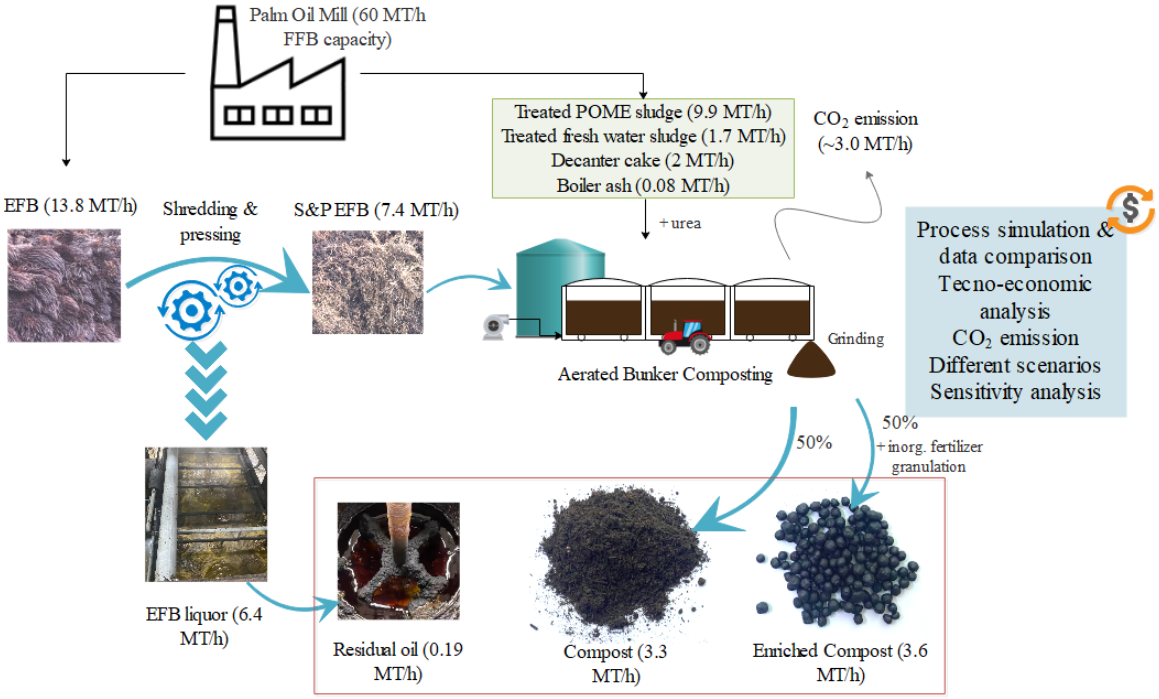
Sustainability-Oriented Feasibility Analysis of Aerated Bunker Composting of Oil Palm Empty Fruit Bunches

Mohd Noriznan Mokhtar *

* Corresponding author: noriznan@upm.edu.my

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GRAPHICAL ABSTRACT



Sustainability-Oriented Feasibility Analysis of Aerated Bunker Composting of Oil Palm Empty Fruit Bunches

Mohd Noriznan Mokhtar *

The techno-economic and environmental performance was assessed for the composting of oil palm empty fruit bunches (EFB) through an aerated bunker composting (ABC) system. The process flowsheet was developed using SuperPro Designer, with process data and operating parameters sourced from prior experimental and industrial studies. Simulation results exhibited agreement with literature data, demonstrating the reliability of the model. The process is potentially able to achieve a 79% reduction in carbon dioxide equivalent (CO_2e) emissions relative to landfilling, underscoring considerable climate mitigation potential. Economic evaluation estimated capital expenditure (CAPEX) at MYR 43.8 million and OPEX at MYR 15.7 million/year, with enriched compost contributing to 73.3% of revenues. The base case yielded a net present value (NPV) of MYR 58.4 million, return on investment (ROI) of 30.5%, and payback of 3.28 years, demonstrating strong feasibility. Scenario analysis revealed that increasing the portion of enriched compost substantially improves profitability, while carbon credit and CAPEX incentives further enhance investment appeal. Sensitivity results highlighted the enriched compost price, annual operating time, and CAPEX as the main determinants of financial performance. Overall, the system provides both substantial environmental benefits and compelling economic viability, offering a scalable pathway for sustainable EFB management.

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Keywords: Empty fruit bunches (EFB); Aerated bunker composting; Techno-economic analysis; Oil palm biomass

Contact information: Department of Process and Food Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia;
** Corresponding author: noriznan@upm.edu.my*

INTRODUCTION

Composting has emerged as a widely recognized biological treatment for organic residues, offering a sustainable approach to waste management while producing value-added soil amendments. Among the available technologies, aerated bunker composting (ABC) systems have gained increasing attention due to their operational efficiency, scalability, and suitability for high-moisture, lignocellulosic residues (Abas *et al*. 2011; Surya *et al*. 2019; Hamdani *et al*. 2023). ABC is a type of aerated static pile (ASP) system, but it is more engineered and confined, compared to the open-pile ASP (Michel *et al.* 2022). These controlled systems rely on forced aeration to accelerate microbial degradation, improve process stability, and reduce greenhouse gas (GHG) emissions compared to conventional open windrow composting. Studies in the United States have demonstrated that ABC systems achieve rapid stabilization with minimal land requirements, enhanced

odor control, and more consistent compost quality than conventional open-windrow systems (EA Engineering, Science, and Technology, Inc. PBC 2024).

