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INTEGRATING LIFE CYCLE ASSESSMENT AND LIFE CYCLE COSTING THROUGH CLUSTER ANALYSIS FOR ENHANCED DECISION-MAKING IN FOOD WASTE MANAGEMENT

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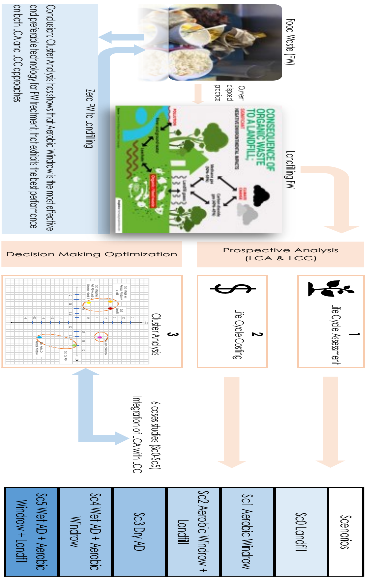
Graphical abstract



Abstract

Evaluating food waste (FW) treatment systems is challenging due to their complexity, encompassing processes like collection, sorting, preprocessing, treatment (e.g., composting and anaerobic digestion), and disposal or reuse. These systems involve numerous variables, including waste types, contamination levels, treatment methods, and environmental factors. Analyzing these systems requires an understanding of their efficiency, effectiveness, environmental impact, and economic feasibility. While life cycle assessment (LCA) is a standardized method for assessing environmental impacts, it does not consider economic performance. The methodology for combining LCA with life cycle costing (LCC) analysis is limited and inconsistent. To address this, a comprehensive framework is proposed, integrating LCA, LCC, and cluster analysis (CA) to evaluate six FW treatment scenarios, including landfilling. This framework involves three steps: LCA to assess environmental impacts, LCC to estimate annual costs, and CA to integrate both results. LCA evaluations has found that anaerobic dry digestion had the least environmental impact across 12 midpoint assessments, including global warming and ozone depletion, and ranked highest in minimizing damage to resource availability, human health, and ecosystem diversity. Economically, the LCC analysis showed that landfill technologies were the most cost-effective. The integration of LCA and LCC results using CA demonstrated that aerobic window composting was the most suitable FW management method. This approach showed a 65% reduction in harmful environmental impact points and a 46% increase in economic benefits compared to traditional landfilling. This framework enables decision-makers to evaluate and compare various FW treatment methods, leading to informed decisions regarding system selection and implementation.

Keywords: Cluster Analysis, Decision Making, Food Waste Management, Life Cycle Assessment, Life Cycle Costing Analysis

Abstrak

Menilai sistem rawatan sisa makanan (SM) adalah mencabar kerana kerumitan yang wujud, merangkumi proses seperti pengumpulan, pengasingan, prapemprosesan, rawatan (contoh: pengkomposan dan pencernaan anaerobik), dan pelupusan atau penggunaan semula. Sistem ini melibatkan banyak pembolehubah, termasuk jenis sisa, tahap pencemaran, kaedah rawatan, dan faktor persekitaran. Menganalisis sistem ini memerlukan pemahaman tentang kecekapan, keberkesanan, kesan alam sekitar dan kebolehlaksanaan ekonominya. Walaupun penilaian kitar hayat (LCA) ialah kaedah piawai untuk menilai kesan alam sekitar, ia tidak mengambil kira prestasi ekonomi. Metodologi untuk menggabungkan LCA dengan analisis pengekosan kitar hayat (LCC) adalah terhad dan tidak konsisten. Untuk menangani perkara ini, rangka kerja komprehensif dicadangkan, menyepadukan LCA, LCC, dan analisis kelompok (CA) untuk menilai enam senario rawatan SM, termasuk tapak pelupusan sampah. Rangka kerja ini melibatkan tiga langkah: LCA untuk menilai kesan alam sekitar, LCC untuk menganggar kos tahunan, dan CA untuk menyepadukan kedua-dua keputusan. Penilaian LCA telah mendapati bahawa pencernaan kering anaerobik mempunyai kesan alam sekitar yang paling sedikit merentas 12 penilaian titik tengah, termasuk pemanasan global dan penipisan ozon, dan menduduki tempat tertinggi dalam meminimumkan kerosakan kepada ketersediaan sumber, kesihatan manusia dan kepelbagaian ekosistem. Dari segi ekonomi, analisis LCC menunjukkan bahawa teknologi tapak pelupusan adalah yang paling kos efektif. Penyepaduan keputusan LCA dan LCC menggunakan CA menunjukkan bahawa pengkomposan windrow aerobik adalah kaedah pengurusan SM yang paling sesuai. Pendekatan ini menunjukkan pengurangan 65% dalam titik impak alam sekitar yang berbahaya dan peningkatan 46% dalam faedah ekonomi berbanding dengan pelupusan sampah tradisional. Rangka kerja ini membolehkan pembuat keputusan menilai dan membandingkan pelbagai kaedah rawatan SM, yang membawa kepada keputusan terperinci mengenai pemilihan dan pelaksanaan sistem.

Kata kunci: Analisis Kelompok, Membuat Keputusan, Pengurusan Sisa Makanan, Penilaian Kitaran Hayat, Analisis Pengekosan Kitaran Hayat

1.0 INTRODUCTION

Food waste (FW) constitutes a significant portion of municipal solid waste (MSW) and is increasing due to rapid urbanization and population growth [1]. Current practices are shifting organic waste management from landfilling to more sustainable methods, such as composting and anaerobic digestion (AD). These methods are favored for their ability to reduce environmental impacts, particularly the emissions of methane (CH_4) and carbon dioxide (CO_2) [2].

Generally, composting techniques are classified into open and closed systems. Open systems use aerobic processes to convert waste into compost, enhancing soil fertility and vegetation nutrients. Closed systems use anaerobic processes to produce biofertilizers and biogas byproducts. Common composting methods include windrows, aerated static piles, covered channels, in-vessel systems, and hyper thermophilic composting [3].

Although composting is an environmentally friendly method, it should not be automatically assumed to be the best option. Careful consideration and analysis are required before concluding which FW disposal method is the most suitable for the environment and the most cost-effective. Analyzing these waste treatment systems are complex due to the varied biological, chemical, and physical processes involved, as well as differing operational costs [4-5]. It is crucial to select effective technologies that minimize environmental impacts and are financially feasible [4-5].

The integration of life cycle assessment (LCA) and life cycle costing (LCC) is increasingly recognized as an effective approach for evaluating the sustainability of FW management systems, as it enables the simultaneous assessment of environmental and economic performance.

The study by Bahramian *et al*. [6] evaluates four household FW management scenarios in Ireland using

LCA and LCC, identifying AD with digestate composting as the most sustainable option due to its environmental benefits and nutrient recovery. Despite higher capital costs (€677,000 – €2,033,000), this scenario demonstrates long-term cost effectiveness with LCCs of €1,016,000 – €3,386,000, partially offset by revenues of €339,000 – €677,000. Elfeky *et al*. [7] similarly demonstrated that the integrated LCA and LCC framework to evaluate the environmental and economic performance of biogas-based organic waste management strategies, highlighting AD and digestate management options as sustainable alternatives to landfilling and incineration amid ongoing challenges in adopting waste-to-energy systems in developing countries.

Meanwhile, cluster analysis (CA) has been applied in waste management research to group treatment scenarios based on similar performance characteristics [8]. The CA is used to identify the most suitable solid waste treatment systems by clustering options that shared common environmental and operational attributes. These examples show that the combination of LCA, LCC, and CA offers a more objective and comprehensive basis for selecting sustainable food waste treatment methods, reducing bias in decision-making and enhancing policy relevance.

The results of the CA analysis can be grouped into different categories based on certain perspectives. The group perspective can be viewed as an independent alternative, or it can synthesize the results by ranking the groups independently.

Previous studies evaluating solid waste management technologies using multivariate CA, such as those by Ghazvinei *et al*. [9] and Huang & Ma [10], have largely been limited to two-dimensional frameworks focused on environmental metrics and subjective tools like the Analytic Hierarchy Process (AHP). While AHP supports structured decision-making, its dependence on expert judgment introduces bias and lacks integration with concrete financial data, reducing its effectiveness for real-world applications like system planning or policy development. This highlights a significant gap in existing research—namely, the absence of a robust, integrated framework that combines both environmental and economic evaluations to guide decision-making in FW management.

To address this gap, the present study proposes an integrated evaluation framework that combines CA, LCA, and LCC. This holistic approach enhances analytical objectivity, identifies key performance indicators, and facilitates more meaningful interpretation of complex datasets. By enabling objective classification of FW treatment scenarios, the framework supports strategic planning and sustainability-driven decision-making. Specifically tailored to Malaysia's unique context—marked by cultural diversity, agricultural intensity, urbanization, and policy evolution—this study aims to provide policymakers with the tools needed to implement effective and context-appropriate FW management strategies.

2.0 METHODOLOGY

To evaluate FW management technologies, three methods will be utilized to generate prospective decisions as depicted by Figure 1: (1) LCA is a quantitative and damage- oriented approach was used to assess the damage impact of a process six technologies scenario 0 to scenario 5 (Sc0-Sc5) for FW management on ecosystem diversity, human health, and resource availability; (2) LCC is a quantitative method used to estimate the annual worth of cost Ringgit Malaysia per ton FW (RM/t FW) for six scenarios under consideration; and (3) CA is utilized to integrate the results of the previous two methods, and to identify the most preferred biotechnology treatment selection.

2.1 LCA using Damage-Oriented Approach in Six Comparative FW Treatment Methods

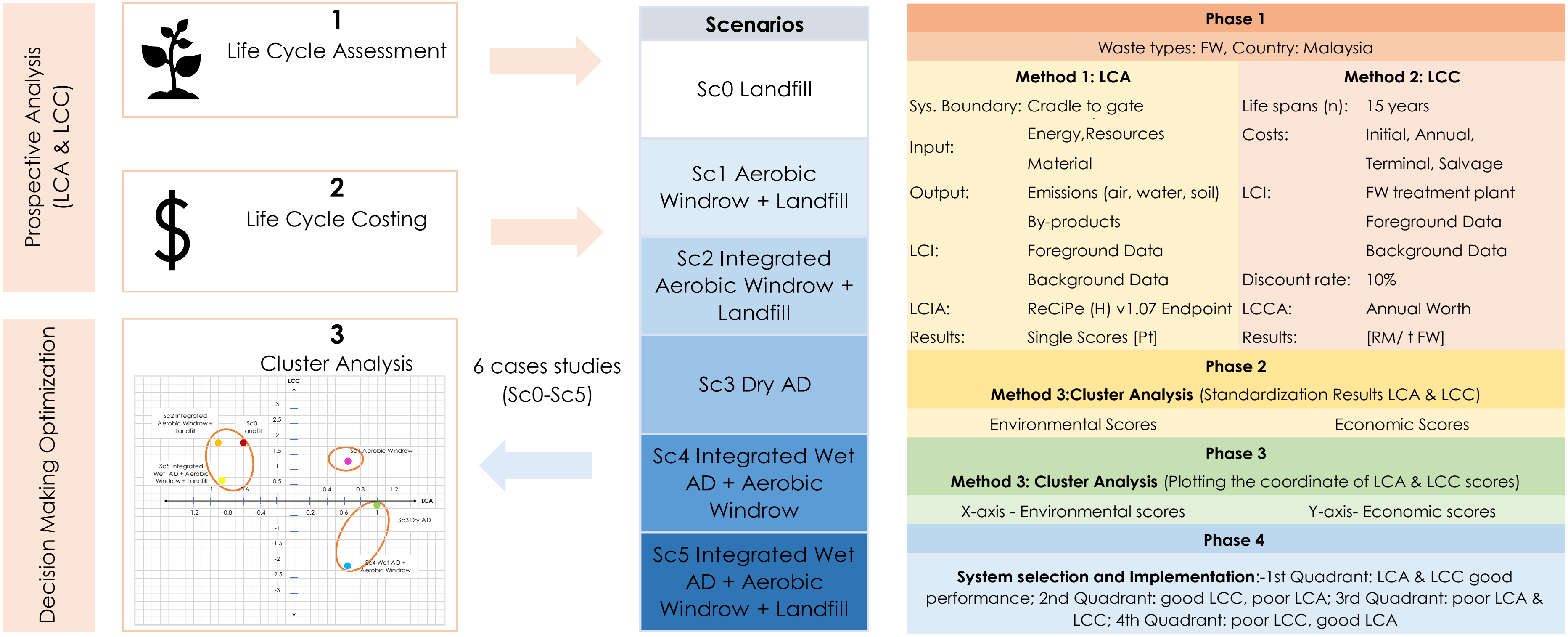
This study utilized the damage-oriented approach of endpoint LCA methodology, which complies with the requirements of ISO 14040 and 14044 (ISO, 2006a, 2006b). Endpoint metrics, are considered further down the cause-and-effect chain of environmental mechanisms, closer to or at the precise endpoint of the chains, which are known as the Areas of Protection [11]. The endpoint LCA methodology involves four phases: (1) defining the goal and scope; (2) conducting an inventory analysis; (3) performing an impact assessment; and (4) interpreting the results.

2.1.1 Goal and Scope Definition

This study is to compare the benefits of aerobic windrow composting, anaerobic dry and wet digestions, landfilling as well as to 3 other possible integrated methods of FW management. The aim is to identify the most environmentally effective FW management system for Malaysia's municipality council, with the potential to extend the findings to other states. The target audience for this research includes managers of windrow composting, AD, and landfill facilities, as well as LCA practitioners and researchers, research institutes, solid waste management organizations, and the Malaysian government.

Functional Unit

The management of 1-ton pre-treated FW.

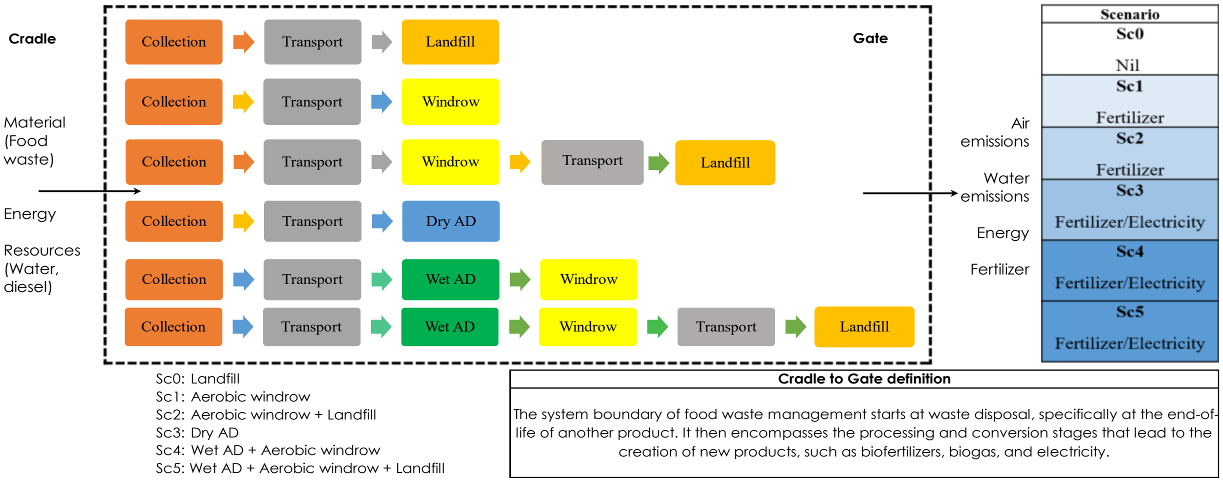


Phase 1			
Waste types: FW, Country: Malaysia			
Method 1: LCA		**Method 2: LCC**	
Sys. Boundary:	Cradle to gate	Life spans (n):	15 years
Input:	Energy,Resources Material	Costs:	Initial, Annual, Terminal, Salvage
Output:	Emissions (air, water, soil) By-products	LCI:	FW treatment plant Foreground Data Background Data
LCI:	Foreground Data Background Data	Discount rate:	10%
LCIA:	ReCiPe (H) v1.07 Endpoint	LCCA:	Annual Worth
Results:	Single Scores [Pt]	Results:	[RM/ t FW]
Phase 2			
Method 3:Cluster Analysis (Standardization Results LCA & LCC)			
Environmental Scores		Economic Scores	
Phase 3			
Method 3: Cluster Analysis (Plotting the coordinate of LCA & LCC scores)			
X-axis - Environmental scores		Y-axis- Economic scores	
Phase 4			
System selection and Implementation:-1st Quadrant: LCA & LCC good performance; 2nd Quadrant: good LCC, poor LCA; 3rd Quadrant: poor LCA & LCC; 4th Quadrant: poor LCC, good LCA			

Figure 1 The overall framework to assess the sustainability of FW facilities using CA

System Boundary

The system boundary, as shown in Figure 2, evaluates the cradle-to-gate stages of FW management. The FW management system boundary for cradle to gate starts with waste disposal, which is the end-of-life of another product. This is followed by processing and conversion stages that result in a new product such as biofertilizers, or electricity (as depicted by Figure 2). This includes collecting FW from commercial and residential areas, transporting it, and treating it through composting and AD (refer Supplementary Data Table S2: System boundary of LCA for all scenarios). The process also involves developing compost products through aerobic windrow composting and biofertilizers, and energy through AD technologies. The system boundary concludes with waste landfilling. In this research, the cradle-to-gate approach has been employed due to its ability to reduce complexity in the assessment process. This approach enables faster insights into internal processes, facilitating a more streamlined analysis [12].



The system boundary of food waste management starts at waste disposal, specifically at the end-of-life of another product. It then encompasses the processing and conversion stages that lead to the creation of new products, such as biofertilizers, biogas, and electricity.

