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MORALITY BEFORE KNOWLEDGE

Discovering the potential of renewable energy from palm oil mill effluent: Environmental impacts, opportunities, and challenges in the development of biogas and bio-cng

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ABSTRACT

Background: Indonesia, as the largest palm oil-producing country in the world, will also produce palm oil mill effluent (POME). POME production from palm oil processing is faced with many environmental problems from the release of emissions. The development of new renewable energy in Indonesia needs to be increased to reduce dependence on fossil energy and commit to reducing greenhouse gas emissions. The purpose of this study is to discuss the potential for new renewable energy from the utilization of POME biogas energy and how the environmental impacts are caused as well as the opportunities and challenges of developing EBT from POME. **Methods**: This research analysis method is LCA, and descriptive. **Findings:** Total CO_2 emission (eq) of biogas production from POME is -24.62 Kg CO_2 (eq), eutrophication is -0.2188 Kg PO_4^{3-} (eq) and acidification is 0.00552 Kg SO_2 (eq). Biogas production from POME in Jambi Province is not optimal and has not been used optimally, the process efficiency is low, and the profitability is low. **Conclusion:** There is a need for a concept to utilize biogas energy that does not only focus on electrical energy but also as a renewable energy source such as bio-CNG which has wider use. **Novelty/Originality of this article:** The novelty of this research lies in the comprehensive analysis of the utilization of Palm Oil Mill Effluent (POME) as a renewable energy source that is not only limited to electrical energy, but also includes the potential conversion of POME into bio-CNG as a more flexible and sustainable alternative.

KEYWORDS: biogas, life cycle assessment., renewable energy, palm oil mill effluent.

1. Introduction

Natural resources are essential materials in ecosystems to support the provision of ecosystem services, including climate regulation, flood control, natural habitats, amenities, cultural services and all that is necessary for technological and economic development, human well-being, and daily life (Chow, 2003; Yu et al., 2016; Yang et al., 2020). The principle of sustainability is very important to support the survival of humans and other living things. Important components of sustainability are the natural resources and ecosystem services that keep us and other life forms alive and support our economy and how human behavior uses the available natural resources (Miller & Spoolman, 2010). The global challenges of natural resource efficiency and climate change mitigation demand the need to integrate sustainable waste and energy management, this integration will be a promising alternative for sustainability (Tock & Schummer, 2017).

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The term sustainability was originally synonymous with ecology, but when the concept of development was added, the ecological paradigm shifted towards society and the economy. This opinion was further strengthened by Wolfgang Sachs when he argued that the concept of sustainability promises to bring harmonization between ecological sustainability and economic development interests. Efforts have been made especially in the last two decades to conceptualize sustainable development by focusing on economic and social growth through science and technology without harming the ecological balance of the universe (Kakoty, 2018). Oil palm plantation areas in Indonesia are spread across 26 provinces, namely all provinces on the islands of Sumatra and Kalimantan, West Java, Banten, Central Sulawesi, South Sulawesi, Southeast Sulawesi, West Sulawesi, Gorontalo, Maluku Papua and West Papua. Of these 26 provinces, Riau Province is the province with the largest oil palm plantation area in Indonesia, namely 2.86 million hectares in 2021 or 19.55 percent of the total oil palm plantation area in Indonesia (BPS, 2022).

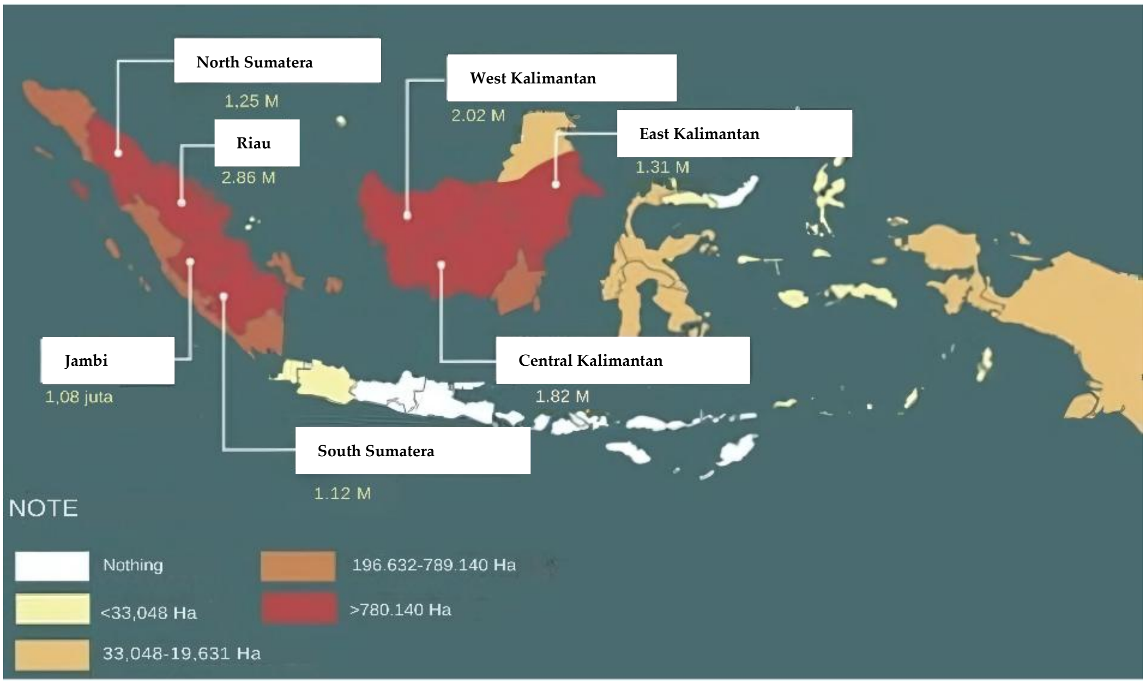

Fig. 1. Area of oil palm plantations in Indonesia by province in 2021

The role of oil palm in economic development and environmental degradation is a highly debated topic. Oil palm is a versatile crop, with palm oil or Crude Palm Oil (CPO) and palm kernel as the main products and various other derivatives used for cooking and making margarine, detergents, and cosmetics. In the last decade, several countries have used palm oil as a biofuel feedstock as they diversify their energy supply (Soh et al., 2003; Murphy, 2007; Ngando-Ebongue et al., 2012, Purnomo et al., 2020). This has led to increased global demand for food, energy, and other industrial processes, and with it, increased demand for palm oil. In addition to the main products mentioned above, in the palm oil production process there are by-products that can still be utilized such as shells, mesocarp fiber, empty bunch fiber and also palm oil mill effluent (POME) which can be used as a source of bioenergy.

