Advanced and Sustainable Technologies
ASET
E-ISSN 2976-2294

Volume 3, No 2, December 2024 [102-112]

Optimization Model for Maximizing Economic Impact of POME Treatment System

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Received 31 August 2024, Revised 12 September 2024, Accepted 24 September 2024

ABSTRACT

This study presents a strategic planning model to optimize economic returns and minimize the environmental impact of Palm Oil Mill Effluent (POME) treatment systems. The model aims to maximize profits while reducing CO_2e emissions by evaluating three treatment options: Anaerobic Digester Tank System (ADT), Covered Lagoon (CL) with biogas capture, and Open Pond System (OP). Constraints considered include fresh fruit bunch (FFB) production, POME generation, treatment system capacity, electricity generation from the existing boiler and additional biogas engine, electricity demand, capital costs, and operating costs. A mixed-integer linear programming model (MILP) is formulated and optimized using GAMS 40.1.0 software, focusing on selecting the treatment system that balances profitability with minimal CO_2e emissions. Applied to a case study of two mills in Papua New Guinea, the model identified the ADT system as the optimal treatment system. In the Economic Mode, the model prioritizes profit maximization, achieving a total annual profit of USD 9,769,439, with electricity sales amounting to USD 12,399,439 per year. The developed model can assist governmental agencies and private sectors in developing strategic pome treatment systems that enhance profitability while minimizing environmental impact.

Keywords: Biogas, Palm Oil Mill Effluents, Optimization Modelling, Green Energy.

1. INTRODUCTION

The conventional treatment of Palm Oil Mill Effluent (POME) typically relies on open pond systems, which necessitate extensive land areas for the construction of various ponds, including cooling, anaerobic, aerobic, and facultative ponds. These ponds are used to treat the effluent. The disposal of POME waste is one of the main financial issues faced by citizens and industries, as the processing of CPO into its final products poses major environmental issues. However, untreated POME is also one of the top priority cases of environmental issues. For instance, POME is a wastewater that is easily dissolved, and the release of suspended particles generates a high volume of extremely contaminating waste products and odors after the degradation process of organic material by the microbes [1]. Furthermore, the breakdown process is relatively complex. However, this method leads to the release of biogas into the atmosphere, thereby exacerbating

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environmental pollution. Methane (CH_4), a highly flammable and lightweight gas produced during treatment, is a significant contributor to atmospheric pollution.

In response to these environmental concerns, technologies such as the Covered Lagoon System (CL) and Anaerobic Digestion Tank (ADT) have been developed to mitigate CO_2 emissions. Critical environmental parameters that are also considered are the reduction of Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD) to permissible levels, which is essential for minimizing the environmental impact of POME. These technologies differ in both cost and environmental impact. Economically, the open pond system is less expensive than CL and ADT; however, it is associated with higher CO_2 emissions. OP system and CL require high land usage to be effective. ADT uses a small area but has high capital and maintenance costs. In contrast, while CL and ADT involve higher capital expenditures, they are more effective in capturing biogas produced during anaerobic digestion. This biogas can be either flared or purified and used in gas engines to generate electricity [2]. The electricity produced can then be sold to the grid, providing additional income, or used internally within the palm oil mill to reduce diesel consumption.

Although the CL and ADT systems require significant investment, they offer the advantage of biogas capture, which not only mitigates greenhouse gas emissions but also provides a potential revenue stream through electricity generation. Additionally, surplus electricity generated from the combustion of palm kernel shell (PKS) and palm kernel fiber (PKF) in boilers can also be sold to the grid, further contributing to income generation. The utilization of palm oil mill effluent (POME) for biogas production represents a sustainable and viable approach to mitigating greenhouse gas emissions associated with POME while concurrently generating economic benefits [3]. Therefore, the industry must carefully select an optimal POME treatment and operational strategy that balances economic feasibility with environmental sustainability.

