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Simulation and techno-economic evaluation of integrated palm oil mill processes for advancing a circular economy

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ABSTRACT

The palm oil industry faces increasing pressure to adopt sustainable and circular production practices, particularly in waste management and greenhouse gas (GHG) emissions reduction. Integrated biomass utilization within palm oil mills (POMs) offers a promising approach to improve both environmental and economic outcomes. This study evaluates the techno-economic and environmental performance of an integrated POM system incorporating palm oil mill effluent (POME) treatment, empty fruit bunch (EFB) composting, and residual oil recovery within a unified flowsheet. A detailed simulation model of a 60 MT/h mill was developed using SuperPro Designer® software, based on actual mill operations and literature data. The model assessed mass and energy balances, capital and operating costs, and carbon dioxide (CO_2) equivalent emissions. Results showed a 5 % increase in revenue through by-product valorization and a 53 % reduction in CO_2 equivalent emissions when combining EFB composting with biogas capture. The system achieved a positive net present value (NPV) of MYR 75.63 million, an internal rate of return (IRR) of 30.08 %, a return on investment (ROI) of 19.20 %, and a payback period (PBP) of 5.21 years. Sensitivity analysis showed that the prices of fresh fruit bunches (FFB), crude palm oil (CPO), and the CPO yield are key factors influencing economic performance. These outcomes highlight the feasibility of implementing circular economy principles, where waste streams are transformed into valuable products such as compost, biogas, and recovered oil, thereby closing material loops and reducing environmental impact.

1. Introduction

The palm oil industry is a vital component of Malaysia's economy, particularly in rural areas, with 446 palm oil mills (POM) across the country as of 2023, producing approximately 119.7 million tons annually (MPOB, 2023). However, the palm oil milling process, which converts fresh fruit bunch (FFB) into crude palm oil (CPO), generates considerable amounts of both solid and liquid waste. The main solid wastes include empty fruit bunches (EFB), mesocarp fibers (MF), and palm kernel shells (PKS), which produce about 20–25 %, 12–15 %, and 5–7 % of the FFB weight, respectively (Onoja et al., 2019; Rahayu et al., 2018). The liquid waste from the FFB is often generated at around 50–60 % and is known as palm oil mill effluent (POME). This waste stream contributes to environmental challenges, including greenhouse gas (GHG) emissions, water pollution, and the disposal of solid waste (e.g., sludge), highlighting the need for effective management.

Based on the visit to POM, it was observed that the mill has adopted several circular economy practices, such as using PKS and MF as a fuel source for the boiler. EFB is used as compost through simple methods such as passively aerated static piles and rotating windrows. Boiler ash, excess PKS waste, and some composts are sold to any company or individual who wants to buy the biomass waste. The remaining compost is used in oil palm plantations to reduce dependence on chemical fertilizers. POME is treated in open anaerobic and aerobic ponds before being released into the river. However, the mill needs to consider adopting better circular economy methods, such as practicing residual oil recovery, co-composting with other POM waste (POME, boiler ash, and sludge from the oil separation section) to avoid landfill, CH_4 capture and biogas treatment section to avoid harm to the environment as proposed in this study.

According to Kurniawan et al. (2020), the utilization of palm oil solid waste remains suboptimal, with a portion being applied as fertilizer

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while the rest is discarded in landfills. Many researchers have explored the potential of converting biomass waste generated by POM into value-added products. Kurniawan et al. (2025) mentioned that biomass waste can be a resource for biofuel, such as EFB can be converted to biohydrogen through gasification, PKS to biochar through pyrolysis, and anaerobic digestion of POME for biogas production, apart from typical usage as mulch, compost or animal feed. These initiatives not only contribute to waste reduction but also support the circular economy and enhance the sustainability of the palm oil industry. By valorizing these by-products, POM can improve their environmental performance while generating additional revenue streams. According to Siagian et al. (2024), the concept of circular economy involves the reduction, reuse, recycling, and regeneration of resources. The circular economy aims to create closed-loop systems by optimizing the materials and resources while minimizing waste generation.

Co-composting of EFB with other biomass wastes in palm oil mills represents a sustainable strategy for managing agricultural residues, reducing reliance on landfilling, and converting waste into valuable organic fertilizer. This process involves converting fibrous residues such as EFB into compost by incorporating nutrient-rich by-products, including oil palm decanter cake and POME (Zakri and Adam, 2021), anaerobic sludge from POME (Hasan et al., 2018), decanter cake slurry (Yahya et al., 2010), as well as boiler ash and sulfur-rich waste from biogas desulfurization (Tabak et al., 2020). To optimize the carbon-to-nitrogen (C/N) ratio, which is crucial for effective microbial decomposition, urea may be added at the initial stage to increase nitrogen levels and achieve the ideal ratio of 25–30 (Serramiá et al., 2010). According to Zakri and Adam (2021), the addition of oil palm decanter cake and POME to EFB significantly speeds up composting and enhances nutrient content due to a reduced C/N ratio. Additionally, the implementation of bunker composting systems provides a semi-enclosed environment with controlled aeration and temperature, which has been shown to accelerate composting by maintaining optimal heat and moisture levels. In such systems, leachate recirculation is employed to regulate moisture content, further enhancing composting efficiency (Woods, 2023). In compost bunkers, aerobic systems can suppress methane gas generation compared to anaerobic systems (Hamdani et al., 2023). EFB is not suitable for use as a fuel in boilers because it has a higher moisture content of around 57 % which requires high-intensity drying, and it also has a high mineral content, such as K which play an important role for organic fertilizers but are not suitable for combustion, as they will cause clogging and fouling in the boiler (Alaw and Sulaiman, 2020).

POME is a viscous, brownish liquid consisting of approximately 95–96 % water, 0.6–0.7 % oils, and 2–4 % suspended solids from fruit debris (Mohammad et al., 2021; Kan et al., 2024). According to Lim et al. (2021), the study highlighted the potential of various organic feedstocks available in Malaysia (food waste, POME, garden waste, landfill leachate, sewage sludge, and animal manure) for biogas production via anaerobic digestion (AD). The findings indicate that POME and food waste are among the most promising substrates, exhibiting high biogas yields and favorable kinetic performance. However, high levels of residual oil in discharged liquids due to inefficient oil recovery in milling can negatively impact biogas production, as excessive oil interferes with the anaerobic digestion process, reducing methane (CH_4) yields and overall biogas efficiency. In a study conducted by Wongfaed et al. (2020), the presence of higher than 0.16 % oil in POME caused an imbalance in anaerobic digestion performance. Addressing these trade-offs is essential for maximizing the benefits of residual oil recovery while maintaining CPO quality and biogas production efficiency. The cooling pond lowers the POME temperature from 70-90 °C to 30–40 °C, which is ideal for mesophilic bacteria activity in the following stages (Sodri and Septriana, 2022). However, the residual oil that has already undergone thermal exposure and degradation in the cooling pond should be recovered and used exclusively as non-edible oil. Incorporating this oil into CPO may compromise its quality due to the presence of degraded lipids, waxes, fibers, and other unwanted compounds. Yong et al. (2023) reported that POM treats POME using covered lagoons with hydraulic recirculation, where the collected biogas passes through a blower, hydrogen sulfide (H_2S) scrubber, and chiller for purification. According to Sodri and Septriana (2022), this biogas can supply the mill's heat and electricity needs.

According to Hanafiah et al. (2022), understanding the Sustainable Development Goals (SDGs) related co-benefits and trade-offs of various mitigation strategies in palm oil production is essential for assessing their overall impact. Biogas and bio-compost production are particularly important for addressing sustainability challenges within the industry. Capturing CH_4 produced from POME during anaerobic digestion is important, as it would otherwise be released into the atmosphere and contribute to greenhouse gas emissions. This process not only mitigates climate change but also produces renewable energy that can either power the mill itself or be exported to the grid, contributing to SDG 13 (Climate Action). Additionally, converting EFB into biocompost plays a critical role in addressing soil health issues in palm oil plantations. Continuous monocropping and the excessive use of chemical fertilizers have led to declining soil fertility, affecting long-term crop yields and environmental sustainability (Reza and Sabau, 2022). Returning organic nutrients to the soil in the form of biocompost helps restore soil health, improve water retention, and reduce reliance on synthetic fertilizers (Gandahi and Hanafi, 2014), which supports SDG 12 (Responsible Consumption and Production) and SDG 15 (Life on Land).

The comprehensive utilization of POM by-products such as EFB and POME promotes circular economy principles and supports sustainable agricultural practices (Yoshizaki et al., 2013). While technologies exist to transform these waste streams into useful products, such as biogas from POME and compost from EFB, many POMs operate with fragmented systems that treat solid and liquid wastes separately, lacking an integrated approach. There is also a lack of techno-economic data and practical simulation models that evaluate such integrated systems within real-world operating conditions. This gap hinders the potential for optimizing resource recovery, minimizing waste, and maximizing economic returns, which in turn makes millers or stakeholders reluctant to adopt new technologies or invest in machinery to advance biomass treatment systems.

This study aims to systematically investigate the integration of EFB co-composting, biogas capture and treatment, and residual oil recovery into a unified POM processing framework. Using SuperPro Designer® (SPD) software, a comprehensive process simulation is developed that encompasses both core milling operations and the integrated biomass waste treatment systems. As highlighted by Canizales et al. (2020), SPD is equipped with features that enable process scale-up, making it a suitable tool for real-world industrial applications. The novelty of this study lies in its system-wide simulation using SPD software, combined with detailed site-specific data from an operational Malaysian mill, which enables both mass-energy balance and techno-economic evaluation at scale. The model is used to assess the scalability, mass and energy balances, and the overall techno-economic feasibility of the integrated system. Economic evaluation is conducted through key financial indicators such as return on investment (ROI), internal rate of return (IRR), payback period (PBP), and net present value (NPV), along with sensitivity analysis to account for market variables like FFB price, CPO price, and oil yield. Furthermore, the study evaluates the environmental benefits of the integrated approach by quantifying CO_2 equivalent emissions and identifying the reduction achieved through biogas utilization and composting. Through this work, the study provides a practical and scalable solution for enhancing sustainability and supporting circular economy principles in the palm oil industry. Further analysis will explore the potential for energy surplus generation and its implications for grid export or internal reuse.

