

Life Cycle Assessment (LCA) of Solid Waste Management System of Padang Beach Tourism Area (PBTA) in Padang City, Indonesia

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Abstract

Urban coastal tourism areas, such as the Padang Beach Tourism Area (PBTA), face significant environmental challenges associated with increasing solid waste generation. This study utilizes Life Cycle Assessment (LCA) in accordance with ISO 14040 standards to compare two solid waste management (SWM) scenarios for an average operating day. Scenario 1 represents the current city-scale system, characterized by limited informal recovery, with most of the collected waste disposed of at the Air Dingin controlled landfill. In contrast, Scenario 2 proposes a planned area-scale system that incorporates waste sorting, composting, and material recovery at a dedicated facility, directing any residual waste to the same landfill. The analysis focuses on a functional unit of 1,892.67 kg (1.893 tonnes) of PBTA waste generated per day, with landfill methane emissions quantified using IPCC 2006 parameters. Characterization is conducted using the CML-IA baseline midpoint method, while the EU25 normalization serves as supplementary interpretative support. Results indicate a Global Warming Potential (GWP) of 1.84×10^3 kg CO₂-eq/day for Scenario 1, compared to 3.87×10^2 kg CO₂-eq/day for Scenario 2, reflecting a 79% reduction primarily due to decreased landfill waste. Findings underscore that enhancing local recovery strategies can significantly improve the environmental performance of SWM practices in coastal tourism areas.

Keywords: coastal tourism area, CML-IA baseline, life cycle assessment, solid waste treatment, sustainable solid waste management

1. Introduction

The issue of solid waste management (SWM) in Indonesia has received considerable critical attention. Rapid population growth has led to increased consumption, which may cause increased waste generation. The tourism area

has been a major area that generates waste (Aziz & Nurunnissa, 2022). Sustainable tourism has become a key concept gaining significant attention in the global tourism industry. However, Indonesia still faces challenges in implementing this concept, as evidenced by its 131 out of 136 countries ranking in the Travel and Tourism Competitiveness Index (TTCI) evaluation regarding tourism performance in environmental and natural resource aspects (World Economic Forum, 2017). This highlights the need for more significant efforts to enhance sustainable tourism practices to support sustainable development in the tourism sector.

The Padang Beach Tourism Area (PBTA), located in Padang City, Indonesia, is one of the most promising tourist destinations in West Sumatra. According to data from BPS (2024), Padang City welcomed 14,662,200 domestic tourists and 63,161 international tourists from January to October 2024. This figure surpassed the target of 13.5 million visitors set for the period. Efforts to enhance the tourism potential of the PBTA are being actively pursued through government- and stakeholder-led development of facilities and infrastructure to improve service quality, accessibility, and overall appeal as a leading tourist destination. In line with the Mayor’s Decision Number 253 of 2014 regarding Padang Beach as the city’s primary tourist attractions area (Fikri et al., 2024).

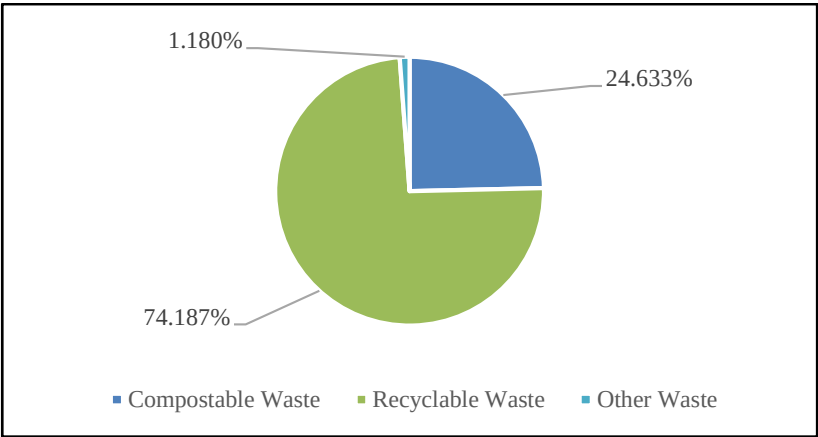


Figure 1. Solid waste composition of Padang Beach Tourism Area (PBTA)

Improper SWM, defined as inadequate treatment or disposal of waste, leads to significant health, environmental, and economic challenges. In the PBTA, solid waste generation in 2018 was 1,536 litres per person per day (l/p/d), consisting of 24.633% compostable waste, 74.187% recyclable waste, and

1.180% other waste, as shown in Figure 1. The recycling potential percentages were 91.732% for food waste, 88.074% for plastic waste, 23.604% for paper waste, 78.947% for metal, 75.758% for glass waste, and 20.115% for wood waste, as shown in Figure 2 (Aziz et al., 2021). The existing SWM system at PBTA includes selection, containerization, collection, processing, transfer, and disposal to landfill, in accordance with the Minister of Public Works Regulation Number 3 of 2013 (Ministry of Public Works and Housing, 2013).