Indonesia is a country committed to implementing and achieving the Sustainable Development Goals (SDGs). Since the SDGs were declared in September 2015, Indonesia has been actively involved in various global forums. The development of new and renewable energy has been contained in the RPJMN 2015-2019 and the National Energy General Plan (RUEN) in order to achieve the National Development Goals and SDGs, especially the 7th goal of Clean and Affordable Energy. Energy plays an important role in achieving sustainable development goals (Santika et al., 2020). Where the target of the new renewable energy mix in 2025 is 23%-36% respectively. Currently, the renewable energy mix is still around 8.4%

in 2018, however, the potential for renewable energy is 41.3%, and the potential for renewable energy that has been utilized has only reached 2% of the total potential available (Bappenas, 2019).

Palm oil in Indonesia is the most important agricultural product and important for economic development, especially in rural areas. However, POME as one of the by-products of palm oil can cause environmental problems due to its high Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) content, POME has a very high COD content of around 15,000 to 100,000 mg/L (Ahmad et al., 2016). Capturing and converting methane into energy offers one way for palm oil mills to reduce their environmental impact and at the same time create renewable energy (Rajani et al., 2019).

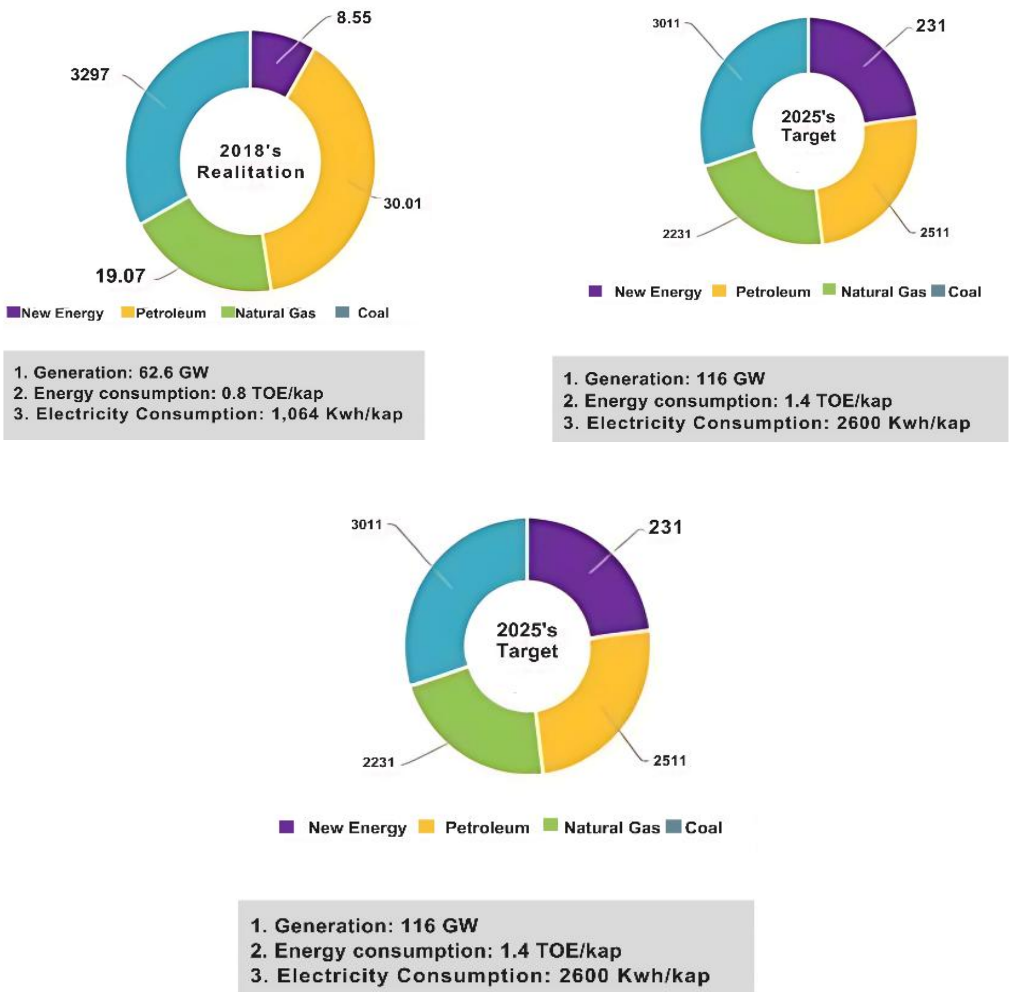

Fig. 2. National energy general plan targets

Jambi Province has an oil palm plantation area of 1,034,804 hectares with a production of 2,884,406 tons of CPO managed by independent farmers, state-owned companies and private companies, where there are 80 palm oil mills in 2020 (BPS, 2020). Where for the production of each ton of palm oil produces about 2.5 to 3.37 tons of POME, with this estimate, the production of POME in Jambi province is 7.2 million tons - 9.7 million tons per year. Most palm oil mills in Jambi have not utilized liquid waste, only managed with a conventional waste treatment system of open ponds, with this system will produce emissions into the atmosphere, if managed by capturing methane gas will potentially be utilized as a source of energy while reducing emissions.

