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Process Efficiency and Integrated Waste Management in Palm Oil Production: A Case Study on Environmental Sustainability

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Abstract

Palm oil mills play a vital role in producing crude palm oil and palm kernels but also generate significant waste with environmental pollution potential. This study analyzes the efficiency of core processing stages—sterilization, threshing, pressing, and refining—as well as supporting processes, focusing on energy use and waste generation. The main waste types include high-BOD and COD liquid waste, and solid waste such as empty fruit bunches and fibre. A descriptive method with a case study approach was used at a selected palm oil mill. Data were gathered through on-site observations, expert interviews, and analysis of production and waste management documents. Waste quality parameters were measured to assess the processing system's effectiveness. Supporting operations such as employee facilities, laboratories, and workshops also produce domestic and hazardous (B3) waste. Domestic waste, including black and grey water, is treated via septic tanks and a domestic wastewater treatment plant. B3 waste is managed through temporary storage before being transferred to authorized handlers. Wastewater sources include processing stages, equipment cleaning, and machine maintenance, which produce oily and sludge residues. Implementing an effective and integrated waste management system is crucial to minimize environmental impacts. This study highlights the importance of improving efficiency across all production and support processes while ensuring sustainable waste management to enhance environmental protection and support the productivity of the palm oil industry.

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1. Introduction

Turning palm oil into crude palm oil (CPO) is carried out through a wet process, where almost all stages use clean water or steam. Each ton of fresh fruit bunches (FFB) requires around 1 m^3 of water to be processed, with a planned production capacity of 20 hours per day. With a processing capacity of 30 tons of FFB per hour, this process's daily clean water requirement reaches around 600 m^3. The source of clean water for this process comes from the river, which is then pumped into a reservoir with a capacity of 65 m^3 per hour. Before being used, the water is first treated in the Water Treatment Plant

(WTP) unit at the palm oil mill with a processing capacity of 40 m^3 per hour (Almardhiyah, Mahidin, Fauzi, Abnisa, & Khairil, 2025; Febijanto et al., 2024; Nizar et al., 2025; Rosdi, Maghfirah, Erdiwansyah, Syafrizal, & Muhibbuddin, 2025). This treatment aims to ensure that the water has adequate quality, both for boiler feed and other factory operational needs.

Liquid waste produced during the processing and washing of equipment is collected in an oil separator pond or fat pit. In the fat pit, oil separation from wastewater occurs based on differences in specific gravity. The upper part of the wastewater overflow is returned to the cleaning unit, while wastewater that still contains a little oil is forwarded to the WTP (Iqbal, Rosdi, Muhtadin, Erdiwansyah, & Faisal, 2025; Jasim, 2020; Muhtadin, Rosdi, Faisal, Erdiwansyah, & Mahyudin, 2025; Muzakki & Putro, 2025). The total sewage produced is estimated to reach 70% of processed FFB, around 420 m^3 per day. Palm oil mill liquid waste mainly comes from several process units, namely the boiling station (35%), clarification process (15%), and factory cleaning activities (50%) (Chew et al., 2022; Gani, Mahidin, Erdiwansyah, Sardjono, & Mokhtar, 2025; Jalaludin, Kamarulzaman, Sudrajad, Rosdi, & Erdiwansyah, 2025; Sumbodo, Yasar, Maulana, & Khalid, 2025). This waste generally has a thick consistency, is brown, and smells, with a fat content of around 60 ppm, oil of 0.8%, and high organic content, including significant BOD and COD levels.

The rest, about 30% of the water from the processing process, remains in the CPO and kernel, is absorbed in the empty bunches, or evaporates due to heating. The liquid waste produced will be processed in a 193.25 m^3 wastewater treatment plant using anaerobic and aerobic systems or biological treatment methods (Gani, Saisa, et al., 2025; Irhamni, Kurnianingtyas, Muhtadin, Bahagia, & Yusop, 2025; Shoukat, Khan, & Jamal, 2019; Talaiekhozani, 2019).

The wastewater disposal process in the leading palm oil processing activities is supported by facilities such as Water Treatment Plant (WTP) for clean water treatment, WTP, employee housing, laboratory, temporary storage for hazardous and toxic waste WTP, office, furnace, and workshop. Waste from the laboratory, WTP, and workshop will be collected and transported by a third party for further handling.

