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POTENTIAL ENVIRONMENTAL IMPACTS OF SOLID WASTE MANAGEMENT IN YOGYAKARTA, INDONESIA: A COMPARATIVE STUDY USING LIFE CYCLE ASSESSMENT

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Abstract

Life Cycle Assessment (LCA) serves as a tool to estimate the potential impacts of a waste management system. Sleman Regency needs a scenario of waste management with a lower environmental impact. The present study aims to determine the potential impact of the existing business as usual (BAU) waste management practice in Sleman Regency and compare it with several alternatives to waste management strategies. The LCA method was applied following ISO 14040 and ISO 14044 standards. The impact was assessed using the CML-1A Baseline and ILCD 2011 Midpoint+ methods, along with data from the Ecoinvent database. In the BAU scenario, the impact values observed in every 1 ton of waste managed were Global Warming Potential (GWP) of 4.90E+03 kg CO_2 eq, Acidification Potential (ADP) of 2.78E-03 kg SO_2 eq, Eutrophication Potential (EP) of 4.92E-02 kg PO_4^-eq, Human Toxicity Potential (HTP) of 2.06E+01 kg 1.4 DB eq, and Land Use Potential (LUP) of 4.71E+01 kg C deficit. Processing waste into biomass pellets and Refuse Derived Fuel accompanied by waste reduction could decrease the GWP value to 34.04 kg CO_2 eq, ADP to 2.96E-06 kg SO_2 eq, EP to 7.33E-05 kg PO_4^-eq, HTP to 3.70E-04 kg 1.4 DB eq, and LUP to 2.11E-03 kg C deficit. The results of waste management with the lowest impact value can serve as a reference for formulating waste management policies in the study area.

Keywords Cradle to grave, environmental impact, life cycle assessment, management, solid waste.

INTRODUCTION

Up to the present, waste remains a serious problem for developing countries, including Indonesia. Poor solid waste management leads to various environmental problems such as water, soil, and air pollution (Abdel-Shafy and Mansour, 2018). Yogyakarta and its neighboring cities are in need of waste management efforts, especially after the Piyungan Landfill, which is the foundation for landfilling waste in Bantul, Sleman, and Yogyakarta Regencies, has stopped operating. This certainly raises concerns for areas included in the scope of Piyungan landfill services. The waste management system in Yogyakarta predominantly applies the end-of-pipe (EOP) principle, with the general operating system still being open dumping. This method is considered incapable of addressing waste problems such as waste piles, the emergence of illegal waste disposal sites, land limitations, and environmental pollution, all of which ultimately have an impact that can be felt by the community (Muthmainah 2007; Radyan Danar et al., 2019). Open dumping is widely used in waste management due to improper planning of the waste management system, low funding, and law enforcement of applicable regulations (Salvia et al., 2021; Yazdani et al., 2015).

In addition to reducing landfill capacity, open dumping operations also may potentially lead to several environmental impacts. These include leachate, greenhouse gases, and heavy metal contamination in soil (Ali et al., 2014; Siddiqua et al., 2022; Vaverková, 2019). Open dumping requires a large area of land to accommodate waste. Before being disposed of in a landfill, waste is usually accommodated in a Temporary Shelter (TPS) or Waste Transfer Depot. However, the existence of temporary shelter has not significantly reduced the amount of waste entering the landfill. As of 2023, Sleman Regency is recorded as the largest contributor to the volume of waste entering the Piyungan Landfill. Several rural areas still do not have a controlled waste management system. This suggests that the EOP method with an open dumping operating system is not an appropriate and sustainable method of waste management in the Sleman Regency.

The amount of generation, location, composition, and characteristics of waste are the most considered factors in waste management (Gallardo et al., 2016). Waste generation and location will affect the fleet requirements for waste transportation. The utilization of fossil fuels during transportation will also contribute to emissions in the environment. The composition and characteristics of waste will be a contributing factor in the formation of leachate, GHG, and contaminants that can be released to the environment such as organic matter and heavy metals.

