LIFE CYCLE ASSESSMENT AND LIFE CYCLE COST ANALYSIS OF RENEWABLE NATURAL GAS FROM BIOMASS WASTE IN MALAYSIA

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ABSTRACT

Converting biowaste into renewable natural gas (RNG) through anaerobic digestion supports sustainable waste management and energy production. When evaluating the environmental and economic outcomes of a biowaste-to-RNG system in Malaysia, a cradle-to-grave approach using Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) highlights key considerations. Using 1 ton of RNG as the functional unit and the ReCiPe 2016 midpoint (H) indicators for impact evaluation, the main environmental contributors are RNG compression, digestate treatment, and pipeline distribution. Combined, these factors result in a global warming potential (GWP) of 286 kg CO_2 equivalent, freshwater consumption (FWC) of 3 m^3, and freshwater eutrophication potential (FEP) of 0.0014 kg phosphorus equivalent per ton of RNG. Model accuracy is validated through Monte Carlo simulation, with variations within a narrow ±9.5% range. A plant with an annual capacity of 500 tons of RNG would require RM 19.07 million in total expenditure, mostly from continuing operating costs. Integrating energy-efficiency strategies and renewable power sources is crucial for enhancing the sustainability and cost-effectiveness of RNG production, as scenario analysis reveals that on-site recycling of renewable electricity reduces life-cycle costs by 8.3% and environmental impacts by more than 90%. The main limitations are the use of proxy grid electricity data and the exclusion of net present value and internal rate of return.

Keywords: *Life cycle costing, anaerobic digestion, environmental impact, sustainability assessment, SDG 7, SDG 11, SDG 13*

INTRODUCTION

The production of solid municipal waste continues to rise across Malaysia, posing significant challenges for disposal and environmental management. Approximately half of the nation's daily production of over 38,000 tons of solid waste is made up of organic materials [1]. Landfilling, which produces methane emissions and increases the risk of soil and water contamination through leachate formation [2]-[3], is a major component of current waste management techniques. This organic waste can be biologically processed via anaerobic digestion to produce biogas, which can then be upgraded to renewable natural gas (RNG) for use as vehicle fuel or electricity [4].

Prior to implementation, waste-to-energy systems must be carefully assessed for both economic viability and net environmental benefits. Anaerobic digestion requires several energy-intensive unit processes, such as feedstock preparation, digester heating, biogas upgrading, and gas compression, even though it can reduce waste quantities and produce renewable energy [5]-[7]. The environmental advantages of the generated RNG may be outweighed by the electrical and thermal energy used in these operations [8]. Additionally, the capital costs of digester tanks, machinery upgrades, and compression facilities, along with operating costs for labour, energy inputs, and maintenance, determine the cost-effectiveness of such systems [9].

Using integrated life cycle assessment (LCA) and life cycle costing (LCC) methodology, this study assesses the economic needs and environmental effects of producing RNG from Malaysian urban biowaste. The specific objectives include determining the capital and operating expenditure requirements for a commercial-scale facility and estimating the potential impacts on global warming, freshwater consumption, and eutrophication across the entire process chain. Using one ton of renewable natural gas as the functional unit for comparison, the analysis examines the mass balance for each process unit, from waste receiving through anaerobic digestion, biogas upgrading, and final gas distribution.

All process phases, including mechanical pre-treatment, mesophilic anaerobic digestion, water scrubbing for biogas upgrading, pipeline distribution, and waste collection to RNG combustion, are included in the system boundaries. To focus on operational impacts, the study excludes infrastructure development and the disposal of end-of-life equipment. This thorough study identifies the process units that have the greatest impact on environmental and cost outcomes,

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providing engineers and policymakers with the information they need to make well-informed decisions about the use of RNG in Malaysia's waste management industry.