The primary raw material that processes 30 tons of FFB per hour into crude palm oil (CPO) comes from the community's gardens around the factory. With operating hours of 20 hours per day, the amount of FFB processed reaches 600 tons or 180,000 tons per year. In this process, water is the primary supporting material, requiring 1 m^3 per ton of FFB so that the total consumption of clean water per day reaches 600 m^3. The water is taken from the river and processed at the Water Treatment Plant (WTP) before being used, with the addition of chemicals such as soda ash (Na_2CO_3), aluminium sulfat, and caustic soda as supporting processing materials.

2. Methodology

The methods used to achieve the research objectives include quantitative and qualitative approaches, with systematic data collection and analysis.

1). Research Methods

The research method used is a case study in a palm oil factory, with a direct observation approach, interviews, and secondary data analysis. This study aims to:

- ✓ Measuring the efficiency of primary production and supporting processes.
- ✓ Analyze factors that affect processing efficiency.
- ✓ Identifying the primary sources of wastewater generation and its composition.

Methods used:

- ✓ Direct observation to understand the production and waste processing processes.
- ✓ Quantitative analysis uses calculations of production efficiency, oil yield, and loss *rates.*
- ✓ Qualitative analysis by interviewing plant operators and management.
- ✓ Laboratory testing is performed to characterize liquid waste and water quality.

2). Data Collection

Data collection is carried out in the following ways:

a) To Analyze Key Process Efficiency

- ✓ Incoming TBS production data and CPO and kernel production results.
- ✓ Measurement of palm oil yield and *oil losses* at various process points.
- ✓ Process time and tool capacity in each stage of production.
- ✓ Temperature, pressure and other operational parameters.

b) To Analyze the Efficiency of Supporting Processes
- ✓ Consumption of clean water processed at *the Water Treatment Plant (WTP).*
- ✓ *Boiler* efficiency and utilization of palm shells and fibres as fuel.
- ✓ The efficiency of Wastewater Treatment Plants (WWTP) is measured based on BOD, COD, pH, TSS, and temperature parameters.

c) To Analyze the Source of Wastewater Generation
- ✓ The volume of wastewater from boiling, clarification and equipment washing stations.
- ✓ Oil and fat content in wastewater in *fat pits.*
- ✓ Composition of organic and inorganic waste from various sources.
- ✓ Effectiveness of separating oil from wastewater before entering the wastewater treatment plant.

3). Data Processing

Data obtained from observations, measurements, and laboratory tests will be analyzed using the following methods:

- Production Efficiency Analysis
  - ✓ Calculating palm oil yield (CPO yield) is done by comparing the weight of oil produced and the weight of processed FFB.
  - ✓ Measuring *oil losses* in pulp, liquid waste, and *empty bunch.*
- Supporting Process Efficiency Analysis
  - ✓ Calculate water consumption per ton of FFB processed and compare it with industry standards.
  - ✓ Measuring biomass utilisation efficiency (shells & *fibre)* as boiler fuel.
  - ✓ Evaluating the effectiveness of IPAL in reducing BOD, COD, TSS, and oil levels in wastewater.
- Analysis of Wastewater Generation Sources
  - ✓ Calculate the contribution of each process to the total volume of wastewater.
  - ✓ Calculating the percentage of wastewater from each stage of production (boiling station, clarification, washing).
  - ✓ Analyze the content of organic matter and oil residue in waste.

With systematic research methods, accurate data collection and processing, and appropriate tools, this research is expected to provide a comprehensive picture of production efficiency, the performance of supporting facilities, and the primary sources of wastewater generation in palm oil mills.