The development of the palm oil industry development in Jambi province causes an increase in energy demand, the palm oil plantation industry is spread across most of Jambi, where in the palm oil production process will produce a number of POME, with the large amount of POME from palm oil processing if managed it can be a potential new renewable energy (EBT) sourced from POME Biogas Energy, with this utilization will be able to reduce the use of fossil energy and affect the environmental impact and will have a social and economic impact, but until now this potential has not been utilized optimally, from around 80 PKS units in Jambi province there are only <10% PKS that utilize POME as a source of biogas energy 10% of PKSs that utilize POME as a source of biogas energy, and those PKSs that have produced biogas have not been optimally utilized, this is due to the fact that the use is still only focused on utilization for electrical energy sources, whereas this biogas energy source should still be utilized for other uses such as for household fuel or for fuel substitutes. The development of biogas energy from POME is very beneficial for economic growth, social community and environmental impact reduction. The life cycle assessment (LCA) approach is used to look at the environmental impacts of POME management in Jambi. The LCA approach for biogas from POME has been conducted in other places such as Malaysia. Based on the above conditions, the research objectives are as follows. First, to analyze the environmental, social and economic impacts of processing POME into biogas at palm oil mills. Second, to develop a strategy for the utilization of POME waste for the optimization of new renewable energy for energy sustainability.

2. Methods

2.1 Research model

The approach used in this research is a quantitative approach. The method used in this research is mixed methods, where quantitative and qualitative data are collected, analyzed and then interpreted in a study where each research objective is analyzed with the appropriate method. In this study, quantitative methods were used to analyze quantitative data such as for energy demand variables, potential energy sustainability and environmental impacts. Qualitative methods are used to explore information about the benefits of renewable energy to companies and communities around the company.

Furthermore, there are two populations in this study, the first population is the Palm Oil Mill (PKS) which carries out the processing activities of fresh fruit bunches to produce palm oil (CPO) and palm oil mill effluent (POME) as a by-product which is further processed in biogas plants in Jambi Province. There are 80 PKS units operating in Jambi Province with varying processing capacities.

The second population is all stakeholders involved in biogas production from POME in Jambi Province. The definition of stakeholders is stakeholders in the form of companies or agencies involved in efforts to develop biogas production from POME in Jambi. The sample was determined by purposive sampling, with the following criteria. First, stakeholders whose working areas are in Jambi Province and willing to be involved in the interview. Second, stakeholders who have interests directly related to biogas production from POME in Jambi Province to carry out their functions.

2.2 Data analysis method

2.2.1 Environmental, social and economic impact analysis methods

Analyzing environmental impacts, the method that will be used in this research is a quantitative approach with the Life Cycle Analyses (LCA) method which refers to SNI ISO 14040: 2016 on "Life Cycle Assessment - Principles and Framework" and SNI ISO 14044: 2017 on "Life Cycle Assessment-Requirements and Guidelines" for environmental impact assessment. First, determine the purpose and scope, which is the first step to determine the purpose of the life cycle assessment, then determine the scope and type of life cycle assessment. In this study, the purpose of using the LCA method is to determine the environmental and social impacts of palm oil processing. Then determine the boundaries of the system to be assessed. In this research, the life cycle assessment referred to in the scope of the assessment is cradle to gate, which assumes the use of databases in applications resulting in the consequences of data characteristics carried over from the cradle.

Second, Life Cycle Inventory (LCI) as the second step determines the LCI of the biogas energy production process in the form of material and product inputs and outputs as well as by-products from the entire production process. This is done by identifying inputs (resources) and outputs in the form of products, air emissions, liquid waste and solid waste. At the LCI stage, all data entered are relevant production process data used to produce, transport, use and dispose of the selected products. In the LCI analysis, the data required are as follows. (1) the analyzed process units; (2) auxiliary equipment of the analyzed units, such as pumps, generators, and so on; (3) input data of the analyzed units, such as resources in the form of water and chemicals or other materials, energy or fuel used in production or other required inputs; (4) output data of the analyzed units, such as emissions and waste generated.

The third step is to assess the possible environmental impacts that may be caused by the production process using the existing LCIA model in SimaPro software so that the midpoint impact of material Input-Output will be obtained. All impacts of resource use and resulting emissions are grouped and quantified into specific impact categories which are then weighted according to their level of contribution. The analysis method chosen is ReCiPe, CML because this method has been commonly used so that it is easier when compared with the results of previous studies. Furthermore, the fourth step the author provides an assessment based on the results of the LCIA assessment and provides an overview of the results of the LCIA analysis. So that it can provide an explanation of the results of the evaluation of recommendations needed to improve sustainability. The analysis method for social and economic impacts uses interviews with relevant parties, namely companies, to analyze how social impacts such as employment opportunities and economic impacts related to profitability are then analyzed descriptively.

2.2.2 Develop a strategy for utilizing POME waste for renewable energy optimization for energy sustainability

In developing a strategy for utilizing POME waste for renewable energy optimization for energy sustainability, a qualitative descriptive method is used. The results of descriptive analysis will be used as a comparison to evaluate sustainability optimization. Data obtained from field observations and literature reviews were collected and categorized. Next, the researchers identified and summarized the potential results. The researcher also developed a strategy to optimize renewable energy from the utilization of POME. The following is an overview of the methods used in this research.

Table 1. Compatibility between research objectives and methods

No.	Research Objectives	Data Analysis Methods Used
1	Analyze the environmental impact, social impact, economic impact, because ofpalm oil processing.	LCA/ Descriptive Qualitative
2	Develop a strategy for utilizing POME waste fornew renewable energy optimization for energy sustainability.	Descriptive Qualitative

3. Results and Discussion

3.1 Environmental and social impacts of processing POME into biogas

Results The goal of this biogas LCA study is to assess the relevant environmental impacts of biogas production from POME used as engine fuel to generate electrical energy or burned in flares. The scope of study in this LCA study is the Biogas Plant of PT ABC. This LCA study is a cradle to gate study of the electricity production process at the PT ABC Biogas

Plant which includes the cooling pond process unit, feed tank, POME Storage tank, digester tank, AnMbr tank, bioscrubber, dehumidifier, engine gas, and flare. The extraction of raw materials from the nursery to the processing of FFB at the PKS is included in this study because this study uses inventory data in the SimaPro application database. The unit of function used in this LCA study is 1 ton of POME.

