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Designing Sustainable Waste Management Systems for a Traditional Market: A Life Cycle Assessment Case Study from Central Java, Indonesia

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ABSTRACT

The nature of traditional market waste is dominated by organic wastes, and hence landfilling and biological treatment options form critical decision nodes for the overall environmental performance of the system. In this context, this paper carries out a life cycle assessment (LCA) of three different waste management scenarios for Kartasura Traditional Market by using a functional unit of 1 tonne of market waste. Scenario S1 includes mixed collection and landfilling of market wastes, Scenario S2 includes partial segregation of wastes with biological treatment of organics and landfilling of inorganics, and Scenario S3 includes advanced segregation of wastes with combined biological and anaerobic digestion (AD) of organics and controlled landfilling of inorganics, along with the generation of electricity from biogas produced during AD. Environmental performance is evaluated using four midpoint indicators: Global Warming Potential over 100 years (GWP100, kg CO_2-eq), Acidification Potential (AP, kg SO_2-eq), Eutrophication Potential (EP, kg PO_4^{3-}-eq), and Photochemical Ozone Creation Potential (POCP, kg C_2H_4-eq), including credits for recovered products and electricity generation. The results indicate clear differences between landfilling and treatment-based systems. GWP100 decreases from 980 kg CO_2-eq t^{-1} in S1 to 520 kg CO_2-eq t^{-1} in S2 and further to 180 kg CO_2-eq t^{-1} in S3. AP and POCP also decline with increasing segregation and biological treatment, with AP decreasing from 3.20 to 2.70 to 2.20 kg SO_2-eq t^{-1} (S1–S3) and POCP decreasing from 0.85 to 0.78 to 0.60 kg C_2H_4-eq t^{-1}. In contrast, EP shows a management-related trade-off: S2 increases EP relative to S1 (1.40 vs. 1.10 kg PO_4^{3-}-eq t^{-1}), whereas S3 reduces EP to 1.00 kg PO_4^{3-}-eq t^{-1}.

1. INTRODUCTION

Traditional markets are more than retail spaces: they are daily infrastructures that connect peri-urban producers, urban consumers, and informal livelihoods. At the same time, they often function as municipal solid waste (MSW) “hotspots” because food-handling practices, high perishables turnover, and packaging practices generate mixed residues that are difficult to manage with conventional collection routines. Recent syntheses of solid waste management emphasize that the environmental burden of current practices, especially disposal-oriented pathways, remains substantial, while implementation gaps persist in many cities where waste segregation and treatment capacity are limited [1, 2]. In this context, waste systems in and around traditional markets deserve specific attention because interventions must fit tight spatial constraints, fluctuating volumes, and the everyday realities of vendors and cleaners.

A growing body of work links more sustainable waste management with broader climate and sustainability objectives. Reviews have highlighted the role of circular economy strategies in moving waste systems toward carbon neutrality by reducing reliance on landfilling and increasing recovery and valorization of materials and organics [3]. At the same time, the policy literature stresses that the quality of evidence behind environmental decision-making matters; life cycle assessment (LCA) is increasingly used as a decision support method because it can identify trade-offs that are otherwise hidden when attention is focused only on one stage of a system [4, 5]. This is particularly relevant in waste management, where technologies that look “clean” locally may shift impacts to upstream energy supply or downstream emissions.

Within waste systems, organic fractions are often decisive. Innovations in composting and biological treatment continue to evolve, with recent work documenting advances in organic solid waste composting and the conditions that influence performance and environmental outcomes [6]. For energy-and-resource recovery, anaerobic digestion (AD) is frequently discussed as a pathway to reduce methane-forming disposal and to produce biogas, and research on food-waste co-digestion continues to expand the technical options for stabilizing and valorizing wet organics [7]. In parallel, the challenge of mixed materials, especially plastics, has sharpened attention on upstream waste prevention and packaging reduction, consistent with the waste hierarchy emphasis on avoiding single-use products and moving toward higher-value options [8]. For Indonesia specifically, debates on plastic flows and regulation underscore that downstream management alone cannot fully address systemic pressures from consumption and trade [9, 10].

Traditional markets introduce additional socio-technical dynamics. Evidence from market contexts suggests that participation-related behaviors, such as traders' willingness and capacity to sort waste, can materially shape operational feasibility and outcomes [11, 12]. Market waste volumes can also vary day-to-day, and forecasting models for market waste collection have been proposed to support more responsive planning [13]. These insights imply that "one-size-fits-all" municipal waste strategies may underperform when applied to markets without design adaptation for local routines, stakeholder roles, and the temporal rhythm of waste generation.

Despite the growing LCA literature, an important gap remains: many studies evaluate waste technologies at city scale or for specialized waste streams (e.g., hospital waste or biodegradable plastics), while fewer studies treat traditional markets as a distinct system boundary with primary field data and design-oriented scenario testing [14, 15]. Moreover, the LCA community has increasingly recognized methodological issues such as temporal dynamics and system modeling choices that affect decision relevance, reinforcing the need for transparent assumptions and context-specific inventories [16, 17]. For market settings, where operational patterns and stakeholder practices strongly influence outcomes, scenario design must be grounded in observed practices rather than generic parameter values.

This study addresses these gaps by designing and evaluating alternative waste management system configurations for the Kartasura Traditional Market, Indonesia, using a LCA approach based on primary field measurements. The analysis compares three system designs: (i) conventional collection and landfill disposal, (ii) partial source segregation with composting of organics, and (iii) advanced segregation combined with composting and AD, reflecting a transition from disposal to recovery-oriented management. The LCA was structured to quantify Global Warming Potential (GWP100), Acidification Potential (AP), Eutrophication Potential (EP), and Photochemical Ozone Creation Potential (POCP), with all scenario results normalized to a functional unit of 1 tonne of market waste, while daily waste generation data were used to characterize field variability. By treating the market as a socio-technical system and explicitly comparing practical design scenarios, the novelty of this paper lies in: (1) producing a market-specific life cycle inventory (LCI) derived from on-site data rather than secondary averages, (2) translating LCA results into system design insights aligned with the waste hierarchy and circular economy, and (3) providing evidence that is directly usable by market managers and local governments for prioritizing interventions. The study, therefore, contributes to design-for-sustainability research by connecting quantifiable environmental impacts with implementable waste management system configurations.