The oil palm industry generates vast amounts of biomass residues, particularly empty fruit bunches (EFB), which account for approximately 20 to 25% of fresh fruit bunches (FFB) weight (Baharuddin *et al.* 2009). In Malaysia, there are 453 palm oil mills, with 53% located in Peninsular Malaysia, having a combined FFB processing capacity of approximately 125 million tons per year (MPOB 2024). Based on this capacity, it is estimated that about 28 million tons of EFB are generated annually. Traditionally, EFB has been managed through mulching and landfill practices (Hansen *et al.* 2012). These processes contribute to CH_4 emissions, pest proliferation, and inefficient nutrient recovery. Although widely practiced, windrow composting of EFB is limited by long processing times (>60 days), high land demand, leachate issues, and inconsistent quality under tropical conditions, while its bulky lignocellulosic nature further hinders degradation and reduces end-user acceptance (Baharuddin *et al.* 2009).

The ABC systems offer potential solutions for the Malaysian palm oil sector (Abas *et al.* 2011). Through improving process control and accelerating stabilization, these systems can shorten composting cycles (25 to 32 days) even without frequent mechanical turning, enhance nutrient recovery, and generate a more uniform organic fertilizer product (Abas *et al.* 2011; Surya *et al.* 2019; Hamdani *et al.* 2023). For example, ABC utilizes confined, aerated bays that improve process efficiency, reduce labor requirements, and enhance the reduction of pathogens and weed seeds (EA Engineering, Science, and Technology, Inc. PBC 2024). In addition, the ABC system has the potential to achieve near-zero CH_4 emissions, as the continuous oxygen supply suppresses anaerobic conditions and sustains aerobic microbial activity, thereby mitigating CH_4 generation during the decomposition process (Hamdani *et al.* 2023). Such a system has been successfully applied to food waste, yard trimmings, and biosolids elsewhere, and adapting it to EFB could align with sustainable palm oil practices (Krishnan *et al.* 2017; Salamat *et al.* 2021).

Despite these advantages, adoption of the ABC system in Malaysia remains limited due to high capital expenditure (CAPEX), high operating expenditure (OPEX), and weak market incentives. The bulk price of compost is relatively low (Abas *et al.* 2011), making it difficult for mills to justify the investment, particularly in the presence of subsidized chemical fertilizers. Prolonged reliance on chemical fertilizers has also caused nutrient leaching, soil acidification, and a decline in soil biodiversity, thereby reducing soil functionality and its ability to support diverse biological communities (Salamat *et al.* 2021). While current policy frameworks emphasize palm oil mill effluent (POME) treatment and emission control, they provide little support for the valorization of solid biomass through composting, which could mitigate the negative environmental impacts of chemical fertilizer overuse and enhance long-term soil health (Salamat *et al.* 2021). The use of EFB for energy combustion is limited by its high ash content, particularly potassium, which lowers ash fusion temperature and promotes slagging and fouling, thereby reducing combustion efficiency and accelerating equipment degradation (Madhiyanon *et al.* 2013).

Existing studies on EFB composting in Malaysia have primarily emphasized technical performance, nutrient characteristics, and environmental impacts, with limited attention to techno-economic aspects. Critical parameters such as CAPEX, OPEX, payback time (PT), and market competitiveness remain insufficiently addressed, constraining large-scale adoption of advanced biomass composting. In addition, strategies to enhance product value, such as producing enriched compost through blending with inorganic fertilizers, have received relatively little focus, despite their potential to improve nutrient balance and

user acceptance. Given Malaysia's extensive oil palm plantations, there is substantial potential demand for soil amendments that enhance soil structure, nutrient retention, and long-term fertility. Enriched compost, typically applied alongside mineral fertilizers, has demonstrated synergistic effects on enzyme activity, macroaggregate formation, and soil organic carbon sequestration (Zhao *et al.* 2020; Jiang *et al.* 2023). Furthermore, integrating composting facilities within palm oil mills could enhance adoption by reducing transportation costs and enabling localized utilization of EFB-derived products.

However, a comprehensive evaluation integrating technical, economic, and environmental dimensions remains lacking. Most existing work does not incorporate process simulation with techno-economic assessment, particularly for ABC systems in the Malaysian context. Therefore, the main objective of this study was to develop and evaluate an integrated, simulation-based framework to assess the techno-economic and environmental performance of EFB composting systems using experimental and industrial data. This approach offers a practical basis for scale-up and scenario analysis, although its accuracy depends on data quality and may not fully capture process dynamics. Addressing this gap is crucial to support decision-making, improve economic viability, and position composting as a key valorization pathway within Malaysia's circular bioeconomy.

METHODOLOGY

Compost Process and Flowsheet Development

EFB and other palm oil biomass compositions were analyzed based on established methods (Sahad *et al.* 2014). All samples were taken from Sungai Tengi Palm Oil Mill. The flowsheet (Fig. 1) was developed using SuperPro Designer v.12 simulation (Intelligen, Inc., Freehold, NJ, USA), requiring detailed representation of unit operations and specification of key process parameters based on experimental and industrial data. For flowsheet development, EFB was initially shredded and mechanically pressed to extract EFB liquor, which was subsequently routed to a residual oil recovery unit. The recovered oil, suitable for non-edible applications (*e.g.*, biodiesel), can be sold externally, while the aqueous phase is routed to the POME treatment system (Nasrin *et al.* 2022), which is outside the scope of this study. The resultant solid fraction, referred to as shredded and pressed EFB (S&P EFB), can be blended with sludge from the POME treatment system, sludge from freshwater (FW) treatment, and decanter cake to form the primary composting feedstock. The moisture content of this feedstock was adjusted (~70%) using partly treated POME (after anaerobic pond).