In this study, a cradle to gate analysis is carried out, which includes the raw material extraction process obtained from the SimaPro application database, electricity production from the biogas power plant. The unit of analysis to be used is per 1 ton of POME. The time span of this LCA study is biogas production from January to December 2021. The potential impacts of the biogas production process are acidification, eutrophication, climate change (global warming potential).

3.1.1 Life cycle inventory

At the Life Cycle Inventory (LCI) stage, the diagram that has been described is identified as an input-output process. From the figure, it can be identified what materials will become inventory data from the biogas production process that occurs at PT ABC in accordance with the predetermined system boundaries. The CPO production process with POME by-products at PT ABC is depicted as in Fig. 3 Flowchart of PT ABC CPO production process.

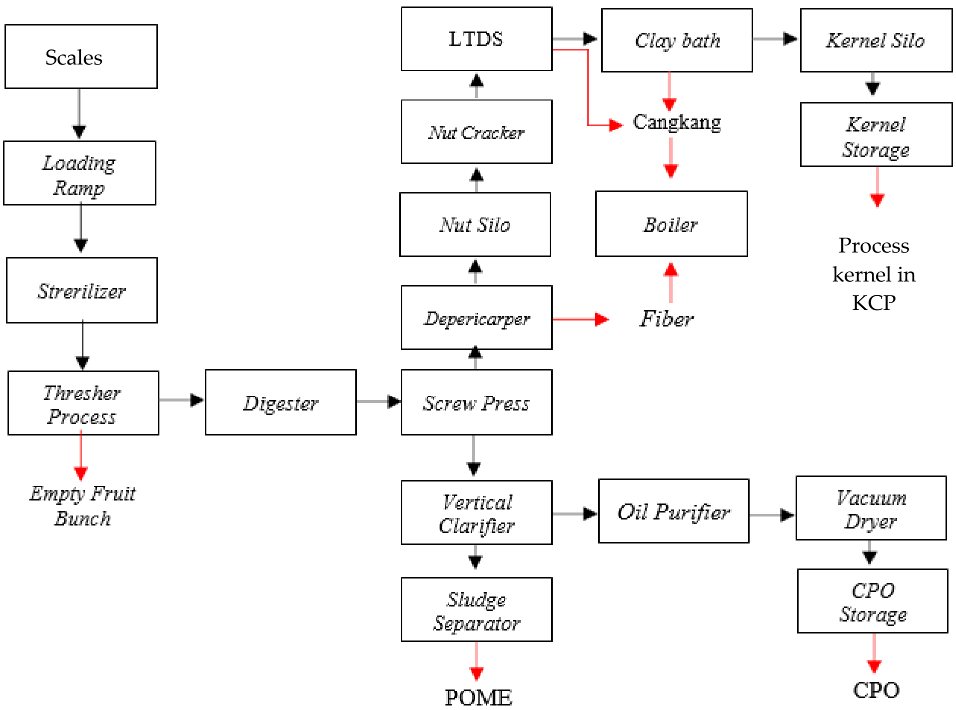

Fig. 3. Flowchart of PT ABC CPO production process.

In this cradle to gate LCA study, a functional unit of 1 ton of POME is used to produce biogas. Inputs for the palm oil mill are raw materials of fresh fruit bunches (FFB), supporting materials, and energy in the form of electricity, diesel, water for boilers, and diesel for dump trucks. The outputs of the palm oil mill are CPO, PK (palm kernel) and emission outputs including liquid emissions, namely POME. The input-output inventory for biogas production from POME can be seen in Table 2. The inputs for biogas production in the biogas plant are POME raw materials from by-products of CPO production, supporting materials such as water, and electrical energy. The outputs of the biogas plant are biogas, and digestate. The biogas formed is then purified through the scrubber media to be used as fuel for the gas engine, unused biogas for the gas engine is usually burned in the flare system.

Table 2. LCI biogas of PT ABC in 2021

Flow	Unit	Amoun	ton POME
POME	m^3	142,917	1.00
Electricity	kWh	1,047,554	7.33
Water	m^3	1,200	0.01
Biogas	m^3	5,489,584	38.41
Electricity	kWh	8,644,560	60.49
Methana	kg	2,449,201	17.14
Carbon dioxide	kg	4,071,200	28.49

3.1.2 Life cycle impact assessment

At this stage the environmental impact according to the system boundary will be determined based on the LCI results. The LCI results are combined with material-based impact categories that contribute to environmental problems (ISO, 2006). This research also uses impact assessment methods such as CML IA and ReCiPe 2016 which are global in nature along with midpoint analysis. LCIA is used to analyze environmental impacts such as carbon footprint, midpoint impacts on biogas production from palm oil processing POME. The impact categories analyzed in this study are Global Warming Potential (GWP), eutrophication and acidification. The global warming potential (GWP) of the life cycle stages of biogas production from POME is shown in Fig. 4. The total CO_2 (eq) emission generated for every 1 ton of POME is 289 kg CO_2 (eq), which is reduced by -4.92 kg CO_2 (eq) from the biogas production process and -19.7 kg CO_2 (eq) from the production of electricity generated from the biogas plant. Biogas production can reduce about 7.84% of the potential impact of global warming.