2. Methodology

2.1. Simulation methodology

In this study, a complete POM including the biomass utilization and POME treatment processes was simulated using the software SuperPro Designer® v12 (SPD) of Intelligence, Inc. The method to construct the POM simulation is based on Heinzle et al. (2008), where the first step is to develop a flow diagram that provides an overview of all processing units and supporting systems, including sterilization, extraction, clarification, and others. The subsequent step involves conducting material balance calculations to ensure precise representation of mass flows across all inputs, outputs, and transformations. As highlighted by Lim et al. (2022), the principles of mass conservation remain applicable even in the presence of chemical reactions and physical transformations during the milling process. The material balance is generated through simulation after key operational parameters, such as temperature, pressure, and flow rates, are specified for each unit operation. This is followed by equipment sizing and cost estimation, utilizing the integrated tools provided within the simulation software. The model then undergoes economic evaluation to calculate financial metrics like total capital investment (TCI), operating cost, NPV, IRR, ROI and PBP. Additionally, waste stream characterization is performed to assess environmental impacts and recovery opportunities.

2.2. Site visit and data collection

A site visit was conducted at confidential POM facilities in Pahang, Malaysia, to gather firsthand operational data and technical insights for the development of a simulation model. During the visit, a structured approach was employed to collect relevant operational data. Direct on-site observations were made across all major processing units to understand the sequence of operations, material flow, and energy usage. Informal interviews and technical discussions with plant personnel were conducted to gather insights into equipment capacities, production yields, utility consumption, and existing waste valorization practices. Visual documentation, including process flow sketches and anonymized photographs (retained for internal use), was compiled to aid in simulation structuring. Key operational parameters such as processing times, yield efficiencies, steam and water consumption, and retention times in treatment units were recorded based on available information. To ensure completeness and consistency, the collected data were cross-referenced with values reported in the literature and national benchmarks provided by the Malaysian Palm Oil Board (MPOB). The validated site-specific information was subsequently integrated into the SPD platform to simulate an industrial-scale POM and assess the techno-economic and environmental performance of a system incorporating integrated biomass utilization strategies.

2.3. Process design description

A conventional POM with a capacity of 60 MT of FFB/h and 5640 annual operating hours (AOH) to produce CPO through a series of interconnected processing and supporting units, as shown in Figs. 1 and 2. Generally, POM consists of several core sections to process the FFB to produce CPO, which are the sterilization section, oil extraction section, oil separation section, mesocarp section, and kernel section, as shown in Fig. 1. Moreover, the POM also includes supporting sections (Fig. 2) such as the feed water system, boiler system, and waste management units, including POME treatment, EFB composting, and residual oil recovery section. The detailed process flowsheet of the overall process design can be found in the supplementary document (Fig. S1).

In this study, horizontal sterilization was chosen as it is employed in most POMs that process FFB using cages. The method employs a horizontal-cylindrical autoclave operating at 140 °C and 3 bar for 90 min. This process is designed to loosen the fruit from the bunch,

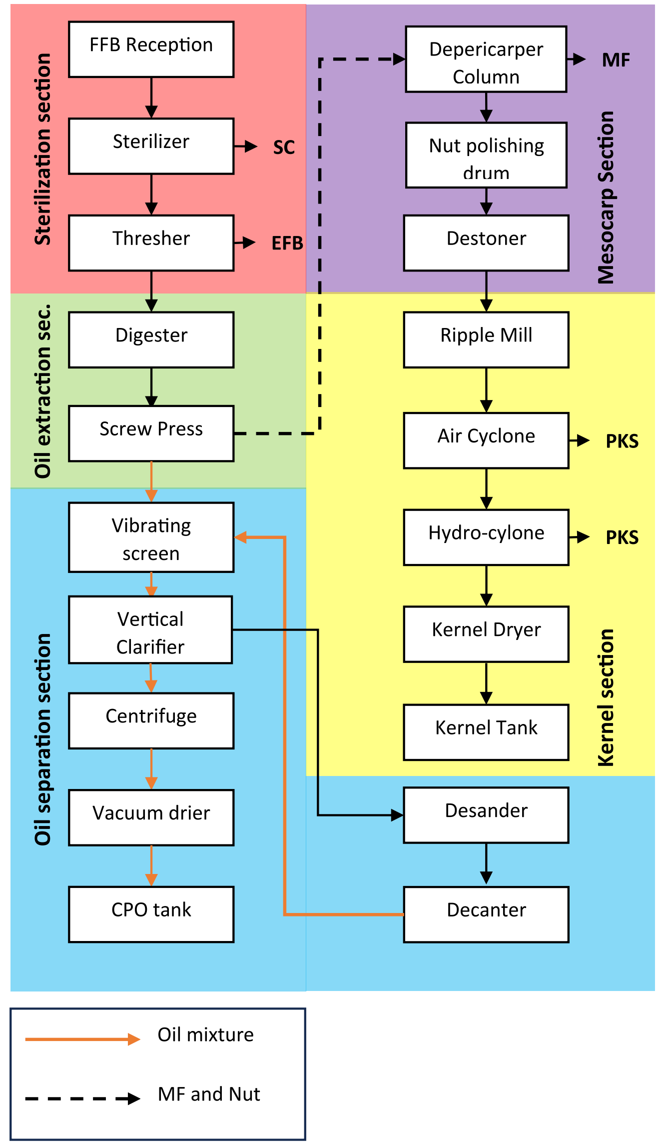


Fig. 1. Block flow diagram for the main processing unit in POM.

deactivate enzymes to prevent an increase in free fatty acids (FFA), and soften the fruit tissue to enhance oil extraction (Sivasothy, 2000). Post-sterilization, the fruit bunches are transferred to a rotating threshing drum, where the fruits are separated, leaving behind EFB as a by-product. In the oil extraction section, the fruitlets are digested in steam-heated vessels called digester, where they are heated and stirred to break down the oil-bearing cells, forming a mash. High-temperature steam (140 °C) is used to reduce the oil's viscosity, facilitating its extraction. The mash is then pressed to separate the oil from the solid material. The liquid phase, containing the oil, is directed to the oil separation section, while the solid phase moves to the mesocarp and kernel sections as depicted in Fig. 1.

The oil separation section is responsible for purifying the crude oil extracted from the fruit mash. Hot water, typically between 90 °C and 100 °C, is added to crude palm oil to reduce the oil's viscosity, thereby enhancing mixing and promoting more efficient separation of impurities. The process utilizes vibrating screens and clarifiers to create two phases: the lighter phase is directed to centrifuges and vacuum drying, while the heavier phase goes to desanders and decanters to remove impurities such as sand, water, cell debris, and fibrous material, before being recycled back to the vibrating screen-clarifier, as shown in Fig. 1. The purified CPO is then stored in CPO tanks to ensure its quality and

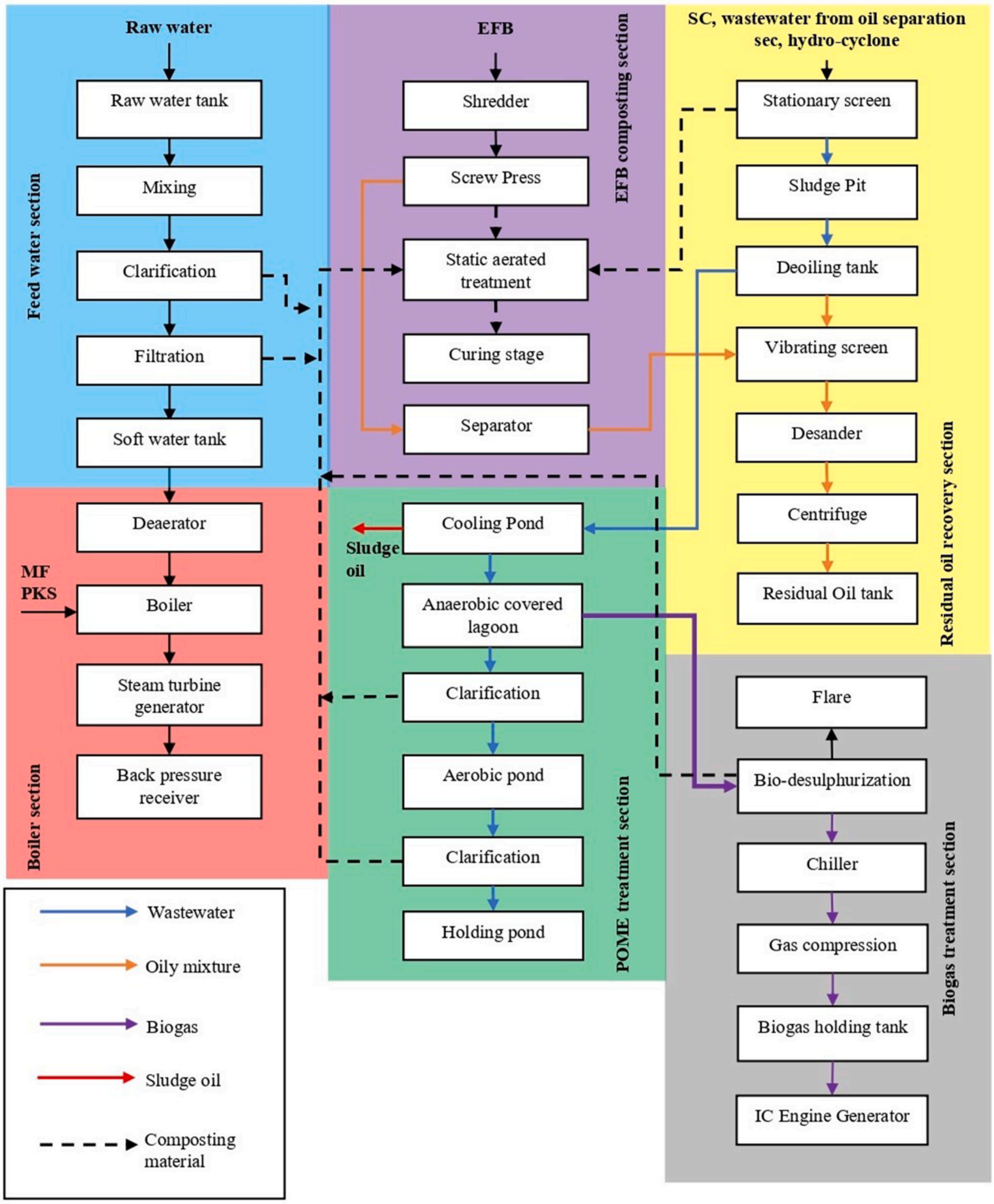


Fig. 2. Block flow diagram of utility systems, waste treatment, and by-product utilization in POM.

stability.

