few pertinent research papers have ever been published. Based on this study, a few further topics should still be investigated, including: (1) the economic feasibility of OPEFB conversion into bio-DME at different locations and various plant capacities, (2) the simulation of OPEFB bio-DME plant using the indirect synthesis method and technical analysis of the pilot plant, and (3) the sustainability of OPEFB-based bio-DME in Indonesia, based on islands with a large concentration of oil palm plantations.

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