In order to ensure that these scenarios are actionable for planning and implementation purposes, these three scenarios were carefully chosen to depict a practical and incremental transition from a predominantly linear waste management practice towards a more circular waste management practice under conventional market conditions (limited space, presence of informal economy, fluctuating waste generation, and limited investment potential). S1 represents conventional practice with mixed collection, transport, and landfilling, which is a baseline for current environmental impacts [18]. S2 presents an intermediate solution with source separation and composting for the dominant organic waste fraction, which is more easily implemented with relatively lower technological and investment demands, while at the same time reducing landfill waste quantities. S3 is an extension of this approach with AD for energy production from organics and a controlled landfill for residuals, which is a more circular approach with methane avoidance and energy substitution benefits [18].

The comparison, though artificial, has significant importance because it is not common for market actors and local governments to directly adopt a new system that bypasses a baseline system that relies on landfills and immediately transitions to an advanced system of circular economy, as this would require incremental steps that call for an increase in levels of segregation performance, operational control, and institutional coordination, as implied by progressing through levels of system sophistication, as defined by S1 → S2 → S3 [19].

From a conceptual perspective, this approach is consistent with widely discussed waste hierarchy and circular economy transition logics in which organics diversion is prioritized, composting is considered an early intervention, and AD is considered when stable segregation and utilization pathways (digestate management and off-take) can be secured [19]. In addition, previous LCA studies on this topic suggest that the relative effectiveness of composting and AD technologies is also strongly influenced by local factors such as transport distances, emission controls, methane leakage, and substitution credits, thereby supporting a clear comparison of these staged approaches using a transparent LCA methodology framework [19].

2. MATERIALS AND METHODS

This research is conducted following the ISO 14040/44 guidelines for LCA with a design-oriented scenario approach for assessing different waste management system configurations. This research follows ISO 14040/14044 guidelines for LCA using a design-oriented scenario approach. All inventory calculations, scenario routing, and life cycle impact assessment (LCIA) characterization were implemented in Python (custom scripts) to ensure transparent and reproducible modeling. Foreground activity data were obtained from field measurements and stakeholder surveys, while background parameters (e.g., transport fuel cycles, electricity supply, and treatment process factors) were represented as parameterized inputs documented in Table 1 and Table A1. The LCA approach is conducted by using a combination of (i) site-specific activity data for waste management dynamics at Kartasura Traditional Market, waste handling routes, and handling routines, and (ii) LCI datasets for upstream and process emissions, such as transport fuel cycles, electricity supply, and treatment process emissions.

The LCI datasets for this research are mainly obtained from an LCI database. The datasets are complemented by literature sources for parameters not represented by this database or requiring adaptations for local conditions. This approach is a common practice for waste LCA research.

2.1 Study area and research context

The study was conducted at Kartasura Traditional Market, Central Java, Indonesia (Figure 1). Traditional markets were treated as a distinct waste-generating system because waste quantities and composition were closely tied to daily trading rhythms and vendor practices, which influenced the feasibility of source separation and the stability of operational routines [11-13]. This framing supported a design-oriented evaluation of interventions that could realistically be implemented within market constraints.

2.2 Study design and life cycle assessment framework

A comparative LCA was applied to evaluate alternative waste-management system designs and to quantify their environmental implications. LCA was selected as a decision-support method because it enabled multi-impact comparison and reduced the risk of burden shifting across stages, which was important when assessing waste strategies that may appear beneficial locally but transfer impacts elsewhere [20, 21]. The work followed the standard LCA structure, goal, and scope definition, LCI, LCIA, and interpretation while emphasizing transparent scenario assumptions to ensure decision relevance [22, 23].

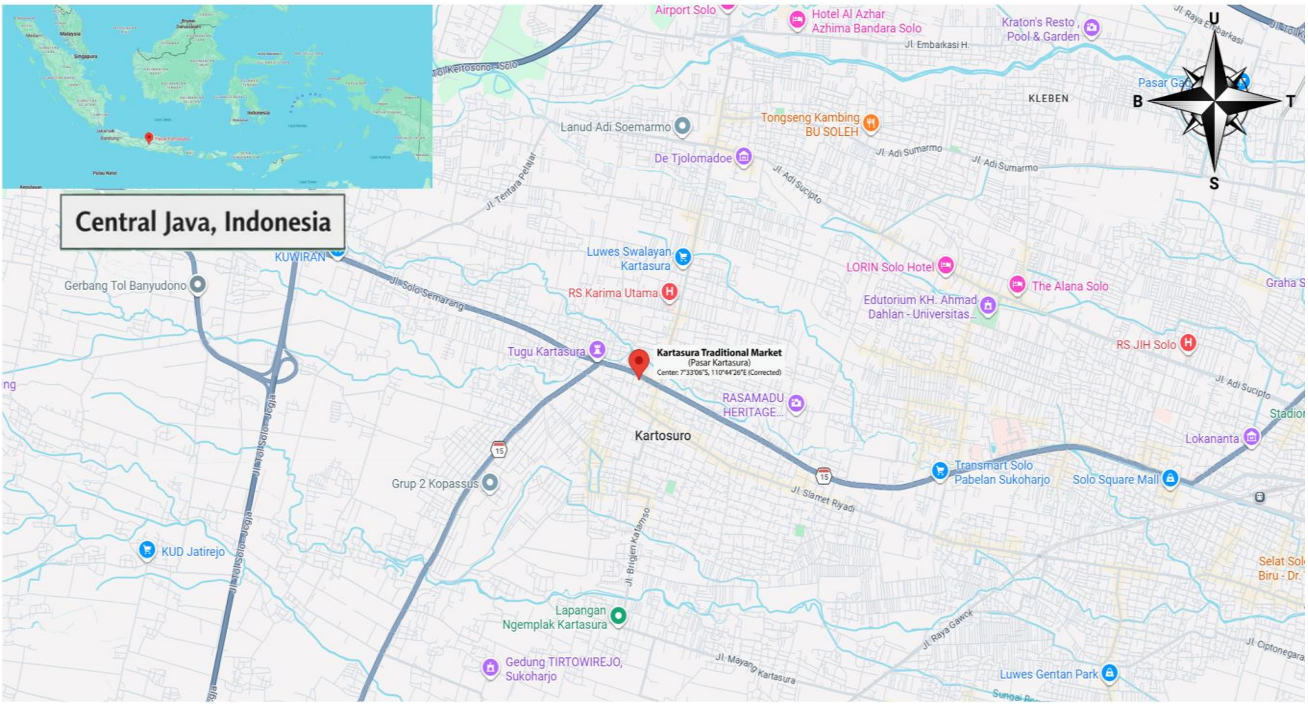

Figure 1. GPS-based location map of Kartasura Traditional Market, Central Java, Indonesia (7.5517465° S, 110.7404621° E)