The solid phase from pressing, consisting of MF and palm nuts, enters the mesocarp section. Here, the MF is separated from the nuts using a depericarper column and polishing drums. The high-calorific value fibers are then stored for use as fuel in the mill's boiler system, providing an energy-efficient solution to waste management. The nuts, comprising PKS and palm kernels (PK), are processed in the kernel section. A nut cracker cracks the nuts, separating the PKS from the PK. This is followed by separation of light PKS using air cyclones and heavy PKS separated using hydro cyclones. Water is added to the hydrocyclone, which uses centrifugal forces to separate the PK from the wet PKS. The PK are dried in a kernel bed dryer to remove moisture before storage, while the PKS are collected for use as boiler fuel, enhancing the mill's energy sustainability. The design of mesocarp and kernel sections were based on the description by Kadir et al. (2020).

Feed water section, as shown in Fig. 2 is where the raw water from waterways such as rivers will be treated. Raw water contains impurities such as turbidity, color, suspended solid, dissolved solid, hardness, and dissolved gas (Arachchige and Sakuna, 2020). Water treatment processes include pH adjustment, sedimentation, filtration, and deaeration, ensuring that impurities are removed to protect the boiler system's performance and longevity. In the boiler section, MF and PKS are used as fuel in a biomass combined heat and power system. While a portion of the PKS and MF powers the boiler, a significant amount of PKS is also sold to external biomass boiler operators. The boiler generates steam to drive turbines for power production and supplies heat for essential mill processes such as sterilization, digestion, clarification, and oil drying. This system efficiently meets the mill's energy requirements, minimizing dependency on external power sources.

Raw liquid effluents generated from the clarification process, sterilizer condensate, and the hydro-cyclone (in kernel section) contain high levels of organic matter and suspended solids, posing environmental risks if not treated properly. This study proposes directing these effluents to a residual oil recovery section (Fig. 2), where residual oil will be skimmed from the sludge pit and de-oiling tank. This recovered oil or skimmed oil obtained from shredded-pressed EFB liquor (from the EFB composting section) will then pass through vibrating screen and desander to remove sand and fibrous materials. The stream will subsequently be directed to a centrifuge to separate the oil from water and remaining impurities. The recovered oil will be sent back to the oil separation section, entering the oil tank after clarification. Finally, the liquid effluents will be transferred to a cooling pond as POME (in POME treatment section).

The remaining solid material, shredded and pressed EFB, will undergo co-composting with nutrient- and nitrogen-rich materials, such as sludges from raw water and POME treatment and decanter cake. Urea is added in the initial stage so that the ratio of C/N is close to 30:1. Throughout the 35 days, the composting material undergoes static aerated treatment in bunker composters as proposed by Surya et al. (2019), progressing through the thermophilic phase (50–70 °C) until the temperature declines, with the aid of microbial inoculant to speed the process. Afterwards, the compost is transferred to the curing stage under passive aeration, where mesophilic activity occurs, followed by a gradual temperature drop. The POME treatment system (Fig. 2) processes this wastewater to make it safe for discharge into rivers, thereby preventing harm to aquatic life. Treatment involves a series of ponds, generally from cooling ponds, anaerobic digestion (AD) ponds, and aerobic ponds. In the cooling pond, low-quality residual oil, or sludge oil, accumulates and deteriorates; because it is not economical for the POM to process this oil, it is typically sold to external parties for recovery and conversion into biofuels like biodiesel and sustainable aviation fuel, contributing to waste reduction and the circular economy.

In the AD stage of the POME treatment section, microbial activity decomposes complex organic compounds such as carbohydrates, fats, and proteins into simpler molecules like glucose, FFA, and amino acids. Acidogenic microbes then further convert these molecules into CO_2, H_2, NH_3, and volatile organic acids. Subsequently, methanogenic bacteria transform these intermediates into CH_4 and CO_2, thus generating biogas (Sodri and Septriana, 2022; Lok et al., 2020). The AD covered lagoon, a large engineered pond with a gas-tight cover, captures the biogas produced during this process. Following AD, the AD-treated POME is directed to clarification tanks for sedimentation; in this study, the digestate sludge will be transferred to the composting section, while the wastewater proceeds to the aerobic pond for further treatment.

Biogas from AD typically contains CH_4, CO_2, H_2S, and moisture. H_2S is removed via biological scrubbers, favored for their low operating costs (Alinezhad et al., 2019). As shown in Fig. 2, moisture is reduced using a chiller, which dehumidifies the gas, removing up to 80 % of water to prevent condensation and acid formation. The biogas is then passed to internal combustion (IC) engine generator to produce additional electricity for the POM. Any excess biogas that cannot be stored or used is safely eliminated through emergency flaring to prevent overpressure in the gas reservoir.

After defining the processes in each section in POM, key operational parameters for each unit were set in SPD simulation. These parameters, crucial for ensuring efficiency and optimal performance, include factors such as temperature, pressure, and mixing ratio. A detailed list of the parameters for each unit is presented in Table 1 below, providing a breakdown of the inputs and set up descriptions required for each section in the POM.

Table 1
Input parameters descriptions and references for POM unit in SPD simulation.

Main Unit	Parameter Description	References
Sterilizer (GBX-106)	Steam with 140 °C and 3 bar Steam utilized around 0.25–0.45 MT/MT FFB Steam lost 0.15 MT/MT FFB	Sivasothy (2000) Foong et al. (2018)
Digester (R-101)	Steam with 140 °C used is 0.13 MT/MT FFB Steam lost 0.09 MT/MT FFB	Foong et al. (2018)
Screw press (SP-102)	Hot water to make up for steam loss (0.09 MT/MT FFB) and facilitate oil extraction	Foong et al. (2018)
Vibrating screen (VSCR-102)	Hot water at 100 °C dilutes crude palm oil to ~ 40 % oil content	Mohammad et al. (2021)
Vertical clarifier (CL-101)	Steam 140 °C is used (0.001 MT/MT FFB) to maintain at 90 °C	
Vacuum drier (GBX-114)	Under vacuum at 0.91 bar and 102 °C	Akhbari et al. (2019); Muarif et al. (2022)
Decanter (DC-101)	Hot water (100 °C) used is approximately 0.0625 MT/MT FFB	Chungsiriporn et al. (2006)
Boiler (SG-101)	Steam conditions at 20 bar and 310 °C	Aravind et al. (2015)
Steam turbine (ST-101)	Exhaust steam at 3.1 bar and 140 °C	Aravind et al. (2015)
Static aerated composting (PFAB-101)	HRT 35 days	Shafawati and Siddique (2013)
	5% O_2 in composting pile	Azim et al. (2017)
Curing stage (composting) (PFAB-102)	HRT 15 days with passive aeration	
Anaerobic digester (covered lagoon) (AD-101)	HRT 50 days	Lok et al. (2020)
Aerobic pond (AB-101)	HRT 6 days	Lok et al. (2020)
IC engine generator (ICEG-101)	Exhaust temperature 480 °C	Varis and Ozkilic (2023)

The data without citation is data from site visit to local POM.

2.4. Mass balance

The digester is one of the key components in the palm oil milling process, playing a critical role in breaking down the cellular structure of sterilized palm oil fruitlets and exposing its constituents, thereby enhancing the efficiency of oil extraction. The composition of the sterilized palm fruitlet was determined using a mass balance approach, based on its specific constituent components. According to Wondi et al. (2021), the composition of sterilized palm oil fruitlets consists of approximately 75.13 % mesocarp, 22.87 % nut. According to Mathews and Ardiyanto (2016), the oil content in the mesocarp is within 42–50 %. Then, it was calculated based on the weight of the fruitlet and represented as a “reaction” with the mass stoichiometric as follows:

$$100\ \text{Sterilized Fruitlet} \rightarrow 31.86\ \text{Oil} + 0.96\ \text{FFA} + 24\ \text{MF} + 21.3\ \text{Nut} + 1.2\ \text{Sugar} + 0.68\ \text{Protein} + 20\ H_2O \quad (1)$$

Other than the digester, the nut crackers also play a role in cracking the nut and exposing the PK as part of POM revenue together with PKS, which can be sold as a by-product for extra income or boiler fuel. In general, the FFB (wet weight) consists of 23 % EFB, 21 % oil, 14–15 % MF, 6–7 % PK, and 6–7 % PKS according to Husain et al. (2002). Based on this composition, the mass stoichiometric of cracked nuts is represented as below:

$$100\ \text{Nut} \rightarrow 51\ \text{PKS} + 49\ \text{PK} \quad (2)$$

The AD process involves four main stages such as hydrolysis, fermentation (acidogenesis), acetogenesis, and methanogenesis. Methanogenesis is a vital step for the production of biogas, which contains 50–75 % CH_4 (Lok et al., 2020). The mass balances for anaerobic digestion, aerobic treatment of POME, and aerobic composting of EFB, expressed in molar stoichiometry, are summarized in Table S1 (Supplementary Document). After anaerobic digestion, POME undergoes aerobic treatment to further reduce COD and BOD by decomposing residual organic matter. Meanwhile, EFB is aerobically composted, breaking down lignocellulosic material into nutrient-rich compost through microbial activity in the presence of oxygen.