Figure 2 System boundary of LCA for all scenarios

Scenarios Assessed

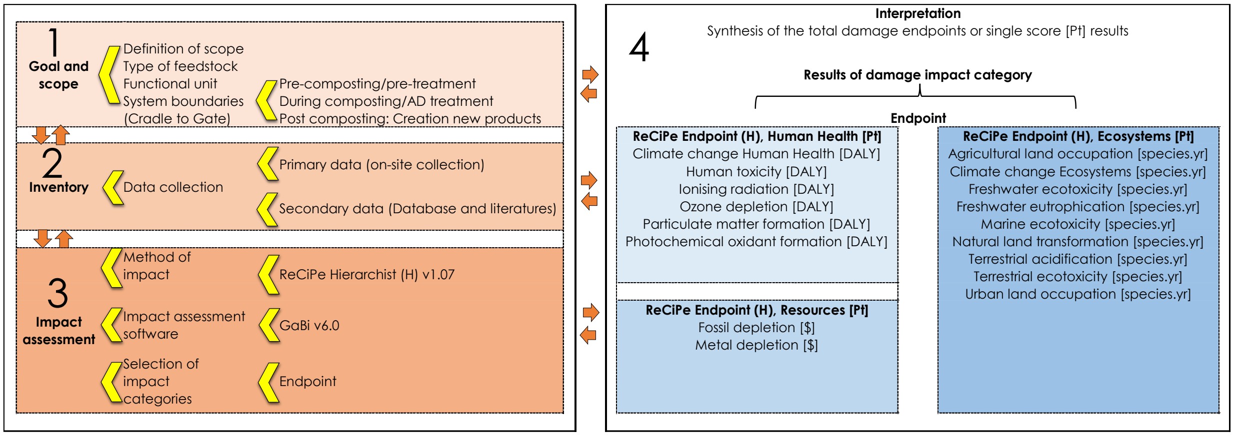
The study evaluated six different scenarios for FW management (refer Supplementary Data Table S2), including: (a) Sc0: The business-as-usual approach of Seelong, Johor Bahru landfilling (b) Sc1: Aerobic windrow composting at the Sutera Folo plant in Tanah Sutera Development Sdn. Bhd. and Folo Farm, Ban Foo Ulu Tiram, Johor (c) Sc2: Integrated aerobic windrow composting combined with landfilling (d) Sc3: Dry AD plant using Cowtec. technology CTM-100 at the Petaling Jaya, Selangor (e) Sc4: Wet AD combined with aerobic windrow composting at Felda Taib Andak in Kulai, Johor (f) Sc5: Wet AD combined with aerobic windrow composting and landfilling.

2.1.2 Life Cycle Inventory

The study used both foreground and background data to collect information on the inputs, outputs, and emissions of the different technologies used to treat FW. (i) Foreground data was obtained from site visits to locations like Seelong landfill for Sc0, composting plants such as Sutera Folo in Johor Bahru for Sc1, and Petaling Jaya for Sc3. (ii) Data from literature studies for Sc0 included references such as Abba [13], Mendes *et al*. [14], Righi *et al*. [15], Hong *et al*. [16], Johari *et al*. [17], Fauziah & Agamuthu [18]. Sc4 data, focusing on Felda Taib Andak Kulai in Johor, was sourced from Zulkepli *et al*. [19]. (iii) Data for Sc3 regarding dry anaerobic digester providers was gathered from CH Green SDN. BHD. and Majlis Bandaraya Petaling Jaya Selangor. (iv) Background data were sourced from the GaBi professional v6.0 database, including Malaysian electricity inventories, truck load capacity inventories, diesel fuel inventories, and others. This inventory list can be found in supplementary data (Table S3: Input and output inventories for landfill, aerobic windrow composting, dry AD, and wet AD).

2.1.3 Life Cycle Impact Assessment

The study used the ReCiPe hierarchist (H) v.1.07's damage-oriented approach (depicted by Figure 3), which is considered the optimal endpoint methodology for assessing environmental impacts based on mature characterization models [20], [21]. In evaluating the performance or satisfaction of FW treatment technologies, utilizing a combination of mid-point, end-point, and single score metrics offers a comprehensive approach [11], as illustrated in *Figure S1(a) Supplementary Data*. The mid-point score serves as a reference point, allowing for comparisons between positive and negative feedback relating to environmental impact performance, highlighting areas of improvement or success. Meanwhile, the end-point score captures the overall impression or outcome at the conclusion of the evaluation period, providing a holistic view of the entire experience in employing the FW treatment technologies. Incorporating a single score synthesizes the various metrics into a simplified yet meaningful representation, facilitating easy communication of results and decision-making processes (Figure 3).



DALY: Disability-Adjusted Life Years
Pt: Point
species.yr: species year
$: Surplus cost

Figure 3 LCA using damage-oriented approach (adapted from [12])

Together, these metrics create a robust assessment framework that balances detail and simplicity, ensuring a thorough understanding of performance while promoting actionable insights for future enhancements for FW management sustainability. The GaBi professional database v6.0 was used as the impact assessment software for data analyses.

2.2 An LCC Analysis using Annual Worth Method in Comparative FW Treatment Methods

This study employs the annual worth method to assess the LCC analysis methodology developed by Dell'Isola & Kirk [22] to conduct an economic comparison of the different scenarios. According to Sharma & Chandel [5] , LCC methodology consists of four steps: (1) defining the goal and scope of the analysis, (2) creating an inventory of the life cycle costs, (3) using the annual worth method to assess the life cycle costs, and (4) interpreting the results, as illustrated in Figure 4.

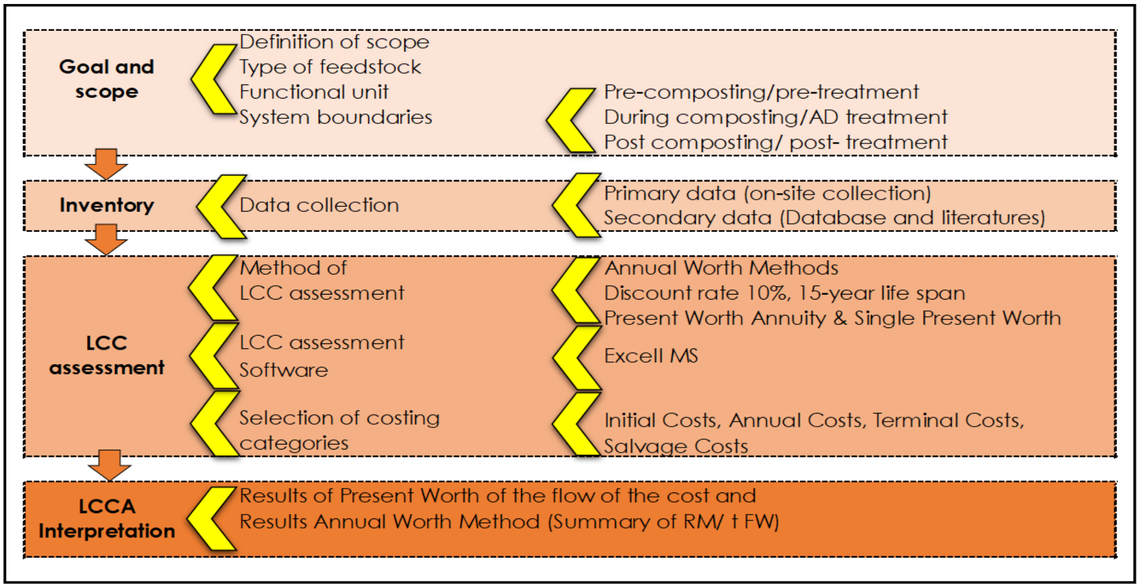


Figure 4 LCC approach

2.2.1 Goal and Scope Definition

To identify the most economically effective FW management system for 15 years life span using LCC of annual worth method.

2.2.2 Life Cycle Costing Inventory

The LCC analysis for four scenarios (Sc0, Sc1, Sc3, and Sc4) considered capital costs, operations and maintenance (O&M) costs, and terminal costs and salvage costs. However, the cost of land was not included except for the landfill scenarios. The costing for Sc0 sanitary landfill was taken from Abduli *et al*. [23], Berge *et al*. [24], and Baldasano *et al*. [25], while for Sc2 windrow composting integrated landfill and Sc5 wet AD integrated windrow composting with landfill, these systems were considered as combination treatments of FW. The number of operational days was assumed as 6 days per week for all treatment systems except the sanitary landfill and dry AD plant (365 days) since this takes a greater amount of time to operate. The Sc0, Sc2 and Sc5 have a real capacity of 1800t/d, Sc1 of 5t/d, Sc3 of 3t/d and Sc4 of 1t/d. Inventory cost for aerobic windrow were taken from the published research as conducted by Lim *et al*. [26], and onsite data of real scale Folo Farm, Ulu Tiram Johor, while dry AD primary data derived from real scale Petaling Jaya Selangor dry AD plant. Finally, the cost data for a wet AD plant with adjusted capacity of 1 ton per day (TPD) of FW was acquired from the Zulkepli *et al*. [19] on FW management in Kulai, Johor. These are all wet digester-based technologies. It is important to note that the adjusted capital and O&M costs for the wet AD combining aerobic windrow scenario (Sc4) were calculated based on the capacity of 1 ton per day (TPD) of FW. This means that if the capacity of the plant were to be increased, the costs may change as well (refer Supplementary Data Table S7: Life Cycle Costing Inventory).

2.2.3 Life Cycle Cost Assessment for Facilities

In this study, the present and annual worth methods were chosen because they allow all costs to be converted to equivalent values at a single point in time. Capital costs, also known as initial costs, refer to the expenses incurred during the construction of the treatment plant, including civil, mechanical, electrical, and other relevant elements. O&M expenses cover labor, energy, repair, maintenance, and replacement of electro-mechanical devices incurred during the plant's operation. The present worth method with a uniform present worth annuity factor was employed to determine the annual O&M cost, as well as laboratory testing, inspection, general and administrative costs. Discounting was not consistently applied in studies related to Malaysian food waste or its management. Some studies only included economic analysis Keng *et al*. [27], or cost benefit analysis for certain costs such as machinery and capital costs as conducted by Zulkepli *et al*. [19] or Bong *et al*. [28], while others did not use any discounting at all Lim *et al*. [26]. As far as discounting methods are regarded, among the reviewed studies there was no prevalence of fixed rates, either assumed or estimated. Therefore, it is challenging to determine the appropriate discount rate for cost analysis of waste treatment facilities in Malaysia. Nevertheless, Menna *et al*. [7] suggested that a discount rate can be assumed or estimated based on the findings of previous studies. For the purposes of this study, total discount rates were assumed. The assumed discount rate of 10% was used and the operational life span of the treatment systems was 15 years. For terminal costs, such as component replacement, it was assumed that 15% of the total capital cost would be spent in 5 years and 20% in 10 years. Using the present worth method, the revenue generated by each scenario was calculated and discounted to its current value. Additionally, the net LCC for all scenarios was determined by subtracting the discounted revenue earned through recycling, biofertilizers, and energy recovery. The current worth factor was used to estimate the overall cost of each phase in each scenario, which was then multiplied by the unit cost for that stage. The sum of all stages' costs equaled the scenario cost.

To account for inflation, an average inflation rate of 4.5% was obtained from statistical data provided by The Bank Negara of Malaysia for the years 2018-2022. All costs expressed in US dollars were converted to Malaysian Ringgit using a currency exchange rate of US$ 1 = MYR 4.75 provided by Bank Negara Malaysia. The costs were then adjusted to the base year of 2022 using an online currency converter (http://googlecurrency2022). Formula used for calculating present worth method for FW management facilities has been provided as can be seen follows:

Present Worth of Annuity

$$PWA = \frac{(1+i)^n - 1}{i(1+i)^n} \tag{1}$$

and **Single Present Worth**

$$PW = \frac{1}{(1+i)^n} \tag{2}$$

The symbol used in these formulas are: *i*: interest rate per period; *n*: number of interest periods; *P*: present amount; *F*: future amount, *A*: uniform sum of money in each period. The *PWA* factor may be used where a present amount at *i*% interest is returned in *n* equal periodic instalments. *PWA* represent uniform present worth, *A* represents the uniform sum of money in such time period, and *P*, the present worth of the instalments, is the unknown. Note that *PWA* is the reciprocal of *PP*.

$$P = A \times PWA \tag{3}$$

$$P = F \times PW \tag{4}$$

$$\mathrm{PW} = \mathrm{IC} + \sum_{t=0}^{t=n} \mathrm{pwaf}\,[\mathrm{O\,\&\,MC} + \mathrm{FC} + \mathrm{LC} + \mathrm{GAC}] + \sum_{t=0}^{t=n} \mathrm{pwf}\,\mathrm{FR1C} + \mathrm{FR2C}] - \mathrm{pwf}\,[\mathrm{SC}] \qquad (5)$$

IC: Initial cost; O&MC: Operation & Maintenance cost; FC: Fuel cost; LC: Laboratory cost/testing/Inspection; GAC: General & Administration cost;FRC: Future Replacement cost; SC: Salvage cost; n: years; pwaf: present worth annuity factor; pwf: present worth factor

Annual Worth Method

The annual worth can be calculated from either the present worth or the future worth is shown in Equation 6.

$$AW = \frac{PW}{\frac{(1+i)^n - 1}{i(1+i)^n}} \qquad (6)$$

Real capacity of treatment/yearly

$$\text{Real capacity} = \text{t/day} \times 365 \text{ days} \qquad (7)$$

Ringgit Malaysia per ton food waste (RM/t FW)

$$\text{RM/ t FW} = \text{AW/ Real capacity} \qquad (8)$$

*Refer Supplementary Data via link: https://drive.google.com/drive/folders/1CndBM-PeZLxaPZIlotXQSi-_mXBALjlI

2.3 Integration of LCA and LCC Utilizing CA

The use of CA involves mathematical mixture models and pattern recognition in statistical analysis [8], [29]. CA is used to identify natural groups or classes within a dataset of individual measurements, as well as to classify individuals according to pre-existing groups. The objective of CA is to group similar individuals together based on an appropriate criterion, in order to better understand the differences among the formulated groups. The study recommends using CA to extend the decision-making framework, integrating LCA and LCC. The coming section shows the standardized LCA point on the X-axis, taken from the total damage point of assessed scenarios, and the standardized LCC point on the Y-axis, taken from the summary of present worth flow of costs for the six considered scenarios in Ringgit Malaysia (RM).

$$S_{LCA} = -[\frac{Pi - Mp}{Mp}] \qquad (9)$$

Where "S_{LCA}" is the standardized LCA point; "P_i" is the LCA point of a scenario "i" which previously the data were extracted from LCA result of alternatives of composting methods; and "M_p" is the mean of all LCA points. The negative sign indicates less environmental impact. Because the results are transformed to positive points as shown in Table 5, they are then multiplied by (-1). The aim of standardization is taking normal data. All points were listed according to the results of total LCA.

$$S_{LCC} = -[\frac{Li - ML}{ML}] \qquad (10)$$

Where "S_{LCC}" is the standardized LCC point; "L_i" is the LCC point of a scenario "i" which previously the data were extracted from LCC result of alternatives of composting methods; and "M_L" is the mean of all LCC points. Because the results are transformed to positive points as shown in Table 6, they are then multiplied by (-1). The aim of standardization is taking normal data. All points were listed according to the results of total LCC.

2.3.1 Plotting the Standardized Results of LCA and LCC

To meet the specified criteria, the standardized LCC points for each scenario were used as a reference point along with the environmental LCA points [10]. The standardized LCC points were transformed into six distinct points that represent the axis scenarios and the distance between two clusters. The distances between all individuals in two groups were averaged to calculate the distances. The Euclidean distance squared was used to measure the distance, which can be calculated as follows:

$$D_{ab} = \sum_{i}^{p} (a_j - b_j)^{\,2} \qquad (11)$$

The coordinates of A and B are represented by the points "a_j" and "b_j" with "j" serving as the axis and "p" as the dimension. To be correctly interpreted, the findings should take the scenario closest to the top and right as the best. In terms of environmental and economic consequences, the scenario closest to the bottom and left is the worst.

3.0 RESULTS AND DISCUSSION

3.1 LCA Single Scores Total Damage Points [Pt] of All Scenarios

This section highlights the environmental impact assessment for the six technologies evaluated relating to the management of the 1-ton FW. The results, as evaluated using the ReCiPe (H) LCIA methodology, encompass 16 midpoint indicators, 17 endpoint indicators, and a final aggregated score reflecting three primary damage categories: human health, ecosystem quality, and resource availability. All values from the midpoint and endpoint assessments are provided in the supplementary data (Table S4: Results of LCA midpoints using ReCiPe v1.07; Table S5: Comparative impact scores for treating 1 ton of waste from this and other similar LCA studies; and Table S6: Sensitivity analysis of eight impact categories). A positive value indicates an increased environmental load, whereas a negative value indicates a reduction in environmental pressure or an improvement in sustainability performance.

Meanwhile, Table 1 displays the comparison of various FW-management scenarios in Malaysian locations based on their damage or severity impacts evaluated by LCIA. To calculate these single scores total damage points, emissions were weighted using the weighted damage factors introduced by the LCIA ReCiPe endpoint (H) v1.07 method. The scenario labelled Sc3 as shown in Figure S2 *Total damage point (Pt) or single scores of assessed scenarios* (Supplementary Data), has the lowest total damage point of 4.44E+01, indicating that it has minimal environmental impacts and can potentially reduce the impact points of other sources such as power plants and composting or fertilizer manufacturing facilities. Hence, Sc3 is ranked highest in minimizing damage to resource availability, human health, and ecosystem diversity, while Sc2 is the least favourable scenario that utilizes a combination of aerobic windrow composting and landfill methods for FW treatment. The scenarios Sc4, Sc1, Sc0, Sc5, and Sc2 are ranked as appropriate options following Sc3.

The Sc3 scenario, involving Dry AD technology with a mesophilic reactor, was found to be more energy-efficient, waste-free, and required a smaller operational area compared to other scenarios [30]. This result aligns with the findings of Van *et al*. [31], and Poeschl *et al*. [21], who also recommended on-site, small-scale AD as the most suitable approach for the evaluated AD categories in their LCA. Additionally, Sc3 offers advantages such as reduced waste collection and transport distances, low operational power requirements, and the potential for biogas and fertilizer production. The use of electricity or biogas, alongside composting in the dry AD scenario, contributed to reduced energy and mineral fertilizer consumption, resulting in a significantly lower damage to resource score of 4.44E+01 Pt. Thus, Sc3 was identified as the most effective option for FW management in Malaysian contexts.

