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# Comprehensive Feasibility Assessment of Integrated Valorization of EFB and POME in a Circular Bioeconomy Framework: Compost and Biogas

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**KEYWORDS**

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**ABSTRACT**

The palm oil industry produces vast amounts of palm oil mill effluent (POME) and empty fruit bunches (EFB), yet current disposal and treatment practices underexploit their resource potential. This study addresses a key research gap: existing works typically evaluate EFB and POME independently and lack a unified techno-economic assessment that quantifies combined capital–operating costs, operational interdependencies, and market-driven feasibility. Additionally, limited attention has been given to how enriched compost pricing and operational stability influence the long-term viability of integrated biorefinery configurations. Techno-economic analysis confirmed strong feasibility, achieving a 21.52% return on investment (ROI), a payback time (PT) of 4.65 years, and a positive net present value (NPV). Unlike electricity export, which had limited impact, project profitability was primarily driven by enriched compost price, operating stability, and capital efficiency. Sensitivity analysis revealed that feedstock cost fluctuations exerted only marginal influence. These findings underscore that market-driven compost valorization and operational optimization are decisive for financial resilience. By transforming waste into revenue-generating products, the approach offers a scalable pathway to enhance sustainability, reduce environmental burden, and strengthen Malaysia's position in the global bioeconomy.



## 1. INTRODUCTION

The Malaysian government has introduced initiatives such as the Malaysian Palm Oil Council and the Malaysian Sustainable Palm Oil (MSPO) certification to improve the palm oil industry's sustainability [1]. However, their effectiveness, especially for independent smallholders, still faces significant challenges [2]. Sustainable palm oil aims to reduce deforestation, GHG emissions, biodiversity loss, and social conflicts. Certification schemes like Roundtable on Sustainable Palm Oil (RSPO) support these goals. Palm oil mills, while central to the supply chain, generate significant biomass and wastewater byproducts, notably EFB and palm oil mill effluents (POME), which pose environmental challenges [3]–[5].

While palm kernel shells and mesocarp fibers are commonly utilized as boiler fuel, EFB and POME remain underexploited resources. Some mills have adopted residual oil recovery from EFB through shredding and pressing, producing shredded-pressed EFB (S&P EFB), a processed biomass material that has been physically broken down into smaller pieces after excess moisture has been squeezed out, which is inexpensive and well-suited for composting [6],[7]. However, its high moisture content (~40%) and elevated ash concentration limit its application as boiler fuel due to operational inefficiencies and environmental concerns. Co-composting S&P EFB with POME sludge, boiler ash, and other residues improves nutrient balance and soil fertility, while additives such as urea and microbial inoculants (e.g.,

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*Rhizobium, Trichoderma*) enhance compost maturity, quality, and crop productivity [7],[8]. To address operational bottlenecks, a bunker composting system denotes a static, aerated, concrete-compartment composting technology which offers significant advantages over traditional windrow methods, including lower operating costs, reduced dependency on heavy turning machinery, and accelerated composting through improved aeration and controlled leachate management [9].

POME is commonly treated through anaerobic digestion (AD), reducing pollutants and producing biogas [10],[11]. Covered lagoon systems are prevalent due to cost-effectiveness but require large land areas [12]. Despite biogas being convertible to electricity or bio-CNG [13], many mills flare it due to high capital expenditure (CAPEX) and system complexity [14],[15]. The economic viability of biogas projects heavily depends on the FiT set by SEDA [16]. However, the combined CAPEX and operating expenditure (OPEX) of integrating composting and biogas utilization in biorefineries remains poorly quantified, posing a major gap in techno-economic assessments.

According to Cheah et al. [17], implementing a circular bioeconomy in the palm oil industry requires more critical emphasis on environmental monitoring and integrated waste valorization strategies, including (1) combined POME treatment, biogas production, and water reuse; (2) in-situ flue gas monitoring; and (3) effective utilization of EFB and other biomass wastes. Despite various studies on individual valorization pathways, there remains a gap in the literature regarding the systematic development of a process flowsheet that integrates unit operations and operating conditions for the holistic conversion of EFB and POME into value-added products aligned with circular bioeconomy principles.

The specific objectives of this study are as follows: (1) to develop an integrated process flowsheet combining composting, anaerobic digestion, and biogas utilization for EFB and POME valorization; (2) to evaluate the technical performance of the integrated system under realistic mill operating conditions; (3) to conduct a comprehensive techno-economic analysis and $CO_2$ emissions; and (4) to assess the influence of key operational and market parameters on project feasibility through sensitivity analysis.

## 2. METHODOLOGY

### 2.1 *Concept of study*

This study investigates the potential of transforming palm oil biomass into value-added products by leveraging integrated and sustainable processing concepts. Specifically, S&P EFB is directed to a co-composting process, where it is blended with other biomass residues from the palm oil mill in the Compost Section, yielding nutrient-rich organic fertilizers. It is then further upgraded by adding inorganic fertilizer. Concurrently, liquid waste, known as POME, is routed through a cooling pond as an initial treatment stage before undergoing subsequent processes, such as AD lagoon-sedimentation tank [18] and aerobic pond-sedimentation tank [19]. Within the POME Treatment Section, biogas can be captured as energy source and minimize environmental impact. Figure 1 provides a simplified block flow diagram of the study.

The study is based on several key general assumptions to ensure the feasibility and relevance of the proposed systems. First, all palm oil mill residues, including S&P EFB, POME sludges, and decanter cake [20], are assumed to be fully utilized within the proposed processes. However, biomass residues like PKS and mesocarp fiber are excluded from the study, as they are already allocated for use as boiler fuel in the mill's steam generation system or sold externally. The proposed system operates without reliance on existing mill utilities such as steam or electricity. However, logistical integration remains necessary for routing S&P EFB, POME, and sludge between process sections. Thus, the system is operationally independent in terms of energy supply but organizationally integrated with mill material flows.