Leachate is a liquid that develops from waste piles when compounds in the waste dissolve as rainwater seeps in (Tchobanoglous & Kreith, 2019). Meanwhile, GHGs are gases resulting from waste decomposition such as CH_4, H_2S, CO_2, and NH_3 which can further lead to an increase in the concentration of greenhouse gases that cause global warming (Reddy et al., 2017; Werkneh, 2022). Several other studies also investigated various environmental impacts, including acidification potential, eutrophication potential, and human toxicity potential (Dangi et al., 2023; Kossakowska & Grzesik, 2019; Sharma et al., 2023; Shekoohiyan et al., 2023). The value of potential environmental impact can serve as one of the approaches to determining a more environmentally friendly waste management scenario (Arushanyan et al., 2017; Aziz & Nurunnissa, 2022). Aiming to consider the best solution for sustainable waste management, Life Cycle Assessment (LCA) is regarded as one of the tools that can be utilized to evaluate waste management performance. According to ISO

14040: 2006, stages of LCA consist of goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation. Several studies employed LCA to determine the appropriate waste management scenario for a particular area (Buratti et al., 2015; Fernández-Nava et al., 2014; Khandelwal et al., 2019). In general, the waste management scenarios considered are based on the generation, composition, and characteristics of waste generated from a specific area. The results obtained from LCA can provide a foundation for decision-making in solid waste management strategies and regulations (Pérez et al., 2020; Rajendran et al., 2021; Torkayesh et al., 2022).

Life Cycle Inventory (LCI) is a crucial component in LCA study (Dangi et al., 2023). Input and output data are collected based on the scope of this study through measurement, estimation, and calculation (Farhan et al., 2024). Emission resulting from waste decomposition and combustion, and fossil fuels are calculated. Waste-to-Energy becomes the most preferred scenario in waste management. This aligns with the waste management triangle, which indicates that waste conversion is a better alternative to landfilling. Waste can be utilized in alternative fuels such as Refuse Derived Fuel (RDF) and pellet fuels (Mohan et al., 2023; Wei et al., 2024). Anasstasia et al. (2020) found that domestic waste with a potential heating value of 3,883 kCal/kg utilized in the cement industry could reduce GWP by 10% compared to open dumping. Additionally, RDF and biomass can also be used as alternatives to fossil fuels for generating electricity (Karpan et al., 2021; Kusumaningrum & Munawar, 2014; Rimantho et al., 2023). Numerous benefits can be obtained by converting waste into alternative fuels such as reducing the rate of waste generation; preventing the spread of diseases caused by waste; minimizing the potential for water, soil, and air pollution caused by waste; achieving economic gains; and obtaining renewable energy sources from waste (Hajam et al., 2023; Rezania et al., 2023). In this study, the Cradle-to-Grave LCA approach was employed to calculate the potential environmental impacts of the existing waste management system in Sleman Regency and to analyze the potential benefits of implementing a waste processing scenario into renewable fuels by comparing the potential impact values.

MATERIALS AND METHOD

Case study area

Waste is generally managed by local governments and non-governmental organizations. Waste management carried out by the local government begins with collecting waste using containers (C) and transporting them using garbage carts to the Transfer Depot (TD) or Temporary Shelter (TPS). The waste is then transported to the landfill communally. On the other hand, non-governmental organizations manage the waste by directly transporting it to the landfill (DD). At TD and TPS, waste reduction is possible to be carried out by processing the waste into compost and selling some that still have economic value. Based on the territory, Solid Waste (SW) comes from urban and non-urban areas (Fig.1).

