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Implementing Biogas Technology as a Liquid Waste Management Strategy in Palm Oil Mills to Promote a Circular Economy

[Penerapan teknologi biogas sebagai strategi pengelolaan limbah cair di pabrik kelapa sawit untuk mendorong ekonomi sirkular]

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ABSTRACT

Liquid waste management in the palm oil industry plays an essential role in minimizing environmental impacts and promoting the application of the circular economy concept. This research analyzed effective strategies for liquid waste management through a case study at two palm oil mills in Riau Province. Both mills implemented palm oil mill effluent (POME) treatment technology by converting it into renewable energy in the form of biogas, which was utilized either in biogas power plants (PLTBg) or directly as boiler fuel (co-firing). The results indicated that this technology was effective in reducing environmental impacts, particularly through lowering greenhouse gas emissions, while also improving energy use efficiency in both mills. The applied waste management strategy was based on the principles of reduce, reuse, recycle, and recovery, consistent with the circular economy framework. The environmental, financial, and social benefits derived from this approach are expected to encourage and serve as a reference for the broader adoption of this technology in other palm oil mills, thereby contributing to the realization of a circular economy in the palm oil industry.

Keywords: Biogas power plant, circular economy, palm oil mill, POME, wastewater management

ABSTRAK

Pengelolaan limbah cair pada industri kelapa sawit berperan penting dalam menekan dampak lingkungan dan mendukung penerapan konsep ekonomi sirkular. Penelitian ini menganalisis strategi pengelolaan limbah cair yang efektif melalui studi kasus pada dua pabrik kelapa sawit di Provinsi Riau. Kedua pabrik tersebut menerapkan teknologi pengolahan POME (palm oil mill effluent) dengan mengubahnya menjadi energi terbarukan berupa biogas yang dimanfaatkan baik sebagai pembangkit listrik tenaga biogas (PLTBg) maupun secara langsung sebagai bahan bakar boiler (co-firing). Hasil penelitian menunjukkan bahwa teknologi ini efektif dalam mengurangi dampak lingkungan, khususnya melalui penurunan emisi gas rumah kaca, sekaligus meningkatkan efisiensi pemanfaatan energi di kedua pabrik. Strategi pengelolaan limbah ini didasarkan pada prinsip reduce, reuse, recycle, dan recovery sesuai dengan konsep ekonomi sirkular. Berbagai manfaat lingkungan, finansial, dan sosial yang diperoleh dari penerapan strategi ini diharapkan dapat menjadi pendorong sekaligus acuan bagi penerapan teknologi serupa secara lebih luas di pabrik kelapa sawit lainnya, sehingga dapat berkontribusi pada terwujudnya industri kelapa sawit berbasis ekonomi sirkular.

Kata kunci: Ekonomi sirkular, limbah pabrik kelapa sawit, PLTBg, POME

Introduction

The rapid growth of the palm oil industry plays a significant role in the Indonesian economy, but it also poses complex environmental challenges due to the generation of solid, liquid, and gaseous waste from the processing process (Ng et al. 2016; Agustina et al. 2021). Effective waste management not only has the potential to increase added value (Sugiharto et al. 2016) but can also minimize negative environmental impacts. The primary outputs of this industry, crude palm oil (CPO) and palm kernel oil (PKO), are generated

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alongside diverse wastes, including empty fruit bunches (EFB), palm kernel shells, mesocarp fibers, sludge, palm oil mill effluent (POME), and greenhouse gas emissions such as methane and carbon dioxide. Improper waste management can trigger water pollution, increased carbon emissions, eutrophication, and acidification. The use of biomass and POME as renewable energy sources has become a strategic issue, as demonstrated by Zamri et al. (2022) through an analysis of the feasibility of substituting coal-based power plants with biomass and POME energy. Furthermore, the use of POME in anaerobic digestion produces biogas with a methane content of 65–75%, which has the potential to be used for electricity and heat (Hwang et al. 2022). Furthermore, the integration of microalgae-based bioprocesses into waste utilization is also being explored as part of the development of a circular bioeconomy (Khanra et al. 2022).