SYSTEM OVERVIEW AND DESCRIPTION

System Definition

A renewable natural gas production system converts food waste and municipal organic waste into usable energy through sequential biological and physical processing stages. The system layout, which comprises ten major unit operations (waste transport, sorting, pre-treatment, anaerobic digestion, biogas upgrading, RNG compression, digestate treatment, pipeline distribution, RNG use, and fertiliser transport) that collectively transform raw biowaste into pipeline-quality RNG and nutrient-rich digestate fertiliser, is shown in Figure 1.

Process Description

The process initiates with waste collection vehicles transporting source-separated organic fractions from municipal and commercial sources to a central processing facility. These diesel-powered trucks cover an average distance of 15 km during collection routes [10].

The mixed biowaste undergoes mechanical sorting and pre-treatment upon reaching the processing facility. A hydrocyclone system separates inorganic contaminants, including metals and plastics, from the organic fraction [11]. Subsequent shredding operations reduce the particle size of the organic material to improve digestion efficiency. The processed feedstock is then mixed with tap water to form a pumpable slurry with approximately 35% total solids, establishing optimal conditions for anaerobic biological processing.

The homogenised slurry enters continuous stirred-tank reactors configured for mesophilic anaerobic digestion [12]. These reactors maintain temperatures between 30–35°C with a hydraulic retention time of 30 days to ensure complete microbial conversion of organic matter [13]. The anaerobic digestion process yields raw biogas containing methane and carbon dioxide, along with a nutrient-rich digestate slurry. The biogas progresses through purification stages including chemical scrubbing for hydrogen sulfide removal, dehydration for water vapour extraction, and carbon dioxide separation via water scrubbing. The CO_2-rich water stream is then passed through a flash separator to release the dissolved CO_2 and recover water for recirculation, to meet pipeline-quality biomethane specifications [14].

The digestate slurry is dewatered and thermally dried to produce solid fertiliser, which is transported by diesel truck to agricultural users over an average distance of 15 km. The upgraded RNG is compressed and delivered through the gas pipeline to the point of use, where it is combusted. Figure 1 shows the detailed process flow diagram, including mass flows (ton), utility inputs (kWh), and emissions within the system boundary.

METHODOLOGY

Life Cycle Assessment Framework

The environmental evaluation follows ISO 14040 and 14044 standards for life cycle assessment, implementing a cradle-to-grave system boundary that encompasses all process stages from raw material extraction through waste collection, processing, energy conversion, and final product utilisation [15]. The assessment defines the functional unit as one ton of renewable natural gas produced, establishing a consistent basis for comparing material flows, energy consumption, and environmental emissions across all unit operations.

The life cycle inventory compiles primary data from mass and energy balance calculations derived from literature sources and