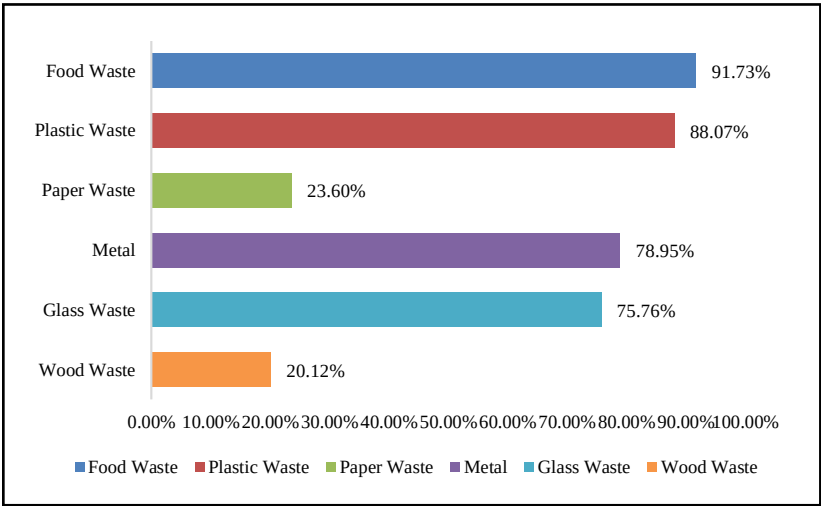


Figure 2. Recycling potential of solid waste Padang Beach tourism area (PBTA)

PBTA in Padang City, encompassing 431.15 ha, is a densely populated urban zone situated in West Padang Sub-district, stretching from the Purus area to the Batang Arau Estuary, with geographical coordinates of 0°56'12" South and 100°21'03" East, as shown in Figure 3. The PBTA has a relatively straight 4-kilometer coastline oriented northwest to southeast and is divided into six sectors arranged from south to north. These sectors range from 0.6 to 1 kilometre in length and are delineated by key landmarks such as river mouths, intersections, monuments, and bridges along the coastal corridor.



Figure 3. Sector division of Padang Beach Tourism Area (PBTA)

Prior planning work by Adufa (2019) and Aziz *et al.* (2021) quantified generation, composition, and a proposed recovery facility. The present paper evaluates the environmental consequences of that proposal using LCA, building on related coastal-tourism LCA studies in Indonesia. Moreover, it observed that the existing condition of SWM systems in the PBTA uses a city scale, waste is not sorted, the container system uses individual and communal storage systems, waste remains unprocessed, and is directly sent to landfill. Improving SWM in PBTA involves reopening the inactive recycling center and providing facilities for efficient storage and sorting. In addition, solid waste is processed based on its composition: food and yard waste are composted; coconut shells and shellfish waste are recycled into valuable products; plastic waste is turned into plastic or handmade items; and paper, glass, metal, and wood are sorted and sold. Finally, remaining waste, such as rubber and textiles, is sent directly to the landfill.

Sustainable SWM can be determined by assessing and comparing SWM impacts using Life Cycle Assessment (LCA). The LCA method provides a structured approach to evaluating environmental performance across a system (Banar *et al.*, 2009). The LCA framework, aligned with the ISO 14040 series, evaluates resource use and environmental impacts through four phases: Goal and Scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation, translating system flows into quantifiable impacts using standardized factors (Ridwan *et al.*, 2024).

LCA has been widely applied to Solid Waste Management (SWM) systems in Indonesia (Aziz *et al.*, 2022, 2024; Aziz & Febriardy, 2016; Aziz & Nurunnissa, 2022; Gunamantha *et al.*, 2010; Nurhuda *et al.*, 2024), China (Zhou *et al.*, 2018), Turkey (Banar *et al.*, 2009; Taşkın & Demir, 2020), Australia (Dastjerdi *et al.*, 2021; Islam & Iyer, 2023) Nepal (Dangi *et al.*, 2023), and India (Pujara *et al.*, 2023), supporting applications such as policy

optimization (Feo & Malvano, 2009), and landfill strategy evaluation (Gunamantha *et al.*, 2010). Moreover, LCA has been used to evaluate the environmental performance of existing SWM systems in coastal tourism areas and has proposed several improvements to promote a more sustainable approach (Aziz *et al.*, 2024; Aziz & Nurunnissa, 2022). Therefore, it is essential to evaluate the impact of the improved SWM systems proposed by Aziz *et al.* 2021) and to identify better strategies that can support decision-making by policymakers and stakeholders related to SWM in coastal tourism areas.

This study presents a comparative analysis of the current municipal solid waste management (SWM) system within a performance-based target allocation (PBTA) framework, alongside a proposed recovery-centric alternative. The evaluation uses a consistent functional unit and follows explicit allocation rules. Additionally, an IPCC-based landfill methane emissions model is used to assess environmental impacts, while a mass-balance closure approach ensures the integrity of the analysis. A sensitivity analysis is also performed to assess the robustness of the findings and provide insights into the potential efficacy of the alternative model compared with the existing SWM chain.

2. Methodology

2.1 Goal and Scope

This study compares the environmental performance of the existing PBTA municipal solid waste management (SWM) chain (Scenario 1) with a planned recovery-centered chain (Scenario 2), encompassing the processes from collection to disposal. The functional unit (FU) is defined as the daily management of solid waste generated in PBTA, quantified as 1,892.67 kg/day, based on composition fractions from Aduza (2019). This value is closely aligned with Aduza's reported generation rate of 0.084 kg/person/day for 22,580 visitors, resulting in a minor discrepancy of 4.05 kg/day (0.21%). The system boundary follows a cradle-to-grave approach, including containerization, collection, and disposal at the Air Dingin landfill, with local composting and material recovery included in Scenario 2. Notably, biogenic CO₂ from aerobic processes is not considered in the CML GWP assessment, while methane and fossil CO₂ are accounted for. This study excluded analyze

processing carried out by the informal sector (scavengers/third party). The system boundaries in the LCA analysis in this study can be seen in Figure 4.

