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Food Waste to Renewable Natural Gas: a Life Cycle Approach to Circular Economy and Climate Change Mitigation

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With the growing concerns over food waste management and the need for low-carbon energy alternatives, valorizing organic waste streams into renewable energy gas (RNG) offers a promising solution for both waste reduction and clean energy production. This study conducts a comprehensive Life Cycle Assessment (LCA) of food waste conversion to RNG, evaluating for four distinct utilization pathways: (1) biogas for electricity generation, (2) RNG for electricity generation, (3) RNG distribution via virtual pipelines and (4) RNG injection into the gas grid. Results indicate that the RNG production pathway from food waste significantly reduces GHG emissions compared to traditional waste disposal methods, such as landfilling or incineration. The substitution of fossil-based natural gas with RNG further enhances the climate benefits, contributing to circular economy goals and renewable energy targets. Sensitivity analysis revealed that transportation distances and energy sources for biogas upgrading are critical factors influencing the overall environmental performance. Overall, the study underscores the environmental feasibility of food waste-to-RNG systems and their potential role in advancing sustainable waste and energy management policies.

1. Introduction

Food waste is a significant issue not only in Malaysia but also globally. A study by Halim et al. (2025) indicate that the amount of food waste doubled in just three years in Malaysia. Out of the 31,000 t of solid waste produced daily, nearly half consists of organic kitchen waste. In 2019 alone, 44.5 % of Malaysia's municipal solid waste was food waste. This poses a serious threat to both waste management and food security. Contributing factors include rapid urbanization and population growth, which increase food demand and indirectly cause more food to be wasted (Halim et al., 2025). In Malaysia, the disposal of food waste is governed by the *Solid Waste and Public Cleansing Management Act 2007 (Act 672)*. However, domestic food waste is often commingled with other solid waste due to ineffective segregation. Current practices are highly reliant on landfills, where, in 2014, 94.5 % of municipal solid waste was disposed, while only 5.5 % was recycled and 1 % composted (Tan et al., 2014). Woon (2021) emphasized that effective separation at source or through advanced sorting technologies is a prerequisite for large-scale renewable energy generation from food waste. For segregated food waste, treatment technologies include incineration, composting, and anaerobic digestion (Gao et al., 2017).
Incineration is the combustion of waste under excess oxygen to produce ash, water and carbon dioxide. Incineration can reduce the volume of waste, contribute towards both waste minimization, while at the same time helping to generate thermal energy. However, the incineration process also produce carbon dioxide which contribute to the global warming, as well as other pollutants including ashes, carbon monoxide, oxides of nitrogen as well as volatile organic compounds (Thew et al., 2023). Composting is the process involving

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microorganism breaking down organic portion of waste into high-nutrient compost which can be used as fertilizer. Composting is very suitable for wet organic wastes due to its low cost and simple process (Hashim et al., 2021). Anaerobic digestion uses the fermentation process to produce biogas as well as leachate and sludge as by product. Compared with composting, anaerobic digestion is more economically attractive and environmental friendly (Lin et al., 2018). Conventional anaerobic digestion generates biogas with a typical methane concentration of 50–70 %, which requires upgrading to biomethane for use as renewable natural gas (RNG). Among the promising technologies, membrane separation has gained increasing attention due to its modularity, relatively low energy demand, and ability to achieve high methane recovery and purity. Zebian and Bouallou (2024) demonstrated the potential of microalgae, specifically *Scenedesmus* species, as an alternative substrate for anaerobic digestion, achieving biomethane purity of approximately 94 % through process modelling in Aspen Plus.

The development of renewable energy is also highlighted in the National Energy Transition Roadmap (NETR) as part of Malaysia's goal to achieve net-zero emissions by 2050 (Ministry of Economy, 2023). Refining biogas from food waste into RNG may advance renewable energy targets and address food waste management challenges simultaneously. Understanding the potential of utilizing RNG through various pathway is key to identify the best way forward in achieving both objectives.

2. Problem identification

Malaysia faces a critical challenge in managing its rapidly growing volume of food waste. The current national strategy is heavily dependent on landfill disposal, a practice that is unsustainable and environmentally detrimental. This over-reliance contributes to land scarcity and significant greenhouse gas emissions, primarily methane, hindering the nation's climate change mitigation goals.

While composting is a promoted alternative, its capacity to handle the large-scale volume of food waste generated in Malaysia is limited. Similarly, incineration, though an option for waste-to-energy conversion, is often deemed too costly and faces considerable public opposition.