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3. Result & Discussion

Main Process Efficiency of Palm Oil Processing

The primary process in a palm oil mill includes several critical stages to produce the best quality Crude Palm Oil (CPO) and palm kernel. The flowchart in **Figure 1** illustrates the palm oil processing process in a Palm Oil Mill (PKS) from the beginning to the production of refined crude palm oil. This process begins with using a boiler, which produces steam from water heated using fuel in the form of fibre and shells. The steam produced is used in palm oil's boiling and refining process. The first stage in processing is sterilization, where the Fresh Fruit Bunches (FFB) are boiled using high-pressure steam to stop the activity of enzymes that can reduce the oil quality. The by-product of this process is condensate, which is then discharged to a wastewater treatment unit. After boiling, the process continues to the stripping station, where the palm fruit is separated from the bunches. The empty fruit bunches (EFB) that have been removed are sent to the burning furnace, producing ash as solid waste.

The palm fruit that has been separated from its bunch enters the digester, where the fruit is crushed to make it easier to extract. The following process is pressing and clarification, which consists of several critical stages. The oil that still contains impurities is processed through a filter press and vibrating screen, then collected in a crude oil tank before entering the sand cyclone to separate sand and impurities. Crude palm oil that has gone through this initial process enters the Continuous Settling Tank (CST), where oil, water, and impurities are further separated through a settling process. The liquid that still contains oil is flowed into the sludge tank, while the oil is further processed in a decanter to remove water and solids. The purer oil is then collected in an oil tank before entering the separator, which separates pure oil from the remaining water and impurities.