2.3 Goal, functional unit, and system boundary

The goal was to support the development of a more sustainable waste management setup for the traditional market through the consideration of the different waste management routes and the identification of environmental hotspot areas. The functional unit (FU) was defined as 1 tonne of market waste entering the management system. Measured daily waste generation data were used to characterize temporal variability and site conditions, but all comparative LCA results were normalized to the functional unit of 1 tonne. This approach ensured the consistency of the comparison between the different scenarios based on the proportion of the waste routed and the amount of output from the waste treatment. The system boundary covered the on-site handling and collection of the waste, transportation of the waste to the facilities for treatment, and subsequent disposal of the waste. The definition of the system boundary was also regarded as an important modeling choice since the transportation of the waste and the auxiliary energy required could influence the outcome of the different scenarios. The goal and the system boundaries were therefore translated into a visual map of the waste management system. The map connected the upstream waste logistics of waste generation and handling, on-site handling and collection/loading of the waste, and the transportation of the waste. The downstream waste treatment and disposal were also connected in the map. The areas where the scenario-based waste routing is incorporated were clearly indicated in the map. The map provided a clear snapshot of the different processes and flows included in the model and where the recovered materials and energy were incorporated. The map also provided an illustration of the differences between the three scenarios (S1-S3) included in the model. Figure 2 shows the system boundaries and the different paths for the different scenarios.

2.4 Scenario development

Scenario development and recovery-oriented modeling were informed by recent LCA-based studies on biogas systems and waste-treatment optimization [24, 25]. Three scenarios were modeled as alternative system designs aligned with the waste hierarchy and circular economy orientation [26, 27]. Scenario 1 (S1) represented mixed-waste collection followed by landfill disposal; this pathway was expected to be climate-intensive, where biodegradable fractions dominated due to methane formation during decomposition [28, 29]. Scenario 2 (S2) represented partial source separation with composting of the organic fraction and landfill disposal of residuals; composting was treated as an organic-waste valorization route widely discussed in circular economy practice, with performance dependent on operational conditions [30]. Scenario 3 (S3) represented advanced separation combined with composting and AD, reflecting a recovery-oriented design intended to stabilize wet organics while recovering energy as biogas; the inclusion of AD was supported by recent work on AD advances for food and organic wastes [7]. Scenario-based comparative modeling was consistent with established practice in waste LCA for evaluating design alternatives and quantifying the impact of increasing diversion and resource recovery [31, 32]. Scenario-based routing was used to represent alternative waste-management system designs and to quantify how changes in segregation levels altered flows to composting, AD, and landfill [15, 28]. For each scenario, the waste flow routed to treatment option t was estimated as:

$$W_{s \to t} = r_{s,t} \times W \tag{1}$$

where, W is the functional unit (e.g., 1 ton of waste entering the system) and $r_{s,t}$ is the routing fraction from scenario s to treatment option t (landfill/composting/AD).

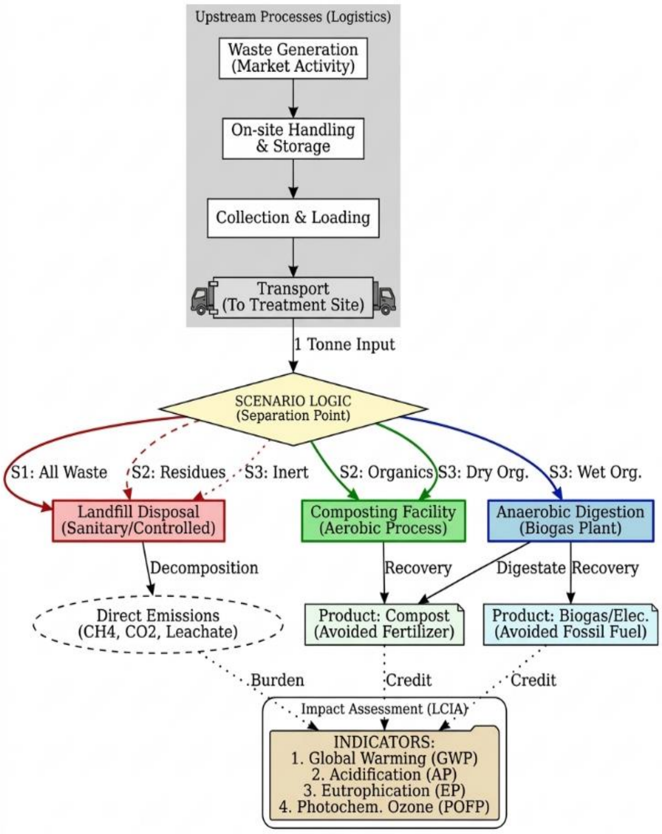

Figure 2. System boundary and scenario pathways for the life cycle assessment (LCA) of Kartasura Traditional Market waste management (functional unit: 1 tonne)

2.5 Life cycle inventory: Data collection and modeling assumptions

The amount of daily waste generated was assessed by directly weighing the wastes over a period of 23 valid days of monitoring, which accounted for the day-to-day variability that is normally seen in a traditional market system. The mass of the wastes generated was then expressed as descriptive statistics to facilitate the use of the functional unit approach and minimize the effect of the assumption of a "typical day." The average mass of the wastes generated per day was found to be 2,730.9 kg day^{-1} with a median of 2,200 kg day^{-1}, ranging from 1,480 to 5,150 kg day^{-1} with a standard deviation of 1,043.1 kg day^{-1} and a coefficient of variation of 0.382.

The LCI was constructed using primary field data to quantify waste generation and composition, observed handling routines, scenario routing shares, and collection/transport activity data. Market systems were assumed to exhibit temporal variation, and therefore inventory development prioritized site-specific characterization rather than relying solely on generic municipal averages [13]. Stakeholder routines and participation were reflected in the operational description because trader participation has been shown to influence segregation feasibility and waste-handling performance in market contexts [33, 34]. Where direct measurement was not feasible, secondary parameters (e.g., process performance and background factors) were adopted from recent peer-reviewed studies and standardized LCA guidance, consistent with common LCA practice combining foreground activity data with validated background assumptions [35, 36]. For recovery-oriented scenarios, inventory structure accounted for outputs such as compost/digestate and biogas because substitution and avoided-burden logic can affect comparative results, particularly when waste systems are evaluated under circular economy objectives [37, 38]. Parameters not directly measured in this study were defined as base-case assumptions to enable transparent scenario illustration. These values should be updated when local facility-specific data or validated background inventories are specified, and sensitivity analysis is recommended for high-influence parameters such as transport distance, methane capture/leakage, and treatment emission factors.