A case study conducted in Papua New Guinea (PNG) reveals that four palm oil mills in the region have upgraded their POME treatment systems to include biogas capture, while others continue to use the traditional open pond (OP) system. Specifically, three of the mills have implemented the Covered Lagoon (CL) system, and one mill has adopted the Anaerobic Digester Tank (ADT) system. The following discussion outlines the gaps identified in the current POME treatment practices in Papua New Guinea. There is a lack of comprehensive evaluations of POME treatment systems, including Open Pond (OP), Covered Lagoon (CL), and Anaerobic Digestion Tank (ADT), particularly concerning their economic impacts, operational costs, and biogas utilization. Addressing this gap would provide critical insights for industries aiming to adopt efficient and environmentally sustainable POME treatment solutions. Additionally, demonstrating clear economic benefits, such as profit margins and return on investment, would further encourage palm oil mill operators to select the most appropriate treatment system. Therefore, this study aims to develop an optimization model for POME treatment systems, considering Open Pond (OP), Covered Lagoon (CL), and Anaerobic Digestion Tank (ADT) systems, that can effectively evaluate both economic benefits and environmental impacts.

2. MATERIAL AND METHODS

The research methodology comprised several sequential steps. It commenced with the definition of the problem, specifically concerning the treatment system for palm oil mill effluent (POME). The identified issues pertinent to determining the optimal POME treatment system encompassed economic factors (profitability), environmental impact (CO_2e), and sustainability. At this stage, challenges associated with POME management in palm oil mills (POMs) were acknowledged. Additionally, the overall cost associated with managing and mitigating pollution was highlighted as a significant concern. The second step involved constructing a superstructure diagram (Figure 1) to represent the problem accurately. Subsequently, this diagram was simplified. A model was then developed for the identified economic problem: the Economic-Profit Mode Model.

Following this, a case study was selected involving the Barema Palm Oil Mill, which utilizes the Anaerobic Digestion Tank (ADT) and Pond system, and the Kumbango Oil Mill, which employs the Covered Lagoon System. Within this context, the identified constraints and assumptions were applied, with a particular focus on the hourly processing capacity of the POM in terms of processed palm kernel oil and POME. Data required for the model were gathered from the case studies, research articles, and relevant authorities.

The formulated models were then coded into optimization software, specifically GAMS Software version 40.1.0. The optimization of the POME treatment systems was conducted using this software, which was programmed with the defined mathematical models and associated data. A sensitivity analysis was performed to evaluate the impact of changes in input parameters on the model's objectives. The model's outputs were subsequently compared across all modes in terms of economic and environmental performance.