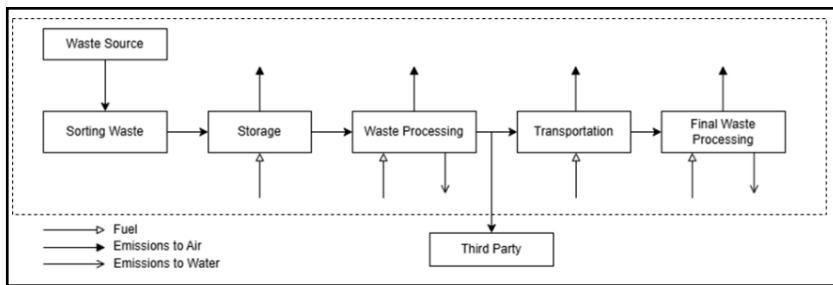


Figure 4. Boundaries system

In Scenario 1, around 30 kg/day of plastic is informally recovered before municipal collection, resulting in 1,862.67 kg/day entering the formal landfill chain. Scenario 2 models formal recovery for the entire 1,892.67 kg/day without double-counting informal routes. The base case applies a cut-off allocation approach, where recycled materials and compost exit the system without avoided-burden credits, and residuals bear landfill burdens. Sensitivity analysis examines avoided-burden credits for compost and major recyclables. Differences between scenarios are attributed to residual mass and recovery operations rather than changes in landfill type, with Scenario 2 focusing on sorting, composting, and material recovery while excluding separate modeling of reduction and reuse.

2.2 Data Collection

Primary information regarding containerization, collection, transfer, transport, and disposal was gathered through field observations and interviews. Secondary data on generation, composition, recycling potential, and facility design was sourced from Aduza (2019) and Aziz et al. (2021). Fuel combustion emissions associated with collection and transport, presented in consistent dimensions (kg pollutant per FU-day), have been retained. Landfill methane emissions were calculated using the IPCC 2006 parameters, while composting methane (CH₄) and nitrous oxide (N₂O) followed the default values established by the IPCC for biological treatment. The quality of the data is summarized as follows: measured composition and generation exhibit good local representativeness; fuel use and tonne-kilometers (tkm) have fair reliability; landfill methane is model-based with sensitivity to the methane correction factor (MCF); leachate chemical oxygen demand/nitrogen

(COD/N) is based on proxy coefficients with a higher level of uncertainty; and machinery diesel consumption is estimated based on rated power and operating time.

2.3 Life Cycle Inventory (LCI)

2.3.1 Mass Balance

For each stage, the input mass equals the sum of the product and the residual, within a rounding tolerance of ± 1 kg (Table 1).

Table 1. Mass balance for the functional unit day

Flow	Scenario 1 (kg/d)	Scenario 2 (kg/d)	Note
Generated (FU)	1,892.67	1,892.67	Aduza (2019)
Informal plastic recovery	30.00	0	Cut-off from formal LCI
Formal collection	1,862.67	1,892.67	Mass balance closed
Composting input	0	466	341 kg compost + 125 kg loss/residue
Recovered materials sold	0	~1,217	Coconut, shell, plastic, etc.
Residual to landfill	1,862.67	209	Air Dingin controlled landfill

2.3.2 Energy Carriers

The inventory distinguishes: fuel consumption (L Peralite or diesel) (i); transport service (tkm), used to document logistics intensity and not double-counted when fuel-based combustion emissions are already included (ii); mechanical energy demand (MJ) from rated power and operating time, used to estimate diesel use when meters were unavailable (iii); no grid electricity for the recovery facility in the available data (diesel-dominated assumption) (iv). Characterisation uses fuel-combustion and process emissions only.

2.3.3 Landfill Methane Model

The generation of methane (CH₄) is quantitatively assessed using the Intergovernmental Panel on Climate Change (IPCC) 2006 methane commitment methodology, calculated on a per tonne basis of wet waste landfilled. This approach is particularly suited for comparative analysis of various pathways on a daily functional unit (FU) basis, represented by Equation 1:

$$E_{CH}^4 = 10^3 \times MCF \times DOC \times DOC_f \times F \times \left(\frac{16}{12}\right) \times (1 - OX) \text{ [kg CH}_4 \text{ t}^{-1}] \quad (1)$$

In this equation, DOC refers to the mass-weighted IPCC wet degradable organic carbon of the PBTA mix, which is quantified at 0.140. The parameters are defined as follows: DOC_f is set to 0.5, F is also 0.5, OX equals 0, and the methane correction factor (MCF) is specified as 0.5 for controlled landfill scenarios (IPCC, 2006). The resulting calculation yields an estimate of 23.3 kg CH₄ generated per tonne of waste landfilled.

Furthermore, the characterization factor for global warming potential (GWP) over a 100-year horizon, as per CML-IA, assigns a value of 25 kg CO₂-equivalent per kg of CH₄. This relationship is formalized using Equation 2:

$$GWP_{landfill, CH^4} = E_{CH}^4 \times M_{landfilled} \times 25 \text{ [kg CO}_2 \text{ - eq day}^{-1}] \quad (2)$$

In addition, the emission of fossil CO₂ attributable to heavy machinery operations is estimated based on diesel consumption related to PBTA residuals, with Scenario 1 approximating 2.5 liters per day, and Scenario 2 approximating 0.27 liters per day. To assess the eutrophication potential arising from leachate contributions, proxy coefficients are employed, quantified at 10 kg of chemical oxygen demand (COD) per tonne of waste landfilled, and 1 kg of nitrogen (N) per tonne of waste landfilled.