Given the dual pressures of unsustainable waste management and the national commitment to achieve net-zero emissions by 2050, a more integrated and scalable solution is urgently needed. Waste-to-energy technologies, particularly anaerobic digestion, offer a promising pathway to address both challenges simultaneously by converting food waste into RNG. As such, quantifying the environmental impact of different food waste to pathway is important to ensure it align with the decarbonization goal and identify the best way forward.

3. Methodology

To understand the environmental impact of producing RNG from food waste via anaerobic digestion, this section outlined the detailed methodology to perform a LCA on the food waste to RNG process using the GaBi Sphera software. The methodology of this study can be divided into three parts: process modelling, data collection, and result interpretation.

In the first step process modelling, the system boundary of the food waste to RNG is defined based on the cradle to gate basis, which includes all processes from the food waste collection up until various utilization of RNG. The entire processes were separated into five different case studies based on different utilization pathways as shown in the superstructure in Figure 1 below. The basis used for this case study is 175 t/d, which is based on the targeted RNG production rate of 1,000 Nm^3/hr. The allocation was done by prioritizing mass-based allocation and only apply energy-based allocation when direct allocation is not possible.

For the second step data collection, both industrial and literature data were collected and input into GaBi to obtain the results. The data used for the LCA studies included the material input and output of all processes, as well as the specific energy needed for each process (including thermal, electrical and fuels). The environmental impact of each of the processes is automatically calculated based on the available database in GaBi Sphera, using the LCA method of ReCiPe 2016 Midpoint (I). This method was selected since it is a recent method developed by combining two pre-established methods: CML 2001 and EcoIndicator 99, which are both widely applied in many other LCA studies over the last decades. Under this method, there are 19 different indicators, each representing a different environmental impact as summarized in Table 1 below. The biogenic carbon is excluded in all indicators except for indicator 2, and it is noted that the indicator 2 will be excluded due to redundancy with indicator 1.

Table 1: Indicators for ReCiPe 2016 Midpoint (I) Method

Indicator	Impact Categories	Normalization Factor
1	ReCiPe 2016 v1.1 Midpoint (I) - Climate change, default, excl biogenic carbon [kg CO2 eq.]	9.2962E-05
2	ReCiPe 2016 v1.1 Midpoint (I) - Climate change, incl biogenic carbon [kg CO2 eq.]	9.2962E-05
3	ReCiPe 2016 v1.1 Midpoint (I) - Fine Particulate Matter Formation [kg PM2.5 eq.]	6.2422E-02
4	ReCiPe 2016 v1.1 Midpoint (I) - Fossil depletion [kg oil eq.]	1.0170E-03
5	ReCiPe 2016 v1.1 Midpoint (I) - Freshwater Consumption [m3]	3.7504E-03
6	ReCiPe 2016 v1.1 Midpoint (I) - Freshwater ecotoxicity [kg 1,4 DB eq.]	7.9551E-02
7	ReCiPe 2016 v1.1 Midpoint (I) - Freshwater Eutrophication [kg P eq.]	1.5387E+00
8	ReCiPe 2016 v1.1 Midpoint (I) - Human toxicity, cancer [kg 1,4-DB eq.]	1.0098E+00
9	ReCiPe 2016 v1.1 Midpoint (I) - Human toxicity, non-cancer [kg 1,4-DB eq.]	1.9627E-02
10	ReCiPe 2016 v1.1 Midpoint (I) - Ionizing Radiation [kBq Co-60 eq. to air]	2.1289E-03
11	ReCiPe 2016 v1.1 Midpoint (I) - Land use [Annual crop eq.·y]	1.6214E-04
12	ReCiPe 2016 v1.1 Midpoint (I) - Marine ecotoxicity [kg 1,4-DB eq.]	1.1367E-01
13	ReCiPe 2016 v1.1 Midpoint (I) - Marine Eutrophication [kg N eq.]	2.1655E-01
14	ReCiPe 2016 v1.1 Midpoint (I) - Metal depletion [kg Cu eq.]	5.1767E-06
15	ReCiPe 2016 v1.1 Midpoint (I) - Photochemical Ozone Formation, Ecosystems [kg NOx eq.]	5.6340E-02
16	ReCiPe 2016 v1.1 Midpoint (I) - Photochemical Ozone Formation, Human Health [kg NOx eq.]	4.8620E-02
17	ReCiPe 2016 v1.1 Midpoint (I) - Stratospheric Ozone Depletion [kg CFC-11 eq.]	1.5307E+01
18	ReCiPe 2016 v1.1 Midpoint (I) - Terrestrial Acidification [kg SO2 eq.]	2.4402E-02
19	ReCiPe 2016 v1.1 Midpoint (I) - Terrestrial ecotoxicity [kg 1,4-DB eq.]	1.4863E-04

For the last step result interpretation, the LCA result obtained from GaBi was first normalized to compare the relative impact on each category by using normalization factor. For each of the case studies, the top 3 impacted categories are summarized and the results from each case studies are compared and discussed.