In contrast, Sc4 promotes the use of biogas as an environmentally friendly energy source, which is gaining popularity due to its efficiency and environmental advantages [32]. When compared to aerobic composting, however, wet AD (Sc4) is more technically complex and demands greater community involvement in waste segregation at the source. Although community guidelines for FW disposal may exist, active participation is critical. Moreover, as noted by Zulkepli *et al*. [19], AD systems can be costly to implement and require robust management to ensure effectiveness.

Table 1 The comparison of various FW-management scenarios based on single scores [Pt] damage impacts

Impact	Acronym	Sc0	Sc1	Sc2	Sc3	Sc4	Sc5
Damage Resource Availability	DRA	2.99E+03	6.61E+02	3.66E+03	4.44E+01	4.48E+02	3.48E+03
Damage Human Health	DHH	1.08E-03	2.18E-03	3.26E-03	9.28E-05	2.26E-02	2.37E-02
Damage Ecosystems Diversity	DED	4.26E-06	7.41E-06	1.17E-05	3.94E-07	1.10E-04	1.15E-04
Single scores [Pt]		**2.99E+03**	**6.61E+02**	**3.66E+03**	**4.44E+01**	**4.48E+02**	**3.48E+03**

Additionally, from an environmental perspective, the air emissions produced by these plants have emerged as a concern. AD plants such as Sc4 that incorporate aerobic composting on-site to generate the final compost product are encountering challenges with emissions that cause unpleasant odours. As a result, some of these plants have been forced to restrict or cease operations [19]. Furthermore, alongside the odour-causing emissions, there is a release of CH_4 into the atmosphere, termed as fugitive emission. In specific instances, this CH_4 emission can be substantial, contributing to an increase in the overall carbon footprint of these plants, which are otherwise regarded as environmentally friendly.

Sc1, which used aerobic windrow composting, ranked third in terms of environmental performance due to the high energy required for waste treatment operations (damage resource availability of (6.61E+02 Pt). In addition, emissions were released without any treatment, such as biofiltering (damage ecosystem diversity, 7.41E-06 Pt). Composting systems can pose a risk of greenhouse gas (GHG) contamination during both treatment and storage, mainly due to poor carbon to nitrogen ratio (C/N) waste and high moisture content. Therefore, parameters such as pH, C/N ratio, moisture content, aeration rate, particle size, and porosity need to be carefully monitored. Improper mixture preparation and adjustment, use of conventional bulking agents, and process inefficiencies can result in odour emissions, elevated environmental damage, and poor-quality compost [33].

In contrast to the other scenarios, Sc0 and the integrated landfill treatments (Sc2, and Sc5) had a high damaging impact (DRA, DHH and DED). Previous studies, such as Kim & Kim [34], have shown that landfills produce the highest GHGs, followed by dry feed, composting, and wet feed. Furthermore, Abduli *et al*. [23] also found that the environmental impact of the aerobic windrow composting integrated landfill scenario (Sc2) was greater than that of the landfill scenario, resulting in more damaging mineral resource implications than a landfill. According to a study conducted by Al-Rumaihi *et al*. [35], windrow composting had the highest environmental impact on acidification, with a value of 9.39x10-1 kg SO_2 eq. On the other hand, the combined windrow composting with AD had a significant impact on human toxicity, with a value of 3.47x10 kg 1,4 DB eq.

3.2 LCC of Annual Worth Method for Summary of Ringgit Malaysia Per Ton Food Waste (RM/t FW)

Based on the summary of the LCC analysis for FW treatment, landfilling and integrated landfill scenarios are the most cost-effective options (Table 2). Specifically, scenarios Sc0, Sc2, and Sc5, which involve sanitary landfilling, have net LCCs ranging from RM40 to RM42 per ton of FW, attributed to the high capacity treatment of 1800 tons per day over a 15-year lifespan. Landfilling is preferred due to its simplicity, versatility, and lower initial costs compared to other methods like incineration and biological composting. Composting and AD are alternative methods for managing organic waste, producing bio-fertilizer and biogas, and reducing harmful emissions. Scenario Sc1, which uses windrow composting, has a net LCC of RM66 per ton of FW and offers low capital costs and moderate operational complexity. However, it poses higher human health risks. Scenario Sc3, involving dry AD, has a net LCC of RM164 per ton and is suitable for urban areas with limited space, though it requires precise management and clean feedstock. Scenario Sc4, which involves wet AD, is the most expensive at RM384 per ton of FW due to high capital and operational costs, and technical complexity. It is less economically feasible due to the challenges of collecting clean feedstocks and the high pretreatment costs required for efficient digestion and compost quality. In summary, landfilling remains the most economical method for FW treatment, while composting and AD present viable but more costly and complex alternatives. The LCC analyses highlight the economic considerations of each method, with landfilling being the most cost-effective despite its environmental drawbacks.

3.3 Integration of LCA and LCC Utilizing CA

To obtain the mean of the LCA points, the standardization equation is utilized (refer calculation by Table S10: Scenario LCA point standardization; and Table S11: Scenario LCA point standardization). Next, the LCA points for each scenario are subtracted from the mean value. The resulting figures are then divided by the mean LCA point for each scenario [9]. The results are presented as positive values in Table 3, but they are multiplied by (-1) due to the transformation that was applied. The standardization equation is employed to obtain the mean of the LCC points. Next, the LCC points of each scenario are subtracted from the mean. The results are then divided based on the average LCC point of each scenario. As depicted in Table 3, since the results are transformed into positive points, they are then multiplied by (-1).

Table 2 Results of LCC

		Sc1		Sc4		Sc3		Sc0		Sc2		Sc5
PW of the flow of the cost 15 years	RM	915,432	RM	1,066,524	RM	1,367,093	RM	197,921,946	RM	205,298,769	RM	209,394,289
Annual Worth	RM	120,357	RM	140,221	RM	179,739	RM	26,021,818	RM	26,991,687	RM	27,530,146
(Real cap. t for 365 days in 1 year)		1825		365		1095		657000		657000		657000
The Annual Worth (RM/t FW)	**RM**	**66**	**RM**	**384**	**RM**	**164**	**RM**	**40**	**RM**	**41**	**RM**	**42**

*cap: capacity, t: ton, PW: Present Worth, FW: Food Waste, RM:Ringgit Malaysia

*The Annual Worth:

**n* :15, *i* :10%

*Real capacity = t/day x 365 days

*RM/t FW = AW/Real cap. t for 365days in 1 year

Table 3 Scenario LCA and LCC point standardization

Scenario	*LCA points	Standardize of LCA points	*LCC points	Standardize of LCC points
Sc0	2990.00	-0.59	RM40	0.67
Sc1	661.00	0.65	RM66	0.46
Sc2	3660.00	-0.95	RM41	0.67
Sc3	44.40	0.98	RM164	-0.34
Sc4	448.00	0.76	RM384	-2.13
Sc5	3480.00	-0.85	RM42	0.66
Average	**1880.57**		**RM123**	

3.3.1 Plotting the Standardized Results of LCA, and LCC

A two-dimensional diagram can be used to illustrate the changes in costs and environmental impacts for multiple alternatives. Based on these observations, a set of guidelines can be established and provided as part of a quality improvement and scenario review process at various stages of the hybridized system.

Figure 5 shows the groups on the coordinate graph in a geometric manner. The LCC will be on the -y-axis, while the LCA and points interpretation plot will be on the x-axis. The following points can be interpreted from the plot: (i) The best performance is achieved when both LCA and LCC approaches perform well, which is indicated by the top and right positions in the first quadrant. (ii) The worst performance is indicated by the bottom and left positions in the third quadrant, where both LCA and LCC approaches perform poorly. (iii) Good performance in LCC but not in LCA approach is indicated by the second quadrant. (iv) Good performance in LCA but not in LCC approach is indicated by the fourth quadrant [9], [10].

From a quantitative perspective, the groups can be classified based on their environmental friendliness and economic feasibility. Both quantitative data should be defined and evaluated as shown in Figure 5. The impact of biotechnology practices on the environment is evaluated through the integration of quantitative LCA and LCC methods, using a multivariate data analysis technique known as CA approach. An ordinal list is commonly used to display and analyze the effects of LCA and LCC approaches. However, the distances between the results are often considered to be distinct.

Consequently, when the results are compared, the adjacent positions in the ordinal list may have significant impacts. This vulnerability can be addressed by using CA, which organizes the assessment results into multiple categories. With this approach, we can clarify and synthesize the effects of these two methods in a given group, rather than just evaluating them individually. The integration of CA has shown that aerobic windrow composting (Sc1) is the most effective technologies for FW treatment, as they exhibit the best performance on both LCA and LCC approaches. Thus, composting play a crucial role in diverting organic waste from landfills, serving as complementary practices rather than substitutes for landfilling. When compared to landfilling, composting whether conducted under aerobic or anaerobic exhibits lower GHGs emissions and reduced eutrophication potential [12].

On the other hand, landfill (Sc0), wet AD integrated aerobic windrow composting with landfill (Sc5), as well as aerobic windrow composting combined landfill (Sc2), are considered to be the second, third and fourth better FW technologies as they demonstrate good performance on LCC approaches but poor performance in LCA approaches.

Meanwhile, dry AD (Sc3) and wet AD combined aerobic windrow composting (Sc4) become fifth and sixth for FW treatment which have good performance in LCA but not in LCC approach as indicated by the fourth quadrant. The scenarios Sc0, Sc5, Sc2, Sc3, and Sc4 are ranked as appropriate options following Sc1 (Figure 5).

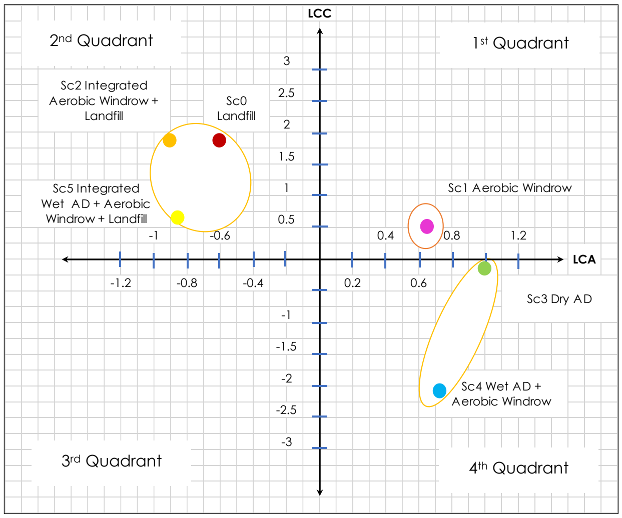


Figure 5 Plotting the standardized results of LCA and LCC

The windrow composting method (Sc1) emerged as the most cost-effective option, with a net LCC of RM66 per ton. In contrast, Dry AD (Sc3) and Wet AD (Sc4) were the least favorable, with net LCCs ranging from RM164 to RM384 per ton, primarily due to their high initial capital costs. As previously identified in (the fourth quadrant of the CA Figure 5), comprising Sc3 (Dry AD) and Sc4 (Wet AD + Aerobic Window), the financial feasibility of these alternatives remains questionable due to substantial capital investment and recurring operational costs. Earlier findings indicate that implementing such systems still demands significant financial outlay, encompassing both infrastructure development and long-term maintenance—placing their cost profile in the same range as that of conventional waste-to-energy (WTE) technologies [19]. As a result, subsidies are essential to render this technology more accessible and affordable for the general population. Another substantial challenge pertains to sourcing clean feedstocks, which has proven to be a major concern even in regions known for their heightened environmental consciousness and waste segregation practices. The quality of the feedstock significantly influences the scale and cost of necessary pretreatment for the material, as well as the effectiveness of the AD process and the resultant compost's quality. The feedstock's quality is intricately linked to the overall economics of these facilities, as it directly impacts the marketability of the compost product and the quantity of biogas that can be generated and utilized for electricity generation.

3.3.2 Comparison with Other Integral Method

Prior research that utilized multivariate CA, such as the work by Ghazvinei *et al*. [9], Huang & Ma [10], focused on a two-dimensional evaluation, emphasizing both LCA and multi-criteria decision-making (MCDM) using the AHP. These studies primarily addressed the selection of effective strategies for solid waste management. For instance, Ghazvinei *et al*. [9] concentrated on institutional waste management, concluding that an integrated system involving refused derived fuel (RDF), composting, AD, and recycling is optimal for handling institutional waste. While existing research provides valuable insights, there is a significant gap in the availability of comprehensive systematic costing procedures specifically tailored for waste management facilities. This highlights the need to incorporate financial considerations into decision-making processes for waste management techniques and product development strategies to drive desired improvements.

There is a lack of consensus in the literature regarding the use of LCC approaches for food products or FW streams, and there is no widely accepted methodology for conducting such analyses [4-5]. Moreover, the LCC is not the same in all countries, and therefore it is important to conduct a detailed analysis of LCC in Malaysia. This can serve as a foundation for the development of a comprehensive feasibility study for establishing an on-site and large-scale organic waste treatment system.

Furthermore, MCDM involves evaluating multiple criteria simultaneously, making it complex and challenging, especially when different stakeholders prioritize criteria differently, leading to potential conflicts and difficulties in reaching consensus. The reliance on subjective judgments during pairwise comparisons of criteria or alternatives can introduce biases and uncertainties. Additionally, the availability and quality of data for criteria assessment are crucial, as inaccurate or incomplete data can impact the reliability and validity of outcomes. Selecting the appropriate MCDM model for a specific decision problem is challenging due to varying assumptions, strengths, and limitations of different techniques. The complexity of mathematical calculations and analysis in MCDM, especially with numerous criteria and alternatives, requires expertise in decision science and modeling. Incorporating diverse stakeholder preferences into MCDM models is difficult, as balancing their needs while ensuring fairness and transparency in decision-making is complex. Moreover, decision-making often occurs in dynamic and uncertain environments, necessitating MCDM models to account for uncertainty and adaptability to ensure robust outcomes.

In most cases, combining multiple decision-making methods involves separate processes. For example, LCA might be conducted first, followed by MCDM or costing analysis, with each method performed independently but aimed at the same objective. This approach is evident in various studies, including those by Bong *et al*. [28] and Martinez Sanchez *et al*. [36]. Several studies have also employed an integrated approach combining LCA and LCC. Although the integrated frameworks developed by De Menna *et al*. [4] using Tree Economic Analysis and Zhu *et al*. [37] through Industrial Symbiosis for combining LCA and LCC are valuable, they often suffer from unclear explanations and excessive complexity. It has been emphasized that decision-making processes need to strike a balance between simplicity [38] and comprehensiveness [39]. Engineers and planners in solid waste management require decision-making methods that not only yield effective results but are also user-friendly, comprehensive, and reasonably time-efficient in producing outcomes [9].

4.0 CONCLUSIONS

This study presents a robust evaluation framework that integrates LCA, LCC, and CA to objectively assess food waste treatment technologies. By balancing environmental and economic dimensions, the framework minimizes bias and supports transparent, evidence-based decision-making. The approach offers practical value for both practitioners and policymakers, enabling them to identify cost-effective and eco-friendly solutions—such as aerobic windrow composting (Sc1)—and communicate these findings clearly through graphical tools and sustainability benchmarks.

For Malaysia specifically, the study addresses key challenges such as limited data on organic waste, low public awareness, and infrastructure gaps. The framework strengthens the regional relevance by offering a structured method for evaluating technologies under local constraints, laying a stronger foundation for context-specific policy and planning. While the current focus is on environmental and economic factors, the findings emphasize the need for future integration of social, cultural, and infrastructural aspects to support a circular and sustainable food waste management system in Malaysia.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

References

[1] Elgarahy, A. M., *et al.* 2023. Sustainable Management of Food Waste; Pre-Treatment Strategies, Techno-Economic Assessment, Bibliometric Analysis, and Potential Utilizations: A Systematic Review. *Environmental Research*. 225: 115558. https://doi.org/10.1016/j.envres.2023.115558.

[2] Abu, R., *et al.* 2023. A Comparative Life Cycle Assessment of Dry and Wet Anaerobic Digestion Technologies for Food. *Waste Management*. 35(2): 317–349.

[3] Thomson, A., G. W. Price, P. Arnold, M. Dixon, and T. Graham. 2022. Review of the Potential for Recycling CO2 from Organic Waste Composting into Plant Production under Controlled Environment Agriculture. *Journal of Cleaner Production*. 333: 130051. https://doi.org/10.1016/j.jclepro.2021.130051.

[4] De Menna, F., J. Davis, K. Östergren, N. Unger, M. Loubiere, and M. Vittuari. 2020. A Combined Framework for the Life Cycle Assessment and Costing of Food Waste Prevention and Valorization: An Application to School Canteens. *Agricultural and Food Economics*. 8(1). https://doi.org/10.1186/s40100-019-0148-2.

[5] Sharma, B. K., and M. K. Chandel. 2021. Life Cycle Cost Analysis of Municipal Solid Waste Management Scenarios for Mumbai, India. *Waste Management*. 124: 293–302. https://doi.org/10.1016/j.wasman.2021.02.002.

[6] Bahramian, M., C. Krah, P. Hynds, and A. Priyadarshini. 2025. An Environmental and Economic Assessment of Household Food Waste Management Scenarios in Ireland. *Recycling*. 10(3): 94.

[7] Elfeky, A., K. Fattah, and M. Abdallah. 2023. Hybrid Environmental and Economic Assessment of Biogas Plants in Integrated Organic Waste Management Strategies. In *Biogas Plants: Waste Management, Energy Production and Carbon Footprint Reduction*. Edited by W. Czekała, chap. 9. Wiley.

[8] Böhm, K., Smidt, E., and Tintner, J. (2013). Application of Multivariate Data Analyses in Waste Management. Multivar. *Anal. Manag. Eng. Sci,* 15–38.

[9] Ghazvinei, P. T., M. A. Mir, H. H. Darvishi, and A. Junaidah. 2017. *University Campus Solid Waste Management: Combining Life Cycle Assessment and Analytical Hierarchy Process*. Springer Briefs in Environmental Science.