The circular economy approach in the palm oil agro-industry is an effort to improve efficient material and energy utilization, minimize waste discharge, and enhance productivity. Its implementation containing using organic as fertilizer, processing EFB, shell and fiber into value added products such as briquettes/feeds, and palm trunk residue into bio pellet had been technically and economically possible (Utomo et al. 2024). Moreover, energy efficiency, clean technology and zero waste concepts are fundamental for the realization of energy independence and sustainable industrial system (Hwang et al. 2022; Cheah et al. 2023). The promotion of a circular economy also highlights the need for cross-sector partnerships between regulation, financial reward and environmental awareness. This strategy is consistent with the Indonesian national "The Future is Circular" strategy (Bappenas, 2022) which highlights the systemic shift to keep materials in the loop and to limit resource extraction and emissions and promote sustainable development.

Conversion of the waste to biomass briquette is proposed to reduce the CO_2 emission which in turn provide the renewable energy, but the energy content only for the range of 16.8–18.8 MJ/kg closer to that of the sub-bituminous coal (Handra, & Indra, 2023). Empty oil palm bunch (EFB) briquettes can be applied in a both household and industry scale, so it suppor ts circular economy that can raise the efficiency and reduce the environmental footprint (Pinassang et al., 2022; Milya et al., 2023). The palm oil agroindustry generates palm oil plantation waste as primary biomass waste in terms of empty oil palm bunches (EFB), palm kernel, and palm oil mill effluent (POME), which have great potential for use as renewable source of energy and industrial materials (Anggraini et al. 2022). EFB and palm kernel are used as fuel for power plants (Zamri et al., 2004b), while POME, through anaerobic digestion, generates biogas that replaces energy (Zamri et al. 2022). In addition, EFB has possibility of processing as composite, light building, or other lightweight product, and POME can be used for organic fertilizer (Chaikitkaew et al. 2015). Not only does this use promote energy diversification, but its products generated are value added within a circular economy concept.

Utilization of biomass waste in the palm oil agro-industry is essential in enhancing resource efficiency, mitigating environmental costs and generating further economic return for the producers. This work is in line with sustainable development by the use of new and renewable energy. In this regard, Biomass Power Plants (PLTBg) and co-firing are in the spotlight as a solution for green energy and upgrading policy for the palm oil industry to more efficient and environmental friendly. This paper describes the concept of PLTBg, analyses co-firing as an integrated solution and looks at its potential application in the palm oil industry.

Methodology

This research used a descriptive quantitative method to analyse liquid waste management of palm oil mills by using biogas technology to support the circular economy. Direct observation was conducted at two palm oil mills in Riau Province that implemented the POME-based biogas technology treatment, the LDA Palm Oil Mill and the TAN Palm Oil Mill for data collection. The two mills have the same capacity of 45 tons of Fresh Fruit Bunches (FFB) per hour but different utility levels. The observations in both plants were emphasized on the POME treatment and PLTBg operating. The new data materialised from this study are

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both primary and secondary sources. Field measurements were taken directly on the site; the mass and energy balance data were collected, such as POME flow, capacity of treatment, emission of greenhouse gases generated, biogas produced, electricity generated from biogas used.Generated data included: Factory management were also interviewed on liquid waste management and biogas technology application. On the other side, secondary data is collected from ancillary information from factory production reports and electricity consumption from secondery source produced by stalk based biogas. Another type of secondary data is information from similar works on the environmental effect and economic perks of using biogas technology in POME waste treatment. A description method was applied with the aim to study the performance of biogas technology in the treatment of liquid waste and its role in the circular economy. Moreover, mass flow analysis (MFA) was carried out to determine the quantity of liquid waste generated by the palm oil mills and biogas production volume. MFA also report energy pulp mill input at each processing station where POME is processed to biogas and the electricity produced has been estimated.