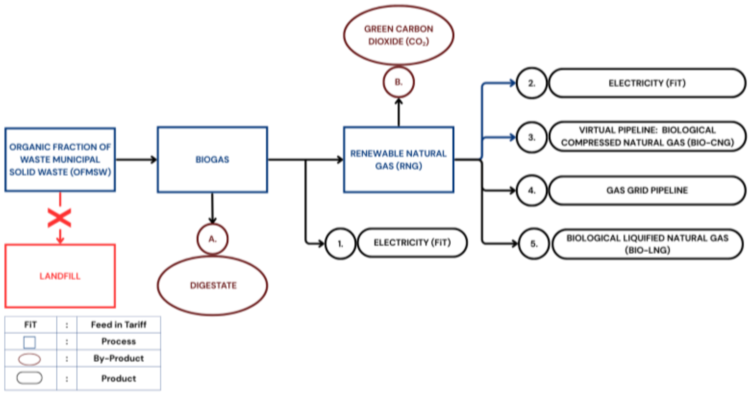

Figure 1: Superstructure of the conversion of food waste to energy

3.1 Process modelling

The process of converting food waste into RNG begins with the collection of 175 t/d. This waste is sourced from hotels and hospitals located within a 50-kilometer radius of the Taman Beringin transfer station. The food waste is fed into an anaerobic digester. Inside the digester, microorganisms break down the organic matter to produce two main byproducts: biogas and digestate. Biogas is a mixture primarily composed of methane and carbon dioxide, along with smaller amounts of other gases. To be converted into usable RNG, the biogas will be upgraded to reach 95 % purity using membrane and can be utilised as a renewable energy source for producing electricity, inject to NG grid or for industrial usage.

For case study 1, the clean biogas is directly fed into generator to generate electricity. The impact mitigation via generating electricity from biogas is compared directly with impact of grid electricity. For case study 2 to 5, the biogas is further upgraded to improve the purity to at least 95 % methane via membrane and becoming RNG. For case study 2, the RNG is used to generate electricity at higher efficiency, and the impact mitigation is calculated similarly to case study 1. For case study 3, RNG is utilized through virtual pipeline via compression into compressed natural gas (CNG) and transported directly to end users, which are targeted to be nearly industrial park. For case study 4, the RNG is directly injected into natural gas grid. For case study 5, the RNG is liquefied into liquefied natural gas (LNG) and transported into nearest port for exportation.

3.2 Data Collection

After the process flow of food waste to RNG is established, necessary data are collected from multiple sources including literature, industrial and small-scale studies to perform the LCA study. For food waste transportation, the vehicle type is assumed to be 10 tonne truck with an average distance of 100 km per round trip between the source of food waste (hotel and hospital) and Taman Beringin Transfer Station. Diesel consumption and its related environmental impact is obtained from the GaBi Sphera database. Since the waste collected is food waste instead of commingled waste, the process required to separate organic fraction from the food waste is assumed to have negligible electricity consumption due to its high organic fraction, which is taken to be 99 % based on the scaled-up data from small scale study, thus required minimal pre-processing. The conversion of organic fraction into biogas and its composition is calculated based on scaled-up data from small scale study as well, which is around 50 Nm3 of biogas per 300 kg of food waste. The composition of crude biogas is assumed to be 62.5 % methane, 35.9 % carbon dioxide, 311 ppm hydrogen, 27.6 ppm hydrogen sulfate and 1.2 % oxygen. The biogas cleaning process is assumed to consume 0.09 kWh of electricity per Nm3 of biogas. For the biogas upgrading process, the electricity consumption was taken to be 0.25 kWh of electricity per Nm3 of crude biogas based on study by Francisco López et al. (2024).
For case study 1, the electricity generation efficiency is 40 % while the electricity generation efficiency for case study 2 is 45 %. The value used for both case studies was based on data collected from pilot study. For case study 3, the electricity consumption for the compression and filling into CNG process was taken to be 0.33 kWh of electricity per Nm3 of RNG. The CNG cylinder is then transported using similar euro truck which is transported to the nearest industrial park at 17.03 km away. For case study 4, the RNG is directly compressed and injected into a gas grid pipeline and the process is taken to consume 0.07 kWh/kg of electricity based on study by Pasini et al. (2019). For case study 5, the RNG is liquefied into LNG which consumes 0.74 kWh/kg of electricity based on similar study. The LNG is then transported to the nearest port at Klang which is 118 km away.