2.3.4 Composting, Recovery, and Impact Equations

Composting emissions follow IPCC defaults of 4 kg CH₄ t⁻¹ and 0.3 kg N₂O t⁻¹ of wet waste composted, with NH₃ included for AP/EP. Diesel emissions resulting from the operation of shredders and hammermills are quantified utilizing process-specific coefficients for carbon dioxide (CO₂), CH₄, and N₂O, measured in kilograms per functional unit-day. The aggregation of midpoint indicators is performed as follows:

- Global Warming Potential (GWP) is calculated using Equation 3:

$$GWP = \sum (m_i \times CF_i) \quad (3)$$

- The Acidification Potential (AP) is defined using Equation 4:

$$AP = 1.2 m_{SO_2} + 0.5 m_{NOx} + 1.6 m_{NH_3} \quad (4)$$

- The Eutrophication Potential (EP) is approximated by Equation 5:

$$EP \approx m_{PO}^4 + 0.42 m_N + 0.35 m_{NH}^3 + 0.13 m_{NOx} + 0.022 m_{COD} \quad (5)$$

This framework facilitates a comprehensive understanding of the environmental impacts associated with composting processes, particularly with respect to greenhouse gas emissions and their subsequent contributions to acidification and eutrophication. Diesel emissions from shredders and hammermills use process-specific CO₂, CH₄ and N₂O amounts (kg per FU-day).

2.4 Life Cycle Impact Assessment (LCIA)

The selection of Global Warming Potential (GWP), Acidification Potential (AP), and Eutrophication Potential (EP) as key indicators for evaluating solid waste management (SWM) burdens is rooted in their prominence as dominant environmental impacts. These metrics are critical since they reflect the primary environmental challenges associated with SWM: greenhouse gas emissions, acidifying air pollutants, and nutrient/COD discharges into aquatic ecosystems (Laurent *et al.*, 2014). While the CML-IA baseline EU25 normalization values are presented to illustrate the relative magnitude of these environmental impacts, they should not be used as a basis for comparative conclusions, particularly given the geographical mismatch of the EU25 reference in the context of Indonesia.

2.5 Interpretation

The process of interpretation involves identifying dominant mechanisms, conducting a comparative analysis of two scenarios, and assessing robustness through sensitivity analysis. Subsequently, it formulates recommendations that are grounded in the findings of the modeled system.

3. Results and Discussion

3.1 Waste Generation, Composition, and Scenario Description

The generation of PBTA (Padang Beach Tourism Area) waste is primarily attributed to tourism activities, support sectors, and public facilities (Adufa, 2019). In the context of an operational framework with a daily waste generation of 1,892.67 kg, the composition of this waste stream is predominantly food waste, accounting for 84.217%. Other notable components include plastic at 9.254%, paper at 2.087%, metal at 2.024%, wood at 1.126%, textiles at 0.229%, glass at 0.112%, rubber at 0.056%, and various other materials constituting 0.895%.

The current waste management scenario, referred to as Scenario 1, involves a city-scale system characterized by mixed waste collection. This system utilizes both individual and communal containers, coupled with motorized tricycle collection methods. Collected waste is then transferred and transported approximately 18 to 19 kilometers to a facility in Air Dingin, where it undergoes compaction utilizing diesel-powered machinery. The leachate produced during this process is managed in a controlled landfill pond. Additionally, it is noteworthy that approximately 30 kg of plastic is informally recovered from the waste stream prior to the formal collection process.

In Scenario 1, the landfill operates as a controlled landfill. Solid waste transported from the PBTA is weighed and disposed of immediately without preliminary treatment. Moreover, it is then compacted and levelled using diesel-powered bulldozers and excavators, which operate for approximately 18 hours per day, excluding rest periods. Finally, leachate management relies solely on a pond system, which is currently not functioning effectively. The process flow for Scenario 1 is illustrated in Figure 5.

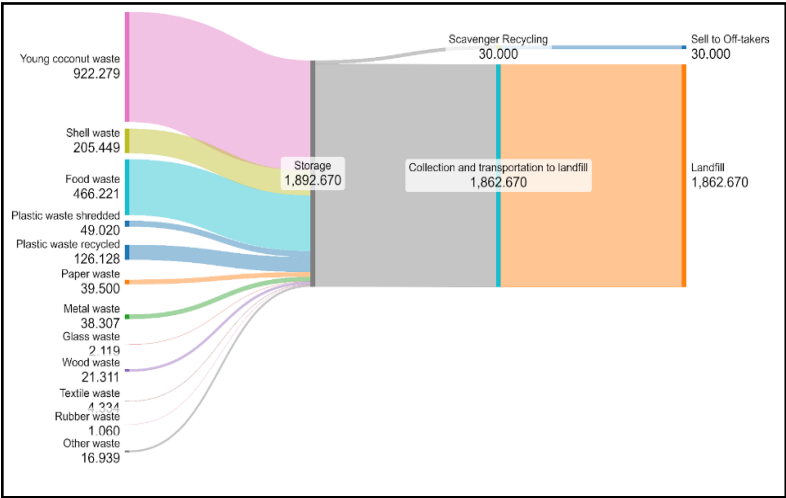


Figure 5. Existing city-scale waste management system with direct disposal to landfill (Scenario 1)

Scenario 2 proposes a solid waste management (SWM) system for PBTA that includes local sorting, composting, and material recovery for various waste types such as coconut fibre, plastics, and glass. The system aims to reduce waste at the source and boost community recycling through a sorting, composting, and material recovery approach, directing residual waste (about 209 kg per day) to a controlled landfill. It utilizes individual and communal containers for waste sorting, with collection mechanisms involving indirect individual collections for establishments and a communal collection schedule. Additionally, a street sweeping system maintains public cleanliness with bi-daily collections.