Result and discussion

MFA Analysis

MFA study of the palm oil mill offers a complete understanding of the material inputs and outputs of the palm oil processing system. At the palm oil mills, CPO is processed at several stages: at reception, sterilizing, threshing, pressing, clarification, and kernel processing. Each of these stations serves a different purpose and generates different produce and rubbish. At the threshing station, EFB is extracted from the fresh fruit bunches, while palm fruit bunches enter pressing process for CPO and fiber. The kernels after pressing are used as a source of palm kernel oil (PKO) and transported to kernel station for further processing. MFA analysis explains the ratio of processed materials and products in use and around 20% of FFB is processed to CPO and 5% in PKO which in line with common palm oil mill yield between 4–6% of FFB. The rest of FFB is byproducts and waste which include EFB, fiber, shells, among others. Also, MFA involves the consumption of liquid substances including water and diesel, which are required in some operations in the palm oil mill. Water is used in the sterilization process and elsewhere in the factory with an average consumption of roughly 1.1 m^3/ton of FFB and diesel is used in tractors and for transport within the factory with an average of around 0.5 liters of fuel/ton of processed FFB. From the MFA, it was estimated that water flows annually required by each mill LDA and TAN are between 159, 066 – 270,659 m^3 and diesel usage ranges from 72, 303—123, 027 liters annually varying with the capacities and usage levels in the two mills. The applications of these resources have impact on the operational efficiency of the factory and even on the total operational cost. Some assumptions performed for MFA analysis are shown in Table 1.

Table 1. Palm oil mills parameters as the basis for MFA analysis

No.	Parameters	LDA	TAN	Unit
1	Mills capacity	45	45	ton FFB/hour
2	Average utility of mills	87	86	Percent
3	Number of operating days per year	275	289	Day/Year
4	Average operating hours per day	22	22	Hour/Day

Note : Table 1 presents the operational parameters of the LDA and TAN mills used as the basis for the Mass Flow Analysis (MFA). Data were obtained from a 2024 questionnaire and field observations.

The table above shows important operational information that each palm oil mills has different capacities in processing FFB per hour. The average utility of the palm oil mills, which reflects the percentage of maximum plant capacity usage, namely LDA and TAN, which each have utilities of 87% and 86%. This utility rate indicates how efficiently each factory utilizes its capacity for daily operations. The number of operating days and average operating hours per day for LDA is 275 days, and TAN is 289 days per year with

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an average operating time of 22 hours per day, indicating that the mills almost operate full-time every day. This information is important for evaluating the operational efficiency and output potential of each palm oil mill. With more operating days and consistent working hours, the mills can maximize CPO and PKO production, but with different utility levels, the output and production efficiency will also vary between factories. MFA analysis is conducted per station in the palm oil mills, each station will have specific inputs and outputs based on the processes carried out at that station (Table 2).

Table 2. Input and output at each processing station

No	Station	Input	Output
1	FFB Receiving and Weighing	FFB	FFB goes in for sterilization
2	Sterilization	Sterile FFB	Sterile FFB, condensate water and condensate steam
3	Thresher	Sterile FFB	Palm fruit bunch, EFB
4	Pressing	Palm fruit bunch	CPO, fiber, nut
5	Clarification	CPO	Clean CPO, sludge oil, water
6	Waste water treatment plant (POME and palm oil mill secondary effluent/ POMSE)	Liquid and solid waste from the processing process of water treatment plants (water, sludge)	POME, POMSE, biogas

The mass flow of FFB processing is presented in an Input-Process-Output (I-P-O) diagram (Figure 1). The input consists of 237.996 tons/year of FFB for LDA mill and 246.054 tons/year for TAN mill, supported by water for sterilization (1,1 m^3/ton FFB) and diesel for machinery (0,5 L/ton FFB). The process includes sequential stages of sterilization (0.5% mass loss as condensate), threshing (producing 23% EFB), pressing (yielding 20% CPO, 12% fiber, and 7% kernel), clarification (1% mass loss as sludge and water), kernel processing (5% PKO and 5% shell), and waste treatment (0,65 m^3 POME per ton FFB). The output includes the main products—CPO (20% of FFB) and PKO (5% of FFB)—along with by-products (fiber, shell, EFB) and biogas from POME utilization.