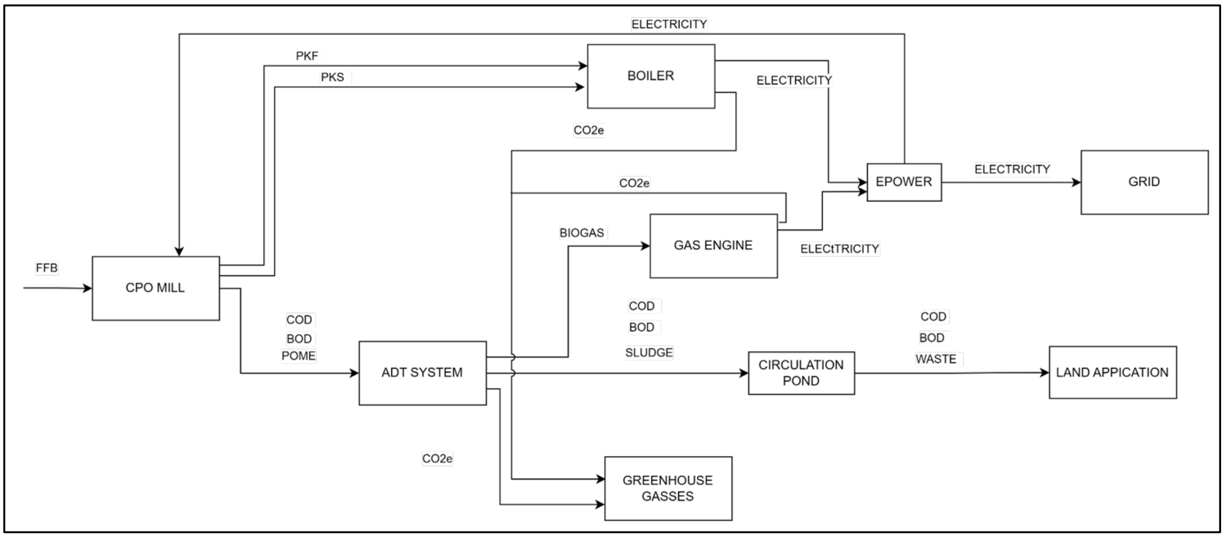

Figure 1: Superstructure diagram of POME treatment system.

2.1 Model Formulation

Mathematical formulations were developed based on the superstructure diagram generated in the previous stage. By constructing a mixed-integer linear programming (MILP) model, it becomes feasible to optimize treatment scenarios, enabling the identification of a POME treatment system that is both cost-effective and reduces carbon emissions.

2.1.1 Objective Function

The objective function is to maximize profitability. The variable PROFIT is representative of the total profit within the context of the PTS as bounded in Eq.1. Within this framework, sales cost denotes the revenue generated from electricity sales, operating cost encompasses the expenses related to the treatment system processes, and capital cost refers to the financial outlay associated with equipment and facilities as formulated in Eq.2 to Eq.4. This delineation of PROFIT components provides a clear understanding of the financial dynamics involved in optimizing the PTS for maximum profitability.

$$PROFIT = SALESCOST - OPERATINGCOST - CAPITALCOST \quad (1)$$

$$SALES\ COST = \sum_{j} elecs_{j,s} \times elecpriceo_{s} \times 1000 + \sum_{j} elect_{j,m} \times elecpricei_{m} \times 1000 \quad (2)$$

$$OPERATINGCOST = \sum_{p} mencost_{p} \times xa_{p} \quad (3)$$

$$CAPITALCOST = \sum_{p} capcost_{p} \times xa_{p} \quad (4)$$

2.1.2 CO_2e Emission, BOD, COD, and Material Balance Constraints

The variable CO_2e is representative of CO_2e from the POME treatment system and emissions from the boiler as formulated in Eq.5. Eq. 6 and Eq.7 were formulated to monitor BOD and COD levels of each treatment system. Eq. 8 to Eq. 16 encapsulate the material conversion and material balance aspects, specifically addressing the transformation of FFB into various components of oil palm biomass. This comprehensive formulation encompasses the conversion processes at POMs and treatment facilities, accounting for the generation of POME, shell, and fibre. These equations serve as a structured representation of the intricate relationships and transformations involved in the conversion of FFB, providing a systematic approach to modelling and analyzing the material balance within the oil palm biomass conversion process.