In Scenario 2, food and yard waste are composted using a rotary kiln. Moreover, young coconut waste is shredded into fibers, dried, and subsequently used for handicrafts. Shell waste is washed and crushed into powder with a hammer mill, which is either sold or used as a cement additive. Plastic and paper waste are transformed into plastic ore and handmade products, then sold to collectors or marketed at souvenir stalls in the PBTA. Solid waste transportation relies on a Hauled Container System (HCS) with 6 m³ arm-roll trucks that operate daily, ensuring consistent and efficient waste collection. Finally, at the Air Dingin controlled landfill with a leachate treatment pond, the solid waste is weighed, compacted, and leveled with

bulldozers and excavators. The schematic diagram of scenario 2 can be seen in Figure 6.

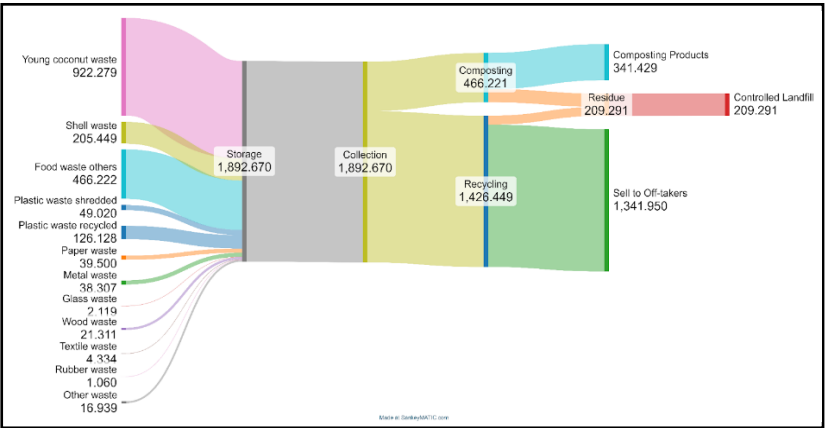


Figure 6. Integrated Solid Waste Management Process (Scenario 2)

3.4 LCA Inventory for All Scenarios

The input and output of solid waste generation are based on the composition of PBTA solid waste. More details can be seen in Table 2. An earlier exploratory model was implemented in SimaPro 9.0; however, several database-derived emission rows failed unit verification and were withdrawn. All characterisation results were therefore recomputed independently using the IPCC-based landfill model and the verified fuel-combustion inventory described above. Table 3 summarises landfill methane parameters. Table 4 lists verified combustion and biological emissions per functional-unit day. Characterisation results (Table 5) were obtained by applying equations 2–5.

Table 2. Process flows

No	Processing Type	Waste Type	Scenario 1			Scenario 2		
			Input (kg)	Output (kg)	Waste (kg)	Input (kg)	Output (kg)	Waste (kg)
1	Containerization	All waste	1,892.67	1,892.67	-	1,892.67	1,892.67	-
2	Informal Recycling	Plastic	30	30	-	-	-	-
3	Collection	All waste	1,862.67	1,862.67	-	1,892.67	1,892.67	-

4	Composting	Food waste	-	-	-	466	341	125
4a	Recycling	Coconut waste	-	-	-	922	922	-
4b	Recycling	Shell waste	-	-	-	205	205	-
4c	Recycling	Plastic waste	-	-	-	49	49	-
4d	Sold	Craft	-	-	-	126	106	20
4e	Sold	Glass waste	-	-	-	2	1	1
4f	Sold	Metal waste	-	-	-	38	30	9
4g	Sold	Paper waste	-	-	-	40	11	28
4h	Sold	Wood waste	-	-	-	21	17	4
4i	Other	Mixed waste	-	-	-	17	-	17
4j	Other	Textile waste	-	-	-	4	-	4
4k	Other	Rubber waste	-	-	-	1	-	1
Total Processing		-	-	-	-	1,892.67	1,683.37	209
5	Transportation	Residue	-	-	-	209	209	-
6	Final Processing	Residual	1,862.67	-	-	209	-	-

3.4.1 Inventory Data for Scenario 1

Scenario 1 analyzes environmental impacts from solid waste collection, transportation, and disposal at a controlled landfill. The collection involves 4 motorized tricycles (3 rotations, 12 L Peralite, 64.7 km) and 4 diesel dump trucks, transporting 1.862 tons of solid waste over 190.2 km (120 L diesel). Scavengers recover 0.030 tons of recyclables. Fuel consumption is 0.185 L Peralite and 0.339 L diesel per tkm. Final disposal at Air Dingin landfill processes 450 tons/day using heavy equipment (18-19 hours), while PBTA solid waste (1.862 tons) requires only 0.08 hours. Energy outputs: 122.41 tkm (tricycles) and 354.15 tkm (trucks).

3.4.2 Inventory Data for Scenario 2

Scenario 2 focuses on a structured SWM system centered at the 3R solid waste recycling centre (Sector 6, PBTA). Solid waste collection employs 8 motorized tricycles (1.5 m³ capacity) fueled by Peralite, operating twice daily for compostable/recyclable solid waste and every other day for other solid waste types. These tricycles transport 1.892 tons of solid waste over 46 km,

consuming 8.53 L of fuel (0.098 L per ton-kilometer) and generating 87.032 tkm of energy. At the facility, 0.341 tons of organic solid waste undergoes composting using a shredder (11.5 HP, 1,108 MJ energy output), a manual rotary kiln, and smoothing machines, while recyclables like coconut, plastic, and shells are processed via dedicated machinery (yielding 1.849 MJ, 0.0027 MJ, and 578.637 MJ, respectively). Residual waste (0.209 tons) is transported 27.5 km to Air Dingin Landfill using a diesel-powered arm roll truck (17.4 L fuel, 3.028 L per tkm). Final disposal utilizes heavy equipment (117 kW excavators and bulldozers) operating for only 0.0084 hours due to the reduced solid waste volume, consuming 0.267 L of diesel in total (0.146 L/MJ for excavators, 0.129 L/MJ for bulldozers) and producing 0.975 MJ of energy. This integrated SWM approach emphasizes efficient fuel use, mechanized processing, and minimized landfill reliance.