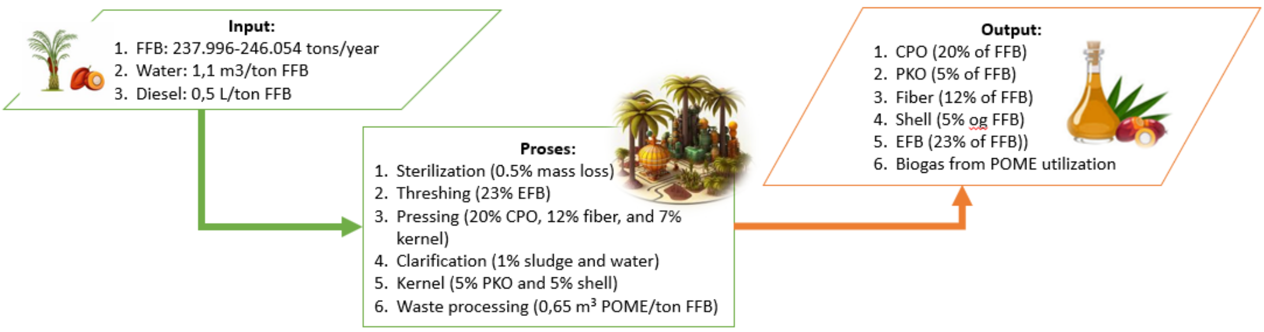

Figure 1. Input-process-output diagram of FFB processing

MFA also includes the use of liquid materials such as water and diesel, which are important for various operations in palm oil mills (Table 3). For example, water is used for sterilization and other processes with an average consumption of around 1,1 m^3 per ton of FFB, while diesel is used to power machinery and transport within the factory, with an average consumption of around 0,5 liters per ton of FFB processed. At LDA and TAN mills, MFA results show that water requirements range from 261.796 to 270.659 m^3 per year and diesel consumption ranges from 118.998 to 123.027 liters per year, depending on the production capacity and utility level of each plant. The use of these resources affects the operational efficiency of the plant and also contributes to overall operational costs. By using the data above, palm oil mills managers can identify opportunities to increase efficiency, optimize resource use and reduce waste. For example, EFB can be processed into biochar or used as fuel, and POME can be further processed to produce biogas, which

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can be used for internal electricity generation. MFA analysis is also important for identifying critical points in the process flow that may require improvement or control to minimize environmental impacts, support sustainable management, and increase overall plant profitability.

Table 3. Mass flow per processing station at LDA and TAN palm oil mills

Station	Parameters	Unit	LDA Mill	TAN Mill
FFB Acceptance	Input FFB	ton/year	237.996	246.054
Sterilization	Output condensate	ton/year	1.190	1.230
	Output FFB Sterile	ton/year	236.806	244.824
Thresher	Output EFB	ton/year	54.739	56.591
	Output Palm Fruit Bunch	ton/year	182.067	188.233
Pressing	Output CPO	ton/year	47.599	49.211
	Output Fiber	ton/year	28.560	29.527
	Output Nut	ton/year	17.566	18.155
Clarification	Output Sludge & Water	ton/year	2.380	2.461
	Output clean CPO	ton/year	47.123	48.719
Waste water treatment plant	POME	m^3/year	154.697	159.935
	POMSE	m^3/year	7.735	7.997
	Biogas	m^3/year	3.093.940	3.198.700
Liquid material (Water & Diesel)	Water	m^3/year	261.796	270.659
	Diesel	liter/year	118.998	123.027