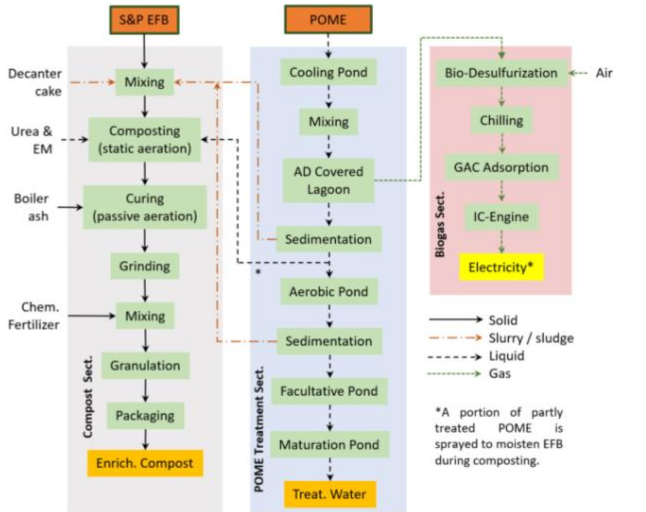


**Fig. 1.** Block flow diagram for concepts of study: Compost Section, POME Treatment Section, and Biogas Section

### 2.2 *Feedstock compositions*

The biomass was estimated based on a 60 MT/h FFB palm oil mill, producing ~13.8 MT/h of EFB (23% to FFB) with ~ 65% moisture, and at 80°C temperature. In mill operations, EFB is shredded and pressed to recover residual oil, leaving ~ 6.8 MT/h of S&P EFB with <40% moisture. The composition of the S&P EFB was recalculated as wet weight from published literature (Table 1). For POME, it originates from sterilization (36%), clarification (60%), and hydrocyclone (4%) processes [21], with a flow rate of 46.5 MT/h (77.5% to FFB) at 70°C for the same capacity of the mill. Its composition varies with mill practices, season, and fruit type. Data for protein, nitrate, phosphate [18], oil & grease [22], and fiber, ash, and carbohydrates [23] were used, as summarized in Table 1.

**Table 1**. Composition of S&P EFB and POME applied in the simulation

| Component (%) | S&P EFB (6.8 MT/h) | POME (46.5 MT/h) |
|---|---|---|
| Ash | 3.00 | 0.60 |
| Fiber | 54.63 | 0.93 |
| Simple carbohydrates | - | 0.75 |
| Oil & grease | 2.23 | 0.60 |
| FFA | 0.13 | 0.16 |
| Protein | 0.76 | 0.43 |
| Sand / inert | 1.06 | 0.14 |
| Water | 38.19 | 96.28 |
| Phosphate | - | 0.013 |
| Nitrate | - | 0.095 |
| References | [24]–[26] | [18],[22],[23],[27] |

### 2.3 Compost Section

S&P EFB (6.8 MT/h) is co-composted with sludges from POME treatment and decanter cake (0.85 MT/h). Urea solution is added at ≤1% to adjust the C/N ratio to 25–30 [8],[28], enhancing microbial activity and accelerating decomposition, especially during the thermophilic phase. Effective microorganism (~ 0.2% dry basis) can be added during this phase. Active aeration using blowers can be applied in a static aerated bunker system [9],[29]. Moisture is maintained around 75% [26] using leachate percolation and partly treated POME. The composting proceeds through thermophilic–mesophilic phases over 4 weeks [9],[30], followed by a 2-week passive aeration curing phase. Boiler ash is added during curing to buffer pH and provide essential minerals, while sulfur-rich bio-desulfurization waste supports microbial sulfur metabolism [31]. Final processing includes screening, fine grinding, nutrient enrichment, granulation, and packaging. Figure 2 shows the ground and enriched-granulated compost. A detailed process flowsheet is shown in Figure 3. The stoichiometry of aerobic degradation for fiber, protein, and oil was adopted from Mokhtar [32] and Misailidis & Petrides [33] (Table 2) for use in the SPD simulation. We propose using three 100 HP tractors and two 12 MT/h bunker filler machines to handle both composting feedstock and the finished compost.

(a) (b)

**Fig. 2.** Compost products, a) after grinding, b) after enrichment and granulation

**Table 2**. Stoichiometry equations for the metabolic reaction in aerobic bio-oxidation (co-composting & aerobic pond)

| **Metabolic reactions in aerobic bio-oxidation (aerobic pond & composting) (molar stoichiometry) [32],[33]** |
|---|
| Protein & amino acids oxidation |
| $\text{Proteins} + 5.3O_2 \rightarrow 0.6\text{Biomass} + NH_3 + 4.5CO_2 + 4.8H_2O$ |
| Sugars (simple carbohydrates) oxidation |
| $\text{Sugars} + 6O_2 + 0.47NH_3 \rightarrow 0.8\text{Biomass} + 5.7CO_2 + 6H_2O$ |
| Fiber oxidation |
| $\text{Fiber} + 6O_2 + 0.47NH_3 \rightarrow 0.8\text{Biomass} + 5.7CO_2 + 6H_2O$ |
| Acetate oxidation |
| $\text{Acetate} + 1.9O_2 + 0.58NH_3 \rightarrow \text{Biomass} + 1.6CO_2 + 1.9H_2O$ |
| Oil oxidation |
| $\text{Oil} + 81.3O_2 + 11.8NH_3 \rightarrow 12.1\text{Biomass} + 54.4CO_2 + 55.4H_2O$ |
| FFA oxidation |
| $\text{FFA} + 25.5O_2 + 3.7NH_3 \rightarrow 3.8\text{Biomass} + 17.1CO_2 + 17.4H_2O$ |
| Biomass decay |
| $\text{Biomass} \rightarrow \text{Dead biomass}$ |
| Dead biomass oxidation |
| $\text{Dead biomass} + 2.3O_2 \rightarrow 0.2NH_3 + CO_2 + 2.7H_2O$ |
| Urea hydrolysis |
| $\text{Urea} + H_2O \rightarrow 2NH_3 + CO_2$ |

### 2.4 POME Treatment Section

POME first flows into a cooling pond where residual oil accumulates and degrades, resulting in darker color and quality decline; part of the oil is recovered as sludge palm oil (SPO). Following Rahayu et al. [10], the flow is homogenized in a mixing tank that recycles sedimentation sludge, adjusts pH, and stabilizes temperature before entering the AD lagoon. Biogas is produced in the AD covered lagoon, and the resulting sludge is sent to the Compost Section. Stoichiometry equations for AD were referred to Misailidis & Petrides [33] (Table 3). The partly treated POME can be further passed to conventional treatments; aerobic, facultative, and maturation pond treatments (Figure 3). Sludge from these ponds is also directed to the Compost Section. Treated POME is either discharged into rivers or reused for irrigation and floor washing.