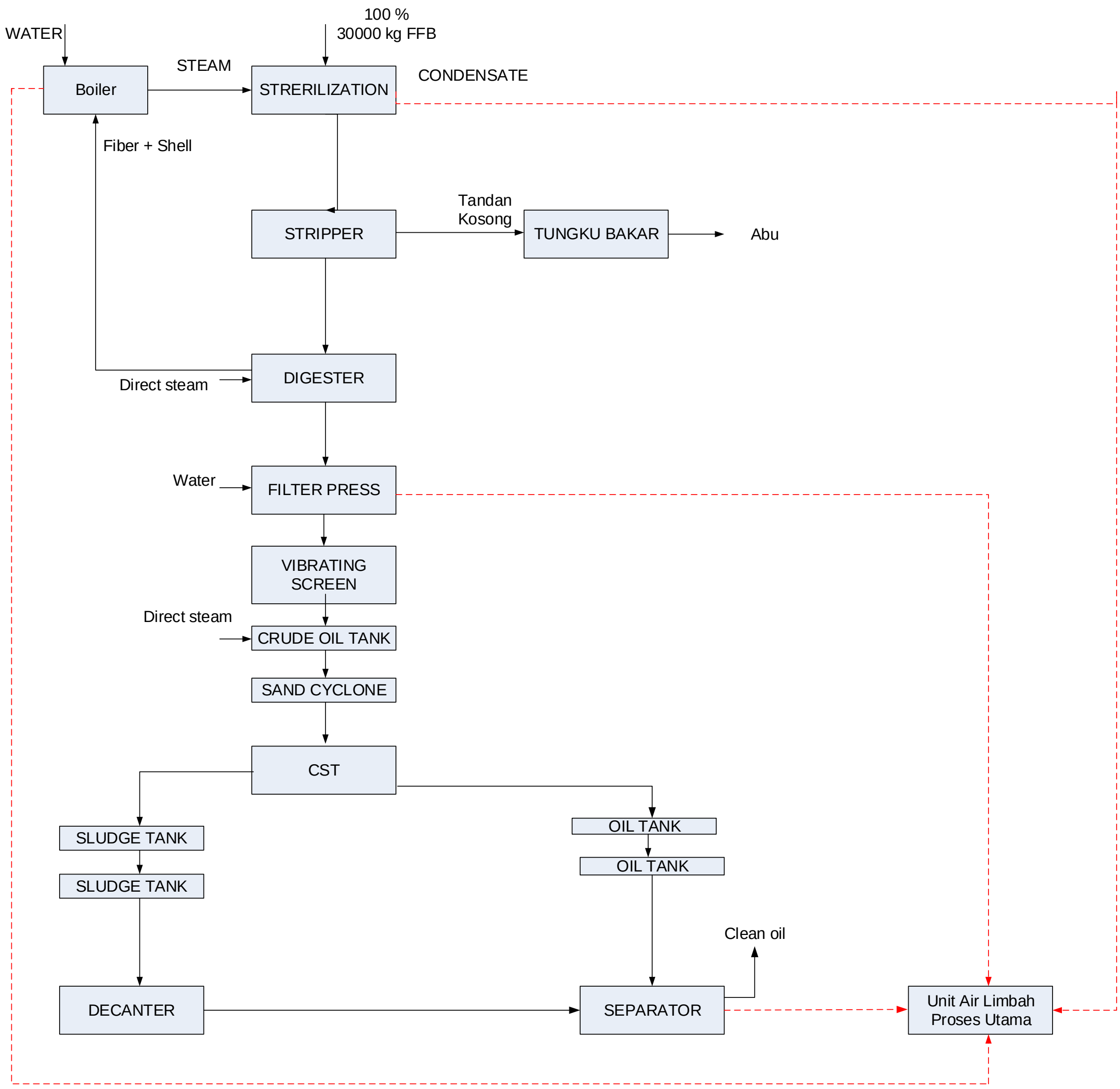

Figure 1: Process Flow Diagram of Main Activities and Wastewater Sources

This process results in clean palm oil, which is ready to be stored in storage tanks or sent to the market. On the other hand, waste generated during the processing process, such as wastewater, empty fruit bunches, and ash, is appropriately managed to reduce environmental impacts. Wastewater from various processing stages is channelled to the wastewater treatment unit, while empty fruit bunches can be reused as fuel or organic fertilizer. Overall, this diagram illustrates a systematic and structured process in palm oil processing, from receiving raw materials to processing crude palm oil and utilizing waste to support the industry's sustainability.

Efficiency of Palm Oil Processing Support Processes

Supporting activities in palm oil mill operations come from the main production process and other supporting activities. One of the primary sources of supporting activities is employee housing, which serves as a place to live for workers and their families. In addition, domestic activities carried out by employees in the office environment and other supporting facilities, such as canteens and places of worship, also contribute to domestic waste. The waste generated from these activities is generally in the form of household waste, including used washing water, kitchen waste, and waste from sanitation facilities. In addition to domestic activities, supporting activities involve laboratories, workshops, and temporary storage for hazardous and toxic waste WTP. The factory laboratory used to test the quality of palm oil and chemicals in production produces liquid waste containing certain chemicals. Likewise, the workshop is used for machine maintenance and repair, which has the potential to produce used lubricating oil and coolant waste. Waste from these facilities requires special handling not to pollute the environment and endanger workers.

The company implements a strict collection system before disposal to manage waste from laboratories, workshops, and WTP. Liquid waste from the laboratory is collected in a special container at WTP, which functions as a temporary storage place before being handed over to a third party with an official permit to process hazardous and toxic waste. By implementing a sound management system, the company ensures that waste generated from supporting activities can be managed safely and following applicable environmental regulations. The diagram of supporting activities and wastewater sources can be seen in **Figure 2**.