A comparison of the MFA results between the LDA and TAN mills shows that although both mills have the same installed processing capacity (45 tons FFB/hour) and similar utility rates (87% for LDA and 86% for TAN), TAN operates more days per year (289 days) compared to LDA (275 days), resulting in a higher annual FFB throughput (246.054 tons vs. 237.996 tons). This difference in operating days contributes to TAN producing higher volumes of CPO (49.211 tons vs. 47.599 tons) and PKO, as well as greater amounts of by-products such as EFB, fiber, and shells. TAN also generated slightly more POME (159.935 m^3/year) and biogas (3.198.700 m^3/year) than LDA (154.697 m^3/year POME; 3.093.940 m^3/year biogas), which can increase renewable energy potential but also requires more robust waste handling capacity. Conversely, LDA shows slightly lower total water and diesel consumption per year due to fewer operating days, which may indicate opportunities for TAN to review resource efficiency. These findings highlight that while both mills apply similar processes and achieve comparable product yields, operational schedules and resource utilization patterns influence overall efficiency and potential areas for optimization.

Liquid waste management at LDA palm oil mill using PLTBg

The palm oil processing process at the LDA palm oil mill includes several processes. Before entering the palm oil mill the FFB will go through weighing, after weighing the FFB will be sent to the loading ramp. The loading ramp is a temporary storage place for FFB, apart from that it functions as a sorting place, separating dirt in the form of sand, gravel and rubbish. The production capacity of the LDA palm oil mill by design is 45 tons of FFB/hour with an operating time of 22 hours/day or the equivalent of 275 days/year. FFB in the LDA palm oil mill is supplied from 40% of core plantations and 60% of plasma plantations (+ third parties). The products produced are (a) CPO with a selling price of IDR 12.631/kg (national) and IDR 14.670/kg (export); (b) PKO with a selling price of IDR 13.640/kg; and (c) palm kernel meal (PKM); with a selling price of IDR 1.653/kg. The production process yield is 22,65%.

The output in the form of waste resulting from the production process at the LDA palm oil mill is kernel, shell, dregs, EFB, fiber and liquid waste. The shells and fiber produced are sold at IDR 1.073/kg and IDR 158/kg. The kernels (palm kernel) produced from the CPO production process at the LDA palm oil mill will be entrusted to the processing unit at the TAN palm oil mill and then sold for IDR 450/kg. The amount of

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PKO and PKM produced is by multiplying the yield provisions for the product, namely PKM 51% and PKO 40,5% of the Palm Kernel produced. Solids obtained from liquid waste solids that have been centrifuged produce 25-30 tons/day. This solid product is sold at a price of IDR 10/kg. The EFB produced will be sold at a price of IDR 9/kg (through the contractor) and processed in the incinerator to produce palm bunch ash and boiler ash. Palm bunch ash is produced as much as 4 tons/day, if it is sold it will be sold at a price of Rp. 1.610/kg. Apart from being sold, palm bunch ash is also used as fertilizer, through the Land Application (LA) method. palm bunch ash can be used as a substitute for the KCl element, where the application area is 245 Ha. Boiler ash is produced at 3 tons/day and then sold for IDR 30/kg (contains carbon and silica).