Incorporation of sludge decreases the initial C/N ratio, which can be further optimized by adding a urea solution (0.1% w/w) to achieve the desired balance of 25 to 30 (Serramiá *et al.* 2010; Paul *et al.* 2019), which is conducive to efficient composting. The composting process is carried out in the ABC system based on information from previous studies (Surya *et al.* 2019; Hamdani *et al.* 2023), where forced aeration maintains oxygen levels above 10% (Baharuddin *et al.* 2009). After 30 days of active composting, boiler ash from the mill is added to the material, which is then subjected to a 14-day curing phase under passive aeration to ensure stabilization. The final compost product undergoes screening to remove foreign materials (*e.g.*, glass, metal) and grinding to achieve uniformity.

This study is based on several key assumptions. First, all palm oil mill residues, including S&P EFB, POME treatment sludge, FW treatment sludge, decanter cake, and boiler ash are assumed to be fully utilized in the proposed process. Second, the composting

facility was modeled as a separate cost center located adjacent to the palm oil mill. Electricity was assumed to be supplied by the mill's biomass- and/or biogas-based power generation system and charged to the composting facility at an internal transfer price equivalent to the prevailing grid tariff. To support material handling within the composting facility, four tractors (100 HP, one standby unit) and two bunker-filler machines (12 MT/h) are proposed for loading, unloading, and transferring composting material within the bunker system.

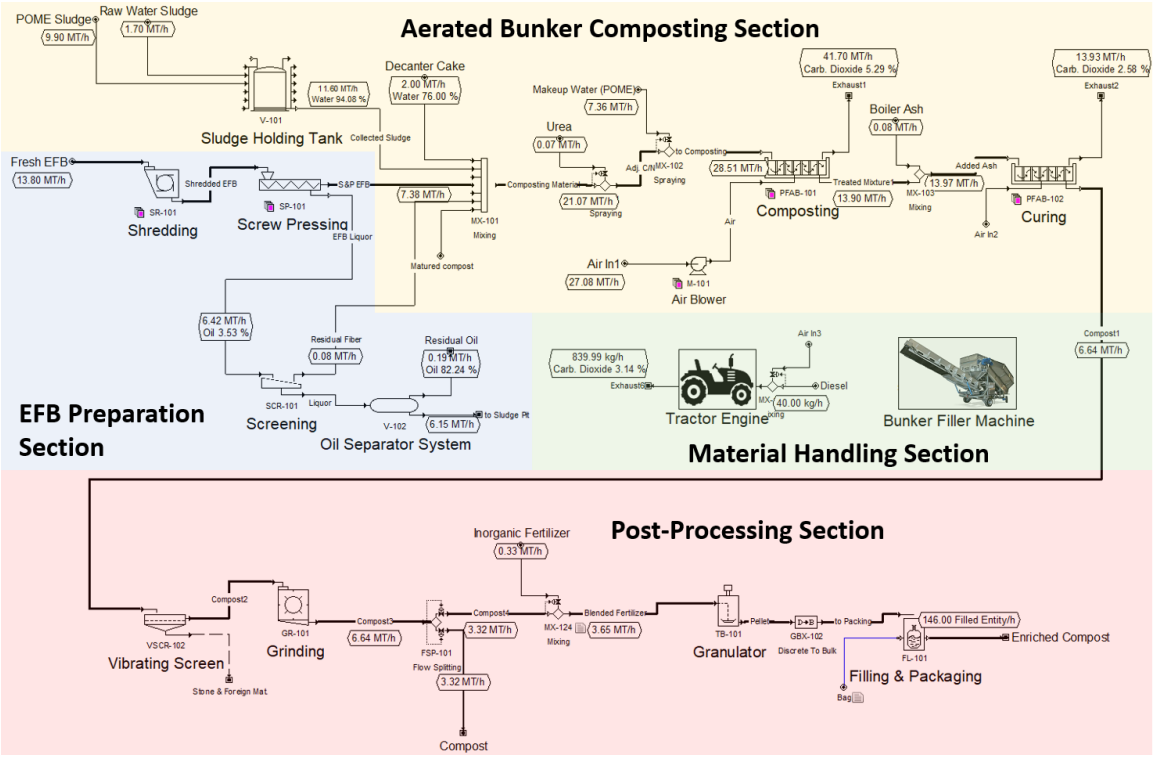


Fig. 1. SuperPro Designer flowsheet for ABC system of EFB with mass balances

In the SuperPro Designer, composting and curing stages were modeled by defining component reactions, with molar stoichiometric equations established for urea hydrolysis, microbial synthesis (from protein, oil, and fiber), microbial decay, microbial cell oxidation, and fiber oxidation (Eqs. 1 through 7) (Misailidis and Petrides 2021; Mokhtar 2022). The defined stoichiometry reflects the underlying biological transformation pathways and serves as a foundation for assessing both the techno-economic performance and the CO_2 equivalent (CO_2e) emission reduction potential of the composting system.