A recapitulation of input and output inventory data from each tool in each PBTA SWM process scenarios 1 and 2 can be seen in Table 2, and emission inventory data from each solid waste processing process can be seen in Table 3.

Table 3. Inventory parameters for controlled-landfill methane
(per tonne wet waste landfilled)

Process / Components	Unit	Amount	Source
Input parameters			
DOC (mass-weighted, PBTA mix)	-	0.140	IPCC 2006 wet DOC × Adfuza (2019) composition
DOC _f	-	0.5	IPCC 2006 default
F (CH ₄ fraction in landfill gas)	-	0.5	IPCC 2006 default
OX (methane oxidation)	-	0	Conservative; no cover credit
MCF (controlled landfill)	-	0.5	IPCC 2006 Vol. 5, Table 3.1
Calculated inventory			
E _{CH₄} (methane commitment)	kg/t landfilled	23.3	Eq. 2: IPCC methane commitment
GWP factor CH ₄ (CML-IA)	kg CO ₂ -eq/kg	25	CML-IA baseline GWP100
GWP from CH ₄ only	kg CO ₂ -eq/t	583	23.3 × 25
COD in leachate (proxy for EP)	kg/t landfilled	10	Proxy coefficient (high uncertainty)
N in leachate (proxy for EP)	kg/t landfilled	1	Proxy coefficient (high uncertainty)
Mass landfilled in this study (FU-day)			

Scenario 1 - mass to Air Dingin	kg/day	1,862.67	FU minus 30 kg informal cut-off
Scenario 2 - residual to Air Dingin	kg/day	209	After local recovery
Scenario 1 - CH ₄ release	kg/day	43.5	1.86267×23.3
Scenario 2 - CH ₄ release	kg/day	4.87	0.209×23.3

Table 4. Life-cycle inventory for collection, recovery and residual transport

Process / Components	Unit	S1	S2	Source
Input - waste & fuels				
PBTA waste generated (FU)	kg/day	1,892.67	1,892.67	Adfuza (2019) composition sum
Informal plastic recovery (cut-off)	kg/day	30	0	Field/planning; outside formal LCI
Waste entering formal collection	kg/day	1,862.67	1,892.67	Mass balance
Waste to composting	kg/day	0	466	Adfuza (2019) facility plan
Waste to material recovery (sold)	kg/day	0	1,217	Coconut, shell, plastic, etc.
Residual to landfill	kg/day	1,862.67	209	Air Dingin controlled landfill
Pertalite - collection tricycles	L/day	12.0	8.53	Operational estimate
Diesel - residual transport	L/day	120	17.4	Operational estimate
Diesel - composting/recovery machines	L/day	0	11.7	Rated power $\times$ time = litres
Diesel - landfill heavy equipment	L/day	2.54	0.267	Allocated to PBTA residual
Output - products (Scenario 2; cut-off, no avoided credits in base case)				
Compost product	kg/day	-	341	Facility mass balance
Recovered materials sold	kg/day	-	1,217	Cut-off (no substitution credit)
Emissions to air - combustion (verified kg/FU-day)				
CO ₂ - collection	kg/day	57.7	41.0	Fuel combustion inventory
CH ₄ - collection	kg/day	0.0012	0.00087	Fuel combustion inventory
N ₂ O - collection	kg/day	0.0002	0.00017	Fuel combustion inventory
CO ₂ - residual transport	kg/day	651	94.4	Fuel combustion inventory
CH ₄ - residual transport	kg/day	0.0179	0.00259	Fuel combustion inventory
N ₂ O - residual transport	kg/day	0.124	0.0179	Fuel combustion inventory

CO ₂ - recovery machines (S2)	kg/day	-	30.4	Shredder/hammermill diesel
Emissions - biological / landfill (calculated)				
CH ₄ - composting	kg/day	-	1.86	IPCC default 4 kg/t × 0.466 t
N ₂ O - composting	kg/day	-	0.140	IPCC default 0.3 kg/t × 0.466 t
CH ₄ - landfill	kg/day	43.5	4.87	Table X × mass landfilled
CO ₂ - landfill equipment	kg/day	6.8	0.72	Diesel × 2.68 kg CO ₂ /L

3.5 Impact Assessment and Comparison

The impact assessment stage in this study includes characterization and normalization. Table 5 shows the impact characterization results, comparing GWP, AP, and EP for each process in scenarios 1 and 2.

Table 5. CML-IA characterization

Indicator (per FU-day)	Scenario 1	Scenario 2	ΔS
GWP (kg CO ₂ -eq)	1.84E+03	3.87E+02	-79%
AP (kg SO ₂ -eq)	1.88	0.73	-61%
EP (kg PO ₄ ³⁻ -eq)	1.63	0.39	-76%
Waste landfilled (kg)	1,862.67	209	-89% mass

In Scenario 1, the Global Warming Potential (GWP) is predominantly influenced by methane emissions from landfilling, which account for approximately 1.09E+03 kg CO₂-eq, in addition to emissions from the combustion associated with collection and transport, totaling around 7.5E+02 kg CO₂-eq. Scenario 2 achieves a significant reduction in landfilled mass, decreasing to 209 kg per day, which consequently mitigates methane emissions. Moreover, the emissions associated with composting and machinery operations remain considerably lower than the methane emissions avoided through landfill diversion. The consistent relative reductions observed across GWP, Acidification Potential (AP), and Eutrophication Potential (EP) suggest that the comparative analysis is largely influenced by the diversion from landfilling, facilitated by a controlled landfill technology. The approximately 89% reduction in landfilled mass is noteworthy, alongside the GWP reduction, which is estimated at around 79%.