The use of energy comes from PLN (Perusahaan Listrik Negara/ State Electricity Company), boilers (shell combustion), turbines and diesel for initial propulsion and heavy equipment. Resource requirements come from steam: 500-600 kg/FFB, water: 1,2-1,5 tonnes/FFB and power sourced from turbines: 15-17 KwH/ton FFB. LDA palm oil mill utilizes POME produced from the CPO production process for co-firing. In a co-firing system, several different fuels are burned in a boiler to produce electricity. The main purpose of co-firing is to replace the main fuel with alternative fuel. Initially, boilers were designed specifically for certain fuels, but now they are more often used for co-firing. Ash desublimation is important for the biomass combustion process because it is related to boiler operating costs. Biomass ash (slag and dirt) deposits on walls and pipes can affect heat transfer and cause losses (Harnowo and Yunaidi, 2021). In 2020, PLTBg at LDA palm oil mill will begin to be designed using POME as a material. The C/N ratio of quality biogas is approximately 20-25 or 20-30 (Pasaribu, 2021). The concept applied is a covered lagoon system which has dimensions: length (83 m); width (55 m); height (6-7 m), with the cover used to line the pool made of high density poly ethylene (HDPE). This system was chosen due to its low construction and operational costs, high methane capture efficiency, and suitability for palm oil mills that generate large POME volumes and have sufficient land for lagoon construction (Surroop et al. 2019). The investment value for the construction of the LDA PLTBg is 18 M. The LDA PLTBg unit start operating in 2021, since then the methane gas produced can contribute as much as 1,5-2% as boiler fuel. By using POME to make biogas, the shells that were originally used for burning can diversify the business and become new income for the company. The characteristics of the biogas produced in the LDA PLTBg unit can be seen in Table 4.

Table 4. Characteristics of biogas at PLTBg LDA

No	Parameters	Value
1	CH_4	63,1 %
2	CO_2	30,5 %
3	O_2	0,3 %
4	H_2S	1440 ppm

Source: LDA palm oil mill (2024)

Liquid waste management at TAN palm oil mill using PLTBg

TAN palm oil mill has a palm oil factory that processes FFB fruit into CPO and palm kernel (Kernel). In the FFB processing process, the TAN palm oil mill has a design processing capacity of 45 tons of FFB/hour. In accordance with the aim of establishing a palm oil factory, it is to carry out palm oil FFB processing activities into CPO and palm kernel (Kernel). The oil palm plant developed on the Inti plantation (owned by PTPN IV Regional 3 TAN) which is the raw material for the TAN palm oil mill is the Tenera variety of oil palm, because from an economic perspective, the Tenera variety produces high oil, thus making a profit for the factory. The area of the TAN palm oil mill is 80 m^3 with a core plantation area of 7.664,22 Ha. The operating time at the TAN palm oil mill is 22 hours/day or the equivalent of 289 days/year with the yield produced in the CPO production process being 23,90%. This higher yield is greatly influenced by the quality of the CPO produced. The quality of palm oil produced as a food ingredient is determined by parameters such as fatty acid content, moisture content, and impurity levels. Additional factors affecting quality standards include melting point, clarity, heavy metal content, iodine value, peroxide value, and others. At the TAN palm oil

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mill, daily analyses are conducted to assess the quality of CPO. The by-products generated from the production process at TAN mill consist of kernels, shells, sludge, empty fruit bunches (EFB), fibers, and liquid waste. The total amount of shells produced is 14.642 tons, most of which will be used as boiler fuel (11.164 tons) and the rest will be sold. Meanwhile, EFB is sold for IDR 2.000/kg, but some is processed in the incinerator into ash which is used as an additional land application (LA). Furthermore, solid is also produced which is used for application to land (LA) covering an area of 149,73 Ha and; as well as fiber which is fully utilized as fuel in the boiler.

For liquid waste, based on December 2023 data, the production is 5% (456 m^3/day). PLTBg TAN has been operating since 2012. The existence of PLTBg with a capacity of 1,6 MW has succeeded in reducing the cost of diesel fuel to IDR 5,8 billion per year with the selling price of electricity to PLN being IDR 1.117/KWh. Apart from that, throughout 2020 PLTBg TAN also contributed additional International Sustainability and Carbon Certification (ISCC) incentives amounting to IDR 9,4 billion. PLTBg TAN also helped reduce the greenhouse threshold figure to reach 358,18 CO_2eq or far below the standard figure usually requested by palm oil buyers of 1.000 CO_2eq. Covered lagoon type anaerobic pond to produce biogas measuring 54 m x 110 m with a depth of 7 m. The pool is covered with 8 m high black HDPE plastic with a plastic lifespan of around 10 years. POME originating from the palm oil mill is channeled to the fat pit pond then to the cooling pond, where it is then continued to the feeding tank. The POME input temperature in the feeding tank is 40-60 °C with a pH of 3-5, but the temperature in the pond is around 28 –34 °C (mesophilic). The pump flows POME with a discharge of 20-30 m^3 to the anaerobic pond. The residence time (HRT) of POME in the pond is 50 days with mixing every 20 minutes/hour. The purpose of this stirring is to remove the layer of oil that may appear on the surface of the pool and neutralize the pH until it is in the range of 7-8. If a layer of oil appears, it will make it difficult for methane gas to escape from POME. The microorganisms used are methanogenic anaerobic bacteria. The volume of POME processed in the pond is 24,000 m^3. It is estimated that each ton of POME can produce 28-30 m^3 of biogas, with biogas content characteristics namely: CH_4: 55-65%; CO_2: 23-48 %; H_2S: 3000 ppm and O_2: 1-3 %.