[10] Huang, C., and H. Ma. 2004. A Multidimensional Environmental Evaluation of Packaging Materials. *Science of the Total Environment*. 324: 161–172. https://doi.org/10.1016/j.scitotenv.2003.10.039.

[11] Hauschild, M. Z., R. K. Rosenbaum, and S. I. Olsen. 2017. *Life Cycle Assessment: Theory and Practice*. https://doi.org/10.1007/978-3-319-56475-3.

[12] Feliciano, M., and M. A. Rodrigues. 2023. Systematic Review and Meta-Analysis on the Use of LCA to Assess the Environmental Impacts of the Composting Process. *Journal of Cleaner Production*. 326: 129567. https://doi.org/10.1016/j.jclepro.2023.129567.

[13] Abba, A. H. 2014. *Assessment of Municipal Solid Waste Disposal Options Using Analytical Hierarchy Process and Life Cycle Analysis*. Thesis, Universiti Teknologi Malaysia.

[14] Mendes, M. R., T. Aramaki, and K. Hanaki. 2004. Comparison of the Environmental Impact of Incineration and Landfilling in São Paulo City as Determined by LCA. *Resources, Conservation and Recycling*. 41(1): 47–63. https://doi.org/10.1016/j.resconrec.2003.08.003.

[15] Righi, S., L. Oliviero, M. Pedrini, A. Buscaroli, and C. Della Casa. 2013. Life Cycle Assessment of Management Systems for Sewage Sludge and Food Waste: Centralized and Decentralized Approaches. *Journal of Cleaner Production*. 44: 8–17. https://doi.org/10.1016/j.jclepro.2012.12.004.

[16] Hong, R. J., *et al.* 2006. Life Cycle Assessment of BMT-Based Integrated Municipal Solid Waste Management: Case Study in Pudong, China. *Resources, Conservation and Recycling*. 49(2): 129–146. https://doi.org/10.1016/j.resconrec.2006.03.007.

[17] Johari, A., S. I. Ahmed, H. Hashim, H. Alkali, and M. Ramli. 2012. Economic and Environmental Benefits of Landfill Gas from Municipal Solid Waste in Malaysia. *Renewable and Sustainable Energy Reviews*. 16(5): 2907–2912. https://doi.org/10.1016/j.rser.2012.02.005.

[18] Fauziah, S. H., and P. Agamuthu. 2012. Trends in Sustainable Landfilling in Malaysia, a Developing Country. *Waste Management & Research*. 30(7): 656–663. https://doi.org/10.1177/0734242X12437564.

[19] Zulkepli, N. E., Z. A. Muis, N. A. N. Mahmood, H. Hashim, and W. S. Ho. 2017. Cost Benefit Analysis of Composting and Anaerobic Digestion in a Community: A Review. *Chemical Engineering Transactions*. 56: 1777–1782. https://doi.org/10.3303/CET1756297.

[20] Cavalett, O., M. F. Chagas, J. E. A. Seabra, and A. Bonomi. 2013. Comparative LCA of Ethanol versus Gasoline in Brazil Using Different LCIA Methods. *International Journal of Life Cycle Assessment*. 18(3): 647–658. https://doi.org/10.1007/s11367-012-0465-0.

[21] Poeschl, M., S. Ward, and P. Owende. 2012. Environmental Impacts of Biogas Deployment—Part II: Life Cycle Assessment of Multiple Production and Utilization Pathways. *Journal of Cleaner Production*. 24: 184–201. https://doi.org/10.1016/j.jclepro.2011.10.030.

[22] Dell'Isola, A., and S. J. Kirk. 2003. *Life Cycle Costing for Facilities*. Wiley.

[23] Abduli, M. A., A. Naghib, M. Yonesi, and A. Akbari. 2011. Life Cycle Assessment (LCA) of Solid Waste Management Strategies in Tehran: Landfill and Composting plus Landfill. *Environmental Monitoring and Assessment*. 178(1–4): 487–498. https://doi.org/10.1007/s10661-010-1707-x.

[24] Berge, N. D., D. R. Reinhart, and E. S. Batarseh. 2009. An Assessment of Bioreactor Landfill Costs and Benefits." *Waste Management*. 29(5): 1558–1567. https://doi.org/10.1016/j.wasman.2008.12.010.

[25] Baldasano, J. M., S. Gassó, and C. Pérez. 2003. Environmental Performance Review and Cost Analysis of MSW Landfilling by Baling-Wrapping Technology versus Conventional System. *Waste Management*. 23 (9): 795–806. https://doi.org/10.1016/S0956-053X(03)00087-4.

[26] Lim, L. Y., C. T. Lee, C. P. C. Bong, J. S. Lim, and J. J. Klemeš. 2019. Environmental and Economic Feasibility of an

Integrated Community Composting Plant and Organic Farm in Malaysia. *Journal of Environmental Management*. 244: 431–439. https://doi.org/10.1016/j.jenvman.2019.05.050.

[27] Keng, Z. X., *et al*. 2020. Community-Scale Composting for Food Waste: A Life-Cycle Assessment-Supported Case Study. *Journal of Cleaner Production*. 261: 121220. https://doi.org/10.1016/j.jclepro.2020.121220.

[28] Bong, C. P. C., *et al*. 2017. Towards Low Carbon Society in Iskandar Malaysia: Implementation and Feasibility of Community Organic Waste Composting. *Journal of Environmental Management*. 203: 679–687. https://doi.org/10.1016/j.jenvman.2016.05.033.

[29] Härdle, Wolfgang Karl, and Léopold Simar. 2013. *Applied Multivariate Statistical Analysis*. 4th ed. Berlin: Springer. https://doi.org/10.1007/978-3-642-17229-8.

[30] Rocamora, I., S. T. Wagland, R. Villa, E. W. Simpson, O. Fernández, and Y. Bajón-Fernández. 2020. Dry Anaerobic Digestion of Organic Waste: A Review of Operational Parameters and Their Impact on Process Performance. *Bioresource Technology*. 299. https://doi.org/10.1016/j.biortech.2019.122681.

[31] Van, D. P., T. Fujiwara, B. L. Tho, P. P. S. Toan, and G. H. Minh. 2020. A Review of Anaerobic Digestion Systems for Biodegradable Waste: Configurations, Operating Parameters, and Current Trends. *Environmental Engineering Research*. 25(1): 1–17. https://doi.org/10.4491/eer.2018.334.

[32] Woon, K. S., Z. X. Phuang, Z. Lin, and C. T. Lee. 2021. A Novel Food Waste Management Framework Combining Optical Sorting System and Anaerobic Digestion: A Case Study in Malaysia. *Energy*. 232: 121094. https://doi.org/10.1016/j.energy.2021.121094.

[33] Cerda, A., A. Artola, X. Font, R. Barrena, T. Gea, and A. Sánchez. 2018. Composting of Food Wastes: Status and Challenges. *Bioresource Technology*. 248: 57–67. https://doi.org/10.1016/j.biortech.2017.06.133.

[34] Kim, M. H., and J. W. Kim. 2010. Comparison through a LCA Evaluation Analysis of Food Waste Disposal Options from the Perspective of Global Warming and Resource Recovery. *Science of the Total Environment*. 408(19): 3998–4006. https://doi.org/10.1016/j.scitotenv.2010.04.049.

[35] Al-Rumaihi, A., G. McKay, H. R. Mackey, and T. Al-Ansari. 2020. Environmental Impact Assessment of Food Waste Management Using Two Composting Techniques. *Sustainability*. 12(4). https://doi.org/10.3390/su12041595.

[36] Martinez-Sanchez, V., D. Tonini, F. Møller, and T. F. Astrup. 2016. Life-Cycle Costing of Food Waste Management in Denmark: Importance of Indirect Effects. *Environmental Science & Technology*. 50(8): 4513–4523. https://doi.org/10.1021/acs.est.5b03536.

[37] Zhu, B. 2013. Life Cycle Assessment and Simplified Life Cycle Costing on Industrial Symbiosis. Master's thesis.

[38] Myllyviita, T., A. Holma, R. Antikainen, K. Lähtinen, and P. Leskinen. 2012. Assessing Environmental Impacts of Biomass Production Chains—Application of Life Cycle Assessment (LCA) and Multi-Criteria Decision Analysis (MCDA). *Journal of Cleaner Production*. 29–30: 238–245. https://doi.org/10.1016/j.jclepro.2012.01.019.

[39] Morrissey, A. J., and J. Browne. 2004. Waste Management Models and Their Application to Sustainable Waste Management. *Waste Management*. 24: 297–308. https://doi.org/10.1016/j.wasman.2003.09.005.

Table S1: Life Cycle Assessment- Description for scenarios assessed

Business As Usual Landfill (Sc_0)
Baseline Scenario-The landfill scenario defined the strategic practices employed through the past decade. In this case, FW was deposited in a landfill. The estimated distance travelled by the collection truck from the waste generation point to the landfill site plant was 45 km. The average garbage load was 5.0 t and the truck trip from the collection point to the landfill for biodegradable waste was twice-weekly. Even though landfill treatment of biodegradable waste was currently discouraged, this scenario has been included in the LCA study to provide a comparison and to determine the extent of the environmental benefits that can be obtained by adopting effective waste management strategies.

Aerobic Windrow (Sc_1)
Scenario 1 (WindrowComp) is the most commonly implemented practice at the community level. The technology is typically preferable for raw FW combined with some garden waste that has a moisture level of less than 60%, since the higher presence of moisture interferes with the oxygen transmitted in composting. A windrow composting system will start with material collection and transportation to a composting centre. Impurities such as plastics, glass bottles, and cans are screened for contaminant removal when the FW arrives at the facility. The production of quality compost comprises shredding of biomass waste, sufficient moisture and aeration, and frequent turning and mixing for 4 to 6 months (Windrow Composting Plant, Johor Bahru). Windrow composting entails arranging mixed. biodegradable waste with bulking materials such as saw dust, sugarcane fibre waste, and so on in long, thin piles or lanes, which are referred to as windrow formations. The FW is then placed on the prepared base and covered with canvas. Canvas is lightly draped over the piles to avoid rainfall from soaking through and forming extra moisture. On a regular basis, the rows are turned using a turner to combine the composting matter, to enhance its permeability and humidity. The turning machine pulls the material from the windrow and then re-disperses it and mixes the material and converts it into a loose mixture. When the turner goes along the windrow, it removes stockpiled heat and gases, combines the ingredients, shatters big particles, and enables clean air to enter the compost. When necessary, water is added while turning to keep humidity at 50-60%. If it is overly moist, it is necessary to turn it more often. The compost is then cured and left exposed for a further couple of weeks before the proper particle size is screened. Before releasing the compost on the market and to verify it conforms to the appropriate standards, a sample is generally obtained to assess the quality of the compost [1].

Integrated Aerobic Windrow with A Landfill (Sc_2)
Scenario 2, the windrow composting combined with landfilling scenario (WindComp & L), is similar to windrow composting, but combined with the current practice of landfilling of the solid fraction of digested matter. In this second scenario, windrow composting is used to treat 70% of the FW, while landfilling is used to treat the remaining 30%. The composting treatment is done by the same composting plant (in the first scenario, a distance of 5 km, one trip per day). The garbage from pre-treatment and post-treatment is deposited in a conventional landfill 45 kilometres away (about two trips per week). Landfills in this scenario have no system for landfill gas filtration.

Anaerobic Dry Digestion (Sc_3)
The first scenario dry AD, the present FW management system was analysed. A dry AD system started with material collection and transportation to a composting centre. Upon arrival, the feedstock materials comprised of FW were pre-treated by employing simultaneous screening to separate the organic wastes from the solid fraction containing impurities like plastics, metals, and others. The biodegradable waste was then shredded to the required size. The maximum dimension of feedstock materials was best between 1 mm long and 2 mm wide. This dry AD was a single-stage high-dry solid batch continuous anaerobic digester (Cowtec. technology). It was fitted with a power source, a 3000 kg capacity mixing and composting tank, a horizontal propeller, a gas scrubber unit, and a discharge pump. No water addition was conducted since it fully utilized the moisture content of the fresh FW substrates. The hydraulic retention time (HRT) was 30 days at a mesophilic temperature ranging from 30 to 35 degrees Celsius (°C). The total solids (TS) content was 25%, and the carbon to nitrogen (C/N) ratio was 10-35:1. The plant used biogas, which had a processing capacity of 2.76-5.52 kg/day. The method was a closed system, with air emissions more likely to be emitted at the end of the process when the compost was discharged, without the generation of leachate. Meanwhile, organic fertilizers, as well as biogas/electricity, were produced as products of this system. The energy in the gas was converted into electricity and consumed by the treatment plant. The digestion residue was passed through a dewatering system, after which the liquid fraction was collected. The dewatered digestate could produce approximately 600kg of solid digested matter per ton of treated FW, which was then composted and sold as a dry fertilizer.

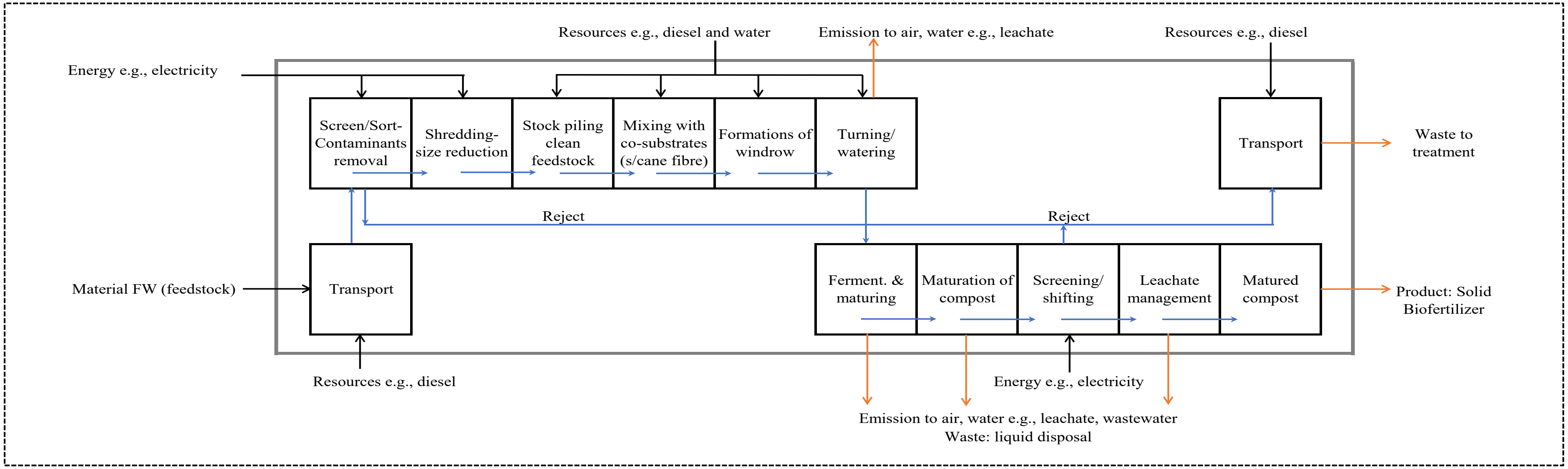
Anaerobic Wet Digestion with aerobic windrow composting (Sc_4)
The wet AD scenario combined with windrow composting. The wet AD assessed in this study was a biogas digester with microorganisms at a mesophilic temperature (around 35 °C) [2]. The complex FW was hydrolysed and fermented into short-chain organic matters, then further decomposed by methanogens to produce biogas. The biogas consisted of 62% CH_4, 32% biogenic CO_2, and 6% of other gas components such as NH_3, VOCs, O_2, and N_2. The biogas was collected through a blower and sent to a gas turbine. In this scenario, the biogas was used to generate

electricity. It should be noted that the biogas was required to undergo a biogas upgrading process (i.e., water scrubbing) to purify the biogas to 98% CH_4 before being used as cooking gas [3]. The transport distance between the wet AD plant and FW collection sites was estimated at 45km. Thus, the average distance travelled by the waste trucks was assumed to be 45 km. Once delivered to the plant, the FW was first fed into a screener which would reject any large pieces of plastic and other non-biodegradable materials, such as glass bottles and metal cans. Simultaneous squeezing was then employed to reduce the particle size of the waste. Water addition was conducted. The highest concentration of putrescible material was pumped into the anaerobic digester for an average of 3 weeks of mesophilic (35 °C) fermentation. The digestion residue was passed through a dewatering system, after which the liquid fraction was reused on-site and drained to the nearby wastewater treatment plant. Finally, the digestate underwent an aerobic windrow process to produce the compound that would be used by the conventional composting process to substitute for the inorganic fertilizer. The dewatered digestate, with a water content of 74%, was co-composted with horticultural wastes (tree trunks, branches, and leaves) for an average of 4 weeks of maturation treatment. The electricity produced (334.29 kWh) was used by the treatment plant and about 225kg of the solid digested matter was sold as a dry fertilizer.