Upon addition to the composting material, urea is hydrolyzed to NH_3 and CO_2 as follows:

$$\text{Urea} + H_2O \rightarrow 2NH_3 + CO_2 \quad (1)$$

Microbial cell synthesis during composting utilizes substrates such as proteins, residual oil, and fiber, as follows:

$$\text{Proteins} + 5.3O_2 \rightarrow 0.6\text{Biomass} + NH_3 + 4.5CO_2 + 4.8H_2O \quad (2)$$

$$\text{Oil} + 81.3O_2 + 11.8NH_3 \rightarrow 12.1\text{Biomass} + 54.4CO_2 + 55.4H_2O \quad (3)$$

$$\text{Fiber} + 6O_2 + 0.47NH_3 \rightarrow 0.8\text{Biomass} + 5.7CO_2 + 6H_2O \quad (4)$$

During composting, microbial decay processes also take place, as follows:

$$\text{Biomass} \rightarrow \text{Dead biomass} \quad (5)$$

Dead microbial biomass is further oxidized during composting, as follows:

$$\text{Dead biomass} + 2.3O_2 \rightarrow 0.2NH_3 + CO_2 + 2.7H_2O \quad (6)$$

During composting, direct fiber oxidation by microorganisms also occurs as follows:

$$\text{Fiber} + 6.6O_2 \rightarrow 6.6CO_2 + 5.6H_2O \quad (7)$$

The GHG emission assessment in this study adopted a gate-to-gate system boundary, encompassing emissions from biomass residue input to compost production. The analysis included direct emissions from composting operations and on-site fuel combustion, together with indirect emissions from electricity supplied by the mill's biomass power generation system. Landfill CH_4 emissions were obtained from the report by Hansen *et al.* (2012).

The economic evaluation of the EFB composting project was conducted using a discounted cash flow framework, with 2025 defined as the base year. Construction was assumed to commence in 2026, involving a 30-month construction period followed by a three-month commissioning and start-up phase. The project lifetime was assumed to be 20 years. The financing structure assumes 70% debt financing of direct fixed capital (DFC) (Arhinful *et al.* 2025) with a 5-year loan period at an interest rate of 5% (Alliance Bank Malaysia Berhad, 2025). Depreciation was calculated using the declining balance method over 14 years, with a salvage value of 5% of DFC, while working capital was recovered at the end of the project lifetime. An annual equipment inflation rate of 4% (Mahmod *et al.* 2021) and a corporate income tax rate of 24% were applied (Mokhtar 2022).

CAPEX, OPEX, and Revenues

The equipment purchase costs (PC) were determined based on information from local suppliers and the SuperPro Designer database. CAPEX was estimated from equipment PC using the software cost model. DFC was derived from the total plant cost (TPC), which comprises the total plant direct cost (TPDC) and total plant indirect cost (TPIC). TPDC includes purchased equipment and its installation, process piping, instrumentation, electrical systems, buildings, yard improvements, and auxiliary facilities. The TPDC was estimated to be 2.4 times the PC (Heinzle *et al.* 2006). The TPIC, along with contractor's fees, contingency costs (CFC), working capital (WC), and start-up and validation costs (SC), was also determined using multiplier factors (Heinzle *et al.* 2006). Consequently, the overall capital investment was estimated using Eqs. 8 through 10. In this report, the CAPEX was calculated for each section, i) EFB preparation, ii) aerated bunker composting, iii) post-processing, and iv) material handling (tractors and bunker-filler machines).

$$\text{TPC} = \text{TPDC} + \text{TPIC} \quad (8)$$

$$\text{DFC} = \text{TPC} + \text{CFC} \quad (9)$$

$$\text{CAPEX} = \text{DFC} + \text{WC} + \text{SC} \quad (10)$$

OPEX, as programmed in the simulation, can be categorized into variable, fixed, and plant-related costs (Heinzle *et al.* 2006). Variable costs include materials, labor, QC laboratory expenses, and utilities, with QC laboratory costs typically estimated at about 15% of the total operating labor cost (Peters *et al.* 2003). Labor requirements, particularly for plant operators, are based on typical staffing needs per process unit, with most variable

cost data in this study obtained from Table A1. Fixed costs, also referred to as facility-dependent costs in SuperPro Designer, comprise depreciation, maintenance and repair, insurance, local taxes, and plant overheads (Heinzle *et al.* 2006). The annual operating time (AOT) was assumed to be 6,000 h/year.

In this simulation study, revenues are generated from residual oil recovery from EFB liquor and from compost. The compost is assumed to be equally divided, with 50% sold in its original form and the remaining 50% further processed into a formulated (10% inorganic fertilizer) and granulated product that can be marketed at a higher market price. The selling prices of these potential revenue streams are summarized in Table A1.

Project Scenarios and Sensitivity Analysis

A scenario analysis was performed based on different compost product ratios (enriched compost to original compost), carbon credit inclusion, and government incentives relative to the base case (50% original and 50% enriched compost without potential carbon credit). Five scenarios (S1 to S5) were modeled, and for each, financial indicators, such as return on investment (ROI), PT, internal rate of return (IRR), and net present value (NPV) at discount rate of 10% (Chung and Halim 2022), were simulated under consistent assumptions to compare the influence of compost ratios, carbon credits, and CAPEX incentives on project feasibility.

A one-factor-at-a-time deterministic sensitivity analysis was conducted by varying each key operational parameter, such as AOT, process throughput, CAPEX, original compost, and enriched compost selling price, inorganic fertilizer and urea price, ratio of enriched compost to original compost, ratio of treated sludge to EFB, and composting day by ± 25% from the base-case values while keeping other variables constant. For each variation, project indicators (NPV, IRR, PT, ROI) were simulated and project horizon as the base case, and results were compared to identify the most influential parameters on overall project feasibility.

RESULTS AND DISCUSSION

The chemical composition of EFB, POME sludge, freshwater treatment sludge, and decanter cake (Table A2) was adopted as simulation input, with values consistent with those reported in previous studies (Sahad *et al*. 2014; Yunos *et al.* 2015), thereby ensuring data reliability. Based on these inputs and process requirements, the ABC system was selected over conventional alternatives (*e.g*., windrow piles, tunnel reactors, and agitated beds), as it offers superior space efficiency, enhanced process stability and operational reliability, simplified operation, and improved emission control (EA Engineering, Science, and Technology, Inc. PBC, 2024). These advantages are particularly critical for integration within palm oil mill environments, where footprint constraints, variable feedstock characteristics, and stricter environmental compliance necessitate robust and controllable composting systems.