Before being used to operate a generator, biogas needs to be purified and dried. The presence of H_2S gas, apart from causing corrosion, also accelerates the decrease in generator oil viscosity. The H_2S content in the TAN palm oil mill biogas produced is around 2.500 ppm. To run the generator, the maximum H_2S content is 800 ppm, so it needs to be cleaned first. H_2S cleaning is carried out biologically (*Tiobacillus sp.* using the BIO Gasclean system, through by injecting 3-7% air into the circulation pump to absorb H_2S, thus producing biogas with an H_2S content of less than 100 ppm. This biogas is then dried by condensing in a chiller. The high water content of the biogas can interfere with the process of converting biogas into electrical energy. The conversion of biogas into electrical energy is carried out directly using an artificial Guascor brand generator Spain. The main requirement for biogas must have a methane content of 58%. The electricity produced is 1200 KWh. Biogas digester design parameters according to production capacity can be seen in Table 5.

Table 5. Biogas digester design parameters

No	Parameters	Palm oil production capacity Tons FFB/Hour		
		30	45	60
1	Biogas Output Design (m^3/hour)	20	30	40
2	Decrease in COD/BOD (%)	90	90	90
3	Estimated biogas production (NM^3/hour)	500-815	815-1.000	1.000
4	Methane gas content (%)	55-65	55-65	55-65
5	Energy value (MJ/hour)	4.204-6.852	6.852-8.400	8.400-11.088
6	Fuel equivalent of shell	0,8-1,3	1,3-1,6	1,6-2,1
7	Electrical energy potential (kWe)	1.000	1.500	2.000

Source: TAN Palm Oil Mill (2024)

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TAN palm oil mill is a pioneer in reducing greenhouse gases and using them as an energy source. POME is processed to produce biogas which is used as fuel in biogas power plants (PLTBg). The electricity produced from this PLTBg is used to replace 1200 kWh (of the total 2 MW needed) for energy needs at the kernel oil processing factory (PPIS TAN) which is located not far from the TAN palm oil mill.

Sustainability benefits of PLTBg

Management of liquid waste at palm oil mill using PLTBg can provide sustainable benefits assessed from three important aspects, through economic, environmental and social (Kaniapan et al. 2021; Siagian et al. 2024). This qualitative assessment is based on opportunities and ease of implementation in the palm oil industry. Anthony et al. (2021), states that the economic benefits obtained are a reduction in fuel costs or economic efficiency felt by the company amounting to USD 522.108.52 during 2019. Environmental benefits include a reduction in waste parameters such as BOD (86,54%) and COD (92%) as well as a reduction in CH_4 emissions (1.365,90 tons of CH_4 or 90,43%). The total biogas produced was 4.172.361 m^3. Meanwhile, the social benefits obtained are that people view POME as an energy source that can save fuel costs in companies as a positive thing. Processing POME into fuel or a renewable energy source by applying biogas technology will produce a circular economy concept, namely reduction (reducing the use of energy sources) and reuse (Gozan et al. 2018; Kumaran et al. 2023). PLTBg can produce electricity from biogas produced by POME, by utilizing this waste for energy production, palm oil mills can reduce dependence on external energy sources and save electricity operational costs. In addition, a PLTBg not only produces energy for the factory's internal needs, but can also sell the excess energy produced to the national electricity grid. This creates an additional source of income for palm oil companies.