**Table 3**. Stoichiometry equations for the metabolic reaction in AD

| **Metabolic reactions in AD lagoon (molar stoichiometry) [33]** |
|---|
| Protein & amino acids degradation |
| $\text{Proteins} \rightarrow 2\text{Acetate} + NH_3 + 4.5H_2 + 0.1H_2S$ |
| Sugars (simple carbohydrates) degradation |
| $\text{Sugars} \rightarrow 3\text{Acetate} + 1.5H_2$ |
| Fiber degradation |
| $\text{Fiber} \rightarrow 3\text{Acetate} + 1.5H_2$ |
| Acetate degradation |
| $\text{Acetate} + 0.5H_2 \rightarrow CO_2 + CH_4$ |
| Oil hydrolysis |
| $\text{Oil} + 3H_2O \rightarrow 3\text{FFA} + \text{Glycerol}$ |
| Glycerol degradation |
| $4\text{Glycerol} \rightarrow 6\text{Acetate} + 7H_2$ |
| FFA degradation |
| $\text{FFA} + H_2 + 8H_2O \rightarrow 5CO_2 + 13CH_4$ |
| $H_2$ to $CH_4$ |
| $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ |
| Biomass formation |
| $\text{Acetate} + NH_3 \rightarrow 3\text{Biomass} + H_2$ |
| Biomass decay |
| $\text{Biomass} \rightarrow \text{Dead biomass}$ |

### 2.5 Biogas Section

Biogas from the AD-covered lagoon undergoes bio-desulfurization ($H_2S$ removal), chilling (moisture reduction), and GAC adsorption (residual $H_2S$ and $NH_3$ removal) [19]. The process flowsheet is shown in Figure 3, with bio-desulfurization stoichiometry adapted from Lok et al. [19] (Table 4). The purified biogas powers an IC engine generator (39.9% electrical efficiency), supplying electricity to the plant, and surplus biogas is flared (Table 4). A comparative simulation was also conducted for a scenario in which all generated biogas is converted to electricity, with any excess electricity exported to the grid.

**Table 4**. Stoichiometry equations for the reaction in bio-desulphurization and flaring

| **Reactions in other units (molar stoichiometry)** |
|---|
| Bio-desulphurization [19] |
| $H_2S$ oxidation 1 |
| $H_2S + 0.5O_2 \rightarrow S + H_2O$ |
| $H_2S$ oxidation 2 |
| $H_2S + 2O_2 \rightarrow H_2SO_4$ |
| Flaring |
| Combustion of $CH_4$ |
| $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ |
| Combustion of $H_2$ |
| $2H_2 + O_2 \rightarrow 2H_2O$ |

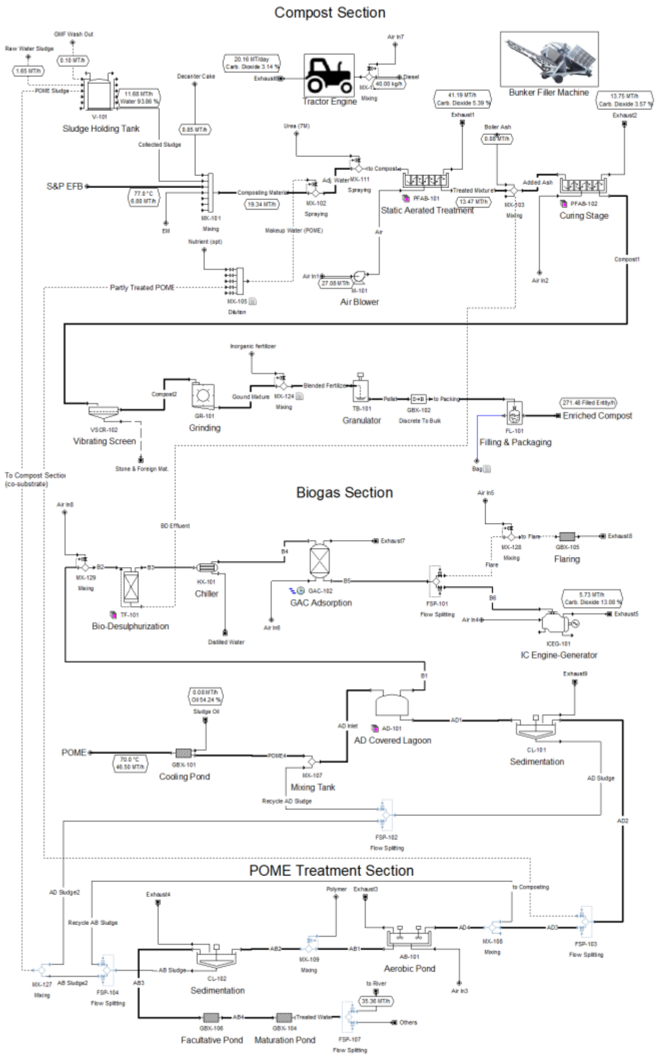


**Fig. 3.** Process flowsheet developed in SPD illustrating the integrated utilization of EFB and POME for the production of enriched compost and biogas-derived electricity

## 2.6 *Process Design and Simulation*

The process was constructed and simulated using SuperPro Designer (SPD) v.12, a software platform for modeling and analyzing industrial-scale process operations. The simulation methodology primarily followed the approach outlined by Heinzle et al. [34]. Detailed process flowsheets were constructed based on the block flow diagram in Figure 1, designed to replicate realistic operational conditions by integrating data from peer-reviewed literature and firsthand observations obtained during site visits to several palm oil mills. The flowsheets illustrated in Figure 3 demonstrate the integration of process streams to evaluate key performance indicators in project feasibility, while also aiming to minimize $CO_2$ emissions and achieve zero biomass discharge. The process scenario underwent an evaluation to assess both technical performance and economic feasibility. The analysis included metrics such as operating cost or OPEX, CAPEX, NPV, ROI, internal rate of return (IRR), and PT, offering a holistic perspective on financial implications.

The economic evaluation of this EFB-POME utilization project considers a time valuation framework with the year of analysis set in 2025 and construction commencing in 2026, spanning 30 months, followed by a 4 months startup period. Full-scale production was expected to begin in 2028 at 100% capacity, with a project lifetime of 20 years. The project was financed with 70% debt (from direct fixed capital, DFC), with a loan period of 5 years at a 5% interest rate. Depreciation follows the declining balance method over 14 years, with a salvage value of 5% of DFC. An equipment inflation rate of 4% was considered, and income tax was set at 24% [32]. These parameters form the foundation for the techno-economic feasibility assessment of the project.

## 2.7 *CAPEX and OPEX*

The equipment purchase costs (PC) were determined based on information from local suppliers and SPD database. CAPEX was estimated to be based on the PC by the SPD software. Direct fixed capital (DFC) was derived from the total plant cost (TPC), which comprises the total plant direct cost (TPDC) and total plant indirect cost (TPIC). TPDC, which covers expenses such as equipment installation, process piping, and electrical systems, was estimated using appropriate multiplier or fractional values [34]. TPIC, along with contractor's fees, contingency costs (CFC), working capital (WC), and start-up and validation costs (SC), were also determined using multiplier factors [34]. Consequently, the overall capital investment was estimated using Equations (1–3).