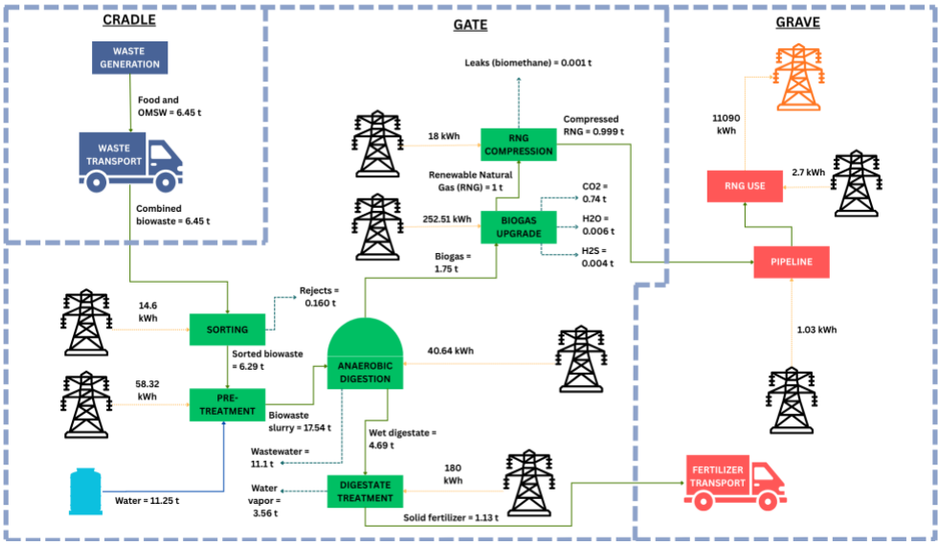

Figure 1 Process flow diagram for renewable natural gas production

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engineering design parameters, supplemented by secondary background data from the Ecoinvent database integrated within GaBi Sphera software [16]. The inventory quantifies all relevant inputs, including electricity, diesel, water, and chemicals, as well as outputs such as air emissions, water discharges, and solid waste generation, for each process stage.

The life cycle impact assessment uses the ReCiPe 2016 Midpoint (H) method to convert inventory data into environmental impact indicators [17]. The analysis focuses on three impact categories particularly relevant to waste management and energy systems: global warming potential (GWP) (kg CO_2 equivalent), freshwater consumption (FWC) (m^3), and freshwater eutrophication potential (FEP) (kg phosphorus equivalent). These categories capture the climate change, water resource, and nutrient pollution aspects of the RNG production process, enabling identification of environmental hotspots across the system.

Life Cycle Costing Methodology

The expenditure analysis uses a life-cycle costing approach aligned with the environmental system boundary, evaluating all relevant costs over the 20-year project lifespan. The analysis considers capital expenditures for process equipment, including waste reception systems, anaerobic digesters, gas upgrading units, and compression facilities, calculated using current market prices for the Malaysian industrial sector [18]. Operational expenditures include energy consumption, chemical inputs, labour requirements, maintenance activities, and administrative overheads, derived from life cycle inventory data and local cost factors.

The costing methodology applies straight-line depreciation for capital equipment and annualises operational costs based on consumption rates and unit prices. All financial values are expressed in Malaysian Ringgit at constant 2024 price levels, excluding inflation effects to maintain comparability across the project timeline. The analysis scales all cost calculations to a standardised plant capacity of 500 tons RNG per year, enabling meaningful comparison with literature values and industry benchmarks for similar waste-to-energy facilities.

Scenario Analysis Framework

To evaluate potential improvements, two alternative system configurations were modelled and compared against the base case:

1. Scenario 1 (On-site Renewable Electricity Integration): This scenario models the use of internally generated RNG to produce electricity for plant operations, creating a closed-loop energy recycling system.
2. Scenario 2 (Pressure Swing Adsorption (PSA) for Biogas Upgrading): Replaces the base-case water-scrubbing system with a PSA unit for CO_2 removal, representing a technology choice with distinct energy and operational characteristics.

These scenarios were evaluated using the same LCA and LCC boundaries and functional unit as the base model to ensure comparability.

RESULTS AND DISCUSSION

Environmental Performance Analysis

The life cycle assessment quantifies the environmental footprint of RNG production across three impact categories. As shown in Figure 2, the base-case system has a GWP of 286 kg CO_2 equivalent per ton of RNG produced. Further analysis identifies three process stages as the dominant contributors to the environmental profile: RNG compression (83.8 kg CO_2 equivalent; 29.3%), digestate treatment (66.7 kg CO_2 equivalent; 23.3%), and pipeline operations (60.5 kg CO_2 equivalent; 21.2%). These three energy-intensive unit operations collectively account for 211.0 kg CO_2 equivalent, or 73.8% of the total climate change impact, primarily due to their significant Scope 2 emissions from electricity consumption sourced from the national grid. The anaerobic digestion process itself contributes only 15.2 kg CO_2 equivalent (5.3%) to the total GWP, indicating that the biological conversion operates with relatively low direct emissions compared to downstream processing stages. This finding aligns with LCA studies of biogas systems, in which downstream energy-intensive processes such as upgrading and compression typically dominate the carbon footprint [19].