If viewed from an environmental sustainability perspective, it will help realize efficient waste management through the perspective of utilizing POME for biogas production, helping to reduce waste management costs (Foong et al 2020). By reducing the volume of waste that must be processed, companies can save operational costs related to waste processing and meeting environmental standards. The implementation and operation of PLTBg requires trained workers for management and maintenance. This contributes to the creation of new jobs in the renewable energy and waste management sectors (Norrrahim et al. 2022). Therefore, according Elizabeth (2021), the use of PLTBg in the palm oil agro-industry not only provides significant economic benefits, such as reducing energy costs, increasing income, and creating jobs, but also supports circular economy principles by reducing waste, greenhouse gas emissions, and increasing environmental sustainability. Thus, PLTBg is an effective solution in encouraging sustainable palm oil agro-industry practices.

Liquid waste management strategy at palm oil mills through the application of biogas technology

The strategy for managing liquid waste in palm oil mills by applying biogas technology to realize a circular economy according to Suprihatin et al. (2024), can be formulated as follows (Table 6).

Table 6. Liquid waste management strategy

No	Management Strategy	Implementation Steps
1	Application of POME-based biogas technology	• Optimize the use of covered lagoons which enable methane capture and reduce the impact of methane emissions on the environment. • Electricity Production: The biogas produced can be used for internal factory power generation, with the potential to sell excess energy to the national electricity grid (Cheah et al. 2023) . • Mitigation of Greenhouse Gas Emissions: Utilizing POME for biogas production contributes to substantial reductions in methane and CO2 emissions.

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2	Integration of circular economy concepts	• Reuse and Recycle: POME is reprocessed into biogas, and the remaining residue can be used as organic fertilizer or supporting material for land applications . • Cross-Sector Partnership: Involves cooperation among palm oil mills, government, and local communities to promote technological innovation and regulatory support for the circular economy.
3	Sustainable value	• Economic Benefits: Reduction of electricity and waste management costs, as well as potential income from energy sales. • Environmental Benefits: Emission and Pollution Control (supports climate change mitigation through the reduction of greenhouse gases and pollutants). • Social Benefits: improving the quality of life of local communities through providing clean energy and creating new jobs.
4	Infrastructure and technology development	• Enhanced Monitoring and Control Technology: Employing advanced systems to oversee and regulate biogas production processes in real time. • Infrastructure Dependability: Ensuring that biogas power plant (PLTBg) facilities operate efficiently with minimal interruptions, thereby fulfilling the energy requirements of the mill.

Managing POME liquid waste through biogas technology is the main step in the management strategy. This process involves anaerobic decomposition of waste to produce biogas which is rich in methane (CH_4). This biogas can subsequently be utilized as fuel for power plants in palm oil mills, thereby decreasing greenhouse gas emissions and reducing reliance on fossil fuels.

Conclusion

Management of liquid waste in palm oil mills using biogas technology based POME in LDA and TAN types an environmentally friendly alternative in order to reduce negative impacts to environment and more efficient in energy savings. With the application of circular economy practices, liquid waste is not only treated to reduce greenhouse gases but also provides tangible financial benefits in energy cost savings and potentially additional revenue from the sale of excess electricity, as well delivering social benefits by creating job and empowering communities. This approach facilitates the sustainability of the palm oil sector and the reduction of green house gases emissions through the efficient management of waste. Nonetheless, our study included only two palm oil mills located in Riau Province, and therefore, the results may not be generalizable to other areas with different operations and regulations. Further studies using a larger sample size, long-term performance of biogas systems, and analysis of the socio-economic impacts will be essential in order to generalises the potential and challenges in scaling POME-based biogas technology up.

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