The simulation demonstrates the strong potential of composting oil palm EFB as a sustainable valorisation route, with several results aligning well with literature values (Table 1). The mass balances of the process can be referred to the SuperPro Designer process flowsheet in Fig. 1. Composting resulted in a substantial mass reduction of 0.33 MT per MT of material, consistent with the range reported by Supriatna *et al.* (2022). Similarly, the observed organic matter loss (30%) falls within reported values (Talib *et al.*

2014), supporting the reliability of the model. Compost properties were consistent with experimental findings, with moisture (35.2%) and ash (7.6%) values closely matching reported data, validating the process assumptions. Residual crude oil obtained from feedstock was 0.34% (to FFB) recovery, which is also comparable from previous record study.

Table 1. Key Simulation Results of SuperPro Designer

Characterization	This study (simulation)	Other studies (if available)
Compost:		
Mass reduction	0.33 MT/MT composting material	0.30 to 0.50 MT/MT composting material (Supriatna *et al.* 2022)
Organic matter loss	30%	29.3 – 40.5% (Talib *et al.* 2014)
Yield (to FFB)	11%	-
Moisture	35.2%	35% (Sayara *et al.* 2020)
Ash	7.6%	8.4% (Baharuddin *et al*. 2009)
Residual oil (crude):		
Oil recovery (to FFB)	0.34%	0.35% (Jorgensen 1985)
Oil recovery (to total residual oil in EFB)	59.1%	49 to 61% (Gomez *et al.* 2015)
Oil content	82.2%	-
CO_2e emission:		
Composting (first phase)	184 kg CO_2e/MT CPO	-
Composting (curing phase)	30 kg CO_2e/MT CPO	-
Tractor engines	2.2 kg CO_2e/MT CPO	-
Electricity (indirect)	32 kg CO_2e/MT CPO$^{\beta}$	
Total CO_2e reduction$^{\lambda}$	79%	76% (Krishnan *et al.* 2017)
60 MT FFB/h capacity of palm oil mill and AOT of 6000 h/year Crude palm oil (CPO) is based on 20% OER $^{\beta}$Electricity generation via oil palm biomass fuel was assigned an emission factor of 0.65 kg CO_2e/kWh (Chung and Menon 2012) $^{\lambda}$Compared to 1,180 kg CO_2e/MT CPO, emission from EFB landfill (Hansen *et al.* 2012)		

From an environmental perspective, composting avoided considerable GHG emissions compared to EFB landfilling. The simulation estimated CO_2e emissions of 184 kg CO_2e/MT CPO during the active composting phase and 30 kg CO_2e/MT CPO during curing, with an additional 2.2 kg CO_2e/MT CPO from tractor use. The plant's electricity consumption is approximately 3570 MWh/year, which can be supplied by the mill's POME biogas power plant (Nasrin *et al*. 2022), contributing indirect emissions of about 32 kg CO_2e/MT CPO. Overall, the process potentially achieves a 79% reduction in CO_2e emissions relative to landfilling (1,180 kg CO_2e/MT CPO), which is comparable with previous study. Emission reductions highlight composting's strong climate mitigation potential in palm oil mills.

The CAPEX for the integrated system was estimated at MYR 43.82 million, with the largest share contributed by the ABC system (66.7%) as shown in Table 2. For comparison, the SG Bunker® System in the USA was reported to cost around USD 11 million (~ MYR 48.5 million) in 2023 (EA Engineering, Science, and Technology, Inc. PBC 2024). This indicates that the estimated cost in this study is almost comparable to the U.S. benchmark.

The OPEX amounted to MYR 15.66 million/year, dominated by raw materials (49.4%) and facility-dependent (32.6%) expenses. Importantly, the OPEX of MYR

189/MT-composting material (EFB) was slightly lower than the previous reported value, MYR 218/MT (Coker 2020). On the revenue side, enriched compost contributed the largest portion (MYR 21.9 million/year), accounting for nearly 73.3% of total revenues, followed by original compost and recovered residual oil. Overall, the system generated total annual revenues close to MYR 30 million, which strongly outweighed OPEX, indicating promising economic feasibility.

Table 2. Project Summary

Economic Evaluation	Cost	Unit
CAPEX (refer to Table A3 and A4):		
EFB preparation (shredding, pressing, and oil separator from EFB liquor)	7.28	MYR mil.
Aerated bunker composting (ABC) system (bunker, sludge tank, *etc.*)	29.23	MYR mil.
Post-processing (grinding, granulating, and filling)	2.79	MYR mil.
Material handling (4 tractors and 2 bunker-filler machines)	4.52	MYR mil.
Total	43.82	MYR mil.
OPEX:		
Raw materials	7.74	MYR mil./year
Facility-dependent	5.10	MYR mil./year
Labor	1.09	MYR mil./year
Laboratory/QC/QA	0.16	MYR mil./year
Utility (~3,570 MWh/year)*	1.57	MYR mil./year
Total	15.66	MYR mil./year
OPEX/MT-composting material (EFB)	189	MYR/MT
Revenues:		
Compost (50% original)	4.98	MYR mil./year
Compost (50% enriched)	21.90	MYR mil./year
Residual oil	3.00	MYR mil./year
Total	29.88	MYR mil./year
60 MT FFB/h capacity of palm oil mill and AOT of 6000 h/year MYR 1 (USD 0.227) * Electricity is supplied from palm oil mill's biomass and/or biogas-based power generation system, and the cost is accounted for using an internal transfer price equivalent to the grid electricity tariff (Nasrin et al. 2022).		