Waste fraction shares were computed to support scenario routing toward organic recovery and residual disposal, consistent with system-design approaches that prioritize valorization of organics and reduction of disposal dependency [3, 6]. LCIA was computed by multiplying inventory flows by characterization factors for each impact category and aggregating across flows, as commonly implemented in LCA studies [5, 17].

Daily waste generation variability was quantified using the mean, standard deviation, and coefficient of variation (CV) to reflect short-term fluctuations commonly observed in market waste streams [13]. The mean daily waste generation ($\bar{W}$) used for scaling was calculated as:

$$\bar{W} = \frac{1}{n}\sum_{i=1}^{n} W_i \tag{2}$$

where, W_i is the measured daily waste mass (kg day^{-1}) on day i, and n is the number of observation days.

Waste fraction shares (f_j) used for scenario routing were computed as:

$$f_j = \frac{w_j}{\sum_{j=1}^{m} w_j} \tag{3}$$

where, w_j is the mass of waste fraction j, and m is the number of fractions considered.

2.6 Key model parameters and data sources

In order to enhance the reproducibility of the results, Table 1 presents the essential foreground and background parameters that are considered during the scenario modeling process. These parameters include segregation/fractionation performance, transport parameters, biological treatment performance, landfill gas management parameters, and substitution parameters of the recovered materials, such as compost/digestate and biogas. The parameters were obtained from field measurement and survey data for the foreground parameters, while the background parameters were obtained from the selected LCI database and literature.

Table 1. Key parameters used in scenario modeling (summary)

Parameter Group	Parameter (Unit)	Value / Assumption
Waste generation (measured)	Monitoring days (day)	23
	Mean daily waste (kg/day)	2730.9
	SD (kg/day)	1,043.1
	Range (kg/day)	1480–5150
Stakeholder baseline (survey)	Respondents, n	224
	Dominant waste: plastic (%)	58.0
	Dominant waste: organic (%)	39.3
Scenario routing	S1: landfill share (%)	100
	S2: compost share/landfill residual (%)	60 / 40
	S3: AD share/compost share/landfill residual (%)	50 / 30 / 20
Transport	Key distances & vehicle assumptions	See Table A1
Process parameters	Composting/AD/landfill methane parameters	See Table A1
Credits	Fertilizer & energy substitution rules	See Table A1

2.7 Life cycle impact assessment

LCIA converted LCI flows into environmental impact indicators using midpoint characterization [39, 40]. Four midpoint categories were assessed: GWP100, AP, EP, and POCP. LCIA was conducted using the CML 2001 (baseline) midpoint method, with characterization factors implemented in a Python-based workflow. For recovery-oriented scenarios (S2 and S3), results are reported as net impacts by subtracting avoided-burden credits (substitution approach) from total burdens, where credits represent compost/digestate replacing synthetic fertilizer and (in S3) biogas electricity replacing grid electricity [41-43]. Four midpoint categories were considered in this study: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Photochemical Ozone Creation Potential (POCP). To ensure reproducibility, the LCIA method, characterization factors, and background datasets required to compute these categories are treated as explicit modeling requirements and are reported through the parameter documentation (Table 1 and Table A1). For recovery-oriented scenarios, results are reported as net impacts by accounting for both burdens and avoided burdens associated with recovered outputs (e.g., compost/digestate substituting fertilizer and biogas substituting conventional energy) [44-46], relevant for nutrient-related pathways and leachate-associated mechanisms [47, 48], associated with NOx/VOC precursors from logistics and operational processes, with consistent reporting supported by standardized emission-metric approaches [49, 50]. For recovery-oriented scenarios, net impacts were reported by accounting for burdens and avoided burdens associated with recovered outputs (e.g., compost/digestate replacing synthetic fertilizer and biogas substituting conventional energy) [7, 24]. LCIA was conducted using the CML 2001 (baseline) midpoint method to quantify GWP100, AP, EP, and POCP. LCIA was computed by multiplying inventory flows by characterization factors and summing across flows:

$$I_c = \sum_k LCI_k \times CF_{k,c} \tag{4}$$

where, I_c is the impact score for category c, LCI_k is the life-cycle inventory flow k(e.g., kg CH_4, kg CO_2), and $CF_{k,c}$ is the characterization factor for flow $k$in category c.

To reflect uncertainty around the estimated mean daily generation under temporal variability, a 95% confidence interval ($CI_{95\%}$) was computed using Student's t distribution [13].

$$CI_{95\%} = \bar{W} \pm t_{0.975,n-1} \frac{s}{\sqrt{n}} \tag{5}$$

where, s is the sample standard deviation and $t_{\alpha/2,n-1}$ is the critical t value. Characterization factors were implemented in the calculation workflow to convert inventory flows into midpoint impacts.

2.8 Interpretation and robustness

Interpretation focused on identifying life-cycle hotspots and explaining how changes in segregation levels and treatment routing drove differences among scenarios. Because waste LCA outcomes can be sensitive to boundary choices and substitution assumptions, key modeling decisions were documented and checked for robustness to maintain decision relevance, consistent with recent methodological discussions in LCA research [51, 52]. Practical feasibility was considered when drawing implications because successful implementation in market settings depends on governance arrangements and stakeholder participation, not solely on technical performance [53, 54].

3. RESULTS AND DISCUSSION

3.1 Waste generation dynamics and implications for system design

Measured daily waste generation at Kartasura Traditional Market showed clear temporal variability across the monitoring period. Over 23 valid weighing days, the mean daily waste mass was 2,730.9 kg day^{-1}, with a median of 2,200 kg day^{-1} and a wide range from 1,480 to 5,150 kg day^{-1}, indicating substantial fluctuations between low and peak trading days. This variability suggested that "typical-day" assumptions could underestimate the operational requirements for collection and downstream treatment capacity, particularly during short-term surges that may create overflow risks and increase leakage to informal storage or unmanaged disposal. The observed dispersion also implied that LCA foreground inventories should reflect real market-specific variation rather than a single average, because scaling errors at the inventory stage can propagate into LCIA results and distort scenario comparisons when the system is sensitive to loads and logistics. Such temporal instability is consistent with evidence that market waste streams exhibit fluctuating collection patterns and that forecasting approaches can improve planning for waste services in market contexts.

The descriptive statistics of measured daily waste generation are summarized in Table 2.

Table 2. Summarizes the descriptive statistics used to anchor the functional-unit scaling

Metric	Value
Number of observation days (n)	23
Mean (kg/day)	2730.9
Median (kg/day)	2200
Minimum (kg/day)	1480
Maximum (kg/day)	5150
Standard deviation (kg/day)	1043.1
Coefficient of variation (CV)	0.382

Figure 3 illustrates the day-to-day pattern in measured waste generation, while Figure 4 shows the distribution of daily mass and highlights the tail of high-generation days relevant for capacity design [13].