2.5. Estimation of TCI and operating cost

TCI refers to the fixed costs associated with the process, and it was calculated as the sum of cost items such as direct fixed capital (DFC), working capital (WC), and startup and validation cost (SC). The DFC is the sum of total plant cost (TPC) and contractor's fee and contingency (CFC). TPC is the sum of total plant direct cost TPDC and the total plant indirect cost TPIC. Starting with finding the equipment purchase cost (PC), other TPDC items, such as the equipment installation, process piping, instrumentation, etc., were estimated by multiplying PC by a suitable factor or multiplier (Peters et al., 2006). PC for the POM sourced from literature and the SPD database. The price and capacity of each main equipment are detailed in the supplementary document, Table S2.

The operating cost was estimated based on raw materials, labor, facility-dependent costs, utilities, and laboratory/QC/QA costs. Labor costs cover all labor-related operating expenses, excluding those associated with laboratory analyses, quality control, and quality assurance, which are accounted for separately under laboratory/QC/QA costs. Facility costs account for equipment maintenance, depreciation, insurance, local taxes, and other overhead-type of factory expenses (Zhuang et al., 2007). All these costs are estimated by SPD simulation.

In the simulation, the price of FFB is MYR 869.87/MT, while the selling prices for CPO, PK, PKS, and compost were also identified and summarized in Table 2. The hourly labor cost of MYR 7.21 in Malaysia is derived from the monthly minimum wage of MYR 1,500, which is the baseline for workers in most industries (Wen and Sieng, 2023).

2.6. Economic analysis

Economic evaluation will be performed using the inbuilt functions of SPD, utilizing simulation results such as NPV, IRR, ROI, and payback period (PBP) to assess the financial viability of the POM. In this study, NPV was calculated based on a 10 % discount rate, while IRR represents the discount rate at which NPV equals zero. These financial indices were all computed using the SPD simulation. Parameters used in these calculations include an income tax rate of 24 %, an installment loan based on 40 % DFC, and Malaysia's average interest rate of 5 % (Mokhtar, 2022). The POM project life is 15 years, with a construction period of 20 months and a start-up period of 4 months.

2.7. Sensitivity analysis

Monte Carlo simulation was then performed using excel spreadsheet to evaluate the impact of variability in multiple input parameters such as FFB price, CPO price, CPO yield, AOH, operator cost, and DFC on the economic indicator (NPV, IRR, ROI, PBP). Each input parameter was assigned a probability distribution based on expected variability, as outlined in Table S3. Thousands of iterations were performed, with each iteration randomly sampling values from the defined distributions and calculating the corresponding output through an economic model. This process provides insight into how variations in input parameters contribute to the overall variance in the economic indicators. By analyzing the output distribution, sensitivity analysis of the model was conducted to evaluate its sensitivity to different input factors and identify which parameters most significantly contribute to the overall uncertainty in the output.

Table 2
Purchasing price or selling price for each material.

Components/Stream	Price (MYR/MT)	References
FFB	869.87	MPOB, 2025
CPO	4095.5	MPOB, 2025
PK	3136.5	MPOB, 2025
PKS	230	Gravitiani et al. (2021)
Compost	225	Huailuek et al. (2019)
Sludge oil	2,800	Acevedo et al. (2015)

2.8. Influences of capacity

Initially, each equipment unit was set at its full capacity. When the capacity of each equipment unit exceeded the maximum limit, several equipment units were included in the SPD simulation. In this study, the POM capacity was reduced from 60 MT/h to 30 MT/h or increased to 90 MT/h. The effects on economic parameters such as NPV, IRR, PBP and ROI at different plant capacities were compared.

2.9. CO_2 equivalent emission

This study employs a quantitative, simulation-based approach using SPD software to model and evaluate CO_2 emissions across the CPO production process. The system boundaries encompass cradle-to-gate stages, which start from FFB reception to CPO production, excluding logistics outside POM, refining, and downstream activities. These stages, modeled in the SPD simulation, include all major operations within the POM: sterilization, threshing, digestion, pressing, clarification, and depericarping, along with energy consumption and emissions and handling of byproducts throughout the production cycle. Based on Sasmita and Lestari (2019), emissions from a POM are classified into four primary sources: generator sets, boiler operations, POME treatment, and transportation. In this study, emissions from the composting process were also considered, as composting is integrated into the POM simulation. To quantify GHG emissions and potential reductions, the study utilizes Global Warming Potentials (GWP) established by the Intergovernmental Panel on Climate Change (IPCC), comparing each GHG's heat-trapping ability relative to CO_2, with GWP factors of 1 for CO_2, 25 for CH_4, and 298 for N_2O (Subramaniam et al., 2021).

Diesel generator is utilized to supply power during the startup phase of the factory (Yusniati and Parinduri, 2018). For diesel generator emission, the simulation calculates CO_2 output based on fuel consumption rate, with a diesel usage rate of 0.53 L/MT of FFB processed (Jamaludin et al., 2018). CO_2 emission from diesel use is determined using reaction stoichiometry of combustion set in SPD simulation. After that, the result is cross-validated with manual calculations in excel sheet. Standard calculations use a net caloric value of the fuel of 36×10^{-6} TJ/L and an emission factor of 74,100 kg CO_2/TJ (Sari et al., 2019a; Sasmita and Lestari, 2019). The diesel consumption of the POM generator was calculated using the equation proposed by Sari (2019b) and Sasmita and Lestari (2019), as follows:

$$E = A \times NCV \times EF \tag{3}$$

where,

E = Emissions (kg CO_2 eq/h).
A = Amount of fuel consumed (L).
NCV = Net caloric value of the fuel (TJ/L).
EF = Emission factor (kg/TJ).

On-site electricity is generated using boilers fueled by MF and PKS, both of which are biomass byproducts of the milling process. The SPD simulation calculates CO_2 emissions based on the composition of exhaust gases from combustion. These results are validated against reported values in the literature to ensure consistency and accuracy.

For POME treatment emissions, the study estimates CO_2 equivalent emissions from both anaerobic and aerobic digestion processes. CO_2 emissions from biogas combustion are also included in the assessment. Specifically, CH_4 produced through anaerobic digestion is routed to an IC engine-generator, where it generates electricity for the mill and releases CO_2 during combustion reaction in SPD. Additionally, any excess biogas that cannot be utilized is flared, producing further CO_2 emissions. The CO_2 emissions from IC, flaring, and aerobic digestion in open ponds are all integrated into the overall emission calculations.

Transportation emissions are estimated based on the diesel consumption of the tractors used for FFB reception and composting operations. Based on Jamaludin et al. (2018), the average diesel consumption is 0.21 L/MT of FFB. It is assumed that the diesel consumption of the tractor is the same for both FFB reception and the composting station. This is because the tractor moves frequently each day, even over short distances, which adds to its diesel consumption. A mass balance approach estimates CO_2 emissions using a diesel emission factor of 2.68 kg CO_2 eq/L (Azeez, 2016), enabling comparison of simulated and calculated emissions (Sasmita and Lestari, 2019; Subramaniam et al., 2021). The transportation emission of the POM was calculated using the equation proposed by Sasmita and Lestari (2019), as follows:

$$E = A \times EF \quad (4)$$

where,

E = Emissions (kg CO_2 eq/h).
A = Amount of fuel consumed (L).
EF = Emission factor (kg CO_2 eq/L).

In composting, CO_2 emissions arise from the aerobic decomposition of EFB and other organic materials. The simulation quantifies these composting emissions and contrasts them with emissions from conventional EFB mulching. This comparison reveals the environmental benefits and emissions reductions achieved through composting as an alternative treatment approach.

3. Results and discussion

3.1. Simulation results

The simulation of a 60 MT/h FFB capacity POM was conducted with 5640 AOH. The detailed flowsheet of the SPD simulation is provided in the supplementary document as Fig. S1. The results of this simulation were compared and analyzed against data from existing mills and relevant literature, as detailed in Table 3. This comparison validates the simulation outcomes and offers insights into the mill's performance relative to industry benchmarks and documented studies. All simulation data must fall within the range of actual mill data for the economic analysis to be accurate. If the data is not within the acceptable range, the simulation must be adjusted until it aligns with validated data.

The simulation data records a CPO yield of 12,249 kg/h, translating to an OER of 20.4 %. This falls within the commonly reported OER range of 19–22 %, aligning well with industrial norms for crude palm oil mills. The OER is a critical parameter for assessing the efficiency of palm oil extraction, and the close alignment with literature confirms the reliability of the simulation model. The simulation's kernel extraction rate (KER) of 4.39 % (yielding 2631 kg/h) aligns with the reported range of 4–6 % relative to FFB, validating the palm kernel extraction efficiency of the simulated model. Ensuring KER consistency with industrial standards is essential, as PK recovery contributes significantly to profitability and resource efficiency.

It also highlights significant biomass generation, where the simulation indicates that EFB, PKS and MF comprise approximately 25.48 %, 5.79 % and 12.88 % of the total FFB, respectively. This aligns with the ranges proposed by Rahayu et al. (2018), which are 20–30 % for EFB, 5–7 % for PKS, and 11–15 % for MF. PKS, MF and EFB are essential by-products used for energy generation and EFB composting. Maintaining their effective utilization is vital for optimizing energy efficiency and reducing waste within the mill. The liquid wastewater, POME, representing 71 % of FFB (43.53 MT/h), also aligns with the literature range between 50 and 75 % (Table 3).

As described in Table 3, the simulation estimates water usage at 1 m^3/MT FFB, within the range of 1–1.2 m^3/MT FFB in the literature. It also estimates the power consumption of 1056 kWh (17.61 kWh/MT FFB), aligning with industry standards (17-19 kWh/MT FFB), reinforcing the energy demands of processing. In terms of energy self-sufficiency, the POM operates independently regarding power consumption. Two main sections contribute to electricity generation: the boiler section, where steam boilers with turbines utilize PKS and MF as fuel, and the biogas section, where IC engine generators use biogas as fuel. The biogas yield from the AD lagoon was simulated at 0.37 m^3 CH_4/kg-$COD_{removed}$, almost similar to the documented yield of 0.39 m^3 CH_4/kg-COD $_{removed}$. CH_4 production reached 7.62 kg/m^3 of POME (331.67 kg/h), which is close to the reported value 10 kg/m^3 of POME. The composition of biogas from the AD lagoon is described in Table S4. COD and BOD removal efficiencies of 83 % and 84 % through AD treatment, which is comparable with the literature (Table 3). The electricity generated by the biogas section is around 1436.21 kWh which is also within the literature range.