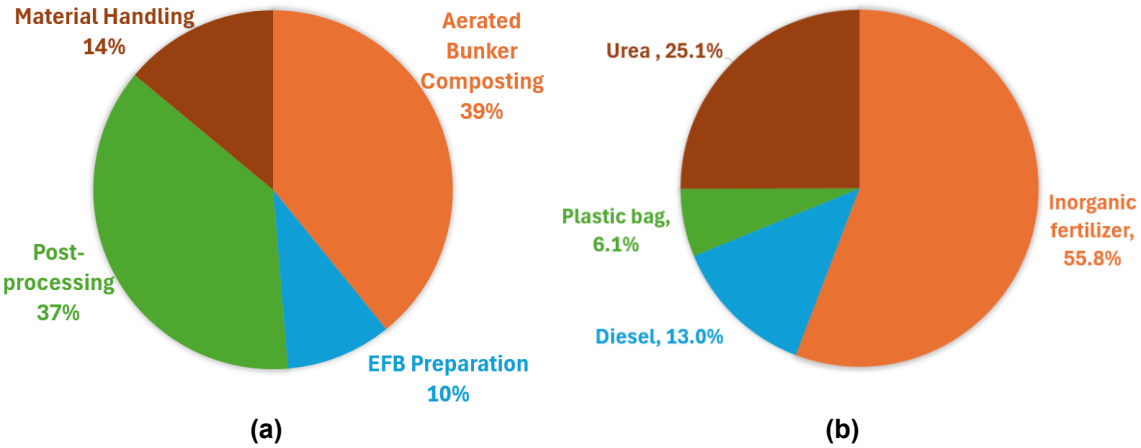


Fig. 2. Breakdown of (a) operating costs by section, and (b) raw material costs

The operating cost allocation of each unit (Fig. 2a) indicates that the ABC system accounted for the largest share, followed by post-processing, making these two stages the most cost-intensive (76%). The high cost of the ABC section is mainly attributed to facility-dependent expenses (MYR 3.2 million/year) and raw materials (MYR 2.0 million/year), which together represent about 84% of the section's OPEX. For the post-processing section, costs are dominated by raw materials for enriched compost production (MYR 4.8 million/year), representing 81.3% of that section's OPEX.

In terms of raw material distribution across the entire project (Fig. 2b), inorganic fertilizer for enriched compost formulation contributed the largest share (55.8%), followed by urea for composting. Collectively, these two inputs accounted for more than 80% of total raw material costs, highlighting nutrient supplementation as the primary cost driver.

Table 3. Comparison with Different Scenarios for Project Indices

Project Indices	Base	S1	S2	S3	S4	S5
ROI (%)	30.50	10.54	15.18	21.68	26.88	32.75
PT (year)	3.28	9.49	6.59	4.61	3.72	3.05
IRR after taxes (%)	39.92	6.95	14.92	25.86	34.14	43.67
NPV (10%) (MYR million)	58.40	-5.71	9.18	22.37	46.51	65.47

A potential carbon credit rate of MYR 38.72/MT CO_2e (USD 8.80/MT CO_2e) was assumed based on average official data from Asian countries such as China and South Korea (ICAP, 2025), with the potential revenue calculated based on an estimated 79% reduction in carbon emissions in this study (total reduction rate, ~ 11.2 MT CO_2e/h)

Base case: 50% original compost and 50% enriched compost, without any carbon credit initiative

S1: 100% original compost, and no carbon credit initiative

S2: 100% original compost, with full carbon credit initiative

S3: 100% original compost, with full carbon credit initiative and an additional government incentive (25% reduction in CAPEX)

S4: 70% original compost and 30% enriched compost, with full carbon credit initiative

S5: 50% original compost and 50% enriched compost, with 50% carbon credit initiative

Table 3 demonstrates how financial performance is influenced by the ratio of enriched compost (formulation–pelleting) relative to original compost, together with carbon credit and CAPEX incentives. The base case achieved strong profitability (NPV MYR 58.4 million, IRR 39.92%, and PT 3.28 years), indicating high feasibility even without any incentives. In contrast, producing only original compost without carbon credit (S1) resulted in poor economic returns (PT 9.49 years, negative NPV). With a 79% reduction in CO_2e emissions, the potential full carbon credit initiative could generate approximately MYR 2.6 million/year. Introducing carbon credit (S2) improved performance considerably (PT 6.59 years), while combining carbon credit with a 25% CAPEX reduction (S3) further enhanced outcomes (PT 4.61 years). Introducing the enriched compost ratio to 30% (S4) under full carbon credit noticeably boosted profitability, approaching the base case scenario. The highest gains were achieved in S5 (the same scenario as base case, but with only half carbon credit), yielding the best NPV (MYR 65.47 million), ROI (32.75%), IRR (43.67%), and shortest PT (3.05 years). Overall,

the results indicate that increasing the proportion of enriched compost noticeably enhances economic feasibility, while carbon credit and CAPEX incentives serve as complementary drivers to improve investment attractiveness. Based on previous study, government subsidy is one of the crucial factors for composting process feasibility (Su *et al.* 2024).