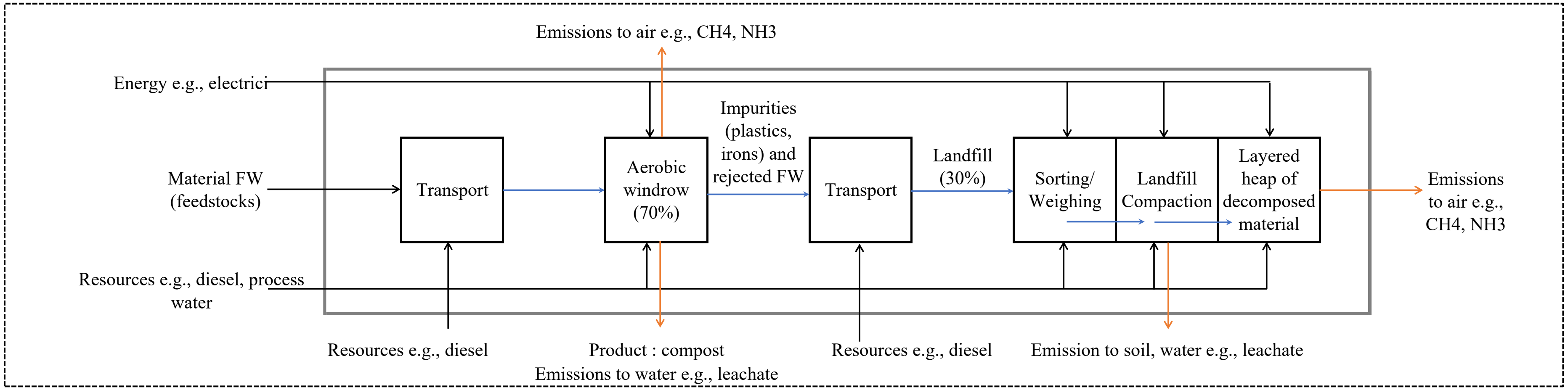
Integrated Wet Digestion combined aerobic windrow composting with A Landfill (Sc_5)

The fifth scenario integrated anaerobic wet digestion with the landfilling scenario. In this scenario, wet AD, aerobic windrow composting, and landfill were independent processes. However, when integrated, they might improve the waste management system's efficiency and achieve environmental advantages. Neither of the treatment options examined could entirely eliminate landfilling, regardless of whether it was in the context of AD or composting. Some percentages of the waste residues of the inorganic substances in the collected waste after sorting were still transported to a landfill for disposal. However, the portion to be landfilled was actually reduced (Righi et al. 2013). The integrated wet AD system in this scenario was the same as in Sc2. However, the remaining approximately 30% of impurities (i.e., plastics, irons) and rejected FW from pre- and post-treatment would be disposed of at a nearby conventional landfill site. The waste disposal in this landfill case had no gas filtering mechanism.

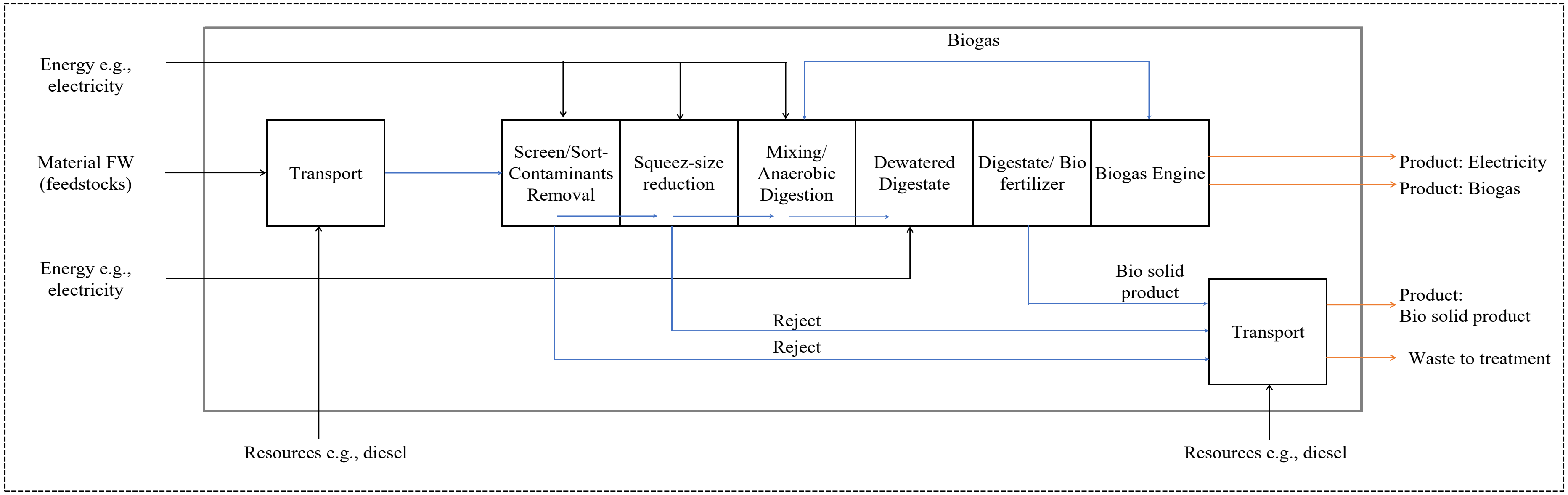
Table S2: System boundary of LCA for all scenarios, a) landfill; b) aerobic windrow; c) aerobic windrow combined landfill; d) dry AD; e) wet AD combined aerobic windrow; f) wet AD combined aerobic windrow and landfill



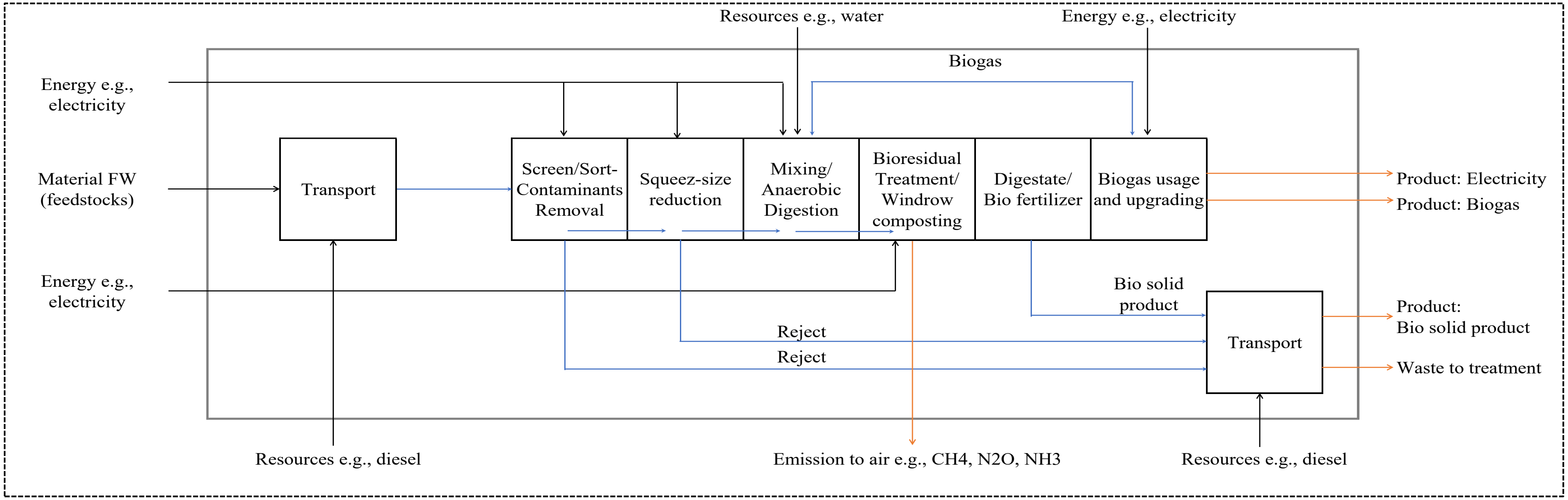
b) Sc_1


Emissions to air e.g., CH4, NH3
Energy e.g., electrici
Material FW (feedstocks)
Resources e.g., diesel, process water
Transport
Aerobic windrow (70%)
Impurities (plastics, irons) and rejected FW
Transport
Landfill (30%)
Sorting/ Weighing
Landfill Compaction
Layered heap of decomposed material
Emissions to air e.g., CH4, NH3
Resources e.g., diesel
Product : compost
Emissions to water e.g., leachate
Resources e.g., diesel
Emission to soil, water e.g., leachate

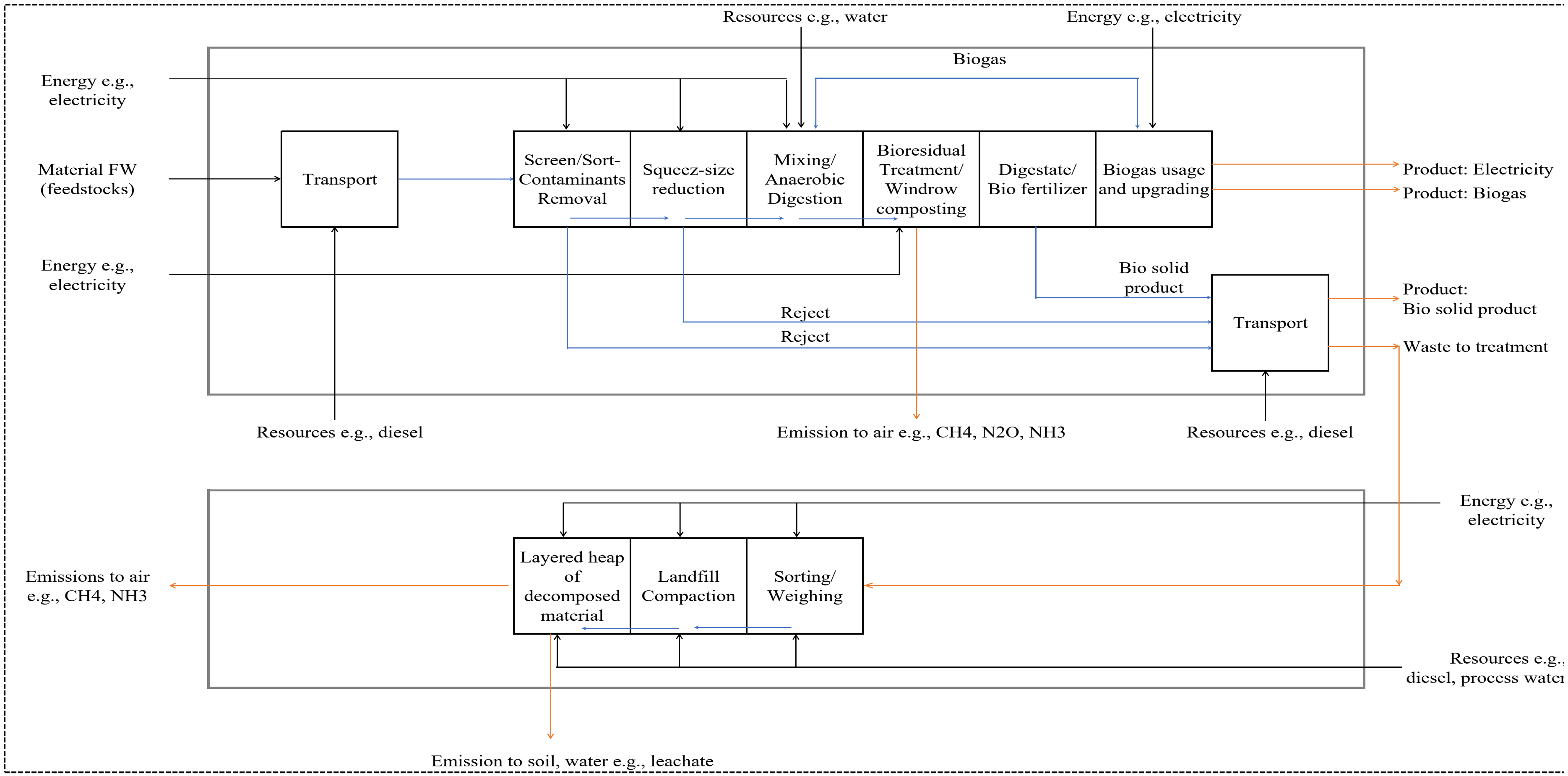
c) Sc_2


Biogas
Energy e.g., electricity
Material FW (feedstocks)
Energy e.g., electricity
Transport
Screen/Sort-Contaminants Removal
Squeez-size reduction
Mixing/ Anaerobic Digestion
Dewatered Digestate
Digestate/ Bio fertilizer
Biogas Engine
Product: Electricity
Product: Biogas
Bio solid product
Reject
Reject
Transport
Product: Bio solid product
Waste to treatment
Resources e.g., diesel
Resources e.g., diesel

d) Sc_3


Resources e.g., water
Energy e.g., electricity
Biogas
Energy e.g., electricity
Material FW (feedstocks)
Transport
Screen/Sort-Contaminants Removal
Squeez-size reduction
Mixing/ Anaerobic Digestion
Bioresidual Treatment/ Windrow composting
Digestate/ Bio fertilizer
Biogas usage and upgrading
Product: Electricity
Product: Biogas
Energy e.g., electricity
Bio solid product
Transport
Product: Bio solid product
Reject
Reject
Waste to treatment
Resources e.g., diesel
Emission to air e.g., CH4, N2O, NH3
Resources e.g., diesel

e) Sc_4


Resources e.g., water
Energy e.g., electricity
Biogas
Energy e.g.,
electricity
Material FW
(feedstocks)
Transport
Screen/Sort-
Contaminants
Removal
Squeez-size
reduction
Mixing/
Anaerobic
Digestion
Bioresidual
Treatment/
Windrow
composting
Digestate/
Bio fertilizer
Biogas usage
and upgrading
Product: Electricity
Product: Biogas
Energy e.g.,
electricity
Bio solid
product
Transport
Product:
Bio solid product
Reject
Reject
Waste to treatment
Resources e.g., diesel
Emission to air e.g., CH4, N2O, NH3
Resources e.g., diesel
Energy e.g.,
electricity
Layered heap
of
decomposed
material
Landfill
Compaction
Sorting/
Weighing
Emissions to air
e.g., CH4, NH3
Resources e.g.
diesel, process wate
Emission to soil, water e.g., leachate

f) Sc_5

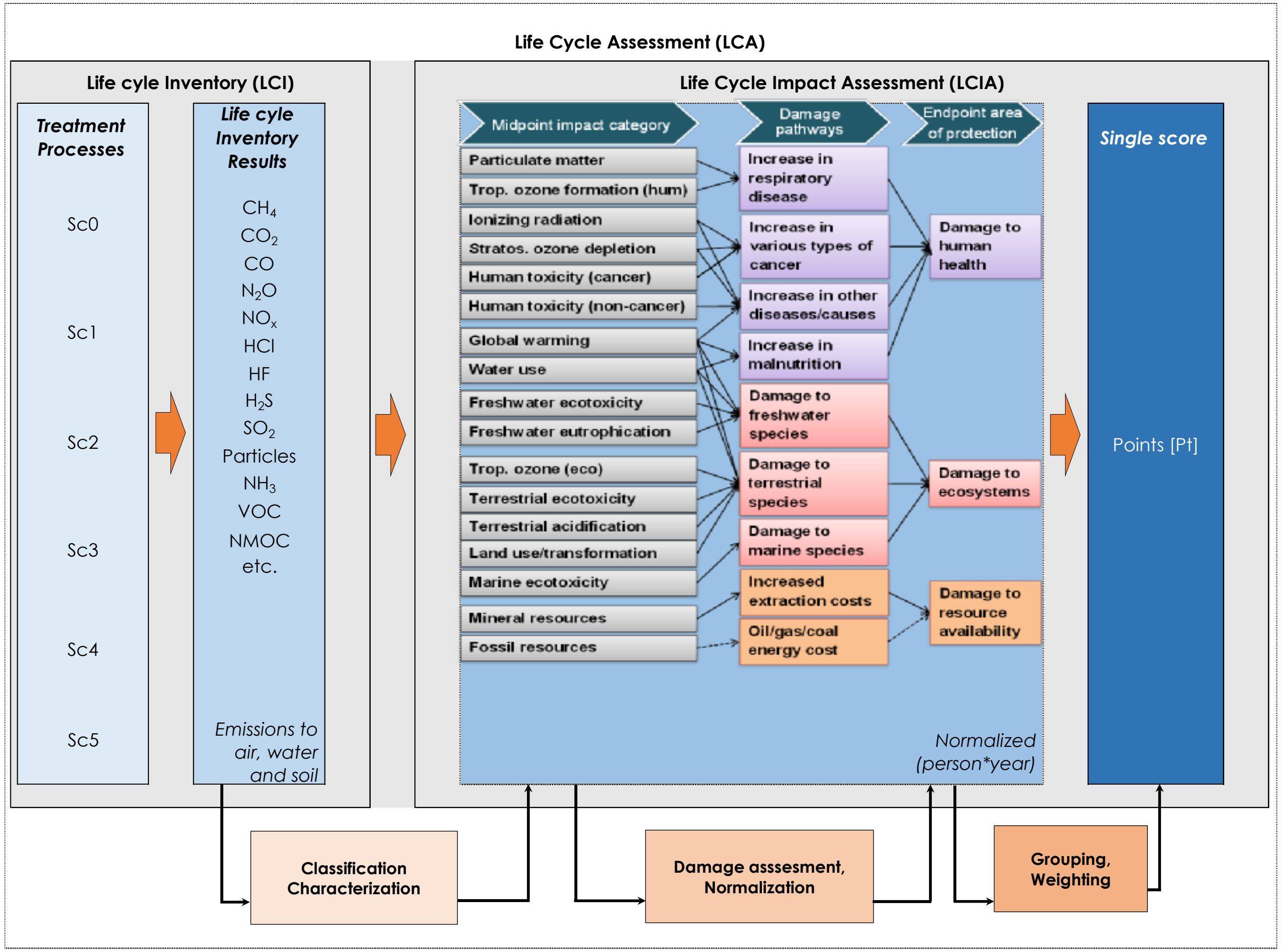


Figure S1(a): The study employed an LCA methodological framework (adapted from Poeschl et al. [4]. Table 1 provided a comprehensive LCI of the scenarios that were examined in the research, while results and discussion presented the outcomes for characterized impact categories and weighted single-score LCA results.