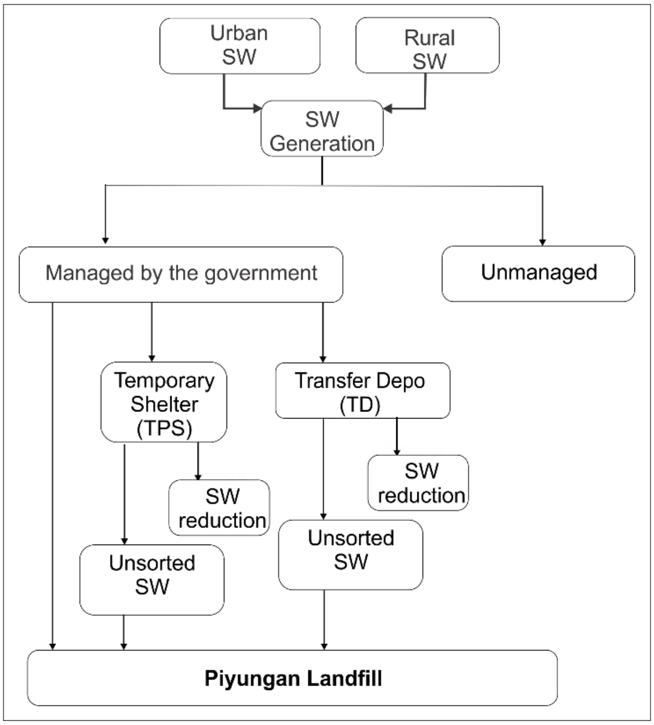

Figure 1. Waste management system in Sleman Regency

Solid waste is generated by a variety of sources, including residental areas, markets, educational institutions, offices, hotels, shops, restaurants, and so on. Waste is transported from the sources to the TPS using motorized carts. Subsequently, the waste is transported from the TD and TPS to TPA Piyungan using dump trucks. SW is disposed of at the TPA Piyungan in a partially controlled landfill or even inclined towards open dumping. Waste originates from two sources: the collection and sorting process units, and directly from the source of waste itself. SW is transported to the TPA using dump trucks, covering an average distance of 20.12 km. It is sent 2 times a day from the Transfer Depot, 2 times a week from the TPS, and 2 times a day from the private sector. The number of active dump trucks is 36 units. In total, there are 14 TD managed by the government and 209 TPS managed by both the government and the private sector (Fig.2).

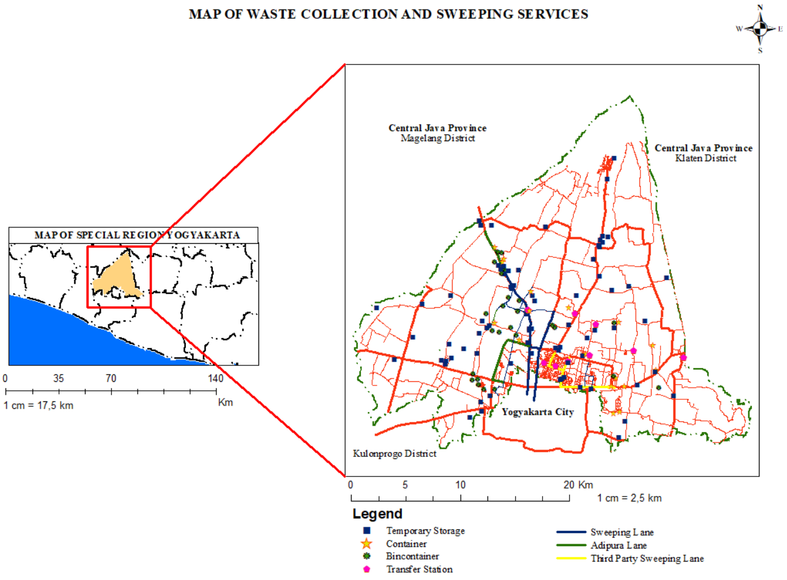

Figure 2. Distribution of temporary shelters and transfer depots in Sleman Regency

Data collection

The waste sampling was carried out in accordance with SNI 19-3964-1994. The samples were collected from the TPS and TD to determine their composition and characteristics. Based on the data taken from the Environmental Agency of Sleman Regency, the average waste generation in this regency from 2028 to 2023 was 31.41% of organic waste, consisting of food waste, vegetable waste, and garden waste. The remaining waste consisted of plastic waste (26.18%), paper (25.13%), glass (5.24%), metal (4.71%), toxic hazardous waste (6.81%), and residue (0.52%).

Scenario

Scenario 1: Business as Usual (BAU).

Generally, waste management in Sleman Regency includes collection, delivery, and open dumping. Throughout 2028-2023, on average, 51% of waste had been managed by the local government, while 49% remained unmanaged (Fig.1). The managed waste is collected at temporary waste disposal sites (TPS) and transfer depots. Once collected, it is then disposed of in the landfills. Meanwhile, unmanaged waste is either burned or dumped on open land, usually in areas outside the range of the Sleman Regional Government, such as rural regions.