Regarding the composting process, the initial biomass weight is 18566 kg/h entering the system. By the end of the composting process, the final compost weight is reduced to 10070 kg/h, representing a 46 % reduction in weight. This reduction aligns with findings by Supriatna et al. (2022), which state that the weight reduction of EFB compost can range from 30 % to 50 % of the initial weight. The decomposition of

Table 3
Result of simulation compared to the previous studies.

Component/ Characterization	Simulation data (60 MT/h FFB)	Previous studies	References
CPO	OER: 20.4 %	OER:19–22 %	Andrew et al. (2017),
FFA	3.13 % in CPO	<5 % in CPO	
PK	4.39 % to FFB	4–6 % to FFB	Hashim et al. (2012)
EFB	25.48 % to FFB	20–30 % to FFB	Rahayu et al. (2018)
MF	12.88 % to FFB	11–15 % to FFB	Rahayu et al. (2018)
PKS	5.79 % to FFB	5–7 % to FFB	Rahayu et al. (2018)
POME	71 % to FFB	50–75 % to FFB	Rahayu et al. (2018)
Water consumed	1 m^3/MT FFB	1–1.2 m^3/MT FFB	Nasrin et al. (2024)
CH_4	331.67 kg/h	200–841 kg/h	Sarwani et al. (2024),
(in biogas)	(50.7 %)	(50–75 %)	Rahayu et al. (2018)
Biogas yield	0.37m^3 CH_4/kg-$COD_{removed}$	0.39 m^3 CH_4/kg-$COD_{removed}$	Yong et al. (2023)
AD treatment			Kan et al. (2024)
COD removal	83 %	80.6 %	
BOD removal	84 %	87.4 %	
Oil loss			Hassan et al. (2012)
Oil loss to fresh EFB	0.70 % to FFB	0.59 %–1.31 % to FFB	
Oil loss to shredded-pressed EFB	0.18 % to FFB		
Oil loss to POME	0.44 % to FFB	0.42–0.5 to FFB (base on 0.6–0.7 % to POME)	Primandari et al. (2013)
Oil loss to press fiber/ MF	0.52 % to FFB	0.25 %–0.55 % to FFB	Subramaniam et al. (2013)
Others (surface of PKS & PK, decanter cake)	0.23 % to FFB		
Total oil loss	1.30 % to FFB		
Total oil loss (without residual oil recovery)	1.70 % to FFB	1.77 % to FFB	Hassan et al. (2012)
Power consumed	17.61kWh/MT FFB)	17-19 kWh/MT FFB	Yusoff (2006)
Power Generated			
Generator (biogas)	1436.21kWh	1250 kW–2500 kW	Nuaini et al. (2018)
Turbine (boiler)	1146 kWh	1200 kWh (60 MT FFB/h),	Yusoff (2006)
	93.55 kWh/MT CPO	102 kWh/MT CPO	Subramaniam et al. (2021)
Compost	0.50 MT/MT EFB	0.30–0.50 MT/ MT EFB	Supriatna et al. (2022)

organic matter, moisture loss through evaporation, the release of volatile organic compounds during decomposition and chemical transformations within the organic matter result in more stable forms that occupy less weight. These combined factors explain the substantial weight decrease in compost produced from palm oil waste.

Apart from biogas capture and composting, the POM focuses on recovering residual oil and increasing revenues. Fresh EFB contains significant residual oil due to its lignocellulosic structure, which adsorbs and retains oil in its fibers, and unstripped bunches (USB), which contribute to oil loss. Nadzim et al. (2020) reported oil losses from EFB as 0.45 % to FFB due to surface adsorption, 0.05 % from USB, and 0.02 % from trapped fruit. Similarly, Walat and Bock (2013) found total oil loss from EFB, including USB, to be about 0.58 % of FFB. In this study, oil loss without shredding and pressing at 0.7 % to FFB is slightly higher than previous findings due to stripping at post-sterilization. Hassan et al. (2012) observed oil losses after sterilization and stripping ranging from 0.59 to 1.31 % to FFB. However, this simulation demonstrated that shredding and pressing fresh EFB reduced oil losses to 0.51 % of FFB, achieving an oil recovery of 25–30 %.

The liquid-oil mixture from the EFB press flows to a separator, where the lighter oil phase, achieving approximately 35 % recovery, is directed to the residual oil recovery section. Meanwhile, the heavier phase is routed to the sludge pit and de-oiling tank, combined with effluents from other sources such as sterilizer condensate, decanter, and hydrocyclone for further oil recovery within the same section. Simulation results indicate that the sludge pit and de-oiling system recover approximately 45 % of the oil, consistent with the 35–55 % recovery range of physical methods like trapping and skimming (Tang et al., 2023). The recovered oil from the sludge pit and de-oiling system is combined with the oil from the EFB press (lighter phase) and directed to vibrating screening, desanding, and centrifugation in the residual oil recovery section. These steps are essential for separating oil from contaminants (e.g., water, fibers, waxes, etc.). The resulting stream, containing ~70 % oil, is transferred to the oil tank (with main CPO) before undergoing centrifugation and vacuum drying in the oil separation section. Improving oil recovery in the sludge pit, de-oiling tank, or a combination of both as an integrated system is crucial to minimizing oil loss in POME. Therefore, further research and the adoption of innovative technologies are highly recommended. For example, applying microbubble technology combined with an optimized skimming technique offers significant potential to enhance residual oil recovery above 85 % (Shen et al., 2022), a method that is currently underutilized in POM.

After passing through the residual oil recovery section, the effluent still contains residual oil, equivalent to 0.6 % of the total oil content. This residual oil flows to the cooling pond in the POME treatment section, contributing to an estimated oil loss of 0.44 % relative to FFB. Over time, the residual oil undergoes chemical and biochemical reactions, resulting in a darker color that indicates lower quality. Some of this oil, often seen floating on the cooling pond surface, can be partially recovered and sold as sludge palm oil. However, not all residual oil is recoverable; heavily contaminated sludge oil in the cooling pond is often uneconomical to process and unsuitable for edible applications. Approximately 0.06 % of FFB of sludge oil is recovered from the cooling ponds.

Oil loss in palm oil mills is a critical parameter affecting the overall efficiency of CPO production. Based on the provided data, the total oil loss in this study is reported as 1.30 % to FFB, which includes 0.23 % attributed to other sources such as PK surface, PKS surface, and decanter cake. However, without a residual oil recovery system, this simulation study estimated oil loss would increase to 1.70 %, consistent with findings from Hassan et al. (2012). It means that the residual oil recovery section can boost the OER by 0.54 %, translating to an additional annual revenue of approximately MYR 7,068,177. This highlights the significance of incorporating an oil recovery system to reduce oil loss and enhance process efficiency, minimizing waste and improving the sustainability of palm oil production.

3.2. Economic analysis

In this section, we evaluate the financial feasibility of the POM after integration with biomass treatment or utilization processes. Table 4 provides a detailed breakdown of the capital investment, categorized into DFC, WC, and SC. Table 5 presents the breakdown of the operating costs, covering raw materials (including FFB), labor, facility-related expenses, laboratory costs, utilities, and miscellaneous expenses (e.g., SES fees). Table 6 outlines the projected revenue generated by the project, while Table 7 compares key financial metrics of this study, including TCI, annual operating costs, PBP, and ROI, with data from previous studies.

The TCI for this study is estimated at MYR 150.84 million as described in Table 4. DFC represents the largest portion, approximately 71 % of the total investment, encompassing key components such as TPC (e.g., infrastructure, equipment, engineering, and construction) and CFC. WC accounts for around 26 %, covering operational expenses to sustain daily operations and manage cash flow. The remaining percentage is allocated to SC, which includes expenses for commissioning, testing, and validating the system. This financial breakdown offers a clear overview of the initial investment required to achieve operational readiness for the integrated POM project. The TCI per mill capacity (MYR 2.51 million/MT FFB) is higher than reported in previous studies, which range from MYR 0.86 to MYR 2.05 million/MT FFB (Table 7). This increase reflects the incorporation of sustainable practices, such as biogas-to-power systems, composting, and residual oil recovery systems. Fig. 3 details the allocation of DFC across all sections, highlighting that the boiler section incurs the highest cost at 23 % of the total. Notably, the additional systems for biogas-to-power, EFB composting, and residual oil recovery contribute 22 % of the total DFC, driving up the TCI. Without these systems, the estimated TCI per capacity would be approximately reduced to MYR 1.75 million/MT FFB.

The annual operating cost for this study is estimated at MYR 325.07 million as depicted in Table 5. Raw material costs, primarily FFB, constitute approximately 92.99 % of the total production cost, which is slightly higher than findings from Omran et al. (2021), who reported that FFB accounted for 88 % of total production costs. This breakdown is consistent with other literature, identifying FFB as a major cost driver in palm oil production. Recognizing FFB as the primary expense allows mill operators to allocate resources more strategically, implement targeted cost-reduction strategies, and protect profitability against price volatility. The second largest cost driver is facility-dependent expenses, totaling approximately MYR 54.68/MT FFB (4.97 %). This category includes costs related to equipment maintenance, depreciation, and other expenses, such as insurance, local property taxes, and potential overhead costs. Labor costs amount to MYR 16.27/MT FFB, accounting for approximately 1.48 % of the total operating costs. Miscellaneous expenses are MYR 4.71/MT FFB, representing 0.43 % of the total. Additional costs include laboratory QA/QC expenses of MYR 1.00/MT FFB (0.09 %), while utilities (excluding electricity supplied by the POM's boiler and biogas systems) contribute MYR 0.4/MT FFB (0.04 %).