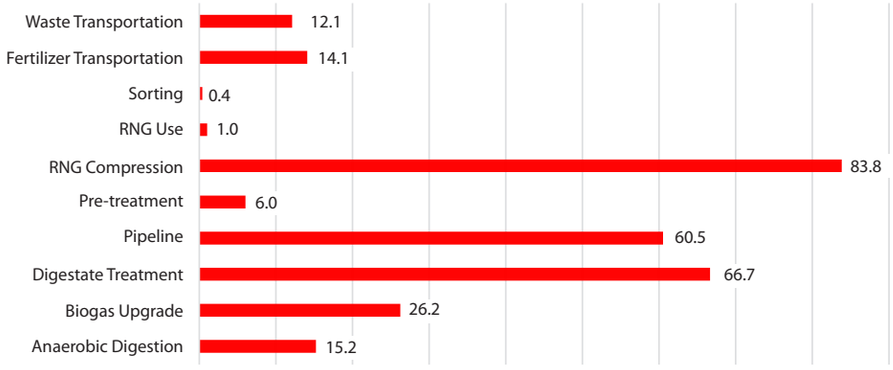

Figure 2 Climate change impact of system processes, including biogenic carbon [kg CO_2 eq.]

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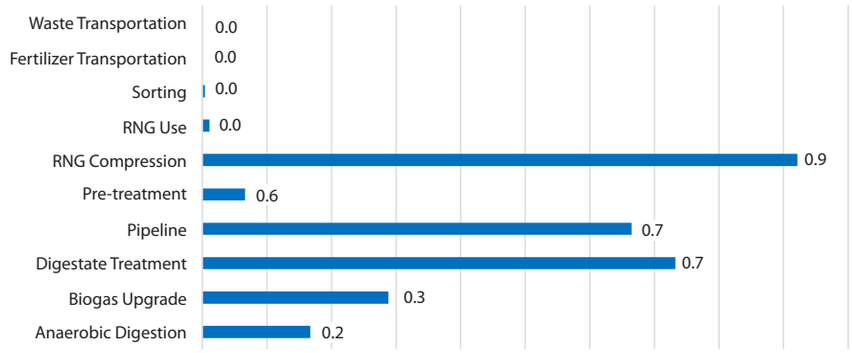

Figure 3 Freshwater consumption of the system processes [m^3]

The system requires 2.86 m^3 of freshwater per ton of RNG produced, as illustrated in Figure 3. RNG compression represents the largest consumer at 0.92 m^3 (32.2%) of this total, followed by digestate treatment (0.73 m^3; 25.5%) and pipeline operations (0.66 m^3; 23.1%). This is mainly due to indirect water consumption associated with electricity generation for these processes, specifically the cooling water demands of thermal power plants [20]. The biogas upgrading unit accounts for 0.29 m^3 (10.1%) of the total water consumption through its water scrubbing system, which requires direct water input for carbon dioxide absorption and process cooling. In contrast, pre-treatment and transportation stages demonstrate minimal influence, accounting for less than 3% (under 0.07 m^3) of total freshwater consumption.

The FEP reaches 0.00141 kg phosphorus equivalent per ton of RNG (Figure 4). RNG compression contributes 0.000455 kg phosphorus equivalent (32.3%) of this nutrient enrichment potential, while digestate treatment accounts for 0.000361 kg phosphorus equivalent (25.6%) and pipeline operations represent 0.000329 kg phosphorus equivalent (23.3%). This consistent distribution across multiple environmental impact categories establishes electricity consumption as the main driver of environmental impacts in the RNG production system. The eutrophication impact is primarily driven by indirect (scope 2) emissions from electricity generation, where coal and natural gas power plants release nitrogen and phosphorus compounds through atmospheric emissions and wastewater discharges.