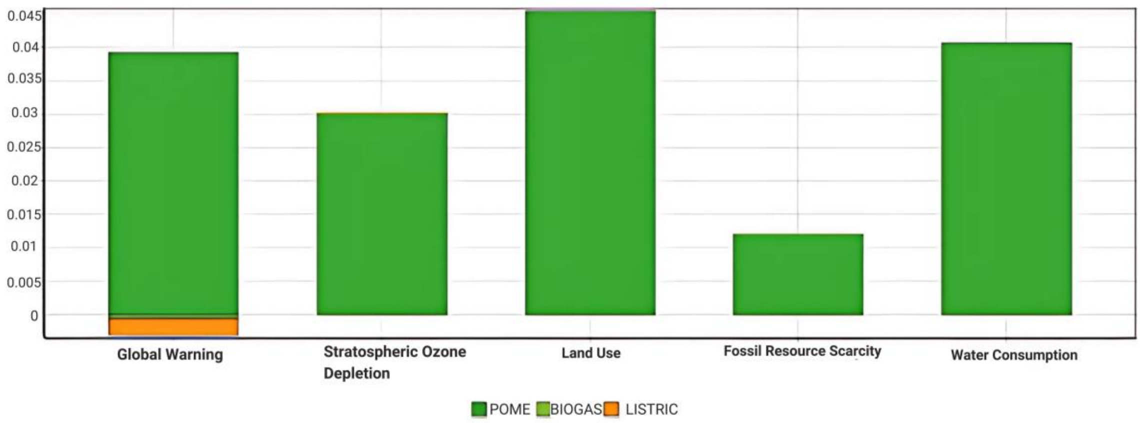

Fig 4. CO_2 emission impact (eq) life cycle of biogas production

Eutrophication generally describes an increase in nutrients that triggers an increase in algal biomass, changes in zooplankton and changes in the species composition of the ecosystem which results in a decrease in water quality such as discoloration, smelly and tasteless water. The impact of eutrophication on waters as seen in lakes, rivers and coastal waters is that it degrades water quality, and results in low visibility and high algae levels on the water surface. Using the CML IA method, the eutrophication impact of biogas production generated from 1 ton of POME is 0.805 kg PO_4^{3-} (eq), at the biogas production stage contributes to reducing the impact by -0.0438 kg PO_4^{3-} (eq), and electricity production from biogas contributes to reducing the impact by -0.175 kg PO_4^{3-} (eq). These impacts show that the biogas production process from POME does not have an impact on increasing eutophication but on the contrary as shown in Fig. 5.

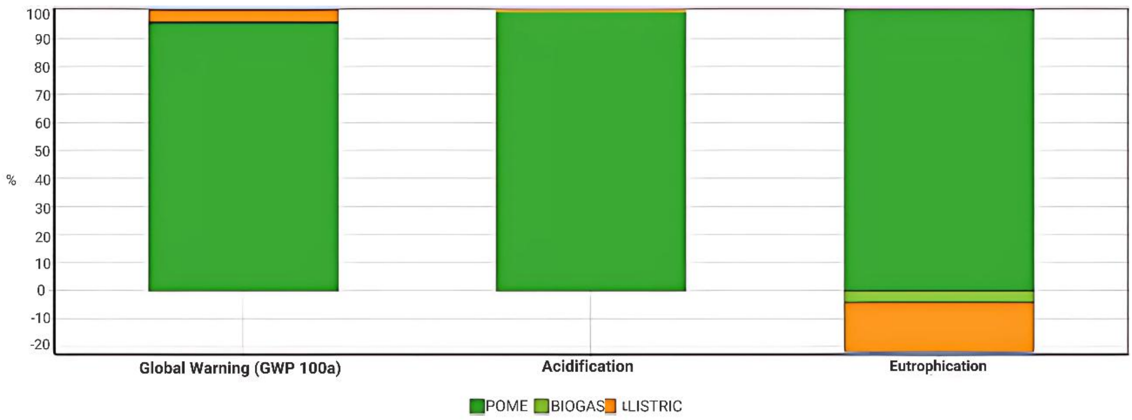

Fig 5. Eutrophication impact kg PO_4^{3-} (eq) biogas production lifecycle

Acidification is a naturally occurring phenomenon, but it increases with human activities such as land clearing for plantations or increasing the number of industries that increase hydrogen ions entering the soil and vegetation. Compounds that cause acidification are Sulfur Oxides, SO_2 and SO_3 or SO_x, acid anhydrides of sulfuric acid H_2SO_3 and sulfuric acid H_2SO_4, Nitrogen Oxides, NO and NO_2 (or NO_x) which are also acid anhydrides because they can be converted to nitric acid through oxidation in the troposphere (Guine´e et.al., 2001). When acidifying compounds enter the soil, they will lower the pH of the groundwater and cause the release of bound metal ions in the soil which will impact soil fertility (Yadav et al., 2020). Potential acidification is usually characterized by the presence of SO_2 compound equivalents (Dincer, 2000). The total potential acidification impact of biogas production for every 1 ton of POME is equal to 1.06 kg SO_2 (eq) where in the biogas production process contributed 0.0011 kg SO_2 (eq) and from electricity production from biogas of 0.00442 kg SO_2 (eq). At the process stage at the PKS and biogas production is not too significant when compared to the plantation stage, where the plantation stage contributes the highest due to the use of NPK fertilizer on oil palm plants.

Based on the results of the life cycle impact assessment (LCIA) that has been carried out, it is obtained that the impact of Global Warming Potential (GWP), eutrophication and acidification in the biogas production process from every 1 ton of POME does not have a significant impact, the impact of global warming potential can be reduced by the biogas production process compared to conventional processing, the impact of eutrophication has no significant contribution from the production of biogas, where the impact at the biogas production stage contributes to reducing the impact by -0.0438 kg PO_4^{3-} (eq), and electricity production from biogas contributes to reducing the impact by -0.175 kg PO_4^{3-} (eq). Meanwhile, the acidification impact of biogas production for every 1 ton of POME contributed to a slight increase in acidification by 0.0011 kg SO_2 (eq) and from electricity production from biogas by 0.00442 kg SO_2 (eq).

3.1.3 Environmental aspects

The treatment of palm oil liquid waste (POME) in open pond systems at conventional palm oil mills results in greenhouse gas (GHG) emissions, mainly methane being released into the atmosphere. Methane is 28 times more reactive than carbon dioxide and has the potential to increase GHG emissions. However, by utilizing a biogas system, methane emissions from POME can be significantly reduced. Sources of GHG emissions in a biogas plant include the utilization of biogas to fuel gas engines and combustion in flare towers, electricity production, fugitive emissions, as well as final effluent flowing into anaerobic ponds. The final effluent that is further processed in the WWTP pond contains sludge with lower COD levels, but still has the potential to emit methane gas. This effluent can also be utilized for irrigation in oil palm plantations.