These results align with previous studies regarding current price and salary levels. Man and Baharum (2011) reported similar cost ranges, including labor costs of MYR 3.84-13.49/MT FFB, water and power costs of MYR 0.04-4.88/MT FFB, laboratory expenses of MYR 0.23-0.69/MT FFB, and CPO tax or miscellaneous costs of MYR 0.52-2.27/MT FFB. Combined costs for effluent treatment, machinery maintenance,

Table 4
Detailed breakdown in TCI of POM (60 MT/h FFB).

Aspect	Cost (MYR)
Direct fixed capital, DFC = TPC + CFC	107,208,115
Working capital, WC	39,234,857
Start-up and validation cost, SC	4,398,661
Total capital investment, TCI	150,841,633

Table 5
Detailed breakdown in annual operating cost of POM (60 MT/h FFB).

Aspect	Cost (MYR/year)
Raw materials	300,063,728
Labor-dependent	4,776,081
Facility-dependent	16,049,895
Laboratory-QC/QA	294,253
Utilities (including water and electricity)	2,499,906 (Electrical price from POM consumption that covered by the boiler and biogas generator is 2,383,863)
Miscellaneous	1,381,654
Total operating cost	325,065,517

Table 6
Revenue and credits of the POM (60 MT/h FFB).

Aspect	Revenue (MYR/year)
CPO	282,928,157
PK	46,543,366
PKS	5,474,487
Compost	11,942,538
Sludge oil	599,767
Power (credit)	5,825,297

building and compound maintenance, storage, dispatch, and depreciation were reported to range between MYR 25.95-32.2/MT FFB. These findings are consistent with Kadir et al. (2019), who identified raw materials as the highest cost component (70–80 %), followed by maintenance and repair (8–25 %), interest (5–10 %), labor (4–12 %), asset depreciation (3–5 %), taxes (2–10 %), and insurance (1–2 %).

In Table 7, when comparing operational costs with other studies, it is essential to separate the cost of raw materials, such as FFB, from the actual operating costs in the simulation result. This is due to cost analysis for POM, FFB is classified as raw material costs associated with the supply chain. Operating costs primarily include expenses related to processing, maintenance, labor, and energy usage at the mill. Based on the simulation results, with an annual operating capacity of almost 300 million MT of FFB, the operating cost is MYR 85.18/MT FFB. The operating costs are higher than traditional POMs without integrated sustainability features, which generally report operating costs as low as MYR 47/MT FFB. Despite the added cost, this increase supports waste reduction efforts and reduces environmental impact through biogas utilization and compost production.

Although the PBP is slightly extended at 5.21 years compared to some references in Table 7, the project's profitability and sustainability potential are confirmed by the NPV of MYR 75.63 million, ROI of 19.20 %, and IRR of 30.08 %. Oktavina and Wulandari (2019) state that a project is acceptable if it achieves a positive NPV. Despite the higher capital investment required for integrating biomass treatment compared to conventional setups, the project remains economically viable. As shown in Table 6, the POM generates annual revenue of approximately MYR 282.93 million from CPO sales and MYR 46.54 million from PK sales. Additional annual revenue streams include MYR 5.47 million from PKS, MYR 11.94 million from compost, and MYR 0.59 million from sludge oil recovery, collectively increasing the mill's overall revenue by about 5 %. Moreover, the mill's capability to generate power from boilers and biogas offers substantial savings by reducing energy costs. Energy credits, valued at approximately MYR 5.82 million annually, further enhance the project's economic viability and sustainability.

Approximately 41 % of the self-generated electricity is utilized by the POM, while the surplus energy holds potential for sale to the grid. According to Nasrin et al. (2024), 135 out of 451 POM in Malaysia are equipped with a biogas capture facility. 64 % of the POM with a biogas plant use it for electricity and mostly under the Feed-in Tariff (FiT) scheme, 11 % use biogas for heat, 24 % just flaring, and 1 % for bio-CNG. Despite its strong potential for renewable energy and reducing GHG emissions, the use of biogas in Malaysian POM faces several challenges. These include limited FiT quotas, especially in Sarawak, where FiT is not available, and technical issues such as poor grid access for mills in remote areas. In this study, both electricity generated is defined as a credit, which means it is used again in the POM to avoid using electricity from the local line for the process. Defining the biogas electricity generation as revenue with a selling price of MYR 0.4669 kW/h and the boiler electricity as credit results in NPV, IRR, ROI, and PBP of 94.19 million, 35.08 %, 19.48 % and 5.13 years. Foong et al. (2021) showed that an integrated biogas and wastewater treatment system in a 60 MT/h POM in Malaysia can export up to 1.9 MW of electrical power or produce

Table 7
Techno-economic analysis and comparative review of previous studies.

Previous studies & capacity	Products	Total capital investment (MYR million/MT FFB)	Annual operating cost (MYR/MT FFB)	Payback Period (Year)	IRR (%)	ROI (%)	NPV (MYR million)
This study - with EFB utilization - 60 MT/h FFB	CPO, PK, PKS, sludge oil, EFB-compost, electricity from boiler and biogas	2.51	85.18	5.21	30.08	19.20	75.63
The Golden Star (2019) 10 MT/h FFB	CPO and PK	1.72	81.88	3.7	25.6	NA	22
Anyaoha and Zhang (2022) 0.67 MT/h FFB	CPO, PK and biogas	1.49	163	3.6	26	20	0.72
Safitri and Gandakusuma (2019) 30 MT/h FFB	CPO and PK	0.86	28	4.3	27	NA	23.77
Chanthawong et al. (2021) 60 MT/h FFB	CPO and PK	0.87	NA	5.21	35.57	NA	68.8
Oktavina and Wulandari (2019) 114 MT/h FFB	CPO	0.93	NA	5.1	47.7	NA	110.96
Omran et al. (2021) NA (4.66 MT FFB/MT CPO)	CPO and PK	1.69	104.17 (if assumed annual CPO production same as this study)	3.6	NA	NA	357.54
Foong et al. (2019) 60 MT/h FFB	CPO and PK	0.77	21.46	NA	NA	NA	NA
MKH Oil Palm (2024) 60 MT/h FFB	CPO and PK	0.88	NA	NA	NA	NA	NA
Man and Baharum (2011) 60 MT/h FFB	CPO and PK	NA	47.87	NA	NA	NA	NA
Romero-Perez et al. (2017) NA (240,000 MT/year FFB)	CPO PKO PK cake	2.05 (if assume hourly capacity same with this study)	193.26	1.43	NA	41.16	1528

NA means not available.

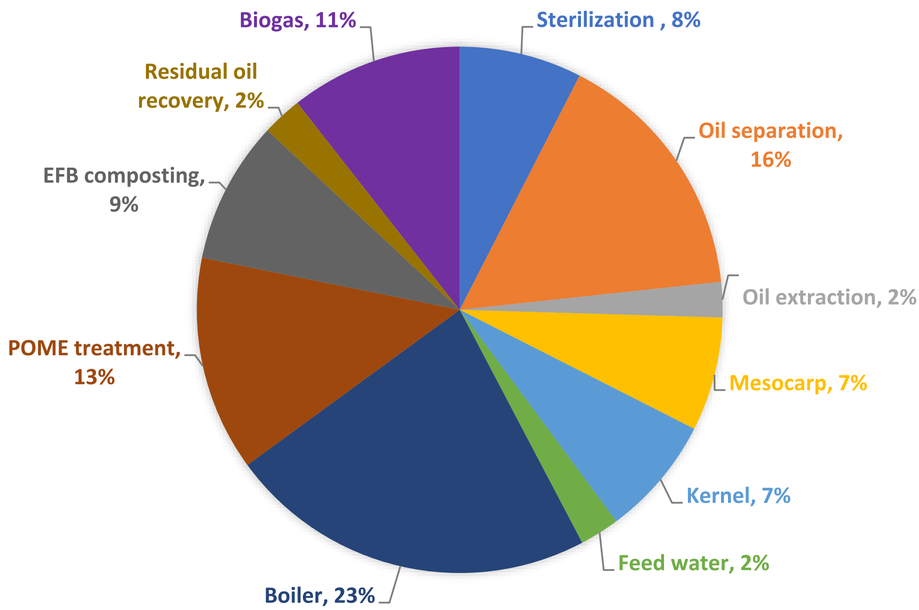


Fig. 3. Pie Chart of DFC percentage for every section in integrated POM (60 MT/h FFB).

110,800 GJ/year of compressed biomethane if grid feed-in is unavailable.

Even though the compost could increase the economic output of the POM, some mills still do not define it as revenue. Instead, they may provide the compost free of charge to local farmers or use it within their estates. At the same time, some of the POM tend to flare their biogas without considering the biogas treatment section. So, in this case, the compost is defined as nil price, and POM proceeds to do flaring, the NPV, IRR, and ROI drop to MYR 29.67 million, 18.20 %, 13.19 % and the PBP increases to 7.58 years. This scenario could be worsened if the POM decides not to incorporate the recovery of residual oil in the POM. Assigning a nil price to compost and removing the residual oil section further reduces the NPV, IRR, and ROI to MYR 5.47 million, 11.48 %, and 12.20 % respectively, with a PBP of 8.20 years. While the project may still yield a positive NPV under these conditions, this scenario is considered unattractive due to economic parameters falling below acceptable ranges.

3.3. Sensitivity analysis

The Monte Carlo sensitivity analysis in Fig. 4 confirms the profound influence of FFB price and CPO prices on the mill's financial outcomes. For NPV, the CPO price emerges as the dominant driver, contributing 37.5 % to its variance. This highlights the strong dependency of project profitability on market prices for crude palm oil. NPV is highly sensitive to decreases in CPO price, as 5 % reduction results in a dramatic 92 % decline from the initial NPV. This finding aligns with Safitri and Gandakusuma (2019), who reported that a 5 % decrease in the selling price of CPO can reduce NPV by more than 100 %. A positive correlation exists between CPO price and profitability, as higher selling prices enhance revenue and improve key financial metrics such as NPV, IRR, and ROI.