$$TPC = TPDC + TPIC \tag{1}$$

$$DFC = TPC + CFC \tag{2}$$

$$CAPEX = DFC + WC + SC \tag{3}$$

**Table 5**. Cost for raw materials, utilities, labor, and selling prices

| Classification | Item | Cost/Price | Unit |
|---|---|---|---|
| Material | Inorganic chemical/fertilizer | 500.00 | USD/MT |
| | Diesel | 0.80 | USD/L(STP) |
| | Effective microorganism culture | 5.00 | USD/kg |
| | Plastic bag | 1.00 | USD/kg |
| | Polymer (coagulation agent) | 1.00 | USD/kg |
| | Urea sol. (7 M) | 1.00 | USD/kg |
| Consumables[a] | Activated carbon (AC) packing (g) | 3.00 | USD/kg |
| Labor [32] | Security guard (certificate holder) | 3.47 | USD/h |
| | Clerk/Maintenance staff (Diploma holder) | 4.07 | USD/h |
| | Plant/Equipment operator (Diploma holder) | 4.78 | USD/h |
| | Plant engineer (Bachelor of Eng. holder) | 6.06 | USD/h |
| Product revenues | Enriched compost (25 kg) | 6.00 | USD/entity |
| | Sludge oil | 600.00 | USD/MT |
| | Electricity (feed-in tariff) [16] | 0.077 | USD/kWh |

[a]SPD database

OPEX is divided into variable, fixed, and overhead costs [34]. Variable costs include materials, consumables, labor, and utilities can be referred to Table 5. QC-laboratory costs are typically estimated at 15% of operating labor [35]. Labor requirements for plant operators follow standard values for each process unit [32]. Fixed costs, or facility-dependent costs, cover depreciation (straight-line), maintenance (10% of plant cost), insurance (1% of DFC), and local taxes (1% of DFC). Factory expense, including support services such as medical, safety, storage, and cafeteria, was set at 1% of DFC in this study.

*2.8 Sensitivity Analysis*

The sensitivity analysis was conducted to evaluate the impact of key variables on overall process feasibility. The parameters examined included fluctuations in the prices of primary feedstocks (inorganic fertilizer and urea) and the selling price of enriched compost. In addition, the effects of annual operating time (AOT) and CAPEX on project viability were assessed. The analysis also considered variations in process throughput, as well as the potential revenue from electricity sales under different FiT schemes and varying POME-to-fresh fruit bunches (FFB) ratios. Simulation models were employed to systematically investigate these factors, providing insights into the financial performance under a ±25% variation range.

## 3. RESULTS AND DISCUSSION

*3.1 Enriched Compost*

Following 30 days of active aeration composting and a subsequent 14-day curing phase, the process resulted in a total mass reduction of 68.5% (Table 6). During active aeration composting, additional moisture (~75%) is maintained using partly treated POME, compensating for significant vapor loss, especially during the thermophilic phase. During the curing stage, when no additional water is supplied, mass reduction primarily results from moisture evaporation, as most degradable organics have already been decomposed. This study's predicted organic matter loss (32%) aligns with Talib et al. [36], who reported 29.3–40.5% loss for static aerated composting. Similarly, Baron et al. [37] observed 38% and 45% organic matter loss using windrow composting with regular turning after 40 and 60 days, respectively. Final compost ash content was slightly higher than in Baharuddin et al. [26], attributed to the addition of boiler ash at the start of curing.

**Table 6**. Comparative analysis of composting and crude SPO simulation results with reported literature data[&]

| Characterization | Simulation results | Previous data (if available) | References |
|---|---|---|---|
| **Compost** (after curing) | | | |
| Mass reduction (% of initial composting material) | 68.5 | - | |
| Organic matter loss (%) | 32.0 | 29.3 – 40.5 | [36] |
| Yield (% of FFB) | 10.3 | - | |
| Moisture (%) | 33.8 | 35 | [43] |
| Ash content (%) | 8.75 | 8.4 | [26] |
| **Crude SPO** | | | |
| Recovery (% of FFB) | 0.14 | - | |
| Oil (%) (excluding FFA) | 54.24 | ~60 | |
| FFA (%) | 30.56 | 1.18 – 86.66 | [44] |
| Impurities (fiber & ash) (%) | 4.32 | 0.05 – 12.89 | |

[&]Based on a 60 MT/h FFB processing capacity of palm oil mill

Since the final compost has low NPK values, upgrading it into a modified compost by incorporating 0.15 inorganic fertilizer per dry weight of the compost, as suggested by Buron et al. [38], along with effective microorganisms, can enhance compost quality [39],[40]. Granulation is essential to produce enriched compost that is both marketable and easy to handle. In contrast, conventional reliance on inorganic fertilizers often causes nutrient leaching, environmental harm, and long-term soil infertility [41]. Integrating organic and inorganic/chemical fertilizers enhances nutrient uptake, improves soil retention, and sustains soil quality [42].

*3.2 POME Treatment and Biogas*

Based on a study by Nasution et al. [6], raw POME is transferred to a sludge pit (or fat pit) to recover residual palm oil, which is then returned to the clarification tank in the palm oil mill. The aqueous effluent, at approximately 70°C, is subsequently sent to a cooling pond. In this simulation, POME is first treated in the cooling pond, primarily for holding and cooling purposes, before undergoing AD treatment. SPO can be skimmed and sold to external parties. To achieve results comparable with the previous study [19], a 20% recovery rate of SPO was set in our simulation, resulting in POME containing 0.4% residual oil entering the mixing tank and then being directed to the mesophilic AD lagoon.

**Table 7**. Comparative analysis of POME treatment and biogas simulation results with reported literature data[&]

| Characterization | Simulation results | Previous data (if available) | References |
|---|---|---|---|
| **POME treatment** | | | |
| AD treatment & 1st sedimentation | | | |
| COD reduction (%) | 93.3 | 95 | [48] |
| BOD reduction (%) | 94.1 | 97 | |
| Aerobic pond & 2nd sedimentation | | | |
| COD reduction (%) | 95.5 | 98 | [50] |
| BOD reduction (%) | 95.5 | 93 | |
| **Biogas** | | | |
| Yield ($m^3$ biogas/MT POME) | 21.8 | 24 - 28 | [49] |
| Yield ($m^3$ $CH_4$/MT POME) | 13.5 | 15.2 – 19.4 | |
| Yield ($m^3$ $CH_4$/kg $COD_{removed}$) | 0.35 | 0.39 | [45] |
| $CH_4$ (% v/v) | 59.31 | 50 - 75 | [10] |
| $CO_2$ (% v/v) | 34.73 | 25 - 45 | |
| $H_2$ (% v/v) | 1.12 | < 1 | |
| $H_2O$ (% v/v) | 4.49 | 2 - 7 | |
| $NH_3$ (% v/v) | 0.06 | < 1 | |
| $H_2S$ (% v/v) | 0.28 | < 2 | |
| **Purified biogas** | | | |
| $CH_4$ (% v/v) | 60.85 | 62.00 | [18] |
| $CO_2$ (% v/v) | 35.59 | 36.42 | |
| $H_2$ (% v/v) | 1.15 | ND | |
| $H_2O$ (% v/v) | 0.33 | 0.13 | |
| $O_2$ (% v/v) | 0.26 | 0.66 | |
| $N_2$ (% v/v) | 1.82 | - | |
| $NH_3$ (ppm) | 12 | 7865* | |
| $H_2S$ (ppm) | 1 | 34* | |
| **IC-engine generator/ electrical power (MW)** [φ] | | | |
| Internal use | 0.95 | - | |
| Internal use & export to grid | 2.19 | 2.1 | [10] |