GHG emissions greatly affect the sustainability of biogas production from POME as it has a direct impact on global warming. The utilization of POME in a biogas plant reduces

GHG emissions significantly. POME, which has a high organic content, can produce large amounts of methane gas, which is then converted into electricity in the biogas plant. This process also reduces the COD content of POME, lowers GHG emissions and adds economic value to the company. According to the 2006 IPCC guidelines updated in 2019, GHG emissions are a key indicator to assess the sustainability of biogas production from POME. Emissions are calculated including biogas combustion in flares or generators, fugitive emissions, emissions from electricity generation, and final effluent emissions in anaerobic ponds (IPCC, 2008; 2019).

Indonesia is committed to reducing GHG emissions, including by promoting renewable energy through Government Regulation No. 79/2014. Indonesia's renewable energy target is 23% by 2025 and 31% by 2050. This target is expected to reduce emissions GHG emissions by 29% by 2030. The biogas sector has great potential in this endeavor, as seen in the UK which has successfully reduced GHG emissions through the biogas sector (Styles et al., 2016). In Indonesia, renewable energy development still faces challenges, especially in terms of capital and business seriousness in developing green energy. The integration of bioenergy systems from the agriculture and forestry sectors can improve water and land use efficiency and reduce environmental impacts (Creutzig et al., 2015).

Utilizing POME as an energy source also plays a role in reducing GHG emissions, which are projected to reduce the global average temperature rise by 3.7-4.8°C by the end of the 21st century (IPCC, 2014). Research has shown that utilizing palm oil residues such as empty bunches, kernel shells, and fiber for energy can meet up to 50% of Indonesia's national bioenergy target by 2025 and reduce emissions by 40 Mt CO_2 eq per year (Harahap et al., 2019). Biomethane from biogas technology can also be injected into natural gas pipelines and help accelerate Indonesia's energy transition (Rianawati et al., 2021).

3.1.4 Social aspects

The utilization of POME for biogas production at PT ABC creates several social impacts, including job creation and improved energy access for local communities. This process requires infrastructure and a trained workforce to manage the treatment system. In this case, the utilization of POME was able to provide employment opportunities in the renewable energy sector involving 6 workers at the biogas plant, both in the construction and operational stages. Most PT ABC employees are local workers who have received training and earn above the Provincial Minimum Wage (UMP) and receive additional compensation in the form of overtime pay. If all mills in Jambi adopt biogas production from POME, this has the potential to improve the welfare of the local workforce through the creation of new positions, especially biogas plant operators.

In addition to job creation, PT ABC' biogas plant also contributes to providing access to electrical energy around the plant. The electricity produced meets the needs of employee housing, including factory employee housing, Taman Raja plantation, Badang plantation, and Bernai plantation. PT ABC also expanded the electricity network to villages around the company, such as Lubuk Bernai village, which previously did not have access to PLN electricity. This energy from biogas supports local needs for cooking, lighting and other purposes, which has a positive impact on the quality of life of local communities.

The utilization of POME also improves environmental management in the company, which has received appreciation from the government in the form of an award for reducing GHG emissions. The award is included in the Company Performance Rating Program in Environmental Management (PROPER) with a blue or green rating. In maintaining the sustainability of biogas production from POME, PT ABC implements various social management programs through Corporate Social Responsibility (CSR) initiatives, air and noise pollution control, recruitment of local labor, and fulfillment of workers' rights. The company also involves village and sub-district officials in the recruitment process, thus increasing the involvement of local communities in the company's operations.

3.1.5 Economic aspects

The presence of biogas power plants in palm oil mills provides significant economic benefits. Factors in the economic dimension that influence the sustainability of biogas production from POME directly and indirectly impact profitability and operational continuity. Based on interviews, the economic dimension is considered the most important in biogas production as it plays a major role in the sustainability of the mill. The development of a biogas plant is highly dependent on the absorption of electricity generated; currently, biogas production is not optimized and is still focused on electricity supply only. The profitability of a biogas plant can be evaluated by measuring Return on Investment (ROI), discounted cash flow, net present value (NPV), capital, and payback period (Peters & Timmerhaus, 1991). In this study, profitability simulation was conducted through the calculation of the payback period, which has also been applied by various previous researchers (Chin et al., 2013; Gozan et al., 2018; Odabaş Baş & Aydınalp Köksal, 2022; Poblete et al., 2020; Begum et al., 2009; Shane et al., 2017; Sodri & Septriana, 2022; Yoshizaki et al., 2012). Based on 2021 data, the payback period of biogas in PT ABC is 9.7 years, similar to the results in Bangka of 10.8 years (Sodri & Septriana, 2022), but still longer than in Malaysia with 4.3 years and 6.6 years (Chin et al., 2013; Gozan et al., 2018). Optimizing biogas utilization can reduce the payback period by reducing the volume of wasted biogas.

Sustainability indicators in the economic dimension include feedstock availability, investment, production costs and profitability. A major challenge in the development of biogas plants is the high investment cost, which is generally only affordable by large, financially stable companies. In addition, production costs, including periodic maintenance on engines and gas engines, are also high. The profit generated from biogas production is an important factor for the sustainable operation of the plant.

POME utilization also plays a role in reducing environmental impacts by reducing methane emissions into the atmosphere, which has a greater global warming potential (GWP) than carbon dioxide. Biogas production can reduce GWP by 357.18 kg CO_2-eq (Nasution et al., 2018) and lower greenhouse gas emissions (Zhou et al., 2021). In addition to increasing revenue, this waste treatment also increases utility efficiency, helps companies achieve energy self- sufficiency (Theo et al., 2017), and has a positive impact on workers and local communities (Muhammad et al., 2019).

3.2 Concept of POME waste utilization strategy for new renewable energy optimization towards energy sustainability

3.2.1 Biogas production at PT ABC

PT ABC is located in Lubuk Bernai Village, Batang Asam District, West Tanjung Jabung Regency, Jambi Province. The company has an HGU of 9.077 Ha covering three estates or plantations, namely Kebun Taman Raja, Kebun Bernai, and Kebun Badang, as well as one Taman Raja palm oil mill (PKS) integrated with a biogas plant. PT ABC's biogas plant is built adjacent to the mill, allowing direct utilization of POME as biogas feedstock. The location of the mill in the middle of the plantation is also quite far from settlements, where the nearest villages, such as Lubuk Bernai Village and Taman Raja Village, are about 1 km away.