Conversely, the FFB price had a negative correlation to the NPV (-33.4 %), which indicated the need for effective cost management in raw material procurement. Negative correlation means that if the FFB price increases, the NPV value will decrease. Even with 5 % increase in FFB price, causing a 91 % decline in NPV. Romero-Perez et al. (2017) noted that their base model could tolerate a 2.2 % increase in raw material costs before becoming unprofitable. These findings underscore the vulnerability of palm oil mills to raw material price fluctuations, contrasting with their greater resilience to variations in operating costs.

The oil yield also significantly impacts NPV, contributing positively by 23.8 %, demonstrating the importance of optimizing extraction processes to maximize returns. Decreasing 5 % in the CPO yield will result in an 88 % decrease in NPV value. Increasing the efficiency of the oil extraction process is crucial to maintaining a high oil yield in POM. Proper handling of FFB is essential to prevent bruising, as damage during harvesting and transportation can lead to oil loss before extraction. Harvesting FFB at the correct maturity is essential, as underripe fruit contains less oil, while overripe fruit leads to significant fruitlet loss (primarily during harvesting and handling), ultimately affecting overall yield. The sterilization process must be optimized, as under- or over-sterilization can lead to the formation of FFA or oil loss. Proper sterilization is essential to facilitate the threshing stage, aiding in the detachment of fruit from the EFB. Following the digestion phase, ensuring efficient mechanical pressing is vital to maximize oil recovery. Reducing mechanical processes, such as conveyors, can help minimize oil loss on the surfaces of both EFB and equipment by mitigating fruit bruising. Maintaining high efficiency throughout the entire process, from FFB handling to pressing, minimizes oil loss and ensures optimal extraction. By prioritizing these critical stages, palm oil mills can enhance oil yield, improving key financial metrics such as NPV, IRR, ROI, and PBP, thereby ensuring long-term profitability and operational sustainability.

Variables like AOH, DFC, and operator costs have smaller impacts but can still incrementally influence profitability when efficiently managed. AOH can vary significantly between palm oil mills due to differences in factors such as location, processing capacity, equipment reliability, and management practices. Increasing AOH improves economic performance by maximizing output and spreading fixed costs over a larger production volume. Decreasing 5 % of the AOH will result in a 13 % decrease in NPV value. This outcome aligns with findings from Man and Baharum (2011), who noted that maximizing operational efficiency is vital for spreading fixed costs and improving financial performance. This efficiency gain illustrates the importance of minimizing downtime and maximizing facility utilization. While longer hours may boost profitability, it is important to balance this with the need for sustainable operations to prevent excessive equipment wear and higher maintenance expenses.

According to Anyaoha and Zhang (2022), the TCI was less sensitive, and the business remained profitable with an up to 20 % increase from the initial value. This implies that additional equipment could be procured (e.g., digester) to enable higher processing capacity while the

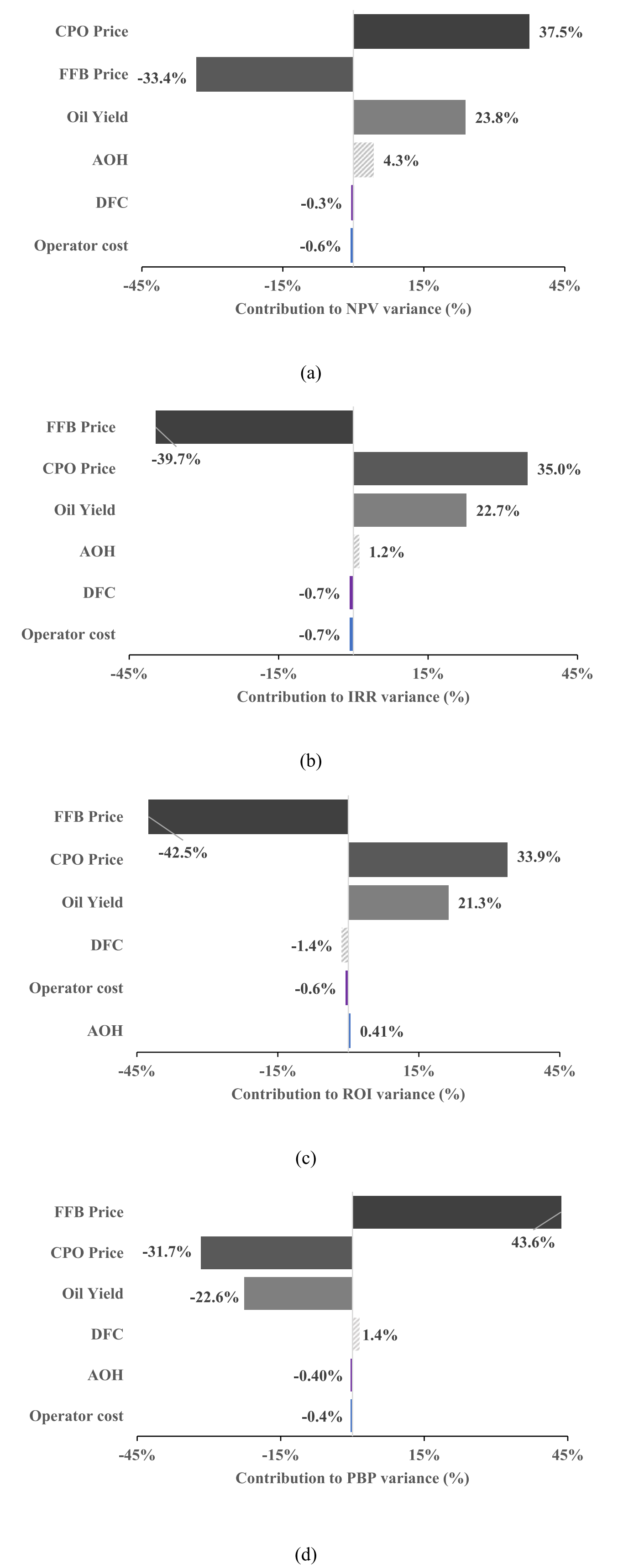


Fig. 4. Contribution of FFB price, CPO price, oil yield, AOH, operator cost, and DFC to the variance of a) NPV b) IRR c) ROI d) PBP based on Monte Carlo sensitivity analysis.

business stays profitable. As well as an additional unit for waste treatment to comply with environmental laws and generate a side profit, was not affecting the overall economic performance of the POM. Operator cost is a major cost in labor costs (more than 70 % of labor costs) has a small impact on financial performance. An increase of 5 % of the labor cost will result in 1 % decline in the NPV initial value. Sensitivity suggests that while labor cost changes do influence financial outcomes, they are less impactful than other variables, such as raw material costs or CPO prices. This manageable impact can encourage mills to invest in fair wages, aligning with social sustainability goals by enhancing worker satisfaction and reducing turnover.

ROI is most sensitive to the FFB price, which negatively contributes -42.5 % to its variance. This finding highlights the critical role of raw material costs in determining profitability, as higher FFB prices can erode returns. On the other hand, CPO price and oil yield positively impact ROI, contributing 33.9 % and 21.3 %, respectively. Variables such as AOH, DFC, and operator costs contribute less than 5 %, indicating their limited influence on ROI variance.

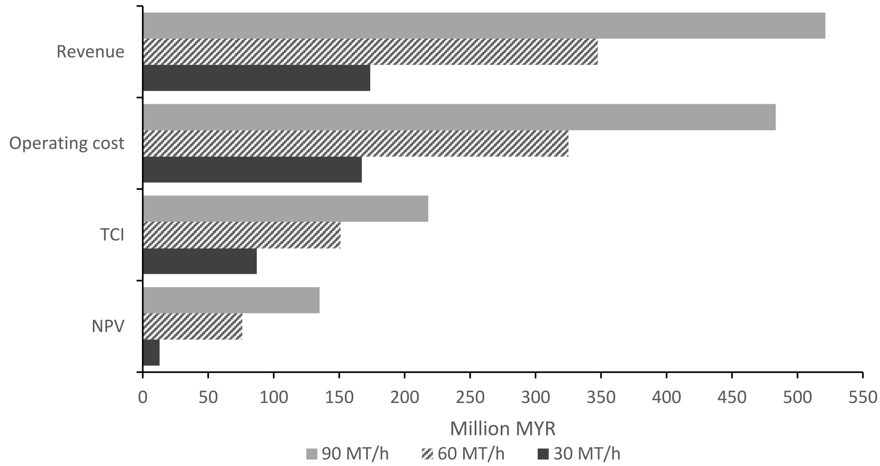
The PBP is most influenced by FFB price, which 43.6 %, indicating that higher raw material costs can delay the recovery of the initial investment. The CPO price and CPO yield are showing a negative correlation of -31.7 % and -22.6 % which means that the PBP becomes shorter when the CPO price and the CPO yield increase. The CPO price helps to accelerate investment recovery when prices are favorable and improved efficiency in oil extraction can reduce the time required for payback. AOH, DFC, and operator costs, while less influential, should still be monitored to maintain overall financial efficiency.

For IRR, the FFB price is the largest negative driver, contributing -39.7 % to variance, emphasizing its critical role in reducing financial returns if not well-managed. CPO price and oil yield, with positive contributions of 35 % and 22.7 %, respectively, remain vital factors in maintaining strong investment profitability. Although AOH, DFC, and operator costs contribute less than 5 %, managing these costs effectively can provide small but meaningful improvements in financial outcomes.