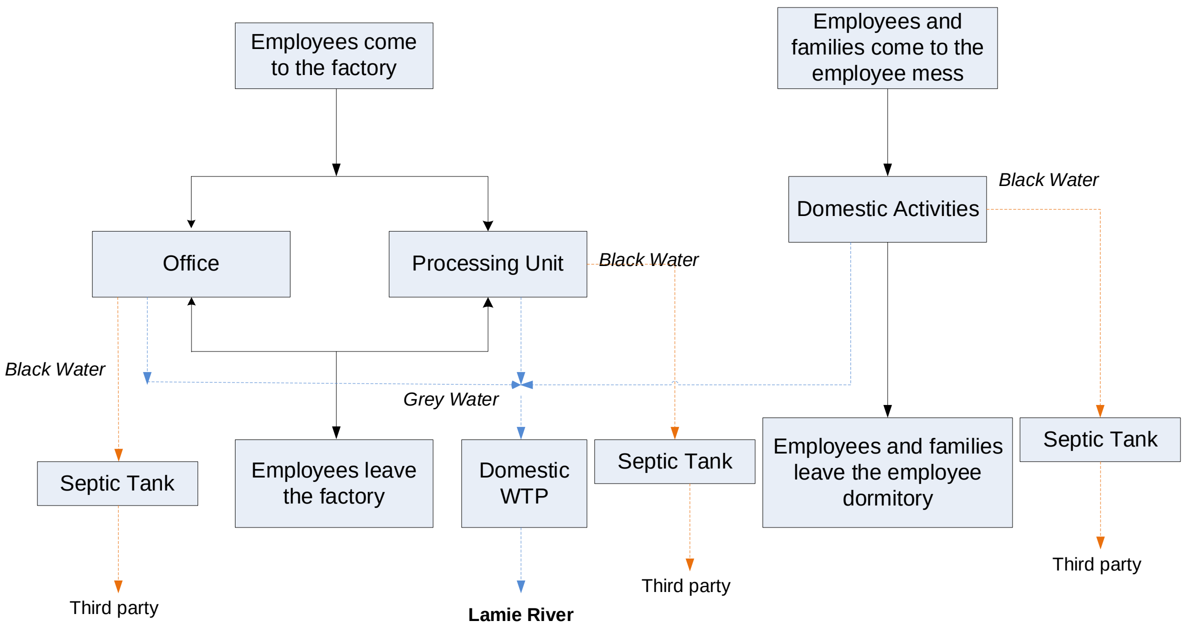

Figure 2: Flowchart of Supporting Activities Process and Wastewater Sources

The flowchart in **Figure 2** above illustrates the process of employee activities in the factory environment and employee mess and how domestic waste is managed. There are two main lines of activity: employees who work in the factory and employees and their families who live in the mess. Employees who come to the factory work in the office and processing unit, while employees and their families carry out various domestic activities in the mess. From these two activities, domestic waste is divided into *Black Water* (waste from toilets and sanitation) and *Grey Water* (waste from other activities such as washing and bathing). The waste management system in this diagram shows that *Black Water* from the office and domestic activities is directly discharged into *a septic tank* before being handed over to a third party for further processing.

Meanwhile, *Grey Water* from the processing unit is discharged into the Domestic Wastewater Treatment Plant (IPAL Domestic) before finally being discharged into a surface water body (River). The separation of these wastewater pathways shows an effort to minimize environmental pollution. However, supervision of the effluent quality from the Domestic IPAL is essential so as not to damage the aquatic ecosystem.

Overall, this system has considered the waste management aspect quite well. However, strict monitoring of the quality of effluent discharged into surface water bodies (Rivers) is needed to comply with environmental standards. In addition, *Black Water management* can be further optimized with modern technology, such as using biogas from septic tanks to support industrial sustainability. A sound system and strict supervision can reduce negative environmental impacts, so factory operations and employee domestic activities can run more environmentally friendly.

Sources of Palm Oil Mill Wastewater

Waste Sources

In the production process of crude palm oil (CPO) in the palm oil mill (POM), various types of liquid waste are produced during the processing stages. This fluid waste comes from multiple processes that convert fresh fruit bundles (FFB) into crude palm oil. Several types of wastewater are produced while processing palm oil into CPO.

Sterilization Station

After weighing, the Fresh Fruit Bunches (FFB) are transported to the boiling station using a perforated steel plate lorry. The lorry is then placed in a sterilizer to be boiled with pressurized steam between 2.2 to 3.0 kg/cm². This process produces condensate containing around 13% palm oil and 15% exhaust steam. Next, the condensate is channelled to the fat pit, while the boiled fruit bunches are sent to the stripping station. The condensate water produced from this sterilization process has a very high BOD content, with a maximum value of 90,000 ppm.

Threshing Station

The fruit bunches that have gone through the boiling process are threshed using a slamming method to release the palm fruit from the bunch. The detached fruit enters the fit conveyor and is immediately directed to the digester. At this stage, the palm fruit bunches are separated from the bunch stalks through two processes using a thresher. This process produces solid waste in empty bunches, estimated to reach 18% of the total raw material. The waste is then transferred to the combustion chamber for fuel. Although this stage does not directly produce wastewater, washing and cleaning equipment produces liquid waste containing oil, fibre, and fine particles.