Table S3: Input and output inventories for landfill, aerobic windrow composting, dry AD, and wet AD

Technologies	Waste Treatment	Flow	Amount	Unit	Ref.
Landfill	**Input**				
	Material (feedstock)	FW	1	T	[a] [5],
	Transportation	Distance	45	km	[b] [6],
		Truck payload	5	t	[c] [7],
	Energy consumption	Electricity	667.4[a, b]	kWh	[d] [8],
	Water consumption	Tap water	52[c]	Kg	[e] [9],
	Resources	Diesel	11.4[d, b]	L	[f] [10]
	Output				
	Emission to air	CH_4	37849[e]	g	
		CO_2	21.24[a, b]	kg	
		CO	0.0236 [b]	kg	
		N_2O	0.002[a]	kg	
		NO_x	0.25[a, b]	kg	
		HCl	0.006[a]	kg	
		HF	0.001[a]	kg	
		H_2S	0.018[a]	kg	
		SO_2	0.0381[a, b]	kg	
		Particles	0.0074[b]	kg	
	Emission to water	Total N	1003[a]	g	
		Hg	1.4[f]	mg	
		Cd	0.06[f]	mg	
		Fe	35.1[f]	mg	
		Mg	1.6[f]	mg	
		Zn	1.33[f]	mg	
Dry AD	**Input**				
	Material (feedstock)	FW	1	t	
	Transportation	Distance	>1[g]	km	[g] (Dry AD plant, PJ),
		Truck payload	1	t	[h] [11],
	Energy consumption	Electricity	98.16[g]	kWh	[i] [12]
	Resources	Diesel	0.007	l	[j] [13],
	Output				[k] [14], [l] [15]
	Emission to air	CH_4	500[h(estimate)]	g	
		O_2	0.1[h(estimate)]	kg	
		H_2	0.2[h(estimate)]	kg	
		NO_3	0.2[h(estimate)]	kg	
	Energy Recovery	Electricity	87.84(estimate)	kWh	
	Valuable materials	Compost	950[g]	kg	
Wet AD	**Input**				
	Material (feedstock)	FW	1	t	
	Transportation	Distance	45	km	
		Truck payload	5	t	
	Energy consumption	Electricity	120(estimate)	kWh	
	Water consumption	Tap water	346[i, j]	kg	
	Resources	Diesel	30 (estimate)	l	
		Lubricant	0.25[j]	l	
	Output				
	Emission to air	CH_4	590[k]	g	[l] [15]
		CO_2	0.5792[k]	kg	

Technologies	Waste Treatment	Flow	Amount	Unit	Ref.
		N_2O	0.00215[k]	kg	
		HF	0.00017[k]	kg	
		H_2S	3.095[l]	kg	
		Particles	0.0002[k]	kg	
		Biogenic CO_2	85.445[l]	kg	
		N_2	5.098[l]	kg	
		O_2	1.942[l]	kg	
		H_2	0.061[l]	kg	
	Other Waste	Plastic	0.13[m]	t	[e] [9]
		Iron	1.1[m]	kg	[j] [13],
		Rejected bio waste	0.19[n]	t	[m] [7],
	Energy Recovery	Electricity	334.29[e]	kWh	[n] (Johor Bahru Composting Plant)
	Waste	Unstabilized Digestate	0.85	t	
Windrow composting	**Input**				
	Material (feedstock) unstabilized digestate from wet AD	FW	1	t	
	Transportation	Distance	<1	km	
		Truck payload	1	t	
	Energy consumption	Electricity	110[j]	kWh	
	Water consumption	Tap water	120[m]	Kg	
	Resources	Diesel	9.641[m, j]	l	
		Lubricant	0.5[j]	l	
		Anti-odour	20[j]	l	
	Output				
	Emission to air	CH_4	1455[m, j]	g	
		CO_2	430[j]	kg	
		CO	0.6[j]	kg	
		N_2O	0.1[j]	kg	
		NH_3	10.04[m, j]	kg	
		H_2S	0.02[m]	kg	
		VOC	36.5[j]	kg	
		NMOC	0.01[m]	kg	
	Emission to water	Total N	3452[j]	g	[j] [13],
		BOD_5	1964[j]	g	[m] [7]
		COD	6392[j]	g	
		Phenol	0.6[j]	g	
		Free chlorine	0.1[j]	g	
		Sulphide	3.9[j]	g	
		NH_3	2934[j]	g	
		PO_4	19.4[j]	g	
		Leachate	0.28[j]	t	
	Valuable materials	Compost	0.8[n]	t	[n] (Johor Bahru Composting Plant)

[a] [5], [b] [6], [c] [7], [d] [8], [e] [9], [f] [10], [g] (Dry AD plant, PJ), [h] [11], [i] [12] [j] [13], [k] [14], [l] [15], [m] [7], [n] (Johor Bahru Composting Plant)

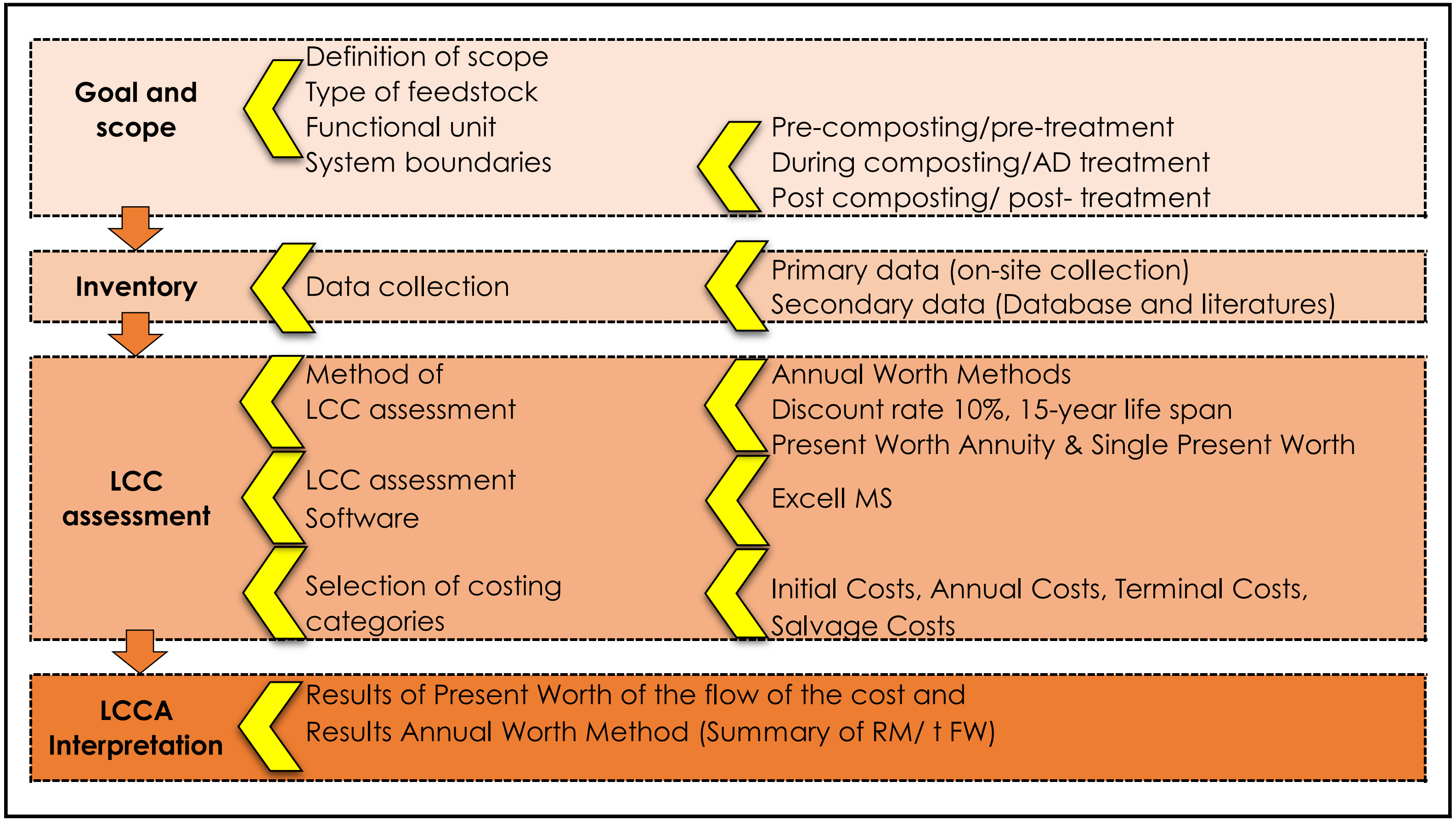


Figure S1(b): LCC methodology through annual worth method

Table S4: Results LCA midpoints using ReCiPe v1.07

ReCiPe 1.07 Midpoint (H)	**Abbreviation**	**Landfill Sc0**	**Windrow Sc1**	**Windrow + Landfill Sc2**	**Dry AD Sc3**	**Wet AD + Windrow Sc4**	**Wet AD + Windrow + Landfill Sc5**	***Ecologically advantageous choice**
Agricultural land occupation [m^2a]	ALOP	2.49E+00	2.00E+00	4.49E+00	2.40E-03	1.96E+00	4.45E+00	Sc3
Climate change [kg CO_2 eq]	GWP	5.34E+02	9.16E+02	1.45E+03	4.94E+01	1.40E+04	1.45E+04	Sc3
Fossil depletion [kg oil eq]	FDP	1.72E+02	3.82E+01	2.11E+02	3.66E+00	2.63E+01	2.01E+02	Sc3
Freshwater ecotoxicity [kg 1,4-DB eq]	FETP	1.05E-02	2.61E-03	1.31E-02	1.52E-04	2.13E-03	1.27E-02	Sc3
Freshwater eutrophication [kg P eq]	FWEP	4.99E-05	6.44E-03	6.49E-03	1.56E-07	6.47E-03	6.52E-03	Sc3
Human toxicity [kg 1,4-DB eq]	HTP	3.02E+01	5.51E+00	3.58E+01	4.58E-01	-3.18E+00	2.71E+01	Sc4
Ionising radiation [kg U235 eq]	IRP	1.03E+03	7.87E+02	1.82E+03	5.50E+00	1.06E+03	2.11E+03	Sc3
Marine ecotoxicity [kg 1,4-DB eq]	METP	1.09E-01	2.06E-02	1.30E-01	1.65E-03	-4.61E-03	1.05E-01	Sc4
Marine eutrophication [kg N eq]	MEP	6.57E-02	9.37E-01	1.00E+00	2.52E-02	9.43E-01	1.01E+00	Sc3
Metal depletion [kg Fe eq]	MDP	1.11E+00	5.45E-01	1.66E+00	1.15E-02	6.30E-01	1.75E+00	Sc3
Ozone depletion [kg CFC-11 eq]	ODP	3.32E-09	1.07E-09	4.39E-09	4.15E-11	6.80E-10	4.02E-09	Sc3
Particulate matter formation [kg PM10 eq]	PMFP	1.20E+00	3.42E+00	4.62E+00	8.27E-02	3.14E+00	4.35E+00	Sc3
Photochemical oxidant formation [kg NMVOC eq]	POFP	1.83E+00	4.94E-01	2.33E+00	3.37E-02	5.97E+00	7.81E+00	Sc3
Terrestrial acidification [kg SO_2 eq]	TAP	2.86E+00	2.51E+01	2.80E+01	5.34E-01	2.48E+01	2.77E+01	Sc3
Terrestrial ecotoxicity [kg 1,4-DB eq]	TETP	1.75E-02	3.34E-03	2.08E-02	2.61E-04	-1.69E-03	1.58E-02	Sc4
Water depletion [m^3]	WDP	1.18E+03	1.97E+02	1.38E+03	1.83E+01	-1.73E+02	1.01E+03	Sc4
Inventory Analysis (Mass [kg], Energy [MJ])								
Blue water consumption [kg]	BWC	1.35E+03	350.90	1697.90	1.97E+01	3.10E+02	1.66E+03	Sc3
Primary energy demand from ren. and non ren. resources (net cal. value) [MJ]	PED	7.46E+03	1656.09	9141.24	1.57E+02	1.10E+03	8.64E+03	Sc3

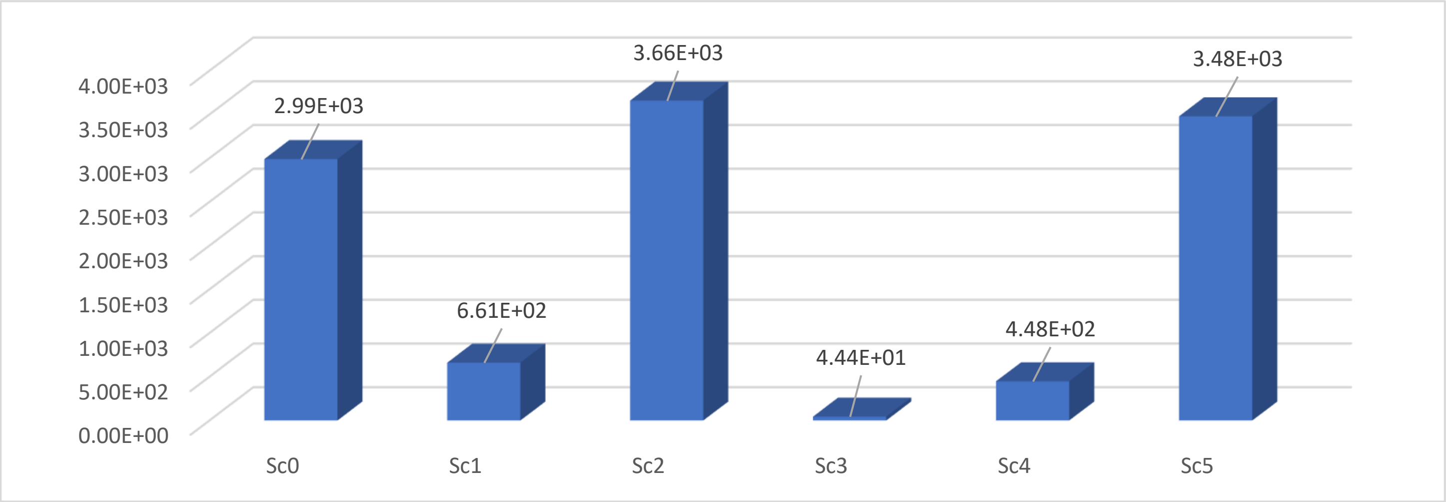


Figure S2. Total damage point (Pt) or single scores of assessed scenarios

Impacts	**Acronym**	**Scenarios**					
		Sc0	**Sc1**	**Sc2**	**Sc3**	**Sc4**	**Sc5**
Damage Resource Availability	DRA	2.99E+03	6.61E+02	3.66E+03	4.44E+01	4.48E+02	3.48E+03
Damage Human Health	DHH	1.08E-03	2.18E-03	3.26E-03	9.28E-05	2.26E-02	2.37E-02
Damage Ecosystems Diversity	DED	4.26E-06	7.41E-06	1.17E-05	3.94E-07	1.10E-04	1.15E-04
Calculations Total damage point (Pt) of all scenarios		**DRA + DHH + DED**	**DRA + DHH + DED**	**DRA + DHH + DED**	**DRA + DHH + DED**	**DRA + DHH + DED**	**DRA + DHH + DED**
Total damage point (Pt) of all scenarios		**2.99E+03**	**6.61E+02**	**3.66E+03**	**4.44E+01**	**4.48E+02**	**3.48E+03**

Table S5: Result Comparison of impact scores per treating 1 ton waste from this and other similar LCA studies

Impact Category	Unit	Sc3: Dry AD This study	Integrated Dry AD [11]	Sc4: WetAD+comp. This study	WetAD+comp. [16]	Sc0: Baseline Landfill This study	Landfill [17]
LCIA		ReCiPe	ILCD	ReCiPe	CML 2001	ReCiPe	Eco-Indicator 99
GWP	kg CO_2-eq	4.94E+01	4.00E+02	1.40E+04	9.41E+04	5.34E+02	3.80E−01
TAP	kg SO_2-eq	5.34E-01	-	2.48E+01	-1.69E+02	2.86E+00	-
FEP	kg P eq	1.56E-07	-	6.47E-03	-	4.99E-05	-
FETP	kg 1,4-DB eq	1.52E-04	-	2.13E-03	-1.13E+04	1.05E-02	-
HTP	kg 1,4-DB eq	4.58E-01	-	-3.18E+00	-2.55E+04	3.02E+01	-
ODP	kg CFC-11eq	4.15E-11	7.00E-05	6.80E-10	-	3.32E-09	-
POFP	kg NMVOC	3.37E-02	4.00E-01	5.97E+00	-	1.83E+00	-
TETP	kg 1,4-DB eq	2.61E-04	-	-1.69E-03	-3.36E+02	1.75E-02	-

Cont.

Continued.

Impact Category	Unit	Sc1: Aerobic Windrow composting	Aerobic Windrow composting	Sc2: Integrated aerobic windrow with landfill	Scenario 2 Integrated aerobic windrow with landfill
LCIA		This study	[18]	This study	[17]
		ReCiPe	CML	ReCiPe	Eco-Indicator 99
GWP	kg CO_2-eq	9.16E+02	67.1	1.45E+03	1.95E−01
TAP	kg SO_2-eq	5.51E+00	0.82	2.80E+01	-
FEP	kg P eq	6.44E-03	-	6.49E-03	-
FETP	kg 1,4-DB eq	2.61E-0	-	1.31E-02	-
HTP	kg 1,4-DB eq	5.51E+00	38	3.58E+01	-
ODP	kg CFC-11eq	1.07E-09	-	4.39E-09	-
POFP	kg NMVOC	4.94E-01	-	2.33E+00	-
TETP	kg 1,4-DB eq	3.34E-03	-	2.08E-02	-
FDP	kg oil eq	3.82E+01	33.5	2.11E+02	-

Table S6: Eight impact groups sensitivity analysis for changes in dry AD

Percentage of Variation (%)	Input Parameters	GWP kg CO_2-eq	ODP kg CFC-11	POFP kg NMVOC	TAP kg SO2-eq	FEP kg P eq	PMFP kg PM10 eq	HTP kg 1,4-DB eq	TETP kg 1,4-DB eq
10%	Diesel	0.00%	0.02%	0.01%	0.00%	0.32%	0.00%	0.00%	0.00%
	Electricity	15.80%	92.80%	79%	7.76%	61%	21.20%	94.70%	94.80%
	Water	0%	0%	0%	0%	0%	0%	0%	0%
	Distance	0.05%	0.23%	0.19%	0.01%	3.26%	0.03%	0.04%	0.03%
Reference	LCIA midpoint	49.4	4.15E-11	0.0337	0.534	1.56E-07	0.0827	0.458	0.000261
-10%	Diesel	0.00%	-0.02%	-0.01%	0.00%	-0.32%	0.00%	0.00%	0.00%
	Electricity	-15.80%	-92.80%	-79%	-7.76%	-61%	-21.20%	-94.70%	-94.80%
	Water	0%	0%	0%	0%	0%	0%	0%	0%
	Distance	-0.05%	-0.23%	-0.19%	-0.01%	-3.26%	-0.03%	-0.04%	-0.03%

Table S7: Life Cycle Costing Inventory

Sc0-Landfill

Item	Thicknes	Cost per unit	Unit	Cost (US$)	Remark
Construction costs					
Land cost		5	$/m^2	250,000	
Construction of buildings				250,000	
Survey of LF		16,000	$/ha	80,000	–a
Excavation		5	$/m^3	2,000,000	
Intermediate covers	0.3	58,500	$/ha	292,500	–b
Clay layer	0.5	164,060	$/ha	820,300	–b
HDP sheet	0.0015	36,010	$/ha	180,050	–b
Geotextile	0.0015	25,480	$/ha	127,400	–b
Gravel layer	0.5	166,600	$/ha	833,000	–b
Gas and leachate collection system				400,000	
Construction of roads		150	$/m	525,000	
Operational costs					
Leachate treatment		0.061	$/liter	4,069,920	–a
Energy production from methane		0.05	$/kw h	-2,632,681	–a
Other utilities				550,000	
				1,987,239	
Closure costs					
Final grades survey		12,400	$/ha	62,000	–a
Compacted clay cap		98,800	$/ha	494,000	–a
Cover and vegetative soil		49,400	$/ha	247,000	–a
Geomembrane cap		49,400	$/ha	247,000	–a
Gas and leachate collection maintenance		5%	capital cost/year	281,878.90	–a
Costs				9,077,367.70	
Engineering cost		1%	costs	90,773.68	–a
Total costs		15.28	$/ton	**9,168,141.38**	

[a] Berge et al. (2009)

[b] Baldasano et al. (2003)

Remark: Data abstracted from Abdulli et al. [17]**; Berge et al.** [19]**; and Baldasano et al.** [20]**.**

As noted on supplementary data Sc0, the LCC data for Sc0 in Appendix is outdated, dating back to 2009 and 2003, and it is not specific to Malaysia. However, the system used corresponds to that of Seelong Landfill in Johor Bahru, Johor Malaysia.