[&] Based on a 60 MT/h FFB processing capacity of palm oil mill
*The process did not involve the use of GAC adsorption after bio-desulphurization
[φ] Electrical efficiency = 39.9%

The organic loading rate (OLR) for AD treatment is 1.0 kg/m$^3$·day, resulting in a $CH_4$ yield of 0.35 m$^3$ $CH_4$/kg $COD_{removed}$, obtained from the simulation data. This result is comparable to those from previous studies, which reported an average value of 0.39 m$^3$ $CH_4$/kg $COD_{removed}$ for the same OLR [45] and is also similar to the IPCC default value of 0.35 m$^3$ $CH_4$/kg $COD_{removed}$ [46]. Yong et al. [45] also observed a declining $CH_4$ yield profile at OLR values exceeding 1.0 kg/m$^3$·day due to the accumulation of volatile fatty acids, which lower the pH and inhibit methanogenic activity. The simulation results indicate that the biogas produced contains a $CH_4$ concentration of 59.31 vol.%, with COD and BOD removal efficiencies of 79.2% and 79.8%, respectively by AD lagoon alone. These findings align with previous studies [45],[47]. However, when the supernatant undergoes sedimentation, COD and BOD removal efficiencies increase remarkably to 93.3% and 94.1%, respectively, as shown in Table 7. This performance is comparable to the results reported [48]. However, the simulated $CH_4$ yield per amount of POME was slightly lower than the experimental value ranges obtained by previous work [49].

### *3.3 Purified Biogas and Electrical Generation*

In the Biogas Section, the biogas stream undergoes a series of purification steps to ensure its quality and minimize potential issues such as equipment corrosion and reduced efficiency in downstream processes. Initially, the stream is subjected to bio-desulfurization, achieving 84% $H_2S$ removal. This is followed by a chilling-dehydration process to remove 85.5% of water vapor, and GAC adsorption to remove residual $H_2S$ and $NH_3$ (Table 7). The resulting purified biogas contains 60.85 vol.% $CH_4$, aligning closely with results reported by previous study [18], which demonstrated an almost similar $CH_4$ content of 62 vol.%. According to previous work [51], final $H_2S$ content should be reduced to below 4 ppm for biogas intended as a natural gas substitute, whereas for stationary power generation, most engine manufacturers require biogas $H_2S$ levels at or below 100 ppm to comply with warranty conditions. Bio-trickling filters used for $H_2S$ removal, as noted by Lok et al. [19], may increase $N_2$ levels in the biogas due to the aeration required for aerobic biological $H_2S$ oxidation.

The treated biogas is utilized in an internal combustion (IC) engine for electricity generation. Under the operating conditions of this plant, the IC engine is estimated to generate approximately 0.95 MW of electrical power, which primarily satisfies the internal energy demand of the process (Table 7). If the entire biogas supply were utilized for power generation, the total electrical output could increase to approximately 2.19 MW. This indicates that nearly 57% of the available biogas remains surplus to the plant's internal requirements and is currently flared. Alternatively, this excess biogas could be utilized for electricity export to the grid, thereby generating additional revenue and improving the overall energy efficiency of the system.

### *3.4 CAPEX, OPEX, Revenues, and Project Indices*

The estimated CAPEX and OPEX distributions are shown in Figure 4(a). The total CAPEX was USD 19.18 million, while the annual OPEX amounted to USD 6.58 million. Within the CAPEX structure, the POME Treatment Section represented the largest share (45.6%), followed by the Composting Section (40.6%) and the Biogas Section (13.8%). This trend is consistent with previous findings [52], which reported that wastewater treatment systems typically dominate CAPEX in palm oil mill biogas projects. For the POME treatment–biogas purification–IC engine generator configuration, the total investment cost was estimated at approximately USD 11.48 million. This figure is slightly higher than the estimate by previous study [14], which, after adjusting for a 4% annual inflation rate from 2013 to 2025, amounted to approximately USD 8.5 million. For EFB composting at a milling capacity of 60 MT FFB/h, CAPEX was previously estimated at around USD 2.6 million (including infrastructure and machinery) [53], adjusted for a 4% annual inflation rate from 2001 to 2025. In contrast, the present study estimates a considerably higher CAPEX of USD 7.84 million, primarily due to the adoption of a more advanced composting system featuring concrete bunkers with roofing, which substantially increases infrastructure costs.