The biogas production process at PT ABC uses the Kubota Anaerobic Membrane Bioreactor System with a closed tank-type reactor equipped with a geomembrane. POME raw materials from PKS are flowed first to the cooling pond to reduce temperature and reduce sand, then stored in the feed tank before being forwarded to the MST (POME Storage Tank). From the MST, the POME is flowed to the digester tank to be processed anaerobically into biogas, with an operating temperature between 45-60°C which is suitable for thermophilic microbes.

At this stage, the POME is stirred using a mechanical agitator to accelerate the decomposition of organic matter. The digester tank is filled to about 75% of the tank volume, while the top is filled with biogas. To prevent corrosion, biogas containing high levels of H_2S is processed by purification. After that, the biogas is condensed in scrubbers and dehumidifiers to reduce water content and temperature before flowing to the gas engine. PT ABC has two gas engine units with a capacity of 1.2 MW each that are operated alternately.

If there is excess biogas production, flaring is done in a flare unit to burn the excess biogas, reducing methane emissions to more environmentally friendly carbon dioxide. This waste conversion technology uses a chemical conversion approach, or methanation, where methane becomes the main component of the biogas produced. To ensure optimal performance of this process, the regulation of variables such as temperature, pH, and organic content of the reactor is crucial, as revealed by Choong et al. (2018). Utilization waste in palm oil mills not only improves energy efficiency but also supports sustainability and economic competitiveness in this industry sector (Booneimsri et al., 2018).

3.2.2 Challenges and opportunities for biogas plant development

The development of renewable energy from POME in Jambi province has not been optimally utilized, this is due to development challenges and obstacles such as limited APBD in implementing RUED and providing incentives to EBT developers, limited energy demand, high dependence on fossil energy sources, relatively large investment costs for EBT development, lack of synergy between stakeholders in the development of new renewable energy sources, uncertainty of absorption of energy produced, thus causing low investor interest. This is revealed from the following interview excerpt.

> *"... the potential for biogas is large in Jambi, but if it is only for selling electricity to PLN, it is limited, that is the problem, so there are factories that have built biogas but do not sell to PLN, so it is constrained, actually many investors are interested, but the absorption capacity if selling to PLN is low, it must be developed in other forms, not only electricity*" - (L, Jambi Province Environmental Service)

Another challenge to the utilization of POME biogas as a renewable energy source is the access to the plantation sites, which are generally far from urban areas and require a large amount of money to build a distribution network. This hinders the delivery of electricity from the mills to the national grid. This is because plants are often located far from the main grid (IEA, 2017). Investment is therefore a big part of the challenge to implement biogas facilities in palm oil mills. A contributing factor to the lack of development of the renewable energy industry is that existing policies have not been fully implemented, especially during times of falling oil prices. There needs to be a policy breakthrough to improve existing policies, by providing convenience for investors in the renewable energy sector, including effective and efficient renewable energy supply chain management (Widya Yudha & Tjahjono, 2019), as well as policies that support the development of renewable energy with a partnership pattern (Mustikaningsih et al., 2019).

Opportunities for the development of new renewable energy from POME biogas in Jambi province actually have considerable potential where many oil palm companies produce POME but the utilization of POME for energy has not been developed, from around 80 PKS units operating in Jambi there are only a few units that utilize POME for energy. This is because the utilization of POME biogas is still focused on power generation, whereas there are actually many other utilization opportunities that can be widely useful such as utilization for household needs, for generator fuel, or for fuel for vehicles. This is revealed in the following interview excerpt.

> *"... actually if this POME is small, maybe yes, that can be distributed to the community, but not electricity, so it is multifunctional, for households, cooking, transportation, or for productive economic sectors, for example for SMEs using generators, the generators from*

diesel are replaced with bio-CNG, there are various user sectors, if the monopoly sucks, it will not develop later" - (S, Energy and Mineral Resources of Jambi Province.)

"... those who have been operating until now are PT XYZ and ABC, many investors are actually interested in biogas, but not only for electricity, the biogas has the opportunity to be sold to hotels or nearby restaurants to replace diesel or LPG" - (L, Jambi Province Environmental Service).

3.2.3 Formulation of a strategy concept for the utilization of POME waste for optimization of new renewable energy for energy sustainability

In developing the conceptual strategy for optimizing renewable energy sources from sustainable POME processing, it is necessary to consider several aspects such as environmental, social and economic sustainability. In line with the direction of the energy transition, LPG is a strategic raw material that is needed in the regions as an alternative fuel to replace kerosene. However, this raises several problems, especially related to scarcity and potential price spikes. The development of the biomethane concept is prospective as a renewable clean energy and has great potential to meet energy demand for vehicle and household fuels, due to limited fossil fuel reserves.