$$CO2 = \sum_{p,a} gasout_{p,a} + \sum_{n,a} gasout2_{n,a} \quad (5)$$

$$BOD = \sum_{n,s} mbodout2_{n,s} \quad (6)$$

$$COD = \sum_{n,s} mcodout2_{n,s} \quad (7)$$

$$pome_{m} = ffb_{m} \times ratiopome_{m}\ \forall\ m \quad (8)$$

$$pome_{m} = \sum_{p} pomet_{m,p}\ \forall\ m \quad (9)$$

$$pomea_{p} = \sum_{m} pomet_{m,p}\ \forall\ p \quad (10)$$

$$shell_{m} = ffb_{m} \times ratioshell_{m}\ \forall\ m \quad (11)$$

$$shell_{m} \geq shellt_{m,n} \forall\ m \quad (12)$$

$$shella_{n} = \sum_{m} shellt_{m,n}\ \forall\ n \quad (13)$$

$$fiber_{m} = ffb_{m} \times ratiofiber_{m}\ \forall\ m \quad (14)$$

$$fiber_{m} \geq fibert_{m,n} \quad (15)$$

$$fibera_{n} = \sum_{m} fibert_{m,n}\ \forall\ n \quad (16)$$

2.1.3 Electricity Generation and Utilization Constraints

Eq. 17 to Eq. 21 constitute a set of formulations dedicated to material conversion and balance, specifically addressing the conversion of oil palm biomass into electricity. These equations intricately capture the processes involved in transforming various components of oil palm biomass—such as shell, fiber, and biogas—into electrical energy. The formulation offers a systematic representation of the material balance during this conversion process. Additionally, Eq. 22 and Eq. 24 specifically quantify the generated electricity required to meet the specified demand, providing crucial insights into the energy dynamics and ensuring the alignment of electricity production with consumption requirements.

$$shella_{boiler} \times ratioelec_{boiler} = elecbs_{boiler} \tag{17}$$
$$fibera_{boiler} \times ratioelec2_{boiler} = elecbf_{boiler} \tag{18}$$
$$elecbf_{boiler} + elecbs_{boiler} = elecb_{boiler} \tag{19}$$
$$biogasa_{gase} \times ratioelec_{gase} = elecg_{gase} \tag{20}$$
$$elecg_{gase} + elecb_{boiler} = electot_{epower} \tag{21}$$
$$electot_j \geq \sum_s elecs_{j,s} + \sum_m elect_{j,m} \tag{22}$$
$$elecs_{j,grid} \geq 0.8 \times electot_j \tag{23}$$
$$elect_{j,cpomill} \geq 0.2 \times electot_j \tag{24}$$

2.1.4 Selection of POME Treatment Facility Constraints

The selection of a treatment facility is constrained to be less than or equal to one treatment system, as expressed by Eq. 25. This formulation ensures that only one treatment system is chosen, reflecting the necessity for a singular selection among available treatment facilities. Simultaneously, Eq. 26 has been devised to guarantee that there is no processed material at an unselected treatment facility. This constraint reinforces the exclusivity of the chosen treatment facility in handling the designated materials, aligning with the precision required in the optimization model.

$$\sum_p XA_p \leq 1, \tag{25}$$
$$pomea_p \leq XA_p \times capacitylimit_p \tag{26}$$

2.2 Case Study and Data Input

Palm Oil Mills at Papua New Guinea (PNG) serves as a chosen case study to elucidate the conceptual framework developed, Barema Palm Oil Mill with ADT and Pond system and Kumbango Oil Mill with Covered Lagoon System. Within this context, the outlined constraints and assumptions are applied, specifically focusing on the yearly processing capacity of POM in terms of processed palm kernel oil and POME (Table 1).

Table 1: Materials Availability, Conversion Ratio and Economic Values.

Material	Unit	Availability/ ratio	Price (USD/ ton or kWh)	References
Fresh fruit bunches (FFB)	ton	324,000	188.89	Berema Palm oil Mill
Palm kernel shell (PKS)	ton/ton FFB	0.06	93.33	[4] (Taqwa & Purwanto, 2019)
Palm kernel fiber (PKF)	ton/ton FFB	0.13	42.22	[4] Taqwa & Purwanto (2019)
Palm oil mill effluent (POME)	m^3/ton FFB	0.6	n.a	[5] (Sinaga et al., 2018)
Biogas	m^3/ m^3 POME	21	0.43	[6] (Choong et al., 2018)

Treated POME	m^3/ m^3 POME	0.010	n.a	[5] (Sinaga et al., 2018)
Digestate	m^3/ m^3 POME	0.025	n.a	Kumbango Oil Mill
Electricity conversion from biogas (biogas engine)	kWh/ m^3 biogas	0.0016	0.08	Berema Palm oil Mill
Electricity conversion from PKS (boiler)	kWh/ ton PKS	3.9098	0.08	Berema Palm oil Mill
Electricity conversion from PKF (boiler)	kWh/ ton PKF	3.7076	0.08	Berema Palm oil Mill

3. RESULTS AND DISCUSSION

The developed Profit Mode model has been encoded into the General Algebraic Modeling System (GAMS) with the objective function centered on maximizing the overall profit of the treatment system. This coded implementation serves as a valuable resource for users seeking to delve into the intricacies of the model, facilitating its execution and optimization with a primary emphasis on maximizing profitability.