***Digester* and *Pressing* Station**

The oil palm fruit undergoing the stripping process enters a digester equipped with a stirrer. At this stage, the palm fruit flesh is separated from the seeds using steam at around 80-90°C. The fruit is then crushed continuously so that the pericarp is released from the seeds, and the oil sacs are broken down. The result of this process is a mixture of oil, water, and solids which is then flowed by gravity to the screw press. In the pressing stage, oil is squeezed from the mixture, while hot water is sprayed from the top as a diluent to help extract the oil. Although the crushing and pressing process does not directly produce wastewater, washing and cleaning the equipment produces liquid waste containing oil residue and dirt. However, the main waste produced from this stage is more dominant in the form of solid waste than liquid waste.

CPO Refining

The oil obtained from the pressing process is still cloudy and contains significant amounts of water, so it needs to be purified to prevent hydrolysis and oxidation. Elements such as Fe and Cu in NOS (non-oil solid) can be catalysts in the oxidation process. Oil purification is carried out through three main stages: filtration, sedimentation, and evaporation. The pressed oil is first collected in a tank equipped with a heating system to optimally support the oil clarification process. In addition, this tank receives oil recovered from other storage tanks. Next, the collected oil will be pumped into a continuous settling tank to separate the oil from the water and the remaining solid particles. As in the previous storage tank, this process is also equipped with heating using hot water vapour (steam) distributed through a network of heating pipes. The separated oil in the upper layer will be distributed to the storage tank, while the sediment mud is directed to the fat pit (oil waste pond). The next stage is further purification, where the

oil is cleaned from remaining dirt and other solid particles. Its viscosity is kept low to ensure the efficiency of separating NOS and water from oil.
After the refining process, the oil is then flowed into a vacuum dryer, where the temperature is kept low to prevent damage to the quality of the oil. The dried oil is stored in a CPO tank with a stable temperature setting through a heating system. This entire refining process produces a large amount of liquid waste with characteristics of high temperature (around 70-80°C), dark brown colour, and dissolved and suspended solids in colloids and oil residues. As a result, this wastewater has a reasonably high Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) value, so it requires special handling before being disposed of or further processed.

Waste resulting from the treatment process
Waste from process water washing is generated from the maintenance activities of water treatment systems that use water from reservoirs for production purposes. Over time, water treatment equipment requires regular cleaning to ensure that its operational efficiency is maintained. Waste from equipment and work area washing comes from routine cleaning of production equipment, floors, and factory buildings. This activity aims to maintain cleanliness, sanitation, and order in the work environment to meet factory cleanliness standards. Waste from engine lubricating oil results from factory machines' maintenance and care processes. This waste is generally sludge collected in a waste oil pond (fatpit) before being further managed. In addition, during the refining process, various types of solids such as fibre, sand, soil, and other dirt are also produced. This material is then collected in a holding tank to be used as a road paving material in the plantation area.

4. Conclusion

The primary process of palm oil processing in the mill involves the stages of sterilization, threshing, pressing, and refining of crude palm oil (CPO). The efficiency of each stage is highly dependent on energy utilization, such as using fibre and shells as boiler fuel to produce steam. In addition, a sound refining system, including a Continuous Settling Tank (CST) and separator, is essential in improving the quality of palm oil produced. Waste management from the primary process is also considered, where liquid waste is directed to the wastewater treatment unit, while solid waste, such as empty fruit bunches, is reused. Supporting activities in the palm oil mill operation include employees' domestic activities, laboratory operations, and machine maintenance in the workshop. Domestic waste, consisting of Black and Grey Water, is managed through a septic tank system and Domestic Wastewater Treatment Plant (IPAL). In addition, waste from the laboratory and workshop, especially those classified as Hazardous and Toxic Materials (B3), is stored in the TPS LB3 before being managed by a third party with an official permit. Efforts to increase efficiency in supporting activities are carried out through a strict management system to ensure that the waste produced does not pollute the environment. Palm oil processing produces wastewater from various stages, from sterilization, threshing, and pressing to CPO refining. Condensate water from the sterilization station has a high BOD content, while waste from the pressing and refining processes contains oil and solid particles. In addition, waste from equipment washing, machine maintenance, and cleaning the work area are also sources of pollution that need to be appropriately managed. Waste lubricating oil and oil sludge from the fatpit is collected and used for paving plantation roads. Proper wastewater management is key to maintaining environmental balance and factory operational efficiency.

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