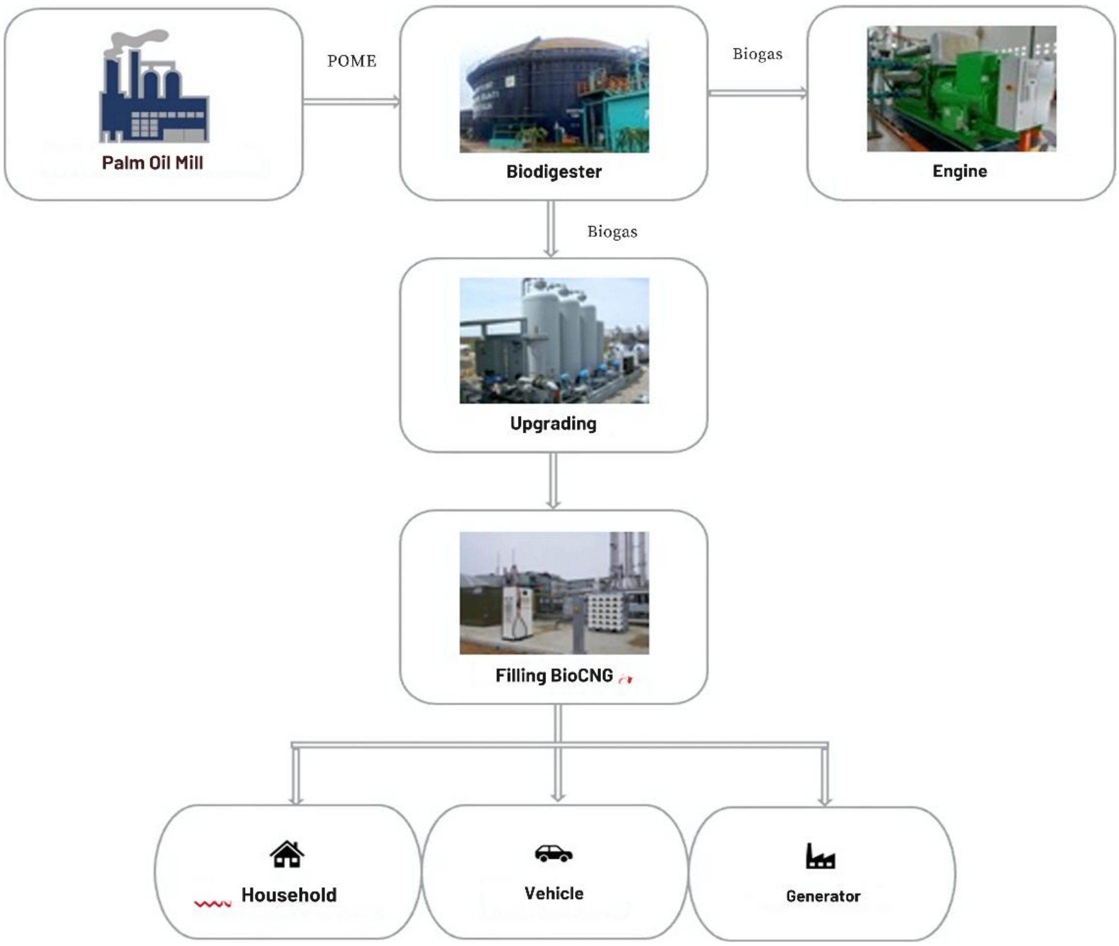

Fig. 6. Concept of optimization of POME biogas utilization as an EBT source

This POME production can be processed to produce biogas. To optimize the utilization of biogas produced can be used as fuel for gas engines, in addition to the potential utilization of biogas, can be increased efficiency into compressed natural biogas (bio-CNG) to facilitate the utilization and storage system (Ullah Khan et al., 2017), before compressed biogas is carried out purification process and compression of biomethane concentration to (95-

96%vol) (Marsˇa´lek et al., 2020). Increasing the purity of biogas from anaerobic digestion of POME can be done by water scrubbing and amine scrubbing methods. The purity of biomethane reaches 97.23% using water scrubbing, and 99.93% using amine scrubbing (Saputro & Sudibandriyo, 2020). This biogas compression system can optimize the use of biogas so that there is no need for biogas to be wasted in flares. Biogas that has been compressed can be used for motor vehicle fuel needs, for generators and household needs.

To optimize the utilization of biogas production, several scenarios are needed as in Fig. 6., the utilization of which is not only focused on one type of utilization, where currently the utilization is still focused on converting biogas into electricity for its own use and some excess electrical energy is supplied to the PLN grid. Some scenarios of biogas utilization are as follows; biogas into electrical energy for own use, this acts as a substitute for the use of diesel fuel which is generally used for power plants in plantations, biogas is used into boilers as thermal energy to reduce the use of shells or other biomass, biogas for cooking is a substitute for LPG, kerosene, biogas can also be used for transportation, namely as a substitute for gasoline or diesel oil.

The utilization of biogas for cooking and transportation requires additional processing, namely converting biogas into bio-CNG, the biogas plant unit only needs to add a scrubber unit and biogas compression equipment. With this biogas compression system, biogas production is not only used for engine gas needs to produce electrical energy, and there is no more residual biogas burned in flares, but biogas can be stored for wider use.

The utilization of renewable energy POME biogas energy from POME waste can be optimized for energy sustainability: The utilization of biogas energy from POME effluent is an important step in maintaining energy sustainability. By optimizing the biogas production process, including efficient waste processing and handling, renewable energy can be generated that can be used to meet energy needs in the long term. In the context of energy sustainability, it is important to ensure that the utilization of POME biogas energy is efficient, economical and environmentally friendly so that it can contribute positively to the transition towards sustainable energy.

4. Conclusions

Based on the results of the explanation that has been described in the results and discussion section comprehensively, the author can conclude several things from this research as follows. First, the utilization of POME as an energy source can reduce the potential impact of global warming by -24.62 kg CO_2 (eq) from biogas production and has an impact on reduced the impact of eutrophication by -0.2188 kg PO_4^{3-} (eq) but slightly contributed to the increase of acidification by 0.00552 kg SO_2 (eq). Second, the utilization of renewable energy POME biogas energy from POME waste still needs to be optimized for energy sustainability. Where biogas that is not utilized to gas engines, which is usually burned in flares, can be compressed into bio-CNG to facilitate storage and can be used as vehicle fuel, generators and household needs.

This research further provides suggestions for the sustainability of renewable energy from POME as follows. Future research is expected to develop an economic valuation of the development of biogas plants, both those utilized for electrical energy, and other uses. In addition, the government needs to encourage oil palm plantation businesses to develop renewable energy from POME, because the potential is quite large and has not been optimally utilized. Furthermore, either the government or PLN as an electricity service provider can accommodate excess energy from the biogas plant and there is price certainty regarding the sale and purchase of energy from renewable energy sources.

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Author Contribution

This research was conducted collaboratively by D. S., E. F., & A. S. D. S was responsible for conceptualization, methodology, investigation, as well as writing—preparation of the original draft. Meanwhile, E. F., & A. S contributed to the writing—reviewing and editing, as well as supervising.

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The authors declare no conflict of interest.

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