3.1 Optimal biomass and electricity flow

The developed Profit Mode Model aims to formulate and optimize a mathematical model that is capable of selecting the most profitable treatment system for POME treatment, considering three distinct scenarios: the Open Pond (OP) system (conventional), the CL system with biogas capture, and the ADT system. The output of the model designates ADT as the most profitable POME treatment system. With an annual FFB production of 324,000 metric tons, the generated POME tend to be 194,400 m3 with potential yields of 4,082,400 m3 of biogas, translating to a potential electricity generation of 9,349 megawatts (MWh) with a total profit of USD 9,769, 439 annually.

Notably, electricity generation from the ADT treatment system accounts for 5.45% of the total system's electricity generation. In contrast, the combustion of palm kernel shells and palm kernel fiber in the mill boiler generates a substantial 162,032 MWh or 94.55 % of total electricity generation, constituting most of the electricity production. The total electrical power generation contributes 20%@ 34,267 MWh for the mill used and 80% @ 137.105 MWh contributing to the grid. It is essential to underscore that the COD and BOD reductions were about 92.50% and 94%, respectively, with the selected ADT system. The produced CO_2e was calculated to be 104,469 t CO_2e. It is crucial to highlight that, based on the model, the ADT POME treatment system represents the most optimal material and energy flow within the POME treatment landscape and has maximum profit, as shown in Figure 2.

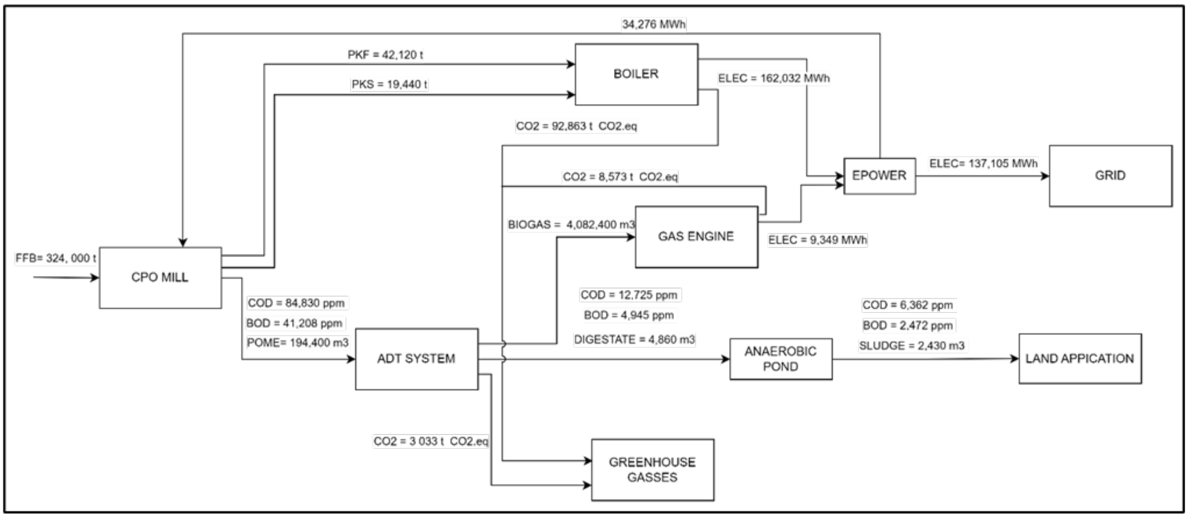

Figure 2: Optimal biomass and utility flow in the POME treatment system.