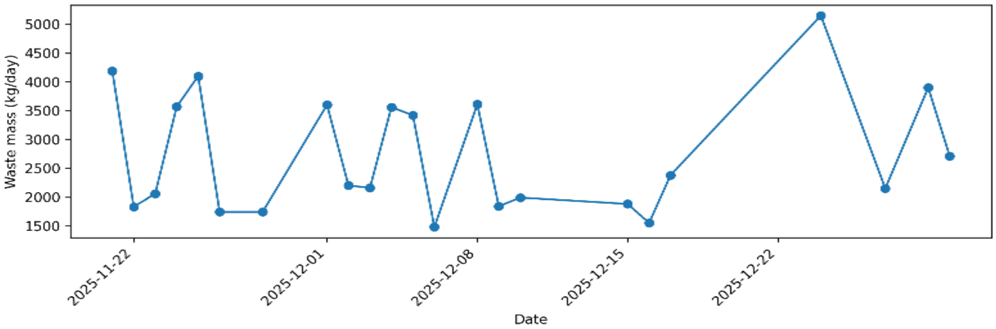

Figure 3. Daily waste generation time series measured at Kartasura Traditional Market

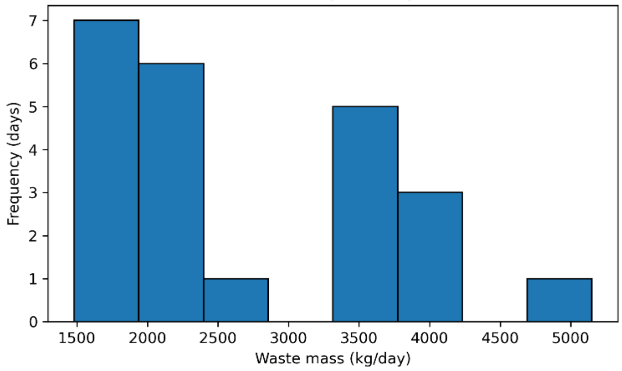

Figure 4. The distribution of daily mass highlights the tail of high-generation days relevant for capacity design

3.2 Waste composition baseline from the survey

Figure 5 shows the respondents' dominant type of waste generated per day (n = 224). Plastic was most often identified as the dominant fraction at 58.0%, followed by organic waste at 39.3%, with paper and other waste types at 0.4% and 2.2%, respectively. This pattern suggests that any staged intervention pathway should not have a sole focus on organic recovery but must combine organic diversion with plastic reduction and recovery measures to reflect the fractions perceived as most prominent by market actors. While this evidence is perception-based, it provides an important socio-operational baseline for the design of feasible source-separation strategies in traditional markets.

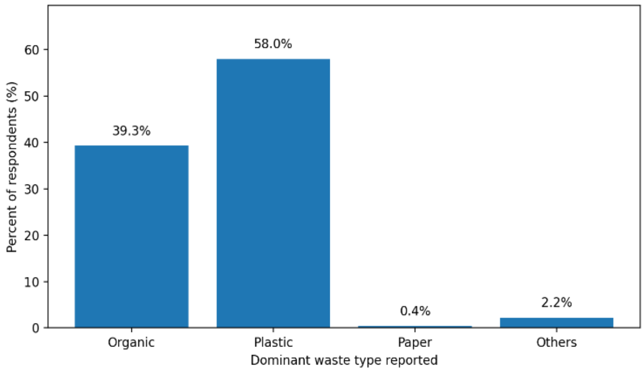

Figure 5. Respondents reported dominant daily waste type (n = 224): Plastic 58.0%, organic 39.3%, paper 0.4%, and others 2.2%

Most respondents identified plastic as the dominant daily waste type (58.0%), followed by organic waste (39.3%). This suggests that staged interventions should prioritize organic diversion (composting/AD) while simultaneously strengthening plastic reduction and recovery pathways to address the largest perceived fraction.

3.3 Scenario routing summary and inventory implications

For the functional unit of 1 tonne of market waste, the scenarios follow a stepwise diversion pathway. In S1, waste is collected as mixed waste and disposed of in a landfill. In S2, the dominant organic fraction is diverted to composting, while the remaining fraction is landfilled as residual waste. In S3, the organic fraction is treated through a combination of composting and AD, and the remaining fraction is landfilled under a more controlled management approach.

The scenario routing summary for the functional unit is presented in Table 3.

Table 3. Scenario routing summary for the functional unit (1 tonne of market waste)

Flow (per 1 Tonne)	S1	S2	S3
To composting	0%	60%	40%
To anaerobic digestion (AD)	0%	0%	40%
To landfill (residual/disposal)	100%	40%	20%
Total	100%	100%	100%

The total LCIA results can be obtained by summing up all burdens associated with collection, transport, treatment, and disposal for all scenarios. In addition, for S2 and S3, avoided-burden credits are subtracted from the total burdens to obtain net impacts (net = burdens - credits), where credits represent substitution effects of compost/digestate replacing synthetic fertilizer and (in S3) biogas electricity replacing grid electricity.

Scenario routing alters the major drivers of inventory. For instance, reducing waste going to landfills has implications for methane potential, while improving biological treatment can increase emissions of process-related gases such as ammonia and nutrient emissions if composting is not managed properly. In Scenario S3, AD for energy production has another offset that can impact the net greenhouse gas potential.

3.4 Life cycle assessment scenario comparison results

Based on the routing and inventory assumptions described in Section 3.3, we present the results for Scenarios S1–S3 per functional unit (1 tonne of market waste managed). We report net impacts (i.e., burdens minus credits), where credits account for resource recovery, including compost or digestate substituting synthetic fertilizer and, in S3, biogas-based electricity substituting grid electricity. We assess four midpoint indicators—GWP100 (kg CO_2-eq), AP (kg SO_2-eq), EP (kg PO_4^{3-}-eq), and POCP (kg C_2H_4-eq)—to compare the scenarios and identify potential trade-offs, before examining hotspot and contribution results.