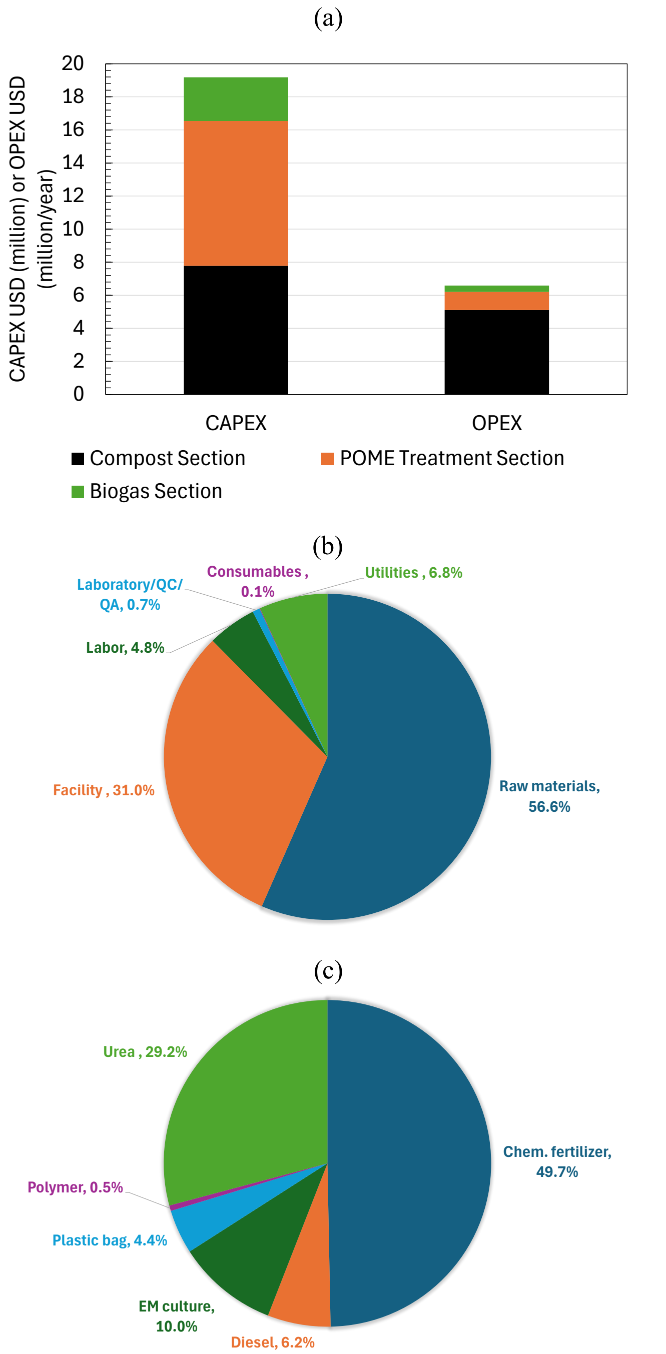


**Fig. 4.** Cost analysis, a) CAPEX, b) OPEX, and c) raw materials

For comparison, the SG Bunker® System in the USA was reported to cost around USD 11 million in 2023, with a treatment capacity of 237,136 MT/year, equivalent to approximately USD 46.39 per MT of yearly capacity [54]. In our case, the CAPEX for bunker units alone was estimated at about USD 5.8 million for a composting material capacity of 116,062 MT/year, or roughly USD 50 per MT of yearly capacity. When adjusted to the current price level (2025), our estimated results are therefore comparable to the U.S. benchmark.

In terms of OPEX, the Composting Section is the dominant cost component, accounting for 77% as shown in Figure 4(a). Figure 4(b) shows that OPEX is predominantly driven by raw materials (56.6%), followed by substantial facility-related expenses (31%), while utilities, labor, laboratory/QC, and consumables contribute minimally. This indicates that the system is fundamentally material-intensive rather than labor- or energy-intensive. The relatively high facility-dependent cost suggests reliance on capital-heavy infrastructure requiring continuous maintenance and compliance-related expenditures. Consequently, improvements in manpower or energy efficiency would offer limited cost reduction, whereas fluctuations in material prices or facility upkeep would significantly influence overall operating costs.

Figure 4(c) further reveals that chemical fertilizer (49.7%) and urea (29.2%) jointly constitute nearly 80% of total raw material expenses, exposing a strong dependency on synthetic additives to meet product quality specifications. While these inputs enhance compost nutrient content, they also introduce vulnerability to price volatility in globally traded commodity markets. The remaining materials such as EM culture, diesel, plastic bags, and polymers represent minor contributions, but still reflect operational dependencies on biological additives, internal logistics, and packaging.

The estimated OPEX/MT composting material is USD 57.85/MT. These findings are higher than the previous industrial report [55], which estimated an OPEX of USD 49.7/MT. However, in this study, the OPEX is also primarily attributed to other sections, including the POME treatment, and biogas-electricity unit. The primary revenue in this study is derived from enriched compost, totaling USD 9.77 million/year, while revenue from sludge oil remains comparatively low (Table 8).

Integrating biogas-generated electricity into Malaysia's national grid presents several challenges, including fluctuating load demand, limited distribution infrastructure, and high transmission costs. To minimize power losses, biogas plants must ideally be located within 10 km of a grid interconnection point, which is often infeasible [56]. Transmission cabling alone costs approximately USD 0.23 million per kilometer [14]. In this study, approximately USD 2.47 million was added to the total project cost, primarily due to the requirement for 10 km of cabling installation and a larger IC engine generator to generate higher electrical power.

In this work, biogas is primarily utilized for electricity generation to meet the plant's internal energy demand, with any excess biogas flared. The project demonstrates favorable economic indicators, with an ROI of 21.52%, a PT of 4.65 years, and a positive NPV. Fully utilizing all excess biogas for grid export slightly reduces project viability (Table 9) due to the high transmission costs. Previous studies support this observation; for instance, Abas et al. [14] reported that, for a similar palm oil mill capacity and a tariff of USD 0.08/kWh, the PT extended to 10 years with an NPV of only USD 1,259, considering the same transmission cabling. Furthermore, Nasrin et al. [15] highlighted that approximately 24% of mills capture biogas but flare it entirely without any internal utilization, underscoring the practical challenges of electricity export in this sector.

**Table 8**. Project revenue$

| Key Assessment | Value |
|---|---|
| Enriched compost | USD 9,773,000/year |
| Sludge oil (cooling pond) | USD 296,000/year |
| Electricity (credit-internal use) | USD 439,000/year |
| Total | USD 10,508,000/year |

$Based on a 60 MT/h FFB processing capacity of palm oil mill, operating for 6,000 h AOT (250 days/year)

**Table 9**. Project indices for electricity scenarios$

| Scenario | PT (years) | ROI (%) | IRR after tax (%) | NPV at 10% (USD) | Key limitation |
|---|---|---|---|---|---|
| Internal electricity uses only | 4.65 | 21.52 | 24.92 | 12.94M | Limited biogas utilization |
| Electricity export via FiT* | 4.83 | 20.69 | 23.67 | 13.31M | High transmission cost; distance to grid |

$Based on a 60 MT/h FFB processing capacity of palm oil mill, operating for AOT of 6,000 h (250 days/year)
*Surplus electricity is exported to the grid under the FiT, total tariff of USD 0.077/kWh [16]. Additional revenue is USD 570,000/year.

Compared with conventional windrow composting, the bunker system offers faster degradation and reduced labor and machinery demand but requires significantly higher upfront CAPEX due to civil structures and aeration units [9],[54]. Similarly, while covered anaerobic lagoons improve biogas recovery and reduce GHG emissions compared with open lagoons, they require skilled operation and regular desulfurization maintenance [10]. These trade-offs highlight the importance of balancing capital intensity with operational simplicity, particularly for small and medium-sized mills.

The integrated EFB–POME valorization model is readily adaptable to other palm-oil-producing regions in Southeast Asia, such as Indonesia and Thailand, where feedstock characteristics, mill configurations, and regulatory environments closely resemble those in Malaysia. The modular nature of the bunker system and the lagoon-based AD design further enables scale-up or replication in mills with varying capacities.

### *3.5 $CO_2$ Emissions*

The primary sources of emissions in this study include diesel combustion from tractor operations, flaring, IC engine exhaust, $CO_2$ released during composting, and aerobic pond emissions. A detailed breakdown of $CO_2$ emissions is presented in Table 10.

For material handling, three 100 HP tractors were assumed, consuming ~0.96 MT/day of diesel for the loading, spreading, and collection of EFB and compost products within the bunker system. The resulting emissions were estimated at 2.2 kg $CO_2$/MT CPO, representing the lowest contribution among all sources.