3.2 Overall Economic

The model has identified the ADT as the most profitable PTS. The analysis indicates that an annual profit of USD 9,769,439 can be achieved through the electricity generated from both the boiler and biogas. In this context, the capital cost associated with the ADT represents 18.55 % of the total sales, underscoring the favorable economic prospects and efficiency of the ADT in comparison to other considered treatment systems (Table 2). The model decided that ADT with economic performances due to the combination of electrical energy supply from boiler and turbine as per in Table 2 showing high profit. The calculated ROI was 109% with a payback period of 0.92 years. The model calculated the annual amount of CO_2e emission was about 104, 469 t CO_2e within the system. The profit compares with other studies showing in the literature reviews that up-flow anaerobic sludge blanket produced high biogas with a profit of USD 7.24 million but the treatment system combined with a cryogenic separator lowered capital and operating costs [7]. The relationship between biogas production and economic profit, economic and GHG (greenhouse gas) profit, and sustainability profit, as well as its impact on supply and its advantages for decision-making [8].

Table 2: Economic Parameter of optimal POME treatment system.

Variable	Description	Value	Unit
PROFIT	Annual profit of POME treatment system	9,769,439	USD/yr
SALES	Annual sales of generated electricity	12,399,439	USD/yr
CAPITALCOST	Annual Capital cost of selected POME treatment system	2,300,000	USD/yr
OPERATINGCOST	Annual Operating cost of selected POME treatment system	270,000	USD/yr
XA	Selection of POME treatment system	ADT system	-
CO_2e	Annual amount of CO_2e emission	104,469	t CO_2e
ROI	Return on Investment	109	%
PB	Payback period	0.92	years

3.3 Sensitivity Analysis

The analysis reveals that profitability is particularly sensitive to changes in FFB availability, showcasing the highest impact with fluctuations influencing up to ± 37.89% of the total profits, as illustrated in Figure 3. The changes follow a linear pattern, with a factor of 12.63 for every 10% increase or decrease in FFB availability. It is noteworthy that the capacity of the ADT, OP and CL systems has no discernible impact on total profitability since it is designed with a huge capacity to treat the produced POME. This sensitivity analysis underscores the critical role of FFB in determining the overall profitability of the chosen PTS.

The sensitivity analysis underscores that total profitability is significantly influenced by the external selling price of electricity, reflecting a substantial ± 37.89% variation. The changes follow a linear pattern, with a factor of 12.63 for every 10% increase or decrease in electricity prices. This aligns with the model's output, where 80% of electricity generation is designated for external sales and the remaining 20% is allocated for internal operation, as depicted in Figure 4. The capital cost of ADT manipulated about 7% of total profit with a 30% variation in ADT capital cost. In terms of capital cost considerations, the model favours the CL for PTS under the condition that the CL pond treatment system achieves a 30% reduction in capital costs, resulting in a noteworthy 2.97% increase in profit. The maintenance cost for the ADT system plays only 1% of the total profit due to the low annual maintenance cost of ADT. It's essential to note that capital and maintenance costs for the OP of PTS have no discernible impact on profit since biogas production exclusively originates from the CL and ADT. This sensitivity analysis provides valuable insights into the pivotal factors influencing the profitability dynamics of the considered PTS options.