Table 4. Net life cycle impact assessment (LCIA) results for the three scenarios (functional unit: 1 tonne of market waste)

Impact Category (Unit per FU=1 t)	**S1: Mixed Collection + Landfill**	**S2: Partial Segregation + Composting + Landfill Residuals**	**S3: Advanced Segregation + Composting + AD + Controlled Landfill**
GWP100 (kg CO_2-eq)	980	520	180
AP (kg SO_2-eq)	3.20	2.70	2.20
EP (kg PO_4^{3-}-eq)	1.10	1.40	1.00
POCP (kg C_2H_4-eq)	0.85	0.78	0.60

Table 4 presents the net LCIA comparison. The climate change potential substantially decreases from S1 to S2 to S3: 980 → 520 → 180 kg CO_2-eq t^{-1}. The data demonstrate that diverting waste away from landfills and harnessing energy through AD can significantly reduce greenhouse gas emissions. The acidification potential decreases step by step: 3.20 → 2.70 → 2.20 kg SO_2-eq t^{-1}. The decrease reflects reduced waste disposal to landfills and reduced waste transport to the disposal sites. Eutrophication potential shows us that S2 has a higher eutrophication potential than S1. The eutrophication potential of S2 is 1.40 kg PO_4^{3-}-eq t^{-1}, while that of S1 is 1.10 kg PO_4^{3-}-eq t^{-1}. However, the eutrophication potential of S3 is 1.00 kg PO_4^{3-}-eq t^{-1}, indicating that the nutrient losses are minimized through AD. The photochemical ozone creation potential also decreases stepwise: 0.85 → 0.78 → 0.60 kg C_2H_4-eq t^{-1}. The decrease suggests that the smog formation potential is lower.

In Figure 6, landfill methane is the major contributor to the global warming potential of S1, which comprises the major portion of the total impact. For S2, even though the reduction of organics reduced the landfill impact, the addition of composting impact still kept the impact much lower than S1 due to reduced landfill impact and fertilizer substitution credits. For S3, the reduced impact of landfill due to the substitution of electricity with biogas resulted in the lowest impact, with avoided electricity contributing to the net impact.

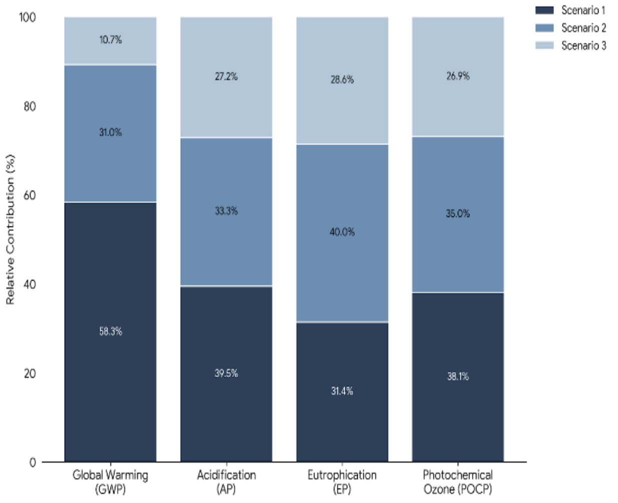

Figure 6. Relative scenario contribution (%) to GWP, AP, EP, and POCP (FU = 1 tonne of market waste)

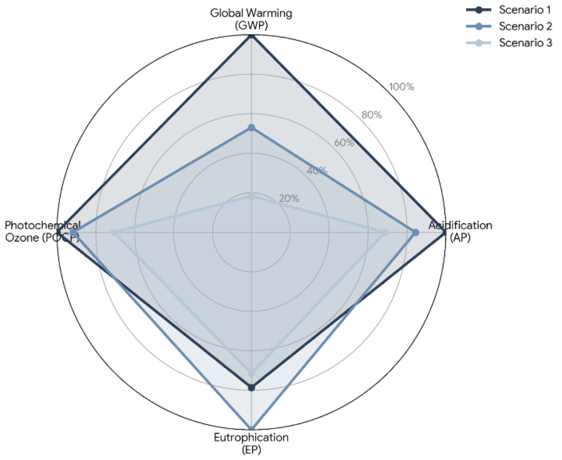

Figure 7. Normalized life cycle impact assessment (LCIA) comparison of scenarios using a radar chart (FU = 1 tonne)

The normalized comparison of the four midpoint indicators across scenarios is shown in Figure 7. In the analysis, it is observed that the hotspot for greenhouse gas emissions in Scenario 1 is landfill methane. Moving towards Scenario 2, the burdens decrease, and the composting burdens increase. The fertilizer substitution credits keep the overall impact low. Finally, in Scenario 3, the overall impact is driven by the avoidance of electricity from biogas, with the lowest global warming potential of all the scenarios. The process-level contribution analysis for GWP is presented in Table 5.

Table 5. Contribution analysis for Global Warming Potential (GWP) (kg CO_2-eq per FU = 1 tonne; net = burdens – credits)

Stage / Process	S1	S2	S3
Collection + transport	70	80	90
Composting process emissions	–	120	80
Anaerobic digestion (process + leakage)	–	–	60
Landfill direct emissions (CH_4 etc.)	900	420	250
Avoided burden: compost/digestate substituting fertilizer	0	–100	–60
Avoided burden: biogas electricity substitution	0	0	–240
Net GWP	980	520	180

Table 6. Sensitivity of net Global Warming Potential (GWP) to landfill gas management assumptions (kg CO_2-eq per tonne)

Assumption Set	S1	S2	S3	Ranking
Optimistic control	850	470	120	S3 < S2 < S1
Base-case	980	520	180	S3 < S2 < S1
Conservative control	1150	650	280	S3 < S2 < S1

The sensitivity analysis adjusted the absolute numbers for the absolute global warming potential for landfill gas management but did not affect the ranking between the scenarios. The sensitivity of net GWP to landfill gas management assumptions is summarized in Table 6. The ranking remained the same: S3 < S2 < S1, proving that the design approaches that emphasize recovery are still better than the others.

3.5 Implications for life cycle assessment interpretation and design-for-sustainability

Taken together, the measured waste dynamics and the survey evidence indicated that the environmental performance of market waste management was shaped by both physical flows and human behavior. High variability in daily generation underscored the importance of logistics design (collection frequency, storage adequacy, and contingency capacity), while the prominence of plastics in trader perceptions pointed to the continuing relevance of waste-prevention and packaging interventions alongside organic recovery strategies. From an LCA standpoint, these insights implied that the comparative scenarios should be interpreted not as purely technological substitutions, but as socio-technical packages whose performance depended on compliance and operational discipline. This perspective aligned with LCA scholarship that positions LCA as a decision tool best used with transparent assumptions, context-specific inventories, and scenario definitions grounded in realistic operational conditions [4, 5, 17].

For the functional unit of 1 tonne of market waste, scenario routing followed a progressive diversion logic. S1 routed 100% of waste to the landfill. S2 diverted the dominant organic fraction to composting while residuals were disposed of in a landfill. S3 increased organics recovery through combined composting and AD, while residuals were disposed of in a controlled landfill. Net LCIA results are reported by aggregating burdens from collection, transport, treatment, and disposal, and subtracting avoided burdens from recovered outputs (compost/digestate fertilizer substitution and biogas electricity substitution).