The EU25-normalised scores utilized in this analysis maintain the existing ranking, with Scenario 2 outperforming Scenario 1. These scores serve primarily for supplementary interpretation, while any comparative

conclusions drawn are fundamentally based on the characterisation results presented in Table 2. This distinction underscores the importance of adhering to defined metrics and characterisation methods as a means to understand the implications of various scenarios in the context of environmental impact assessments.

Within the examination of recovered products, the base case applies a cut-off criterion, indicating that the advantages of Scenario 2 represent a lower bound, particularly in cases where substitution credits are deemed positive. System-expansion credits, estimated at approximately 1 to 2 kg CO₂-eq per kilogram of recovered plastic or metal, in addition to a minor fertiliser credit per kilogram of compost, further enhance the benefits associated with Scenario 2. However, it is noteworthy that elevated levels of methane emissions from composting can diminish this advantage without altering the overall ranking of the scenarios, as supported by studies from Rigamonti *et al.* (2009) and Laurent *et al.* (2014).

The sensitivity analysis conducted through one-at-a-time tests reveals several critical insights. Notably, an increase in the MCF from 0.5 to 0.8 elevates the global warming potential (GWP) for Scenario 1 to approximately 2.5E+03 kg CO₂-eq/day, while Scenario 2 remains comparatively lower. The examination of various factors, such as a methane factor adjustment and variations in collection fuel use, indicate a modest effect, primarily due to the dominance of landfill methane emissions in Scenario 1. Additionally, an increase in composting methane from 4 kg/t to 10 kg/t contributes only a slight increase in GWP for Scenario 2. The findings highlight the robust direction of improvement given various conditions, though the absolute magnitudes of these impacts remain uncertain. In practical terms, this research emphasizes the significance of source separation, operational reliability of local recovery facilities, residual-rate monitoring, and collection fuel efficiency as pivotal priorities for enhancing sustainability outcomes.

3.4 Limitations

Limited local-government budgets for solid waste management (SWM) in Indonesia contribute significantly to the operational failures of recovery facilities, as highlighted by LCDI Indonesia (2022). While this Life Cycle Assessment (LCA) provides a contextual understanding of economic implications, it refrains from quantifying costs, tariffs, or net present value. It is important to acknowledge several limitations inherent to this study: the

functional unit (FU) reflects an average day and does not account for seasonal visitor fluctuations or variations in moisture; visitor numbers were not independently resurveyed; leachate factors utilized are considered proxies; and primary measurements of landfill gas at Air Dingin were unavailable. Additionally, the analysis omits categories related to capital goods, toxicity, and water scarcity, and the base case does not include considerations for avoided production. Notably, the sanitary landfill configuration, discussed in other sections of the underlying thesis, falls outside the scope of this two-scenario comparative analysis.

4. Conclusion and Recommendation

The findings of this study indicate that transitioning from nearly complete disposal of PBTA at the Air Dingin controlled landfill in Scenario 1 to a model that incorporates local composting and material recovery, resulting in a significantly reduced residual load at the same landfill in Scenario 2, can lead to reductions in Global Warming Potential, Acidification Potential, and Eutrophication Potential for the specified daily functional unit. An approximate reduction of 79% in Global Warming Potential has been observed in the base case, primarily facilitated by the diversion of waste from landfilling. Based on the model's outputs, we recommend implementing several key strategies, including enhanced source separation, the establishment of reliable operations for recovery facilities, rigorous monitoring of residuals, and optimizing waste collection processes. Additionally, broader interventions such as upgrades to gas treatment systems, advanced leachate management practices, and tariff reform warrant evaluation in future research endeavors. Furthermore, integrating economic and social considerations into the environmental model would provide a more comprehensive framework to support informed decision-making.

5. References

Adfuza, G.P. (2019). *Planning of a solid waste management system for the Padang Beach tourism area* (Undergraduate thesis). Department of Environmental Engineering, Faculty of Engineering, Universitas Andalas, Padang, West Sumatra, Indonesia.

Aziz, R., & Febiardy. (2016). Analysis of the solid waste management system of institutional sources in Padang City using the life cycle assessment method. *Journal Environmental Engineering UNAND*, 13(2), 60–67. <https://doi.org/10.25077/dampak.13.2.60-67.2016>

Aziz, R., & Nurunnissa, S. (2022). Comparative life cycle assessment for improvement of the solid waste management system of the Pariaman coastal tourism area. *Indonesian Journal of Environmental Management and Sustainability*, 6(2), 42–52. <https://doi.org/10.26554/ijems.2022.6.2.42-52>

Aziz, R., Adfuza, G.P., & Arbi, Y. (2021). Preliminary study of solid waste treatment of Padang beach tourism area. *Journal of Vocational Technology Education*, 4(1). <https://doi.org/10.24036/jptk.v4i1.16323>

Aziz, R., Fitria, D., & Ruslinda, Y. (2022). Environmental impact evaluation of improved market waste processing as part of municipal solid waste management system using Life Cycle Assessment (LCA) method. *Ecological Engineering and Environmental Technology*, 23(2), 60–69. <https://doi.org/10.12912/27197050/144955>