Uncertainty Quantification

The Monte Carlo analysis provides statistical validation of the life cycle assessment results, showing normal distributions for all three environmental impact categories with 95% confidence intervals within ±9.5% of the mean values shown in Figure 5. The global warming potential ranges from 259 to 313 kg CO_2 equivalent per ton of RNG across 100 iterations, while freshwater consumption ranges from 2.59 to 3.13 m^3. The freshwater eutrophication potential ranges from 0.00128 to 0.00154 kg phosphorus equivalent. The narrow uncertainty ranges indicate strong model structure and parameter selection, with the highest sensitivity observed for electricity consumption factors and biogas yield assumptions. The consistent behaviour across effect categories demonstrates that total uncertainty is driven by common parameters, particularly those associated with energy consumption in the processes of digestate treatment, upgrading, and compression.

Life Cycle Cost Analysis

The life cycle cost assessment for an RNG facility with a capacity of 500 tons per year estimates a total capital expenditure (CAPEX) of RM 2.95 million. This investment is allocated across the main capital cost components illustrated in Figure 6. Process equipment accounts for the largest share, at RM 1.81 million, or 61.3% of total CAPEX. Within this category, anaerobic digesters contribute RM 0.53 million (18.0%) of the overall capital cost, gas storage systems account for RM 0.41 million (13.9%), and biogas upgrading units represent RM 0.29 million (9.8%). The remaining RM 0.58 million (19.6%) of process

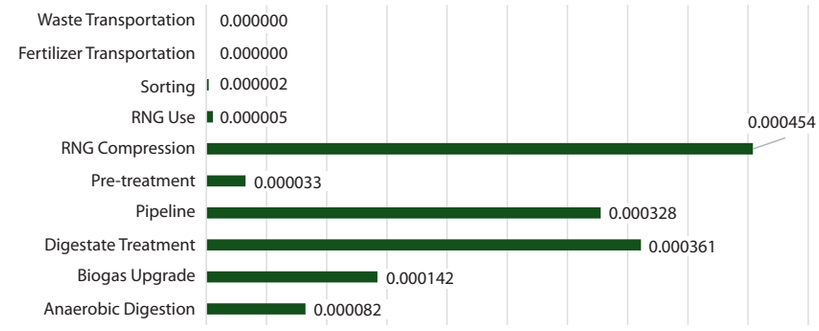

Figure 4 Freshwater eutrophication potential of the system processes ×10^-3 [kg P eq.]

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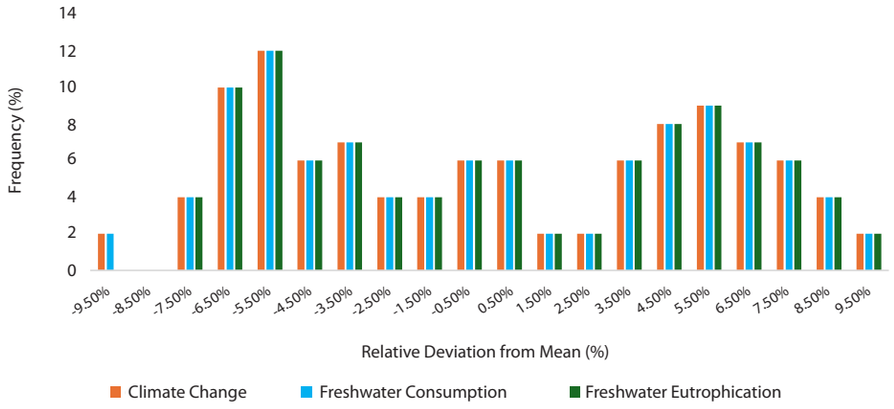

Figure 5 Monte Carlo analysis of environmental impact variability

equipment costs covers critical auxiliary components, including feedstock pre-treatment systems, pumps, separators, control and monitoring systems, and safety infrastructure. Engineering, procurement, and construction (EPC) costs constitute the second-largest portion at RM 0.54 million, or 18.4% of total CAPEX, reflecting expenses for detailed design, site development, and project management. Piping and instrumentation account for RM 0.45 million, or 15.3%, encompassing pipelines, valves, sensors, and control instrumentation required for coordinated plant operation. A contingency provision of RM 0.15 million, or 5.1%, is included to accommodate unforeseen costs and potential market uncertainties. The notable contribution of indirect costs, such as EPC, piping, and contingency, emphasises the importance of comprehensive system design, integration, and installation in biochemical processing facilities, aspects that are often underestimated in early-stage life cycle cost evaluations.