3.6 Survey evidence on waste characteristics and operational drivers

Survey responses provided complementary evidence on perceived waste characteristics and the operational drivers that influence the feasibility of improvement strategies. In terms of the most salient waste type generated by traders, plastics were reported most frequently, followed by organics, while paper and other categories were less prominent. Although these responses reflected perception rather than mass-based composition, the finding indicated that packaging-related waste was highly visible and operationally important for traders, which may shape compliance and support for interventions. This pattern aligned with broader arguments that reducing single-use packaging and moving upward in the waste hierarchy requires context-specific interventions that respond to everyday practices and incentives rather than relying on downstream treatment alone.

Survey findings were reported as proportions of valid responses to make category comparisons transparent and reproducible. This emphasis on response-based indicators is important in traditional market waste systems because trader participation and day-to-day practices can directly influence the feasibility of source separation and, consequently, the performance of downstream management options [11, 12]. Therefore, the percentage for each response category j was calculated using:

$$\%_j = \frac{n_j}{N} \times 100\% \tag{6}$$

where,

n_j = number of respondents who chose category j (for example, those who answered "Plastic")

N = total valid respondents for that question (those who were not blank/NA)

$j\%$ = percentage of that category

Table 7. Distribution of perceived dominant waste types

Waste Type	n	%
Plastic	130	58
Organic	88	39,3
Other	5	2,2
Paper	1	0,4

The distribution of perceived dominant waste types is reported in Table 7.

The self-reported daily waste amount distribution per respondent is presented in Figure 8. Self-reported waste quantities per trader further suggested that the system consisted of many small sources rather than a few dominant generators. Most respondents reported producing less than 1 kg day^{-1}, with a smaller share in the 1–5 kg day^{-1} range and only a minor tail above 5 kg day⁻¹. From an operational perspective, this structure implied that convenience and accessibility of collection infrastructure mattered, because participation depended on whether traders could dispose of waste with minimal disruption to trading activities. Prior studies in market settings similarly highlighted that trader knowledge, attitudes, and participation influenced waste management outcomes and the effectiveness of sorting initiatives. The concentration of responses in the lowest waste-quantity category is further illustrated in Figure 9.

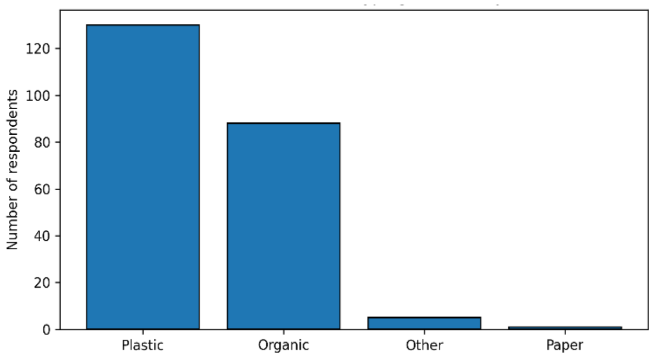

Figure 8. Self-reported daily waste amount distribution per respondent (n = 224)

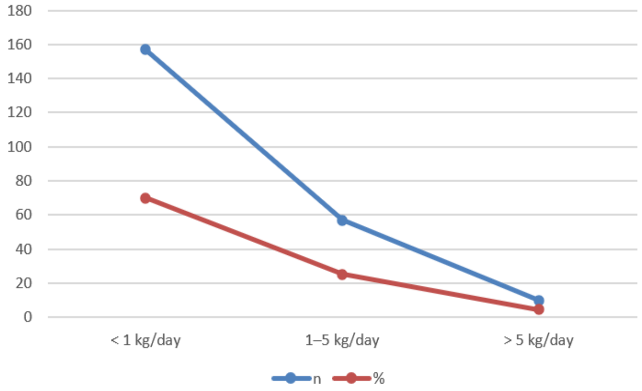

Figure 9. The concentration in the lowest waste-quantity category

3.7 Stakeholder priorities and readiness for scenario-based improvements

Respondents' stated priorities for improving market waste management revealed an important socio-technical insight: governance and behavioral interventions were perceived as more urgent than technology deployment alone. Education for traders and the community was the most frequently selected priority option, followed by source separation at origin and improvements to Temporary Waste Storage Sites (*Tempat Penampungan Sementara*, TPS), the designated intermediate storage areas where market waste is consolidated before municipal transport, while composting and biogas were selected by only a small fraction as the primary priority. This pattern suggested that, although organic recovery technologies are widely discussed as environmentally beneficial pathways, market stakeholders often viewed the enabling conditions, knowledge, routines, and shared responsibility as the critical bottleneck for sustainable implementation. These findings aligned with the broader literature emphasizing that waste-management transitions toward circular economy outcomes depend on institutional readiness and stakeholder participation, not only on the availability of treatment technologies.

This stakeholder evidence strengthened the logic of the scenario design used in the LCA framework. In particular, scenarios that assumed higher segregation rates (and therefore higher diversion to composting or AD) should be interpreted as requiring not only physical infrastructure but also behavioral and managerial interventions to sustain separation quality. The results, therefore, implied that scenario improvements could be realistically staged: early improvements would focus on education, containerization, and simple segregation, followed by scaling of organics recovery as separation performance stabilized. Such a staged pathway was consistent with the idea that recovery-oriented systems generate net benefits when upstream capture is reliable, and it also reduced the risk of underperformance due to contaminated organics or inconsistent collection. Stakeholder priorities for improving market waste management are presented in Figure 10.