Aziz, R., Ruslinda, Y., & Hukmi, R. (2024). Study of sustainable solid waste management system of Carocok Beach Painan tourism area using Life Cycle Assessment (LCA) method. *International Interdisciplinary Conference on Green Development in Tropical Regions*. <https://doi.org/10.1088/1755-1315/1306/1/012040>

Banar, M., Cokaygil, Z., & Ozkan, A. (2009). Life cycle assessment of solid waste management options for Eskisehir, Turkey. *Waste Management*, 29(1), 54–62. <https://doi.org/10.1016/j.wasman.2007.12.006>

BPS-Statistics Indonesia Padang Municipality. (2024). *Number of foreign and domestic tourists*. Retrieved from <https://padangkota.bps.go.id/en/statistics-table/2/MTMxIzI=/jumlah-wisatawan-mancanegara-dan-domestik-.html>

Dangi, M.B., Malla, O.B., Cohen, R.R.H., Khatiwada, N.R., & Budhathoki, S. (2023). Life cycle assessment of municipal solid waste management in Kathmandu city, Nepal – An impact of an incomplete data set. *Habitat International*, 139. <https://doi.org/10.1016/j.habitatint.2023.102895>

Dastjerdi, B., Strezov, V., Kumar, R., He, J., & Behnia, M. (2021). *Comparative life cycle assessment of system solution scenarios for residual municipal solid waste management in NSW, Australia*. *Science of the Total Environment*, 767. <https://doi.org/10.1016/j.scitotenv.2020.144355>

Feo, G. De, & Malvano, C. (2009). *The use of LCA in selecting the best MSW management system*. *Waste Management*, 29(6), 1901–1915. <https://doi.org/10.1016/j.wasman.2008.12.021>

Fikri, I., Riani, E., & Nedi, S. (2024). Marine tourism suitability index in the Padang Beach Tourism Area, West Sumatra. *Jurnal Penelitian Pendidikan IPA*, 10(3), 1281–1291. <https://doi.org/10.29303/jppipa.v10i3.5109>

Gunamantha, M., Fandeli, C., Djalal Tandjung, S., & Sarto, S. (2010). Life cycle assessment of solid waste management options: A case study of the Kartamantul regions, Province of D.I. Yogyakarta. *Journal of People and the Environment*, 17(2), 78–88. <https://doi.org/10.22146/jml.18706>

Intergovernmental Panel on Climate Change. (2006). *2006 IPCC guidelines for national greenhouse gas inventories: Volume 5 – Waste*. Hayama, Japan: Institute for Global Environmental Strategies.

International Organization for Standardization. (2006). *Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006)*. Geneva, Switzerland: ISO.

Islam, M.T., & Iyer, R.U. (2023). Life cycle assessment of e-waste management system in Australia: Case of waste printed circuit board (PCB). *Journal of Cleaner Production*, 418. <https://doi.org/10.1016/j.jclepro.2023.138082>

Laurent, A., Bakas, I., Clavreul, J., Bernstad, A., Niero, M., Gentil, E., Hauschild, M.Z., & Christensen, T.H. (2014). Review of LCA studies of solid waste management systems – Part I: Lessons learned and perspectives. *Waste Management*, 34(3), 573–588. <https://doi.org/10.1016/j.wasman.2013.10.045>

LCDI Indonesia. (2022). *Institutional analysis, planning, and funding options for waste management*. <https://lcdi-indonesia.id/wp-content/uploads/2024/01/Kajian-Keberlanjutan-Fasilitas-Pemilahan-dan-Pengolahan-Sampah-di-Indonesia.pdf>

Ministry of Public Works of the Republic of Indonesia. (2013). *Regulation of the Minister of Public Works of the Republic of Indonesia Number 03/PRT/M/2013*.

Nurhuda, W.U., Aziz, R., & Komala, P.S. (2024). Environmental impact evaluation of existing solid waste management practices in Padang pariaman regency using life cycle assessment (LCA). *AIP Conference Proceedings*, 2891(1). <https://doi.org/10.1063/5.0202996>

Pujara, Y., Govani, J., Patel, H.T., Pathak, P., Mashru, D., & Ganesh, P.S. (2023). Quantification of environmental impacts associated with municipal solid waste management in Rajkot city, India using Life Cycle Assessment. *Environmental Advances*, 12. <https://doi.org/10.1016/j.envadv.2023.100364>

Ridwan, M.F., Aziz, R., & Regia, R.A. (2024). Application of life cycle assessment on processing of beef rendang products using steam cauldron technology. *Ecological*

Engineering and Environmental Technology, 25(9), 298–310.
<https://doi.org/10.12912/27197050/190384>

Rigamonti, L., Grosso, M., & Giugliano, M. (2009). Life cycle assessment for optimising the level of separated collection in integrated MSW management systems. *Waste Management*, 29(2), 934-944. <https://doi.org/10.1016/j.wasman.2008.06.005>

Taşkın, A., & Demir, N. (2020). Life cycle environmental and energy impact assessment of sustainable urban municipal solid waste collection and transportation strategies. *Sustainable Cities and Society*, 61. <https://doi.org/10.1016/j.scs.2020.102339>

World Economic Forum. (2017). *The travel & tourism competitiveness report 2017*. Retrieved from https://www3.weforum.org/docs/WEF_TTCR_2017_web_0401.pdf

Zhou, Z., Tang, Y., Dong, J., Chi, Y., Ni, M., Li, N., & Zhang, Y. (2018). Environmental performance evolution of municipal solid waste management by life cycle assessment in Hangzhou, China. *Journal of Environmental Management*, 227, 23–33. <https://doi.org/10.1016/j.jenvman.2018.08.083>