Scenario 2: Full Landfilling.

This scenario begins with the collection of waste from residential areas, offices, markets, and so on. Waste is collected using motorized garbage carts or pickups and then transported to the landfill. It is assumed that Sleman Regency still uses the Piyungan landfill.

Scenario 3: Full Pellet and RDF.

This scenario follows the same initial stages as scenario 3, except that it applies to all waste generated. Therefore, no waste is burned openly or disposed of in landfills. This scenario does not require landfills for landfilling. The processing of RDF and biomass pellets is performed at the TPS or TD.

Scenario 4: Pellet, RDF, and several unmanaged waste.

The initial stages of this scenario are similar to those of scenario 1, except that the waste managed by the Local Government is processed into RDF and Pellets. Ecoenzymes are utilized to process organic waste and residues into pellets (Winaningsih et al., 2023; Wu et al., 2022). Meanwhile, the remaining waste such as combustible solid waste is shredded to become RDF. There are two assumptions of scenario, with the waste group already segregated when received at TD and TPS.

LCA framework

Goal and scope definition.

The current study aims to calculate the potential environmental impact of waste management in Sleman Regency and compare it with WTE-based waste management as an alternative scenario. The purpose of the alternative treatment scenario provided is to improve the performance of waste management in Sleman Regency with lower environmental impact. The Functional Unit in this study is the total amount of waste managed in Sleman Local Government within a single year. System boundary in this study is illustrated in Figure 3. The scope of this study is Cradle-to-Grave, encompassing the entire lifecycle of waste from its entry to the end of its life phase.

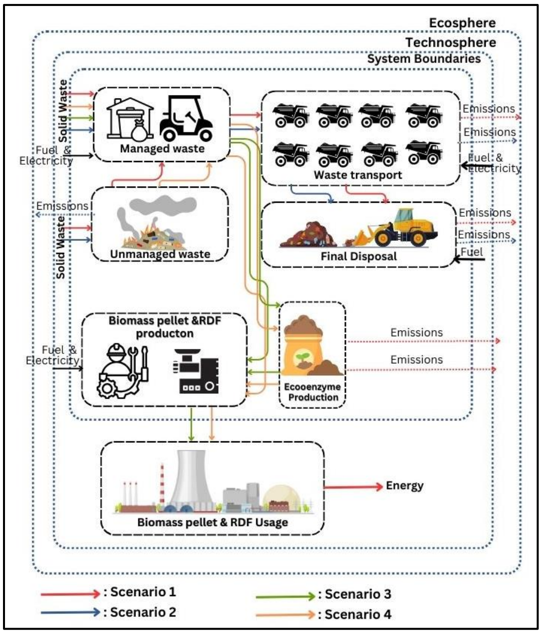

Figure 3: The system boundary of the solid waste management

Life cycle inventory.

Inventory data were obtained from the input and output data of each process unit, which were derived from field measurements, calculations, interviews, and literature data. The inputs included the use of resources, energy, and fuel, while the outputs included emissions, waste, and products produced (Table 1). Data related to waste generation and composition were obtained from the inventory data of the Environmental Agency of Sleman Regency. Meanwhile, the characteristics of waste were obtained from the results of waste sampling derived from TPS and TD.

Haulage, bulldozer, and excavator emissions

Emission from the use of diesel fuel was calculated based on with Equation 1 . The results revealed that in one year, the garbage trucks traveled an average distance of 27,819.33 km/truck and an average diesel fuel needed was 4,164.22 liters/truck.

$$\text{Emission} = \sum_a (Fuel_a x EF_a) \qquad (1)$$

Where: Emission= CO_2, CH_4, and N_2O (kg); Fuel= Fuel Consumed (liter); EF= Emission Factor (CO_2=74.52 t/TJ; CH_4=0.005 t/TJ; N_2O=6.00E-04 t/TJ).