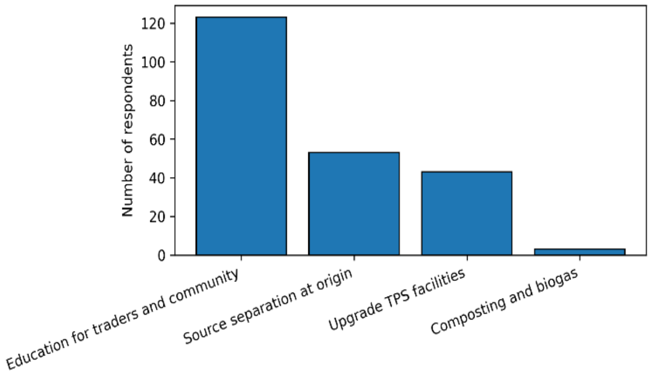

Figure 10. Stakeholder priorities for improving market waste management (n = 224)

4. CONCLUSIONS

This study investigated three different waste management scenarios for the Kartasura Traditional Market using LCA and taking 1 ton of the market waste as the functional unit. From the LCIA results, it is clear that the scenarios move from a disposal-oriented approach to a more recovery-oriented approach. For example, the global warming potential decreases from 980 to 520 and then to 180 kg CO_2-eq/t from scenarios S1 to S2 to S3, respectively. This indicates that methane emissions from landfills are the major contributor to GWP. In addition, the acidification and photochemical ozone creation potential also decrease step by step. For example, the acidification potential decreases from 3.20 to 2.70 and then to 2.20 kg SO_2-eq/t, while the photochemical ozone creation potential decreases from 0.85 to 0.78 and then to 0.60 kg C_2H_4-eq/t. These results indicate that co-benefits to the environment also exist. For eutrophication potential, scenario S2 increases eutrophication potential compared to scenario S1, while scenario S3 decreases eutrophication potential to a level lower than scenario S1. Therefore, the results from the LCA show that it is better to start from segregation and composting, which can reduce the environmental impacts by about half. Then, moving to organic recovery using AD can result in the best environmental profile, provided that the operation is good and all stakeholders are involved.

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NOMENCLATURE

W	Functional unit (market waste entering the system)
W_i	Measured daily waste mass on day (i)
$\bar{W}$	Mean daily waste mass
n	Number of observation days
s	Standard deviation of daily waste mass
CV	Coefficient of variation $CV = \frac{s}{\bar{W}}$
m_j	Mass of waste fraction (j)
p_j	Share of fraction (j)
k	Number of waste fractions
s (scenario)	Scenario index (S1–S3)
t (treatment)	Treatment option (landfill/composting/AD)
$W_{s \to t}$	Waste flow routed from scenario (s) to option (t)
$r_{s \to t}$	Routing fraction from scenario (s) to option (t)
I_c	Impact score for category (c)
LCI_k	Inventory flow (k) (e.g., emissions, energy use)
$CF_{k,c}$	Characterization factor for flow (k) in category (c)
I_c^{burden}	Total burden impact for category (c)
I_c^{credit}	Avoided burden/credit for category (c)
I_c^{net}	Net impact $\left(I_c^{\text{burden}} - I_c^{\text{credit}}\right)$
n_j	Number of respondents selecting category (j)
N	Total valid responses for a question
$\%_j$	Percentage of responses in category (j)
$CI_{95\%}$	95% confidence interval of the mean
$t_{0.975,n-1}$	Student's t critical value

APPENDIX

Table A1. Full parameter list and base-case assumptions for scenario modeling

Parameter Group	Parameter	Symbol	Unit	S1	S2	S3
Foreground – waste generation	Monitoring days	n	day	23	23	23
	Mean daily waste generation	$\bar{W}$	kg/day	2,730.9	2,730.9	2,730.9
	Standard deviation	s	kg/day	1,043.1	1,043.1	1,043.1
	Range (min–max)	–	kg/day	1480–5150	1480–5150	1480–5150
Foreground – stakeholder baseline	Survey sample size	–	respondent	224	224	224
	Dominant waste type: plastic	–	%	58.0	58.0	58.0
	Dominant waste type: organic	–	%	39.3	39.3	39.3
	Dominant waste type: paper	–	%	0.4	0.4	0.4

	Dominant waste type: others	–	%	2.2	2.2	2.2
Waste fractionation (assumed)	Organic fraction	f_{org}	%	60	60	60
	Plastic fraction	f_{pl}	%	20	20	20
	Paper fraction	f_{pap}	%	10	10	10
	Other fractions	f_{oth}	%	10	10	10
Scenario routing (mass allocation)	Share to landfill	r_{LF}	% of (W)	100	40	20
	Share to composting	r_{C}	% of (W)	0	60	30
	Share to anaerobic digestion	r_{AD}	% of (W)	0	0	50
Transport (assumed)	Distance market → landfill	d_{LF}	km	20	20	20
	Distance market → composting facility	d_{C}	km	0	15	15
	Distance market → AD facility	d_{AD}	km	0	0	25
	Vehicle type	–	–	Diesel truck	Diesel truck	Diesel truck
	Payload capacity	P	tonne	3.0	3.0	3.0
	Load factor	LF	%	70	70	70
	Transport emission factor	EF_{tr}	kg CO_2/tonne-km	0.12	0.12	0.12
Composting process (assumed)	Composting emission factor (CH_4)	EF^{C}_{CH4}	kg CH_4/tonne input	0	4.0	4.0
	Composting emission factor (N_2O)	EF^{C}_{N20}	kg N_2O/tonne input	0	0.3	0.3
	Composting emission factor (NH_3)	EF^{C}_{NH3}	kg NH_3/tonne input	0	3.0	3.0
	Electricity use	–	kWh/tonne input	0	15	15
	Compost yield	Y_{C}	kg compost/tonne input	0	300	300
Anaerobic digestion (assumed)	Biogas yield	Y_{bg}	m^3/tonne input	0	0	120
	Methane content in biogas	x_{CH4}	%	0	0	60
	Methane leakage rate	L_{CH4}	% of CH_4 produced	0	0	2
	Energy conversion efficiency	η	%	0	0	35
Landfill methane management (assumed)	Methane collection efficiency	η_{cool}	%	50	50	50
	Oxidation factor	OX	%	10	10	10
	Gas utilization	–	–	Flaring	Flaring	Flaring
Credits/substitution (assumed)	Fertilizer substitution rule	–	–	None	1:1 (mass)	1:1 (mass)
	Energy substitution baseline	–	–	None	None	Grid electricity
	Allocation rule (if any)	–	–	None	None	None
GWP100 (kg CO_2-eq), AP (kg SO_2-eq), EP (kg PO_4^{3-}-eq), POCP	CML 2001 baseline (midpoint), characterization	–	–	CML 2001 baseline CF implemented in Python	CML 2001 baseline CF implemented in Python	CML 2001 baseline CF implemented in Python

(kg C_2H_4-eq); net impacts reported as burdens − credits (S2–S3)	factors implemented in Python					
	GWP100 (kg CO_2-eq), AP (kg SO_2-eq), EP (kg PO_4^{3-}-eq), POCP (kg C_2H_4-eq)	–	–	Impact categories (midpoint): GWP100 (kg CO_2-eq), AP (kg SO_2-eq), EP (kg PO_4^{3-}-eq), POCP (kg C_2H_4-eq).	Planned: GWP/AP/EP/POCP	Planned: GWP/AP/EP/POCP