Based on a review of literature, researchers have encountered obstacles in collecting real-time costing data, such as when approval is not granted by the facilities involved (SWM Environment SDN BHD). In such cases, past studies have advocated for utilizing similar systems and relying on literature data for cost calculations [17], [21].

To address the outdated data issue, the values from 2009 and 2003 were converted to their present worth using the following formula: Present Value = (1+0.045) ^12 [22]. Then

Estimation price at year 2022 = Price as at January 2011 (USD) x Present value.
The calculations have been done as shown by the Table 4.4 LCC analysis of Sc0 scenario by total present worth of the cost flow with costing breakdown.

The reasons for not taking data from Seelong Landfill have been justified.

The justifications are as follows:

i. **Data Availability:** Current data from Seelong Landfill may not have been readily accessible or available due to restrictions or limited cooperation from the landfill authorities.
ii. **Data Relevance:** The specific parameters or aspects of data required for the study might not have been comprehensively documented or accessible from Seelong Landfill records.
iii. **Data Consistency:** The consistency and reliability of historical data from Seelong Landfill might be questionable, especially if significant changes or upgrades have occurred in their systems or operations since the data was collected.
iv. **Comparative Analysis:** Utilizing data from different sources allows for a broader comparison and validation of results, ensuring a more comprehensive understanding of the topic beyond a single data point.

Sc1-Aerobic Windrow

Costing breakdowns, saving, and revenue gained from scenario Sc1_Aerobic Windrow

Item	**Sc1_Aerobic Windrow**	**Remark**
i) Cost breakdown and compost revenue (MYR/Mth)		
A) Capital Cost		
Site construction	450, 000	Accommodation for workers, workshop and seedling area; farming area; composting site with leachate collection
Infrastructure	98,700	Site with water and electricity supply
Tractor	70,000	2t truck
Screener	20,000	
Shredder	2,500	
Bobcat	40,000	Model: S175 from Teck Soon Sdn. Bhd.
Waste collection bin	16,000	MYR 160 x 100 units
Chimney system	1,000	
Tilling Machine	1,800	Model: VMT500
Total A	**700,000**	
B) Operational cost		
Labour cost		
Composting process monitoring	2,000	1 worker x MYR 2000/mth
Farming	8,000	4 worker x MYR 2000/mth
Total B(i)	**10,000**	
Fuel cost		
Transportation (diesel, L/mth)	900	
On-site machinery (diesel, L/mth)	200	
Total B(ii)	**1,100**	Diesel cost = MYR 2.10/L
Laboratory quality control cost		
Laboratory analysis	1,050	Quality check: C/N, N, P, K - MYR 100/sample Heavy metals - MYR 500/sample Pathogens - MYR 100/sample three tests per year, 6 samples each test
Total B(iii)	**1,050**	
Total B(iv)	**2,000**	Utility cost (electricity and water bill and maintenance fee)
Total B (MYR/mth)	**14,150**	
C) Cost saving from compost utilization		
Chemical fertilizer	-506.8	MYR 120/50kg fertilizer Fertilizer application rate in Malaysia = 1,689.40 kg/hectare land in 2015 (The World bank 2018)
Pesticide & herbicde	-300	MYR 100/100 cc pesticide & herbicide
Total C (MYR/mth)	**-806.8**	

Sc3-Anaerobic Dry Digestion

Initial Cost		
Machine at cost (acquisition cost)	RM	700,000.00
Annual Cost		
Operational Cost	RM	52,500.00
Maintenance Cost	RM	3,600.00
Microb Treatment Cost	RM	1,100.00
General & Administration Cost	RM	17,500.00
Terminal Cost		
Major replacement cost - Component 1 (5th year)	RM	105,000.00
Major replacement cost - Component 1(10th year)	RM	140,000.00
Salvage Cost		
Biofertilizer	-RM	2,000.00
Scrap Value	-RM	21,000.00

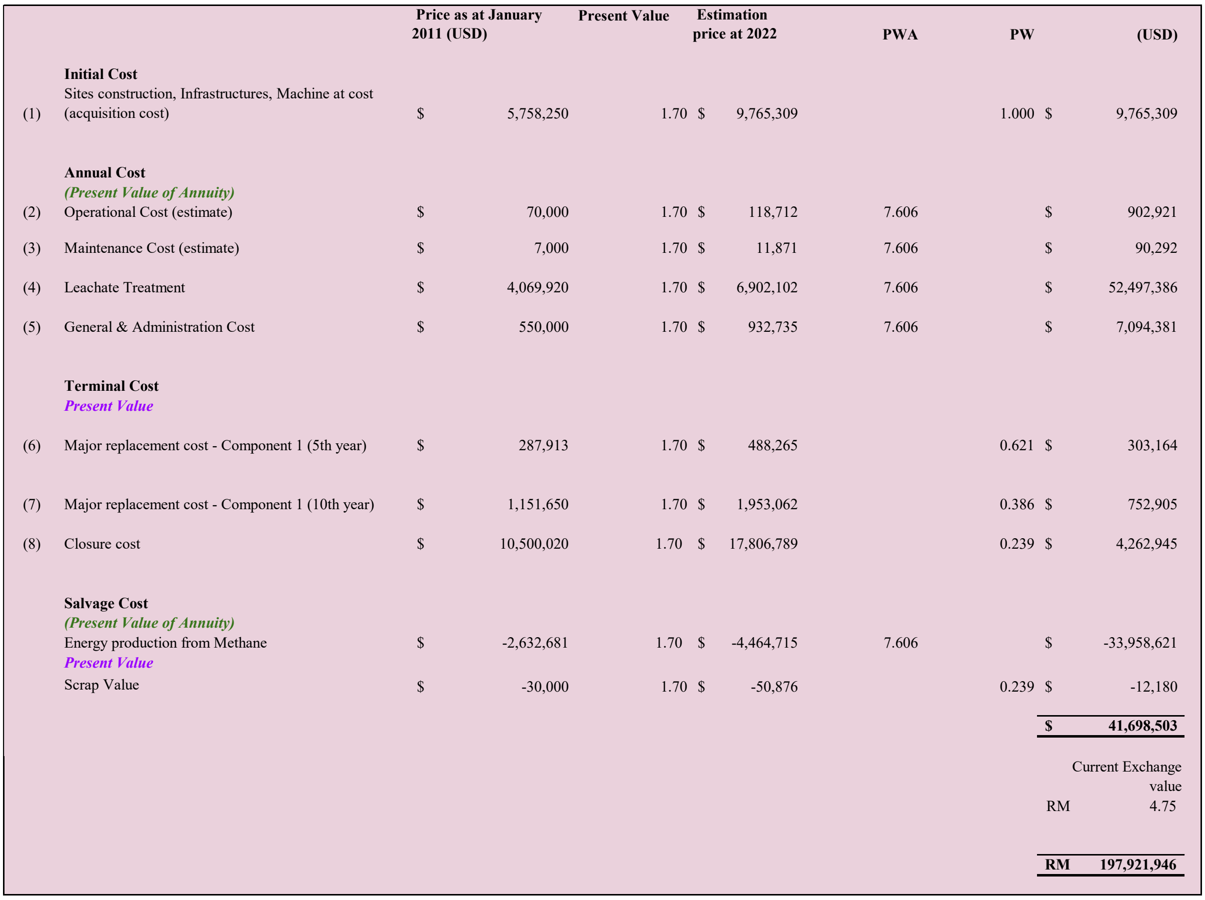
Sc4-Anaerobic Wet digestion

Parameter	**Capacity (TPD of OFMSW)**	
Waste generation	0.2 (0.8 kg/person of waste for 50 household)	
Average distance from transfer station to hub (km)	7	
Capital Cost (MYR)	**19,323**	Capital cost was normalised for 20 y
Operation and Maintenance Costs (MYR)	**1,000**	For transportation vehicles, site, miscellaneous.
Electricity production from biogas (kWh/m^3)	2.1	
Heat production from biogas (kWh/m^3)	2.5	
Biogas production (m^3 /t MSW)	203.6	
Fertiliser production (t/y)	1.07	
Total Cost (MYR)	20,323	

***1ton/day (considered)**	**(MYR)**
Capital cost	**96,615**
Operation and maintenance	**5,000**
Total	**101,615**

Table S8: Result Comparison of LCC per treating 1 ton waste by scenarios considered

LLC of Sc0 Landfill



		Price as at January 2011 (USD)	Present Value	Estimation price at 2022	PWA	PW	(USD)
	Initial Cost						
(1)	Sites construction, Infrastructures, Machine at cost (acquisition cost)	$ 5,758,250	1.70	$ 9,765,309		1.000	$ 9,765,309
	Annual Cost ***(Present Value of Annuity)***						
(2)	Operational Cost (estimate)	$ 70,000	1.70	$ 118,712	7.606		$ 902,921
(3)	Maintenance Cost (estimate)	$ 7,000	1.70	$ 11,871	7.606		$ 90,292
(4)	Leachate Treatment	$ 4,069,920	1.70	$ 6,902,102	7.606		$ 52,497,386
(5)	General & Administration Cost	$ 550,000	1.70	$ 932,735	7.606		$ 7,094,381
	Terminal Cost ***Present Value***						
(6)	Major replacement cost - Component 1 (5th year)	$ 287,913	1.70	$ 488,265		0.621	$ 303,164
(7)	Major replacement cost - Component 1 (10th year)	$ 1,151,650	1.70	$ 1,953,062		0.386	$ 752,905
(8)	Closure cost	$ 10,500,020	1.70	$ 17,806,789		0.239	$ 4,262,945
	Salvage Cost ***(Present Value of Annuity)***						
	Energy production from Methane	$ -2,632,681	1.70	$ -4,464,715	7.606		$ -33,958,621
	Present Value						
	Scrap Value	$ -30,000	1.70	$ -50,876		0.239	$ -12,180
							$ 41,698,503
							Current Exchange value
							RM 4.75
							RM 197,921,946

LLC of Sc1 Aerobic Windrow

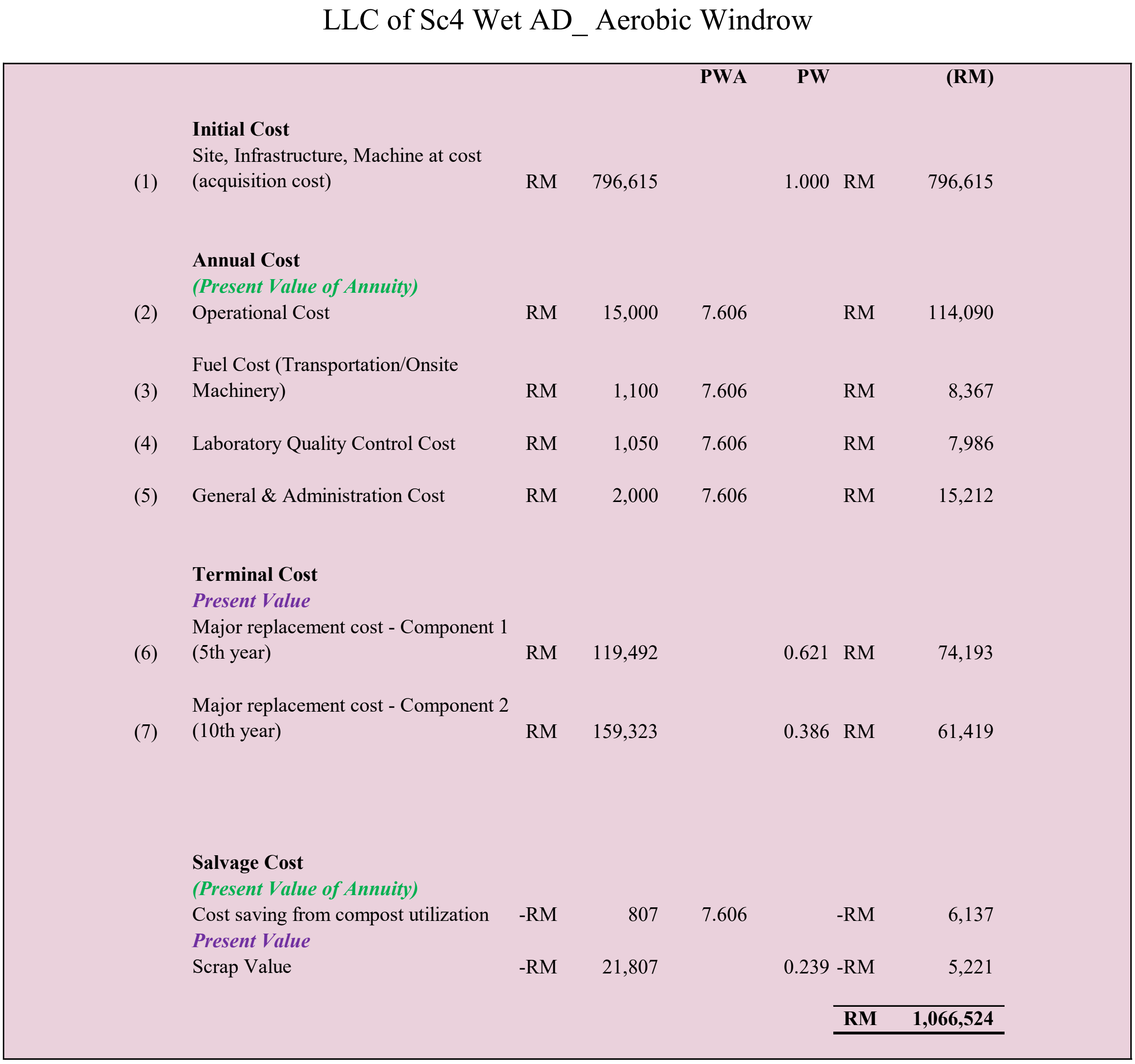
				PWA	**PW**		**(RM)**
	Initial Cost						
(1)	Site, Infrastructure, Machine at cost (acquisition cost)	RM	700,000		1.000	RM	700,000
	Annual Cost						
	(Present Value of Annuity)						
(2)	Operational Cost	RM	10,000	7.606		RM	76,060
(3)	Fuel Cost (Transportation/Onsite Machinery)	RM	1,100	7.606		RM	8,367
(4)	Laboratory Quality Control Cost	RM	1,050	7.606		RM	7,986
(5)	General & Administration Cost	RM	2,000	7.606		RM	15,212
	Terminal Cost						
	Present Value						
(6)	Major replacement cost - Component 1 (5th year)	RM	105,000		0.621	RM	65,195
(7)	Major replacement cost - Component 2 (10th year)	RM	140,000		0.386	RM	53,970
	Salvage Cost						
	(Present Value of Annuity)						
	Cost saving from compost utilization	-RM	807	7.606		-RM	6,137
	Present Value						
	Scrap Value	-RM	21,807		0.239	-RM	5,221
						RM	**915,432**

LLC of Sc2 Aerobic Windrow_Landfill

		Price as at January 2011 (USD)	Present Value	Estimation price at 2022	PWA	PW	(USD)
	Initial Cost						
(1)	Sites construction, Infrastructures, Machine at cost (acquisition cost)	$ 6,459,250	1.70	$ 10,954,122		1.000	$ 10,954,122
	Annual Cost						
	(Present Value of Annuity)						
(2)	Operational Cost (estimate)	$ 80,000	1.70	$ 135,671	7.606		$ 1,031,910
(3)	Maintenance Cost (estimate)	$ 7,000	1.70	$ 11,871	7.606		$ 90,292
(4)	Leachate Treatment	$ 4,069,920	1.70	$ 6,902,102	7.606		$ 52,497,386
(5)	General & Administration Cost	$ 552,000	1.70	$ 936,127	7.606		$ 7,120,179
(6)	Fuel cost (Onsite transport and machinery)	$ 1,100	1.70	$ 1,865	7.606		$ 14,189
(7)	Laboratory quality control	$ 1,050	1.70	$ 1,781	7.606		$ 13,544
	Terminal Cost						
	Present Value						
(8)	Major replacement cost - Component 1 (5th year)	$ 392,913	1.70	$ 666,333		0.621	$ 413,726
(9)	Major replacement cost - Component 1 (10th year)	$ 1,291,650	1.70	$ 2,190,485		0.386	$ 844,432
(10)	Closure cost	$ 10,500,020	1.70	$ 17,806,789		0.239	$ 4,262,945
	Salvage Cost						
	(Present Value of Annuity)						
	Energy production from Methane	$ -2,632,681	1.70	$ -4,464,715	7.606		$ -33,958,621
	Cost saving from compost utilization	$ -807	1.70	$ -1,368	7.606		$ -10,407
	Present Value						
	Scrap Value	$ -51,807	1.70	$ -87,858		0.239	$ -21,033
							$ 43,252,664
							Current Exchange value
							RM 4.75
							RM 205,298,769