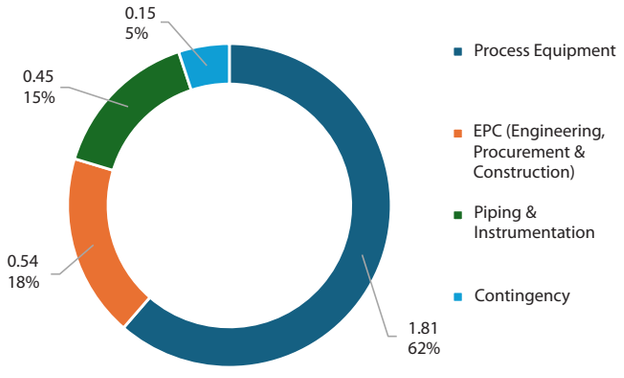

Figure 6 CAPEX distribution (RM million and percentage share)

Annual operational expenditure (OPEX) is estimated at RM 805,636, equivalent to RM 1,611.27 per ton of RNG produced, as shown in Figure 7. Labour constitutes the largest share of operating costs at RM 230,000, or 28.6%, reflecting the requirement for eight full-time personnel to ensure continuous operation, process supervision, maintenance coordination, and compliance with safety standards. Maintenance expenses represent RM 164,000, or 20.3% of total OPEX and include routine servicing, component replacement, and corrective maintenance of mechanical and electrical systems. Insurance and overhead costs contribute RM 124,000, or 15.4%, covering plant insurance, administrative functions, regulatory obligations, and general overhead expenses. Electricity consumption, mainly associated with biogas compression, upgrading processes, and digestate handling, accounts for RM 134,000, or 16.6% of operational costs. The remaining RM 153,000, or 19.0%, comprises variable expenses such as diesel for auxiliary equipment, process water usage, chemicals for gas upgrading and digestate treatment, and other consumables. With OPEX accounting for 84.5% of the total life cycle cost, the results indicate that the long-term financial performance of RNG facilities is strongly influenced by operational efficiency, workforce management, and energy consumption. This finding is particularly relevant for investors, plant operators, and policymakers assessing the economic viability and planning strategies of waste-to-energy initiatives in Malaysia.

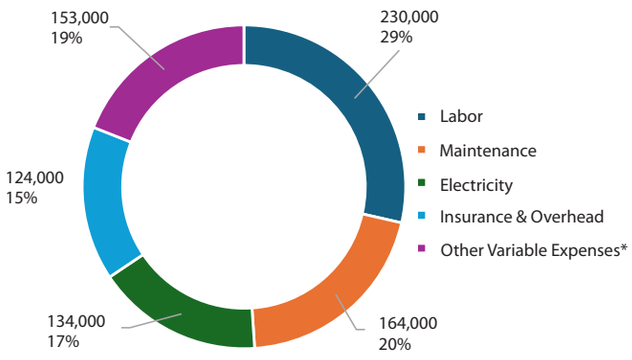

Figure 7 Distribution of OPEX (RM and percentage share)

A sensitivity analysis was performed on the cost inputs to identify which most affect the economic result of the RNG production system. Figure 8 shows that CAPEX has the strongest effect on the total LCC (RM 18.70 to 19.43 million; swing of RM 0.73 million), because it is the least certain input at the design stage, being estimated from market prices rather than firm quotations. Electricity cost follows (RM 0.58 million). The energy-intensive units set a fixed demand throughout the 20-year operation, so only the tariff varies,

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making it the most volatile operating input. Labour (RM 0.40 million) and maintenance (RM 0.27 million) have moderate effects because crew size and maintenance schedules are fixed by the plant design, and only the unit costs change. Diesel has the smallest effect (RM 0.14 million) because it is used only for transport and auxiliary equipment, resulting in low consumption.