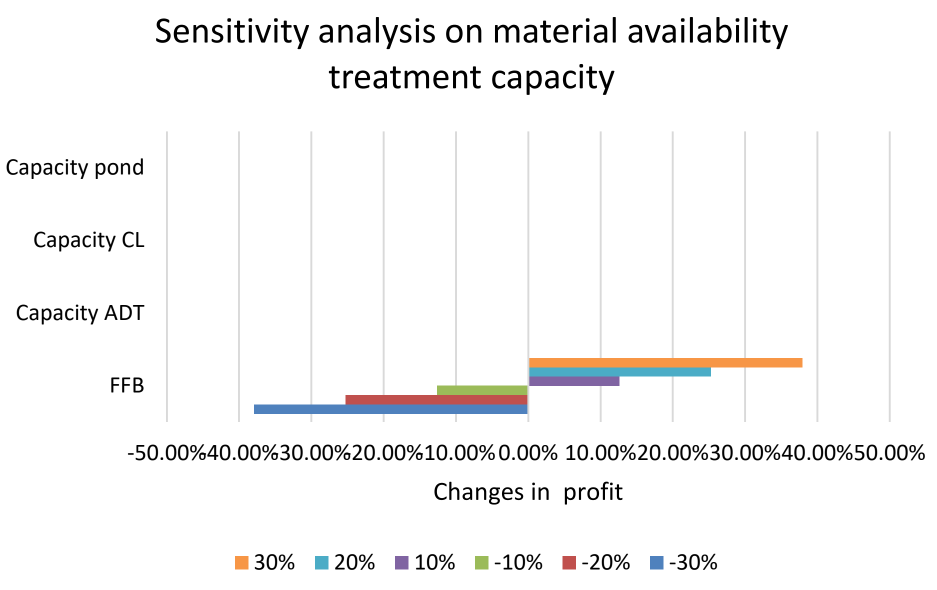

Figure 3: Sensitivity analysis of POME availability and treatment capacity of the POME treatment system.

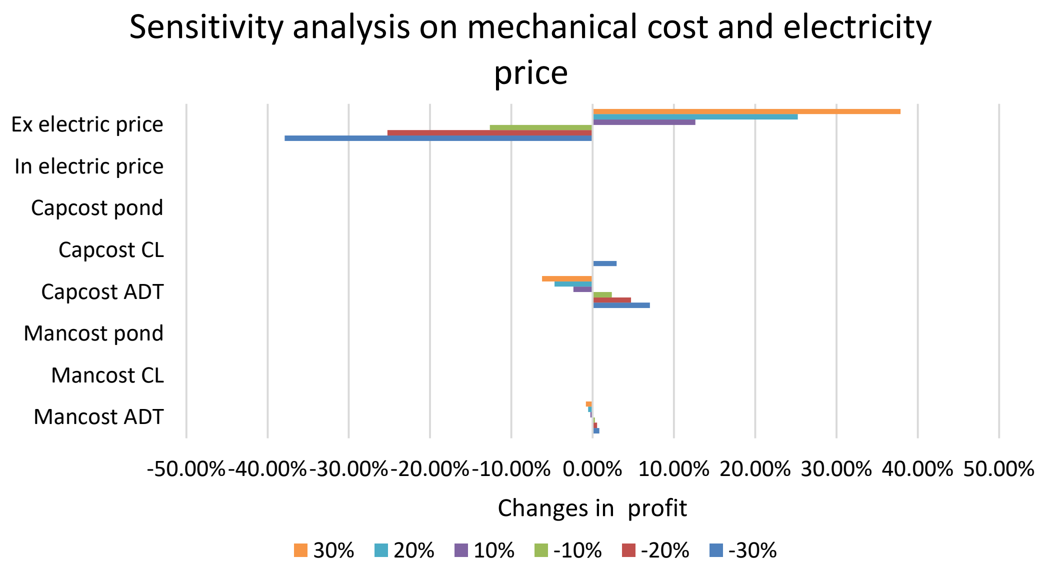

Figure 4: Sensitivity analysis of capital cost, operation cost, and electricity price of POME treatment system.

4. CONCLUSION

The developed model, namely the Profit Mode Model has been formulated and optimized to maximize the total profit. The Profit Mode Model capable of selecting the most profitable treatment system for POME treatment, considering 3 distinct scenarios: the Open Pond (OP) system (conventional), the CL system with biogas capture, and the ADT system has been developed. The output of the model designates the ADT system as the most profitable POME treatment system. It has been identified and selected as the most profitable POME treatment solution, with the potential to generate an annual profit of USD 9,769,439 through electricity generation from both the boiler and biogas, with yearly electricity sales of USD 12,399,439. The developed model is most affected by changes in FFB availability and electricity prices. Variations of +/- 30% in these parameters result in changes of +/- 35% in the total annual profit.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to University Putra Malaysia for providing the financial support necessary to conduct this research. We are also deeply thankful to Hargy Oil Palms Ltd. Papua New Guinea for offering the facilities and resources that contributed to the successful completion of this study.