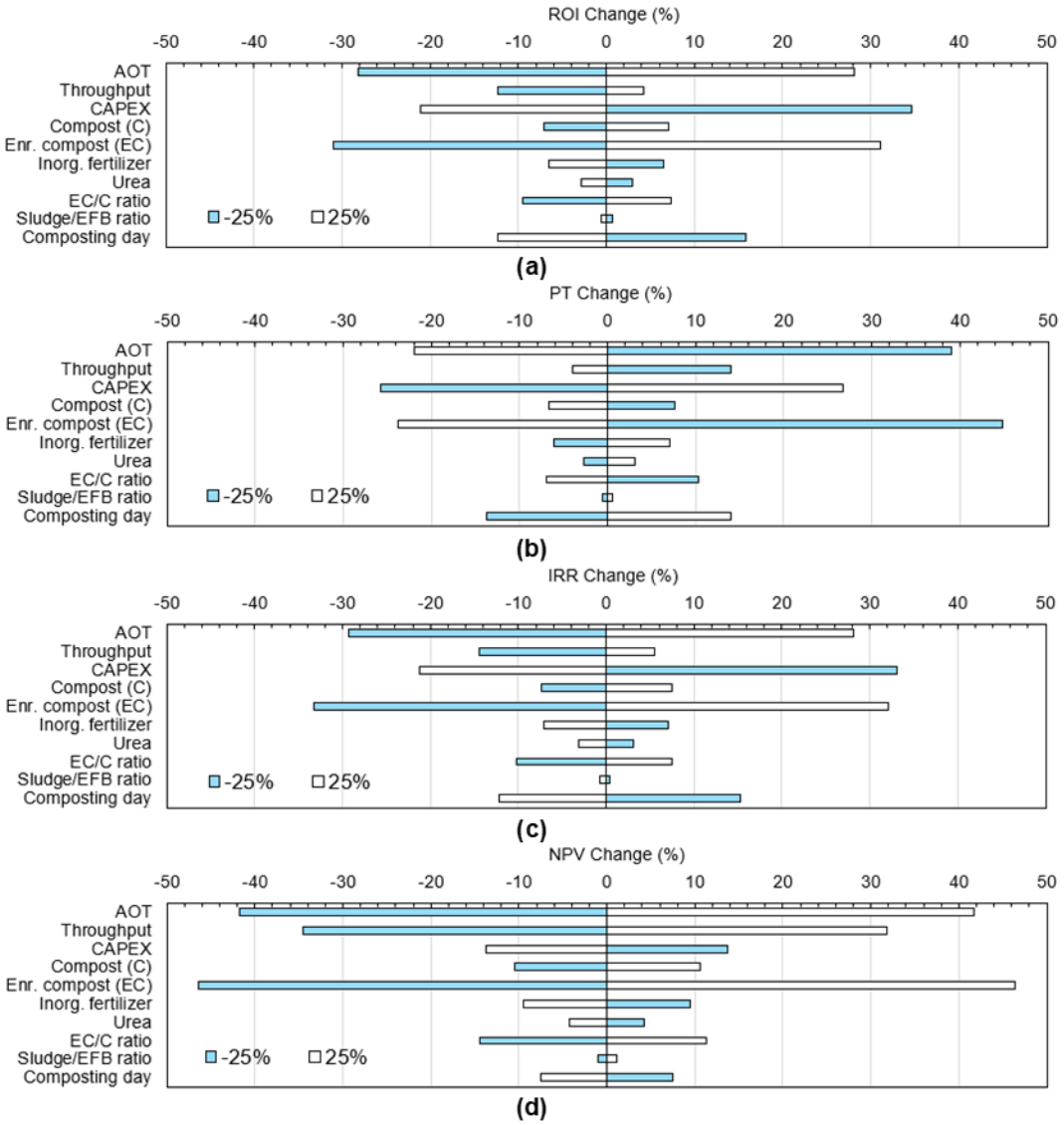


Fig. 3. Sensitivity analysis of a) ROI, b) PT, c) IRR, and d) NPV based on ± 25% variation from default values (base case)

The sensitivity analysis (± 25% from the base case), as shown in Fig. 3, identified enriched compost selling price, AOT, and CAPEX as the most influential parameters across the key economic indicators. For ROI, variations in enriched compost selling price resulted in a change between –31.0% and +31.1%, AOT between –28.1% and +28.2%, and CAPEX between +34.6% and –21.1%. Similarly, the PT was highly sensitive to these parameters, with enriched compost price shifting values by –23.8% to +44.8%, AOT by –22.0% to +39.0%, and CAPEX by –25.8% to +26.7%. These results indicate that product market value, operational duration, and investment cost are the principal determinants of short-term project performance.

The IRR also exhibited changes, with CAPEX causing shifts between –21.3% and +33.0%, enriched compost selling price between –33.3% and +32.1%, and AOT between –29.4% and +28.2%. These substantial variations emphasize the strong dependence of internal profitability on efficient capital management, favourable product pricing, and reliable operational performance. In terms of NPV, the enriched compost selling price demonstrated the greatest sensitivity (–46.4% to +46.4%), followed by AOT (–41.7% to +41.7%) and process throughput (–34.6% to +31.8%). According to previous finding (Albtoosh *et al.* 2024), a 5% increase of compost selling price could potentially increase NPV to 10%. This highlights the combined importance of revenue potential and feedstock processing stability in securing long-term financial viability.

Parameters, such as composting day, the ratio of enriched compost to original compost (EC/C), inorganic fertilizer price, urea price, and original compost selling price, exhibited comparatively lower effects, indicating that adjustments in these areas would only marginally influence overall project performance. Among all factors, the sludge/EFB ratio demonstrated the least impact on economic feasibility. In contrast, the results clearly highlight that strategic emphasis should be placed on enhancing the market value of enriched compost, maintaining high AOT, and optimizing CAPEX management, as these represent the most effective levers to strengthen both feasibility and resilience of the project. This outcome aligns with the previous findings (Su *et al.* 2024), who reported that product price and processing throughput are the principal factors influencing economic indices, thereby reinforcing the consistency of the present study with broader techno-economic assessments in the field.