4. Results and discussion

The results were analysed and compared to assess the most significant environmental impacts for each of the case studies to identify the best pathway in terms of impact mitigation.

4.1 Case Studies

The results of each case study after normalization are shown in Figure 2 below. On the vertical axis, positive values represent the environmental impact generated by a specific process. Conversely, negative values indicate the environmental impact being mitigated by utilisation of biogas or RNG.
The mitigation effect is a result of substituting conventional, fossil-based energy sources with the renewable energy produced from food waste. For case studies 1 and 2, the positive environmental impact (the negative value on the chart) comes from using the generated biogas to produce electricity, which offsets the need for electricity from the national power grid. Similarly, for case studies 3, 4, and 5, the negative values reflect the environmental benefits of using RNG to replace conventional, fossil-based natural gas to be injected into the NG grid or for industrial applications. This substitution is the key factor in demonstrating the overall positive environmental impact of the waste-to-energy process.
The results reveal that the top three most significant environmental impact categories for all five case studies are climate change (indicator 1), terrestrial ecotoxicity (indicator 19), and fossil depletion (indicator 4). Of these, climate change is the most dominant factor. The impact from climate change is nearly a magnitude larger than the next most significant category, terrestrial ecotoxicity. These finding highlights that the overall environmental footprint of converting food waste to RNG is overwhelmingly tied to greenhouse gas emissions. The other potential impacts, while present, are almost negligible in comparison.
Figure 3 below shows the comparison between all 5 case studies for indicator 1 (climate change). As can be seen, the positive impact of generating electricity represented by the large negative yellow bars is significantly greater than the environmental impact caused by all the processes involved, from transportation to upgrading. This shows that the environmental benefits of displacing fossil-fuel-based electricity from the grid far outweigh the environmental impact of producing the biogas or RNG. Case study 1 resulted in 967 kg CO_2 eq/MJ mitigation while case study 2 resulted in 736 kg CO_2 eq/MJ mitigation. In contrast, for Case Studies 3 to 5, the environmental impacts from additional processes like compression, filling, and liquefaction are much more pronounced, leading to a smaller overall net climate benefit. The quantified impact mitigation for Case study 3, 4 and 5 are 16.5 kg CO_2 eq/t, 8.6 kg CO_2 eq/t and 16.3 kg CO_2 eq/t respectively. Case study 1 has the highest impact mitigation ratio, where the impact mitigated is 2.56 times the impact generated, while case study 3 has the lowest impact mitigation ratio, where the impact mitigated is only 0.57 times the impact generated by the process.