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Conflict of interest statement: The authors declare no conflict of interest.

Author contributions statement: Conceptualization, S. Pallikodathan & H.C. Man; Methodology, T. Idaty; Software, M.F. Shukery; Validation, S. Pallikodathan & G. Nagarajoo; Formal Analysis, A. Sulaiman; Investigation, S. Pallikodathan; Resources, S. Pallikodathan & G. Nagarajoo; Writing – Original Draft Preparation, S. Pallikodathan; Writing – Review & Editing, S. Pallikodathan & H.C. Man; Supervision, H.C. Man, T. Idaty & A. Sulaiman;

APPENDIX

List of Symbols

Indices	**Description**
m	Index for primary process
p	Index for POME treatment system
n	Index for secondary process
j	Index for electricity power generation
s	Index for product/by-product application
a	Index for CO_{2eq} emission
Parameters	
$capcost_p$	Capital cost at treatment system p per year in USD/yr
$convbiogas_{p,n}$	Biogas generation scale at p to n
$convfer_{pond,land}$	Fertilizer generation scalar at p to s
$convwaste_{cirpond,land}$	Waste generation scalar at n to s
$elecpricei_m$	Electricity price for internal usage in USD/kWh
$elecpriceo_s$	Electricity price for external usage in USD/kWh
ffb_m	Amount of fresh fruit bunches at m in tons/yr
$mencost_p$	Maintenance cost at treatment system p per year in USD/yr
$ratiofiber_m$	Fibre conversion ratio at m
$ratioshell_m$	Shell conversion ratio at m
$ratiopome_m$	POME conversion ratio at m

Continuous Variables

$biogas_{p,n}$	Amount of biogas generates from *p* to *n* in m^3/yr
$biogase_{gase}$	Amount of biogas generates at gase in m^3/yr
$CAPITALCOST$	Total annual capital cost in USD/yr
$CO2e$	Amount of annual CO_2 equivalent
$CO2_{max}$	Amount of annual maximum CO_2 equivalent
$CO2_{min}$	Amount of annual minimum CO_2 equivalent
$elecbf_{boiler}$	Amount of electricity generates at boiler in kWh/yr
$elecs_{j,s}$	Amount of electricity transfer from *j* to *s* in kWh/yr
$elect_{j,m}$	Amount of electricity transfer from *j* to m in kWh/yr
$fiber_m$	Amount of fibre generated at *m*
$fibera_n$	Amount of fibre available at *n*
$fibert_{m,n}$	Amount of fibre transfer from *m* to *n* in tons/year
$liqfer_{pond,land}$	Amount of liquid fertiliser transferred from pond land in ton/yr
$pome_m$	Amount of POME generated at *m* in ton/yr
OBJ	Degree of satisfaction
$OPERATINGCOST$	Total annual maintenance cost in USD/yr
$pomea_p$	Amount of POME at *p* in ton/yr
$pomet_{m,p}$	Amount of POME at *p* in ton/yr
$PROFIT$	Amount of annual profit in USD/yr
$PROFIT_{max}$	Amount of maximum annual profit in USD/yr
$PROFIT_{min}$	Amount of minimum annual profit in USD/yr
$SALESCOST$	Amount of annual sales from electricity generation in USD/yr
$shell_m$	Amount of shell produces at *m* in ton/yr
$shella_n$	Amount of shell at n in ton/yr
$shellt_{m,n}$	Amount of shell transfer from *m* to *n* in ton/yr
$sludge_{p,n}$	Amount of digestate transfer from p to *n* in ton/yr
$sludgea_{cirpond}$	Amount of digestate at *n* in ton/yr

Binary Variables

xa_p	Selection of POME treatment system