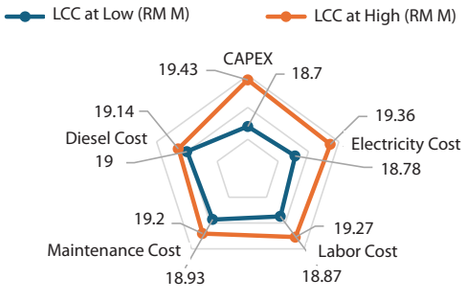

Figure 8 Sensitivity to variations in economic parameters (RM millions)

Scenario Performance Evaluation

The evaluation of alternative system configurations shows significant differences in economic and environmental performance. As summarised in Table 1, Scenario 1 (on-site renewable electricity generation) reduces GWP by 40.9% to 26.2 kg CO_2 equivalent per ton of biowaste processed, while eliminating Scope 2 emissions and the associated freshwater consumption and eutrophication impacts from grid electricity. The elimination of grid electricity purchases accounts for the 8.3% reduction in life cycle cost to RM 17.48 million. This scenario demonstrates the connection between economic and environmental objectives by converting power from a variable operating expense to a fixed capital investment. Substantial reductions in GWP and resource use through the integration of renewable energy have also been reported in LCA studies of biogas systems in Malaysia [21].

Scenario 2 (pressure swing adsorption for biogas upgrading) performs poorly across all metrics. As shown in Table 1, the GWP increases by 170.6% to 119.9 kg CO_2 equivalent, freshwater consumption increases by 157.8% to 1.16 m^3, and eutrophication potential increases by 161.5% to 0.000570 kg phosphorus equivalent. The life cycle cost rises by 0.8% to RM 19.22 million, reflecting the system's more complex operation and higher energy consumption. These results indicate that selecting technologies based primarily on gas purity, without considering energy intensity, can lead to unfavourable sustainability outcomes, particularly in regions like Malaysia, where Scope 2 emissions from carbon-intensive electricity grids dominate the environmental profile. Comparative studies of biogas upgrading technologies confirm that PSA systems generally have higher specific energy demands than water scrubbing, making them less environmentally favourable in contexts where grid electricity is carbon-intensive [22].

Table 1 Comparative LCA and LCC results for scenario analysis

Scenario	Total LCC (RM)	GWP [kg CO_2-eq]	FWC [m^3]	FEP [kg P eq.]
Base	19,067,261	44.3	0.45	0.000218
1	17,476,541	26.2	0.00	0.00000
2	19,219,761	119.9	1.16	0.000570

Figure 9 provides a normalised comparison of the two scenarios against the base model across all evaluated LCC and environmental indicators, clearly illustrating the superior performance of Scenario 1 in both economic and environmental dimensions.

Comparison with Previous Studies

Table 2 compares the base case with published life cycle studies of anaerobic digestion, expressed per ton of biowaste. Reported GWP values depend on the LCA approach adopted [23]. The base case GWP of 44.3 kg CO_2 equivalent lies within the range reported for generic anaerobic digestion facilities (-375 to 111 kg CO_2 equivalent) [24], but above the values reported for specific facilities (-95 to 4), anaerobic digestion with biogas utilisation (-25.87) and composting (19.15) [25]. This positive value reflects the reliance on carbon-intensive grid electricity. The freshwater consumption of 0.45 m^3 falls within the reported range of 0.2 to 1.0 m^3 [26]-[28], and the eutrophication potential of 0.000218 kg phosphorus equivalent lies between the negligible value reported for a biogas plant in India [29] and 0.000458 kg phosphorus equivalent for a full-scale plant in Sri Lanka [30]. Regarding costs, a 2025 techno-economic