LLC of Sc3 Dry AD

				PWA	**PW**		**(RM)**
	Initial Cost						
(1)	Machine at cost (acquisition cost)	RM	700,000		1.000	RM	700,000
	Annual Cost						
	(Present Value of Annuity)						
(2)	Operational Cost	RM	52,500	7.606		RM	399,315
(3)	Maintenance Cost	RM	3,600	7.606		RM	27,382
(4)	Microb Treatment Cost	RM	1,100	7.606		RM	8,367
(5)	General & Administration Cost	RM	17,500	7.606		RM	133,105
	Terminal Cost						
	Present Value						
(6)	Major replacement cost - Component 1 (5th year)	RM	105,000		0.621	RM	65,195
(7)	Major replacement cost - Component 1(10th year)	RM	140,000		0.386	RM	53,970
	Salvage Cost						
	(Present Value of Annuity)						
	Biofertilizer	-RM	2,000	7.606		-RM	15,212
	Present Value						
	Scrap Value	-RM	21,000		0.239	-RM	5,027
						RM	**1,367,093**



LLC of Sc4 Wet AD_ Aerobic Windrow

				PWA	PW		(RM)
	Initial Cost						
(1)	Site, Infrastructure, Machine at cost (acquisition cost)	RM	796,615		1.000	RM	796,615
	Annual Cost						
	(Present Value of Annuity)						
(2)	Operational Cost	RM	15,000	7.606		RM	114,090
(3)	Fuel Cost (Transportation/Onsite Machinery)	RM	1,100	7.606		RM	8,367
(4)	Laboratory Quality Control Cost	RM	1,050	7.606		RM	7,986
(5)	General & Administration Cost	RM	2,000	7.606		RM	15,212
	Terminal Cost						
	Present Value						
(6)	Major replacement cost - Component 1 (5th year)	RM	119,492		0.621	RM	74,193
(7)	Major replacement cost - Component 2 (10th year)	RM	159,323		0.386	RM	61,419
	Salvage Cost						
	(Present Value of Annuity)						
	Cost saving from compost utilization	-RM	807	7.606		-RM	6,137
	Present Value						
	Scrap Value	-RM	21,807		0.239	-RM	5,221
						RM	**1,066,524**

LLC of Sc5 Wet AD_ Aerobic Windrow_Landfill

		Price as at January 2011 (USD)	**Present Value**	**Estimation price at 2022**	**PWA**	**PW**	**(USD)**
	Initial Cost						
(1)	Sites construction, Infrastructures, Machine at cost (acquisition cost)	$ 6,555,865	1.70	$ 11,117,970		1.000	$ 11,117,970
	Annual Cost						
	(Present Value of Annuity)						
(2)	Operational Cost (estimate)	$ 80,000	1.70	$ 135,671	7.606		$ 1,031,910
(3)	Maintenance Cost (estimate)	$ 12,000	1.70	$ 20,351	7.606		$ 154,786
(4)	Leachate Treatment	$ 4,069,920	1.70	$ 6,902,102	7.606		$ 52,497,386
(5)	General & Administration Cost	$ 552,000	1.70	$ 936,127	7.606		$ 7,120,179
(6)	Fuel cost (Onsite transport and machinery)	$ 1,100	1.70	$ 1,865	7.606		$ 14,189
(7)	Laboratory quality control	$ 1,050	1.70	$ 1,781	7.606		$ 13,544
	Terminal Cost						
	Present Value						
(8)	Major replacement cost - Component 1 (5th year)	$ 983,379	1.70	$ 1,667,694		0.621	$ 1,035,471
(9)	Major replacement cost - Component 1 (10th year)	$ 1,311,173	1.70	$ 2,223,594		0.386	$ 857,195
(10)	Closure cost	$ 10,500,020	1.70	$ 17,806,789		0.239	$ 4,262,945
	Salvage Cost						
	(Present Value of Annuity)						
	Energy production from Methane	$ -2,632,681	1.70	$ -4,464,715	7.606		$ -33,958,621
	Cost saving from compost utilization	$ -807	1.70	$ -1,368	7.606		$ -10,407
	Present Value						
	Scrap Value & Cost saving from compost utilization	$ -51,807	1.70	$ -87,858		0.239	$ -21,033
							$ 44,115,514
							Current Exchange value RM 4.75
							RM 209,394,289

S9 (i) Result of LCC Present Worth of the cost flow

The results of the life cycle costing analysis using present worth of the cost flow for six different waste management facilities have found that all landfill scenarios, including Sc5, Sc2, and Sc0, had the highest costs ranging from MYR 197,921,946 to MYR 209,394,289 (Table 4.5). These high costs were due to the expenses required for constructing and maintaining a sanitary or integrated landfill facility [21]. Conversely, the composting system was economically beneficial despite generating little revenue. This was because the windrow composting method used for the system was low-cost. The Sc4 wet AD system required larger reactor sizes, resulting in higher initial and operating costs due to the increased volume of the substrate. As there was no demand for district heating in Malaysia, the excess heat from the biogas CHP had not been absorbed, resulting in an inadequate discovery of the benefits of biogas [23]. However, the Sc3 dry AD system had lower initial costs and generated revenue through product sales such as compost. Landfilling with landfill gas (LFG) produced the highest revenue from power but only offset 45.7% of the upfront cost when compared to other options.

S9 (ii) LCC analysis of scenarios by costing breakdown

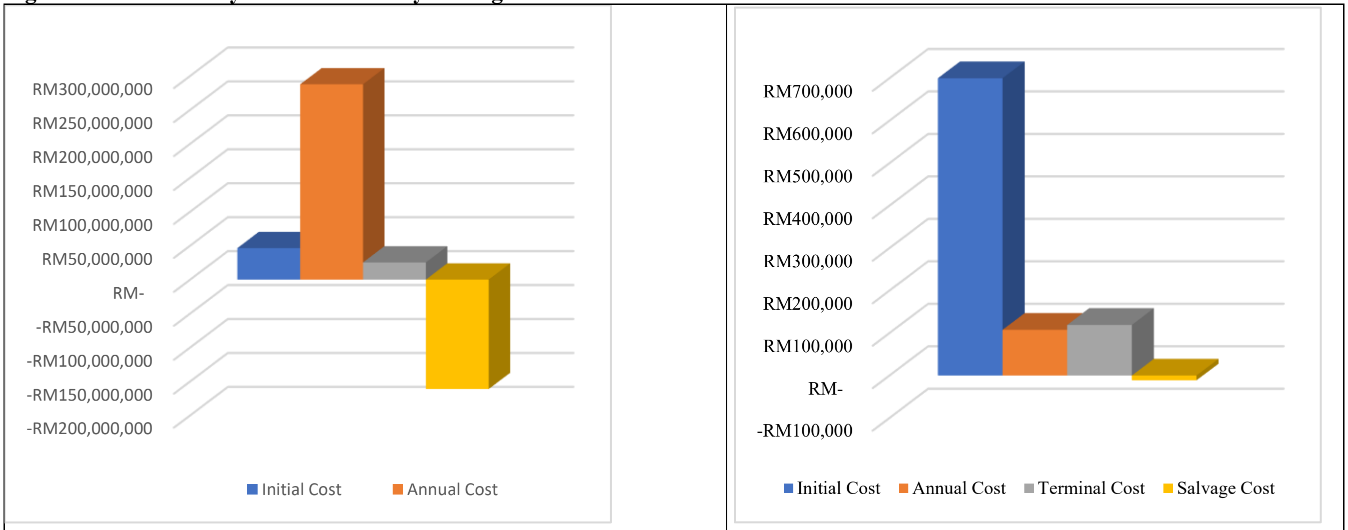
To facilitate discussion, the expenses in this section have been categorized as initial costs, annual costs, terminal cost, and salvage value. Typically, in analyzing the life cycle cost, the project's initial investment, energy, operation and maintenance, and replacement costs are considered significant and vital. Other expenses, such as design or redesign costs, changes, terminal costs like downtime expenses, and functional usage costs, are usually evaluated on a case-by-case basis. In Table 4.2, six breakdown costs resulting from the present worth calculation (see Appendixes B) are presented for the scenarios. The scenarios are compared to one another in terms of life cycle costing analysis, as outlined in Lee et al., [24], and the breakdown costs are displayed in a column chart in Figure S10.

Table S9(ii): LCC analysis of scenarios by costing breakdown

LCC	Acronym	Scenarios					
		Sc0	Sc1	Sc2	Sc3	Sc4	Sc5
Initial Cost	IC	46,351,040	700,000	30,658,830	700,000	796,615	52,771,443
Annual Cost	AC	287,566,608	107,625	288,432,934	568,168	145,655	288,739,057
Terminal Cost	TC	25,246,704	119,165	26,205,918	119,165	135,612	29,217,613
Salvage Cost	SC	-161,242,406	-11,357	-161,333,824	-20,239	-11,357	-161,333,825
Total Present Worth of the cost Flow (MYR)		**197,921,946**	**915,432**	**205,298,769**	**1,367,093**	**1,066,524**	**209,394,289**

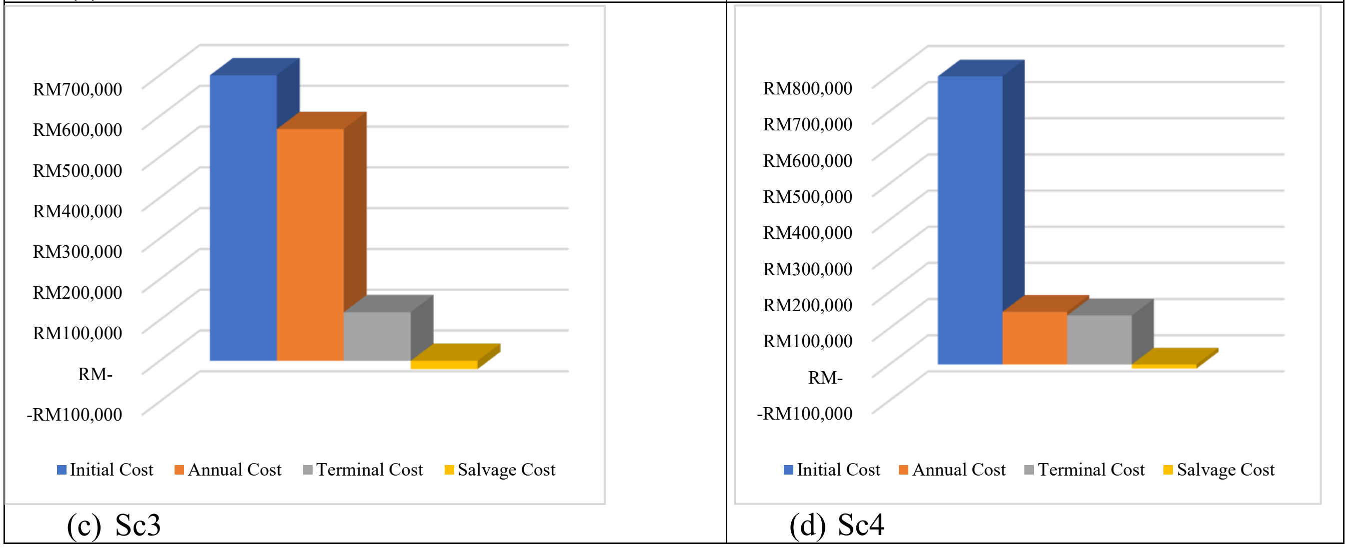
MYR: Malaysia Ringgit

Figure S10: LCC analysis of scenarios by costing breakdown



(a) Sc0; ~Sc2; ~Sc5

(b) Sc1



(c) Sc3

(d) Sc4

(i) Sc0_sanitary landfill (baseline), Sc2, and Sc5 (integrated landfill system) life cycle costing analysis

Abduli et al. [17] stated that the cost of an Sc0 facility encompasses capital investments, operational and maintenance expenses, phase closing expenses, and post-closure expenses. The annual cost was found to be the most significant contributor (~78%) to the life cycle cost for facilities in Sc0, Sc2, and Sc5 scenarios, as shown in Table *i, iii,* and *vi* (refer to the Appendix B). The baseline scenario, Sc0, ranked third in life cycle cost in this comparative study. Additionally, the use of sanitary landfilling in the current design necessitated various landfill equipment. As gas and leachate treatment facilities were present, the initial cost, annual cost, and terminal cost alone produced higher LCC than non-integrated landfill treatment, as demonstrated by the Sc1, Sc3, and Sc4 alternatives.

(ii) Sc1_aerobic windrow composting life cycle costing analysis

Table (ii) in the Appendix B reveals that the life cycle cost for aerobic windrow facilities was the least expensive. The capital costs for windrow composting, which treats the FW fraction of MSW, were obtained from the actual aerobic windrow Folo Farm Ban Foo Ulu Tiram, Johor. The initial costs cover facilities and equipment costs, such as conveyors, trommels, gravity separators, etc. Other initial costs related to material handling costs include the expenses for vehicles, such as tractors, screeners, shredders, bobcats, waste collection bins, chimney systems, tilling machines, etc.

The estimated useful life of the equipment was assumed to be 15 years, including the cost of their installation. The O&M cost was calculated by taking into account (i) labor costs, such as composting process monitoring and farming; (ii) fuel costs, including transportation (diesel, L/month) and on-site machinery (diesel, L/month); and (iii) miscellaneous costs, such as laboratory analysis and other utility expenses (electricity and water bills, and maintenance fees).

The operating and maintenance costs of the composting system were computed, and a discount rate of 10% per year was utilized for the life cycle cost analysis. The cost savings derived from utilizing compost instead of chemical fertilizer and pesticides/herbicides were estimated to be MYR-506.8 and MYR-300, respectively. It was assumed that the price of compost generated was MYR 120/50kg fertilizer, and the fertilizer application rate in Malaysia in 2015 was 1,689.40 kg/hectare land. There are various large-scale facilities (>10 tons) that are effectively operating in different cities around Johor, such as those managed by Folo Ban Foo Ulu Tiram and Sutera Folo Tanah Sutera Development Sdn. Bhd.

(iii) Sc3 -dry anaerobic digestion life cycle costing analysis

The fourth highest LCC for dry AD was found in six comparison scenarios. While there are a few operational plants in various cities in Selangor, Malaysia, this new technology has not yet been effectively utilized on a larger scale. Data from the Petaling Jaya Selangor dry AD plant showed that there were several costs involved, including the initial acquisition cost of the machine, annual costs that included operational, maintenance, microbe treatment, and administrative costs, terminal costs that factored in major replacement costs, and salvage costs that took into account the scrap value. Dry AD systems can earn incentives for the biogas, power, and dewatered sludge they produce, which can be used as biofertilizer. For more detailed information and individual costs, please refer to Table *(d)* in the *Appendixes*, which provides a description of the Sc3_dry AD scenario.

(iv) Sc4_wet AD_ aerobic windrow life cycle costing analysis

This could be one of the most effective solutions to decrease the organic percentage of municipal solid waste (MSW) in Malaysia. Malaysian waste is highly biodegradable and contains a significant amount of moisture [25]. In addition, it can generate revenue through power and compost production. The digested sludge from the system can be dried and used as biofertilizer, with an expected generation rate of 1.07 tons of organic waste per year [26]. A detailed description and individual costs of the Sc4 wet AD combined aerobic windrow scenario are provided in Table (*v*) (see *Appendix B*). The life cycle cost (LCC) of the wet AD combined aerobic windrow system was found to be the second lowest among six comparative scenarios. As previously mentioned, the financial viability of these plants remains uncertain. Based on the prior analysis, it is evident that this technology is still considerably costly, with both the initial investment and ongoing operational expenses falling within the range of waste-to-energy (WTE) plants. Consequently, subsidies are necessary to make this technology more accessible and affordable for the general public.

Another significant challenge is the collection of clean feedstocks, which has proven to be a major issue even in regions known for their heightened environmental awareness and waste separation practices. The quality of the feedstock plays a crucial role in determining the scale and cost of pretreatment required for the material, as well as the efficiency of the anaerobic digestion process and the resulting compost's quality. The feedstock's quality is closely tied to the overall economics of these plants, as it directly influences the marketability of the compost product and the quantity of biogas that can be generated and utilized for electricity production.

Table S11 (i): Scenario LCA point standardization

Scenario LCA point standardization

Scenario	*LCA total damage points (single scores) points	Standardize of LCA points
Sc0	2990.00	(2990-1880)/(1880) x(-1)= **-0.59**
Sc1	661.00	(661-1880)/(1880) x(-1)= **0.65**
Sc2	3660.00	(3660-1880)/(1880) x(-1)= **-0.95**
Sc3	44.40	(44.4-1880)/(1880) x(-1)= **0.98**
Sc4	448.00	(448-1880)/(1880) x(-1)= **0.76**
Sc5	3480.00	(3480-1880)/(1880) x(-1)= **-0.85**
Average	**(2990+661+3660+44.4+448+3480)/(6)= 1880.57**	

Table S11 (ii): Scenario LCA point standardization

Scenario LCC point standardization

Scenario	*LCC points	Standardize of LCC points
Sc0	RM40	(40-123)/(123) x(-1)= **0.67**
Sc1	RM66	(66-123)/(123) x(-1)= **0.46**
Sc2	RM41	(41-123)/(123) x(-1)= **0.67**
Sc3	RM164	(164-123)/(123) x(-1)= **-0.34**
Sc4	RM384	(384-123)/(123) x(-1)= **-2.13**
Sc5	RM42	(42-123)/(123) x(-1)= **0.66**
Average	**(40+66+41+164+384+42)/(6)= RM123**	