**Table 10**. $CO_2$ - equivalent emissions[$]

| **Key Assessment** | **Value** |
|---|---|
| Tractor engines (3 units) | 2.2 kg $CO_2$/MT CPO |
| Composting (active aeration) | 185.0 kg $CO_2$/MT CPO |
| Composting (curing) | 40.9 kg $CO_2$/MT CPO |
| Biogas flaring & IC-engine generator | 143.7 kg $CO_2$/MT CPO |
| Aerobic pond | 5.3 kg $CO_2$/MT CPO |
| Total | 377.1 kg $CO_2$/MT CPO |
| Potential reduction to AD open lagoon (%)[χ] | 85.6% |
| Potential reduction to EFB landfill (%)[π] | 80.9% |
| Potential total reduction to AD open lagoon and EFB landfill (%) | 82.7% |

[$]Based on a 60 MT/h FFB processing capacity of palm oil mill, operating at a 20% OER and AOT of 6,000 h (250 days/year)

[χ]Closed AD lagoon (based on flaring & IC-engine), compared to 1,000 kg $CO_2$/MT CPO, emission from AD open lagoon [57]

[π]S&P EFB co-composting, compared to 1,180 kg $CO_2$/MT CPO, emission from EFB landfill [58]

By contrast, the active aeration composting phase was identified as the single largest contributor, with estimated emissions of 185 kg $CO_2$/MT CPO. This high value is attributed to peak microbial activity, rapid organic matter degradation, and intensive aeration, all of which drive oxygen demand and $CO_2$ release [59]. In comparison, the curing phase released only 40.9 kg $CO_2$/MT CPO, as microbial activity slows, oxygen demand declines, and complex compounds gradually stabilize into humus [60].

Biogas combustion for electricity generation and emergency flaring contributed a further 143.7 kg $CO_2$/MT CPO. While significant, these emissions were still lower than those from active composting. Importantly, biogas utilization offsets the need for fossil fuel-based electricity, while flaring prevents uncontrolled $CH_4$ release, a gas with 25 times the global warming potential of $CO_2$. Aerobic ponds added 5.3 kg $CO_2$/MT CPO, a comparatively minor source.

When compared with conventional systems, the mitigation benefits of the integrated POME–EFB strategy are substantial. Open anaerobic lagoons for POME management can generate up to 1,000 kg $CO_2$/MT CPO [57], largely from uncontrolled $CH_4$ emissions. Similarly, unmanaged EFB disposal (landfilling or thick mulching) contributes an additional ~1,180 kg $CO_2$/MT CPO [58]. By contrast, the present study demonstrates that closed AD lagoons combined with controlled EFB composting achieve overall emission reductions of ~82.7% relative to this baseline. Specifically, EFB composting reduced emissions by ~80.9% compared to landfilling, while $CH_4$ capture via covered AD lagoons contributed reductions exceeding 85.6%.

For comparison, Krishnan et al. [61] reported ~110 kg $CO_2$/MT FFB (equivalent to 550 kg $CO_2$/MT CPO) from POME sludge–EFB co-composting with $CH_4$ capture, representing a 76% reduction relative to conventional practices. In the present study, the integrated system achieved a substantially lower footprint of 377.1 kg $CO_2$/MT CPO, reflecting further reductions through the combined use of covered AD lagoons and controlled composting. These results highlight not only the effectiveness of integrated waste management systems as $CH_4$ mitigation strategies in palm oil mills but also their potential to generate carbon credits, providing an additional revenue stream and enhancing the overall sustainability of mill operations.

The substantial GHG mitigation achieved positions the system to benefit from emerging carbon market mechanisms, such as VERRA methodologies for $CH_4$ avoidance and composting. Compliance with MSPO and RSPO climate-related indicators also enhances Environmental, Social, and Governance (ESG) reporting potential for participating mills [62].

### *3.6 Sensitivity Analysis*

Among all parameters evaluated, the selling price of enriched compost exhibited the highest influence on project profitability as shown in Figure 5(a). A 25% increase in compost price resulted in substantial improvements in ROI, IRR, and NPV by 45.0%, 59.6%, and 101.2%, respectively, while simultaneously reducing PT by 30.97%. Conversely, a 25% decrease in compost price caused severe deterioration in the economic indicators, with ROI, IRR, and NPV declining by 45.0%, 63.3%, and 105.6%, respectively, accompanied by a considerable increase in PT of 81.7%. This indicates that project profitability is highly dependent on market acceptance and selling price stability of enriched compost products, which is similar to the trend reported in previous study [63].

AOT was identified as the second most influential parameter affecting project economics as in Figure 5(b). A 25% increase in AOT improved ROI, IRR, and NPV by 28.2%, 37.6%, and 63.4%, respectively, while reducing PT by 22.1%, whereas a reduction in AOT adversely affected all profitability indicators. Process throughput, as in Figure 5(c), also influenced project feasibility, although to a lesser extent than AOT. A 25% increase in throughput improved ROI, IRR, and NPV by 8.8%, 12.6%, and 43.0%, respectively. In Figure 5(d), CAPEX showed an inverse relationship with economic performance; a 25% increase in CAPEX considerably reduced ROI, IRR, and NPV by 22.9%, 33.9%, and 51.6%, respectively, while increasing PT by 29.7%. These results indicate that operational efficiency and capital investment are critical determinants of project financial viability.

The influence of feedstock prices (inorganic fertilizer and urea) on project economics is relatively limited compared to the above parameters, as shown in Figure 5 (e-f). Variations in inorganic fertilizer and urea prices showed comparatively lower impacts on ROI (approx. ±8.8% and ±5.2%), IRR (approx. ±12.0% and ±7.0%), and NPV (approx. ±20.0% and ±11.7%), respectively. While these costs contribute to OPEX, their impact is overshadowed by the enriched compost price and AOT.

The sensitivity analysis reveals that, for a palm oil mill project with electricity export, the price of FiT has a relatively modest but consistent influence on financial outcomes, as shown in Figure 5(g). A ±25% change in FiT price alters ROI (approx. ±2.5%), IRR (approx. ±3.3%), and NPV (approx. ±6.0%). While the magnitude of change is not as large as that observed for compost price or AOT in the earlier scenario, FiT still plays a critical role because it directly determines revenue from electricity sales. This indicates that stable policy support and long-term FiT security are important for financial predictability, though the overall project economics are not overly sensitive to small FiT variations.