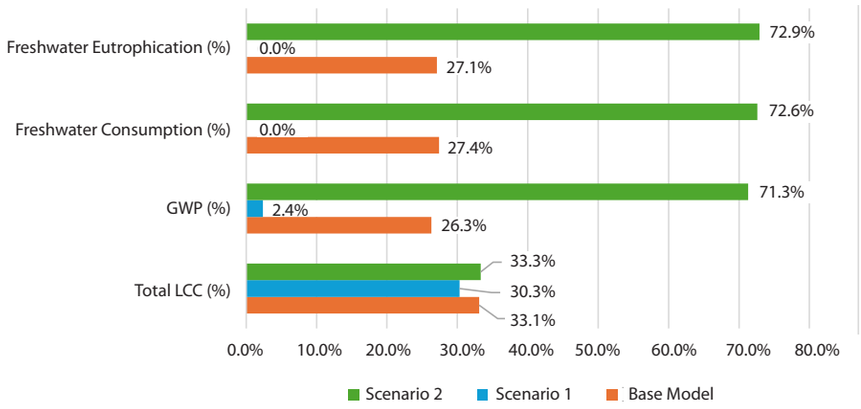

Figure 9 Normalised comparison of scenarios across LCC and environmental indicators

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Table 2 Comparison of the base case with published studies (per ton of biowaste)

Indicator	This study	Literature range	References
GWP [kg CO_2 equivalent]	44.3	-375 to 111 (generic anaerobic digestion); -95 to 4 (specific anaerobic digestion); 19.15 (composting); -25.87 (anaerobic digestion with biogas utilisation)	[24]-[25]
FWC [m^3]	0.45	0.2 to 1.0	[26]-[28]
FEP [kg phosphorus equivalent]	0.000218	0.000000 to 0.000458	[29]-[30]

assessment of a 50,000-ton-per-year food waste biomethane plant in Ireland found high capital and operating costs [9]. However, its scale differs from the 500-ton-per-year RNG plant studied here, so unit costs are not compared directly. A life cycle cost-benefit analysis of energy generation from palm oil mill effluent in Malaysia also combined cost assessment with policy insights [31].

CONCLUSION

This study assessed the sustainability of producing RNG from Malaysian biomass waste using an integrated LCA and LCC approach. For every ton of processed biowaste, the LCA found environmental impacts of 44.3 kg CO_2 equivalent, 0.45 m^3 of freshwater use, and 0.000218 kg of phosphorus equivalent, primarily from electricity-intensive processes. The LCC estimated a cost of RM 19.07 million over a 20-year project, of which 84.5% is attributable to operational expenses. Scenario analysis shows that on-site renewable electricity generation yields the greatest improvement, reducing life-cycle costs by 8.3% and environmental impacts by over 90%. RNG compression, digestate treatment, and pipeline operations are priority areas for optimisation because they contribute significantly to both costs and environmental impacts; improvements in energy efficiency benefit both. The system also supports SDGs 7, 11, and 13. Future improvements should focus on compressor efficiency, heat recovery, digestate dewatering, and lower-energy distribution. A major limitation was the reliance on proxy electricity grid data, as no Malaysian-specific datasets were available in the LCA software. Future research should use localised Malaysian electricity profiles and include a techno-economic analysis, including net present value (NPV) and internal rate of return (IRR), to support investment decisions.

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CONFLICT OF INTEREST

The author declares no competing financial interests or personal relationships that could have influenced the work reported in this paper.

AUTHORS' CONTRIBUTION

Ibrahim Sian Saeed carried out the data collection, LCA and LCC modelling, and analysis, and drafted the manuscript. Dr Chai Yee Ho supervised the research, provided guidance on the study design and methodology, supported the GaBi Sphera modelling, and critically reviewed and edited the manuscript for intellectual content. The authors jointly conceptualised the study. All authors read and approved the final version of the manuscript.

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