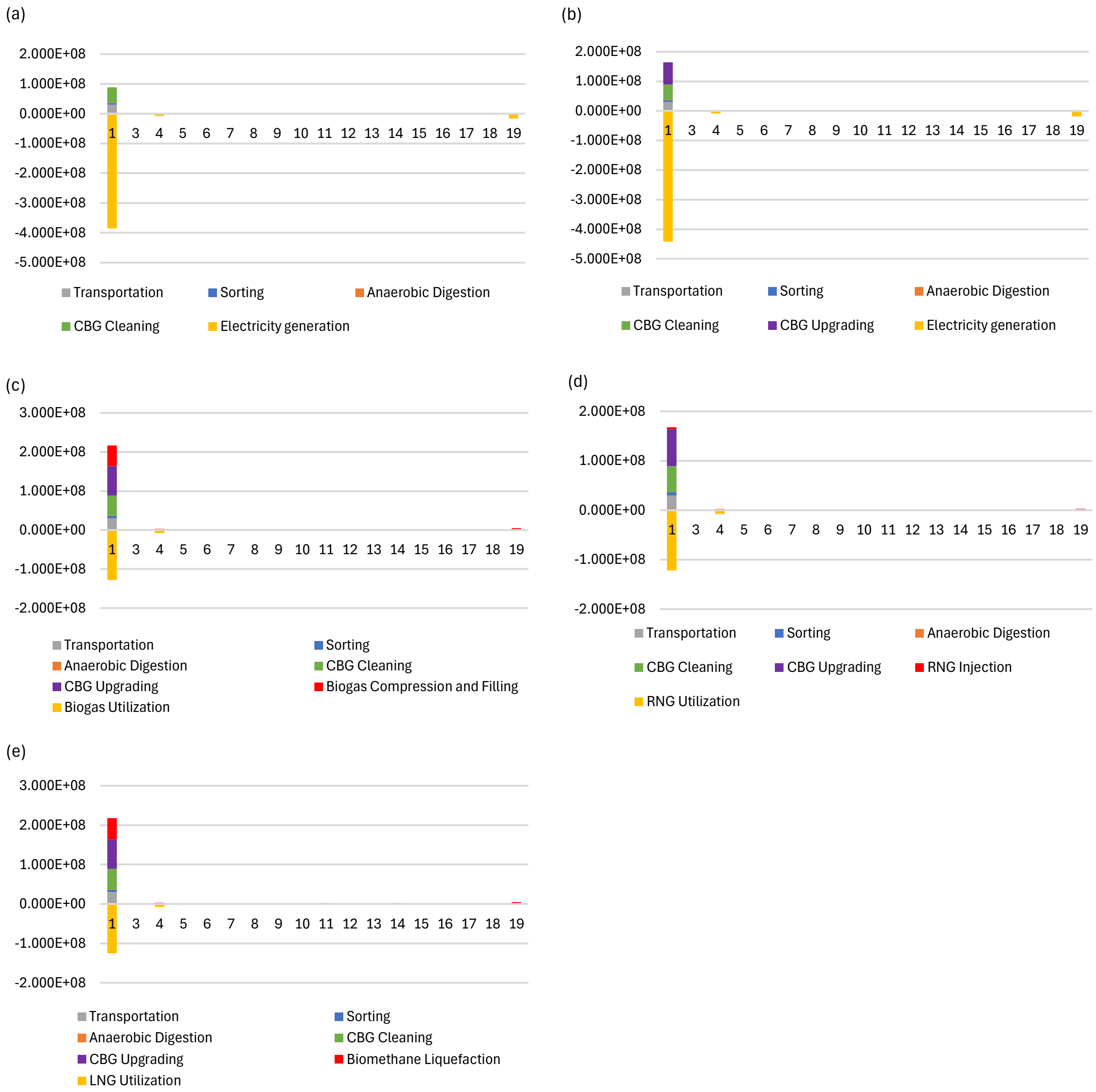

Figure 2: LCA results after normalization for case study; (a) biogas to electricity; (b) RNG to electricity; (c) RNG to Virtual Pipeline; (d) RNG to Pipeline Injection; (e) RNG to LNG

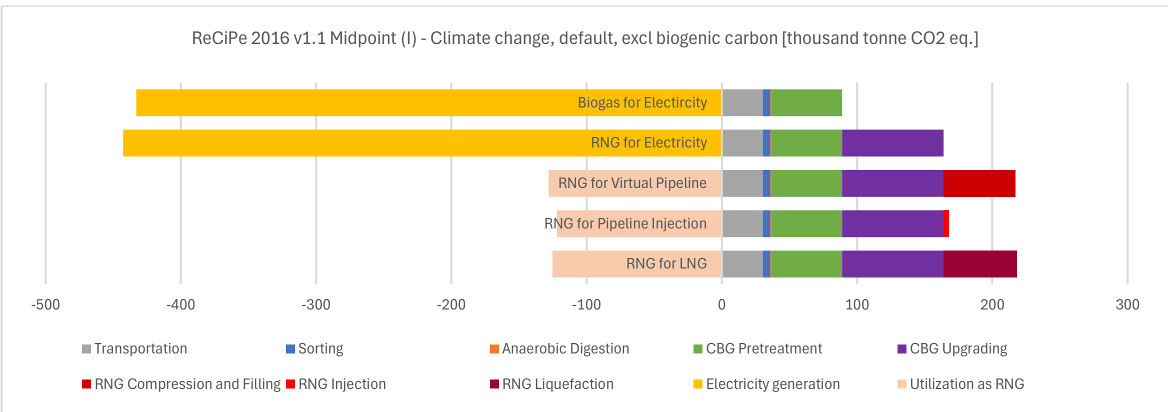

Figure 3: Comparison of climate change Impact (Indicator 1) for five different food waste to RNG pathways

5. Conclusions

This study successfully identified and compared the environmental impacts of five different pathways for converting food waste to RNG. The results show that climate change (indicator 1) is the most significant impact category across all five case studies. Case studies 1 and 2, which utilize RNG for electricity generation, demonstrate a net environmental mitigation. The similar finding also applies to Case studies 3 to 5, which use RNG for other applications. The analysis indicates that using RNG to generate electricity mitigates a significantly larger environmental impact compared to other uses. This is primarily because electricity generation requires fewer additional processing steps, which can themselves create new environmental impacts. It can be concluded that using RNG for electricity generation to reduce the demand of grid electricity is the most sustainable approach compared to using it to fulfil industrial natural gas demand. For future work, it is highly recommended to explore similar pathway but with decentralized system, as well as considering the utilization of byproducts such as digestate and green CO_2 into consideration.

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