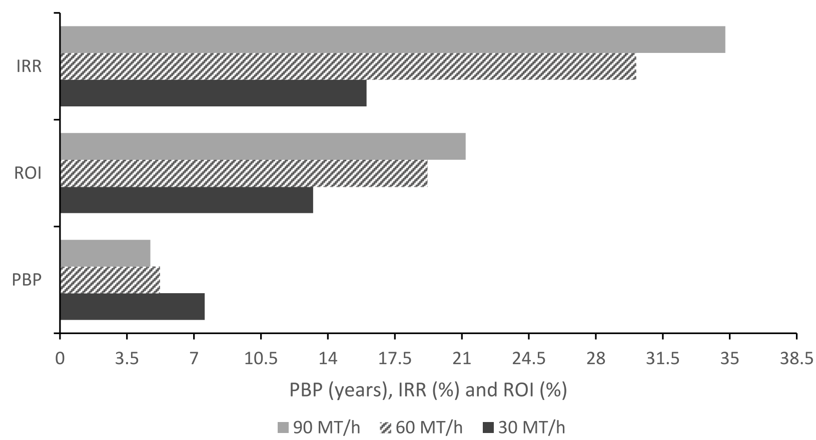
Overall, the Monte Carlo analysis reveals that CPO price, FFB price, and oil yield are the most significant variables influencing all economic parameters. CPO price and oil yield consistently show positive contributions, highlighting the importance of market-driven strategies and process optimization to enhance profitability. In contrast, the negative impact of FFB price across all metrics underscores the need for cost-effective raw material sourcing strategies. While AOH, DFC, and operator costs have relatively minor roles, maintaining operational efficiency remains essential for ensuring financial stability. By prioritizing efforts to address the sensitivities of these key variables, the project can enhance its resilience to market fluctuations and improve overall economic performance.

3.4. Influence of POM capacity

Fig. 5 illustrates how varying POM processing capacities influence key economic indicators. As shown in Fig. 5a, the TCI and operating cost for a 30 MT/h capacity are the lowest, at MYR 87.11 million and MYR 167.32 million, respectively. When the capacity is increased to 60 MT/h, TCI and operating costs rise by approximately 42 % and 49 %, respectively. This increase is expected due to the need for additional equipment units, higher raw material cost, and greater utility consumption. The revenue and NPV at 30 MT/h are also the lowest, at MYR 173.74 million compared to the higher capacity. Nonetheless, the POM with a capacity of 30 MT/h remains financially feasible even with the inclusion of composting, residual oil recovery, and biogas treatment sections. The upward trend in NPV with increasing capacity highlights improved investment attractiveness. At 60 MT/h, the revenue increases by approximately 50 %, indicating the presence of economies of scale. This occurs because fixed costs such as equipment, and infrastructure are spread across larger output volumes, thereby reducing unit costs (Azman, 2014). Additionally, variable costs, including raw materials, labor, and



(a)



(b)

Fig. 5. Economic performance of POM at varying processing capacities: a) NPV, TCI, operating cost, and revenue; b) IRR, ROI, and PBP.

utilities, may be lowered through bulk purchasing or value and improved operational efficiency.

In Fig. 5b, the 30 MT/h capacity shows the lowest IRR and ROI, at 16.02 % and 13.23 %, respectively. As capacity increases to 60 MT/h, both IRR and ROI improve to 30.08 % and 19.20 %. This suggests that higher capacities enhance project profitability. In terms of PBP, the 30 MT/h capacity has the longest at approximately 7.56 years. The PBP shortens as capacity increases, making higher-capacity investments more attractive. While the proposed circular economy method is still economically viable, its lower NPV, IRR, ROI, and longer PBP may discourage millers from adopting such a configuration. To promote the adoption of better circular economy practices in POMs, regulatory authorities should consider implementing supportive policies, incentives, or financing schemes to offset the initial capital burden and encourage investment in sustainable technologies.

3.5. CO_2 equivalent emissions analysis

This section quantifies the GHG emissions and potential savings derived from the simulation of a conventional POM and summarizes them in Table 8. The use of the generator set in the POM simulation consumes 26.71 kg of diesel/h, resulting in CO_2 equivalent emissions of 70.53 kg CO_2 eq/h, which amounts to approximately 5.76 kg CO_2 eq/MT of CPO. Through calculation adopted from the previous study, the total CO_2 equivalent emissions would be 85.33 kg CO_2 eq/h, which is approximately 6.97 kg CO_2 eq/MT of CPO. The results from the simulation and the calculations are nearly identical, with only a slight difference of approximately 17 %.

Next is the use of boilers in POM, where MF and PKS are used as fuel. According to the simulation, the boiler exhaust emits approximately 12094 kg CO_2 eq/h, which amounts to around 987.40 kg CO_2 eq/MT of CPO. Comparatively, Hong (2023) reported that boiler emissions could be as high as 170 kg CO_2 eq/MT of CPO. The higher emissions in this study are due to differing assumptions about biomass combustion. Azar (2011) mentioned that biomass is often regarded as carbon-neutral, as the CO_2 released during its combustion is assumed to be offset by the CO_2 absorbed during the plant's growth. This assumption relies on the idea that, over its lifecycle, biomass does not increase net atmospheric CO_2 levels, unlike fossil fuels.

The POME treatment in the POM simulation generates biogas consisting of 331.67 kg/h of CH_4 and 558.43 kg/h of CO_2. Using the densities of CH_4 at 0.656 kg/m^3 and CO_2 at 1.977 kg/m^3, as reported by

Table 8
CO_2 equivalent emissions of POM.

Sources	CO_2 equivalent emissions (kg CO_2 eq/MT CPO)		References
	This study	Previous study	
Generator set (diesel)	5.76	6.97	Calculated using the formula proposed by Sari (2019b) and Sasmita and Lestari (2019), as shown in Equation (3).
Tractor (diesel)	3.16	3.77	Calculated using the formula proposed by Sasmita and Lestari (2019) as shown in Equation 4
Boiler (PKS & MF)	987.4	170	Hong (2023)
EFB			Hansen et al. (2012)
Landfill	NA	890	
Composting	106.04	NA	
POME			Hong (2023)
Without biogas capture	725.78	637-1,131	
With biogas capture – IC Engine	122.99	82–134.5	
Total emission			
Without composting & biogas capture	2612.09		
With composting & biogas capture	1225.34		

NA is not available.

Choo et al. (2011), the corresponding volumes are 282.46 m^3/h for CO_2 and 505.59 m^3/h for CH_4. This results in a composition of approximately 28.4 % CO_2 and 50.8 % CH_4. So, for the CH_4 with GWP = 25, the emission is equivalent to 8291.75 kg CO_2 eq/h. Total emission from the POME treatment, including emission from both aerobic and anaerobic processes, is 8890.05 kg CO_2 eq/h which is equivalent to 725.78 kg CO_2 eq/MT CPO. According to Hong (2023), the emissions from POME digestion range between 637 and 1,131 kg CO_2 eq/MT of CPO produced.

Transportation involves the movement of tractors for operation at the FFB reception area and the composting station. From the simulation, diesel used for moving 60 MT of FFB at the FFB reception and 18.36 MT of compost is 14.63 kg/h and results in 38.66 kg CO_2 eq/h, which amounts to approximately 3.16 MT CO_2 eq/MT of CPO. Considering the emission factor for diesel fuel is approximately 2.68 kg CO_2 eq/L, the total CO_2 equivalent emissions calculated to be 46.14 kg CO_2/h, which is approximately 3.77 MT CO_2 eq/MT of CPO. The results from the simulation and the calculations are nearly similar, with only a slight difference of approximately 16 %.

POMs typically have the option to use EFB either as compost, mulch, or landfill, primarily due to the low cost associated with these practices. From the simulation of POM, the composting process produces CO_2 emission of 1298.9 kg CO_2 eq/h or approximately 106.04 kg CO_2 eq/MT of CPO produced. In composting, organic waste undergoes controlled aerobic decomposition, which limits the anaerobic conditions that typically produce CH_4. In contrast, mulching involves spreading EFB directly onto the plantation soil, where it decomposes naturally. While this method enriches the soil, it can create anaerobic conditions if the mulch is thick, which can lead to CH_4 production during decomposition. Another common practice used by millers is the landfilling of EFB or POME sediment. According to Hansen et al. (2012), leachate formation and anaerobic degradation are major contributors to CH_4 emissions during landfilling.

To reduce CO_2 equivalent emissions in POM, millers often capture CH_4 produced during the anaerobic digestion of POME. In the simulation, the captured CH_4 is utilized as renewable energy to power the mill. The simulation indicates that capturing and using CH_4 for energy results in emissions of 1466.60 kg CO_2 eq/h from the generator set. The total emission in the POME section is then reduced to 1506.46 kg CO_2 eq/h (122.99 kg CO_2 eq/MT CPO). Consequently, the total emissions reduction in the POME section is 83 % of the CO_2 eq emissions reduction. The result is similar to that of CH_4 capture by Sasmita and Lestari (2019), with a total reduction of CO_2 equivalent emissions of 83.5 %.

Table 8 highlights the significant environmental benefits of adopting composting and CH_4 capture processes at the palm POM compared to traditional landfilling practices without CH_4 capture. By incorporating these advanced processes, the POM achieves a significant reduction in total CO_2 equivalent emissions, resulting in a 53% decrease. This reduction is primarily attributed to the efficient management of CH_4, which is typically emitted from the anaerobic decomposition of organic waste. Composting further mitigates emissions by stabilizing organic residues into a valuable soil amendment, reducing the need for chemical fertilizers, and enhancing the circular economy. These results highlight the crucial role of CH_4 capture and composting in reducing the environmental impact of POM operations while promoting sustainable waste management practices.

4. Conclusion

This study successfully demonstrated the potential of integrating waste utilization processes, such as biogas generation from POME, EFB composting, and residual oil recovery, into palm oil milling operations. The integration significantly enhanced environmental sustainability by addressing the food-energy-environment nexus, reducing greenhouse gas emissions, and promoting circular economy practices through effective waste management. Economically, the approach improved profitability by creating additional revenue streams from by-products and optimizing resource efficiency. The sensitivity analysis revealed that factors such as raw material costs, product prices, and processing efficiency have a substantial impact on economic performance, highlighting the importance of strategic management and operational optimization to ensure profitability under varying market conditions. Furthermore, the system demonstrated operational feasibility by enabling self-sufficient energy generation and reducing waste disposal challenges. These findings underscore the importance of adopting integrated and sustainable practices in POM to address environmental and economic challenges while contributing to broader sustainability goals.

CRediT authorship contribution statement

Siti Naderah Sulin: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Mohd Noriznan Mokhtar:** Writing – review & editing, Supervision, Software, Methodology, Formal analysis, Conceptualization. **Azhari Samsu Baharuddin:** Writing – review & editing. **Mohd Afandi P. Mohammed:** Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2025.100323.

Data availability

Data will be made available on request.

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