(a)

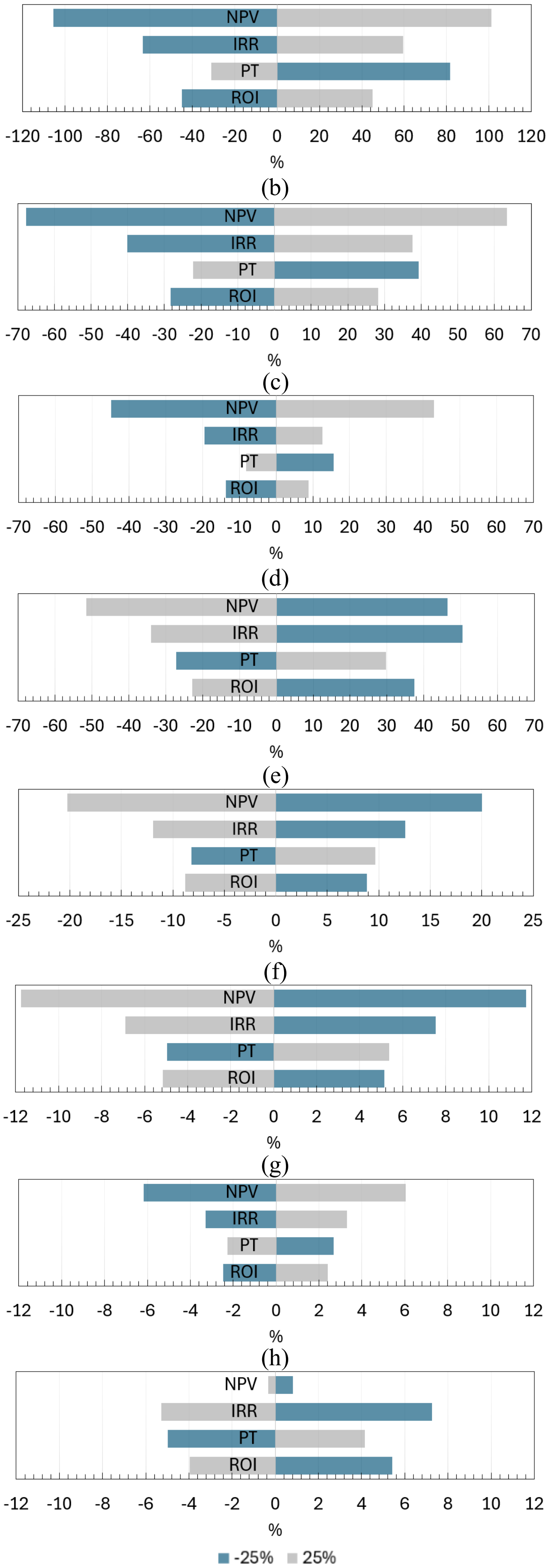


**Fig. 5.** Sensitivity analysis of ROI, PT, IRR, and NPV by changing ± 25% of a) price of enriched compost, b) AOT, c) process throughput, d) CAPEX, e) price of chemical fertilizer, f) price of urea, g) FiT, and h) POME to FFB ratio

In contrast, the POME/FFB ratio shows a more pronounced impact on returns, as shown in Figure 5(h). A 25% decrease in POME/FFB improves ROI by +5.4% and IRR by +7.3%, while a 25% increase results in negative shifts (ROI –4.0% and IRR –5.3%). NPV also changed in response to variations in the POME-to-FFB ratio but was relatively small. This indicates that the amount of POME available for biogas generation substantially influences profitability, given its direct link to biogas yield and electricity generation potential. Although higher POME generation increases biogas yield, the associated treatment and handling costs outweigh the additional revenue, thereby reducing overall financial performance. Conversely, lower POME intensity improves system efficiency and overall returns.

The sensitivity analysis shows that enriched compost, although the dominant revenue contributor, also represents the greatest source of financial uncertainty. Fluctuations in compost price lead to disproportionately large shifts in ROI, IRR, and NPV, indicating that market volatility is the most critical determinant of economic performance. This vulnerability is further amplified by external factors such as competition from subsidized synthetic fertilizers, inconsistent farmer adoption, evolving quality standards, and regional distribution limitations. Ensuring reliable demand and maintaining competitive pricing are therefore essential to safeguard profitability and reduce investment risk.

Several practical strategies can help mitigate these sensitivities. Long-term purchasing agreements with plantations or product diversification through nutrient blending can reduce exposure to market fluctuations. CAPEX-related risks may be lowered by adopting modular or phased installation of composting and biogas units. Additionally, maintaining high AOT, supported by preventive maintenance and redundancy in key equipment such as blowers and pumps, helps stabilize performance and improve economic resilience.

### *3.7 Overall Synthesis of Key Findings*

The integrated assessment demonstrates that coupling EFB composting with POME-based anaerobic digestion creates a complementary biorefinery configuration capable of delivering strong technical, economic, and environmental performance. The results show that composting drives the financial viability of the system, with enriched compost emerging as the primary revenue stream, whereas electricity export provides only marginal economic benefit, particularly for mills located far from transmission infrastructure. On the environmental side, the integrated system substantially reduces $CH_4$ emissions from POME treatment and diverts EFB from open decomposition or landfill pathways, achieving more than 80% GHG mitigation compared with conventional mill practices. Overall, the combined findings confirm that dual-waste valorization is technically feasible, financially promising under stable compost pricing, and environmentally superior to current industry norms.

Broader viability is also shaped by policy and stakeholder readiness. FiT stability remains relevant for mills pursuing biogas-to-electricity pathways, while MSPO and RSPO certification frameworks increasingly incentivize responsible waste management and GHG reduction. Adoption by mill operators depends on operational familiarity with bunker composting, confidence in the compost market, and access to financing mechanisms for CAPEX-intensive installations.

Smallholder uptake, in particular, is influenced by perceptions of compost quality, availability of distribution networks, and competition from subsidized synthetic fertilizers. These considerations highlight the importance of coordinated policy signals and stakeholder engagement for successful implementation.

Despite the strengths of the integrated framework, several limitations should be acknowledged. The simulation assumes consistent feedstock characteristics, although mills often experience seasonal fluctuations in EFB quantity, POME strength, and sludge generation. Biogas yields were modelled under idealized loading and operating conditions, which may differ under real-world mill constraints. Compost price stability is also uncertain due to market variability and fertilizer-policy dynamics. While the model incorporates validated industrial and literature data, future pilot-scale testing would further refine key assumptions and enhance confidence in long-term performance projections.

## 4. CONCLUSION

This study developed and evaluated an integrated EFB–POME valorization system that uniquely couples composting, anaerobic digestion, and biogas utilization within a single mill-level biorefinery framework. Unlike previous studies that treat these waste streams in isolation, the proposed configuration demonstrates a dual-waste valorization strategy capable of converting both EFB and POME into enriched compost and renewable electricity. The simulation results confirm the technical feasibility of the integrated flowsheet and highlight important system interactions, particularly the necessity of linking POME treatment with EFB composting to manage sludge effectively and enhance overall resource circularity. Feedstock-related fluctuations, including inorganic fertilizer and urea prices, exerted only a marginal influence on project feasibility. The system delivers substantial $CO_2$ emission reductions compared with conventional mill practices, indicating strong potential for carbon-credit monetization. The sensitivity analysis further reveals that market access for enriched compost and operational stability are the dominant drivers of financial viability. Overall, this work contributes a comprehensive mill-scale, simulation-driven assessment of an integrated EFB–POME biorefinery, demonstrating how dual-waste transformation and strategic system coupling can enhance both economic performance and environmental outcomes.

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