CONCLUSIONS

1. Composting oil palm empty fruit bunch (EFB) through the aerated bunker composting (ABC) system potentially achieved substantial stabilization of organic matter and mass reduction in this simulation study, while delivering a 79% reduction in CO_2e emissions compared to landfilling. These findings demonstrate the sustainability potential of integrating this technology within palm oil mills.
2. The integrated system showed strong profitability in the base case (NPV MYR 58.4 million, ROI 30.5%, and PT 3.28 years), with enriched compost accounting for ~73.3% of revenues. Although the ABC system contributed the largest share of CAPEX and OPEX, its role in enabling enriched compost production and process efficiency makes it the cornerstone of economic viability. Incentives, such as carbon credits and CAPEX reductions, further enhanced profitability.
3. Sensitivity analysis confirmed that enriched compost selling price, AOT, and CAPEX were the most influential parameters across ROI, PT, IRR, and NPV. Enhancing enriched compost market value, ensuring high operational uptime, and managing the investment costs are the critical levers to strengthen both financial resilience and environmental benefits.

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Conflict of Interest

The author has no relevant financial or non-financial interests to disclose.

Use of Generative AI

The author declares that AI (ChatGPT) was only used to assist in improving the language of this manuscript.

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APPENDIX

Table A1. Selling Prices and Major Cost Factors (Raw Materials, Utilities, Labor)

Category	Price/cost	Unit
Raw Materials:		
Inorganic fertilizer	2,200	MYR/MT
Diesel	3.52	MYR/L
Plastic bag	4.40	MYR/kg
Urea (7 M)	4.85	MYR/L
Labor (Mokhtar 2022):		
1 Security guard (Certificate holder)	15.00	MYR/h/staff
1 Clerk and 1 maintenance staff (Diploma holder)	18.00	MYR/h/staff
Plant/Equipment operators (Diploma holder)*	21.00	MYR/h/staff
1 Plant engineer (Bachelor of Eng. holder)	27.00	MYR/h/staff
Products:		
Compost	250	MYR/MT
Compost (enriched) (each package, 25 kg)	25	MYR/package
Residual oil (crude)	2500	MYR/MT
Utility:		
Electricity	0.44	MYR/kWh
AOT is 6000 h/year *Equipment operators were based on typical staffing needs per process unit (Table A3)		

Table A2. Chemical Composition of EFB, POME Sludge, Freshwater Treatment Sludge, and Decanter Cake from 60 MT FFB/h Mill Capacity Used in Simulation

Composition	13.8 MT/h EFB (%)	9.9 MT/h treat. POME sludge (%)	1.7 MT/h treat. FW sludge (%)	2.0 MT/h decanter cake (%)
Ash	2.1	2.7	3.9	1.0
Fiber	30.0	2.6	-	16.6
Residual oil	2.5	-	-	3.3
Proteins	0.9	0.3	-	1.2
Sand/stone	1.0	0.7	-	1.9
Water	63.5	93.7	96.1	76.0
Values are reported as averages				

Table A3. List of Equipment Allocation of the Project (60 MT FFB/h, AOT 6000 h/year)

No	Name	Description	Unit	Capacity (each)	Material of Constr.	PC (MYR)	Equip. operator (staff/unit/ shift)
	EFB Preparation:						
1	SR-101	Shredding of EFB	3	4.6 MT/h	CS	860,000	0.1
2	SP-101	Pressing of EFB	2	6.9 MT/h	CS	998,000	0.25
3	SCR-101	Screening	1	6.4 MT/h	CS	9,600	0.05
4	V-102	Oil separation tank (skimming)	1	2 m^3	SS316	20,000	0
	Sub-total					1,887,600	

	Aerated Bunker Composting:						
5	V-101	Sludge holding tank	1	309 m^3	FRP	30,000	0.05
6	PFAB-101	Aerated bunker composting	17	1310 m^3	Concrete	6,370,000	0.1
7	PFAB-102	Curing	4	1260 m^3	Concrete	1,420,000	0.1
8	M-101	Air blower	4	7784 m^3/h	CS	120,000	0.05
	Sub-total					7,940,000	
	Post-Processing:						
9	VSCR-102	Vibrating screening	1	6.68 MT/h	SS304	88,000	0.05
10	GR-101	Grinding compost	1	6.68 MT/h	CS	310,000	0.1
11	TB-101	Granulator	1	3.68 MT/h	CS	110,000	0.1
12	FL-101	Filling & packaging	1	25 kg/pack	CS	71,000	0.5
	Sub-total					579,000	
	Material Handling:						
13	GBX-107	Tractors (including tractor shed)	4	100 HP	CS	680,000	1
14	GBX-108	Bunker filler machine	2	12 MT/h	CS	500,000	1
	Sub-total					1,180,000	
	Total					**11,586,600**	

Table A4. CAPEX Estimation of the Project (60 MT FFB/h, AOT 6000 h/year)

Section	TPDC = 2.4PC	TPIC = 0.35 TPDC	CFC = 0.08 (TPDC +TPIC)	DFC = TPDC+TPIC +CFC	WC (30 days)	SC = 0.05DFC	CAPEX = DFC+WC +SC
	MYR million						
EFB Preparation	4.53	1.59	0.49	6.61	0.34	0.33	7.28
Aerated Bunker Composting	19.06	6.67	2.06	27.78	0.06	1.39	29.23
Post-Processing	1.39	0.49	0.15	2.03	0.66	0.10	2.79
Material Handling	2.83	0.99	0.31	4.13	0.19	0.21	4.52
Total	27.81	9.73	3.00	40.54	1.25	2.03	43.82