- Landfill gas estimation

In scenarios 1, 2, and 3, the emission values resulting from landfilling were calculated based on IPCC (2006), utilizing Equation 2 to Equation 6, assuming that greenhouse gases would be formed in approximately 6 months (Toha & Rahman, 2023)

$$Q\ (T,X) = A\ x\ K\ x\ MSWT\ x\ MSWF\ x\ MCF\ x\ Lo(X)\ x\ e^{-K(T-X)} \qquad (2)$$

$$A = \frac{(1-e^{-k}\ )}{k} \qquad (3)$$

$$K = \frac{ln\ 2}{t.5} \qquad (4)$$

$$Lo = MCF\ x\ DOC\ x\ DOCf\ x\ F\ x\ \frac{16}{12} \qquad (5)$$

$$DOC = 0.4A + 0.17B + 0.15C + 0.30D \qquad (6)$$

Where: K = Methane generation constant; Lo = Potential methane production; A = correction factor; t.5= the half-life the waste (3 years); DOC = Degradable Organic Carbon; DOCf= dissimilated organic carbon; F= Fraction of Methane (F=0,50); A= paper+ rags; B= leaves+hay+straw; C=fruit and vegetables; D= Wood.

- Estimation of leachate production

Leachate formed from the landfills was calculated using a standard method that is relatively easy and does not include many parameters, assuming that 75% of it originates from rainfalls, according to equation 7 (Choden et al., 2022; Ibrahim et al., 2017). According to BPS Data 2023in Yogykarta Province, the average annual rainfall is 221.92 mm.

$$V = 0.15\ x\ R\ x\ A \qquad (7)$$

Where: V= volume of leachate discharge in a year (m^3.$year^{-1}$); R= annual rainfall (m); A= surface area of the landfill (m^2)

Table 1. Life cycle inventory of every 1 ton of waste management

Scenario	Input		Unit	Output		Unit
SC-1:BAU	Solid waste	1.00E+00	t	Solid waste. in landfill	1.91E-01	t
	Diesel	4.20E+00	l	Ash	4.04E-02	t
	Electricity	7.81E+00	kWh	CO_2	2.55E+00	t
	Land	1.26E-06	l	CH_4	2.51E-02	t
	Soil cover	1.44E+01	m^3	N_2O	9.07E-05	t
				Leachate	4.20E-03	m^3year-1
				Cd	1.60E-02	kg
				Cr	9.32E-02	kg
				Cu	1.84E-01	kg
				Fe	7.87E+00	kg
				Ni	1.78E-02	kg
				Pb	1.52E-01	kg
				Zn	7.35E+00	kg
				SiO_2	1.99E-02	kg
				Ca	1.42E+02	kg
				Mg	2.68E-02	kg
				K	1.12E+01	kg
				Na	8.91E+00	kg
				BOD	8.41E-03	kg
				COD	6.30E-03	kg
				TOC	1.26E-02	kg
				TSS	8.41E-04	kg
				Nitrogen	4.20E-05	kg
				Ammonia	4.20E-05	kg
				Nitrat	2.10E-05	kg
				Phosphorus	2.10E-05	kg
				Calcium	8.41E-04	kg
				Magnesium	2.10E-04	kg
				Potassium	8.41E-04	kg
				Sodium	8.41E-04	kg
				Chloride	8.41E-04	kg
				Sulfate	2.10E-04	kg
				Iron	2.10E-04	kg
SC-2: All Open Dumping	Solid waste	1.00E+00	t	Solid waste. in landfill	1.00E+00	t
	Diesel	1.74E+01	l	CO_2	9.56E+03	t
	Electricity	7.81E+00	kWh	CH_4	3.12E+00	t
	Land	5.35E-06	ha	N_2O	3.72E-01	t
	Soil cover	6.09E+01	m^3	Leachate	1.78E-02	m^3year-1
				BOD	3.56E-02	kg

Scenario	Input		Unit	Output		Unit
				COD	2.67E-02	kg
				TOC	5.34E-02	kg
				TSS	3.56E-03	kg
				Nitrogen	1.78E-04	kg
				Ammonia	1.78E-04	kg
				Nitrat	8.90E-05	kg
				Phosphorus	8.90E-05	kg
				Calcium	3.56E-03	kg
				Magnesium	8.90E-04	kg
				Potassium	3.56E-03	kg
				Sodium	3.56E-03	kg
				Chloride	3.56E-03	kg
				Sulfate	8.90E-04	kg
				Iron	8.90E-04	kg
SC-3: RDF & Pellet	Solid waste	1.00E+00	t	Biomass	2.40E+05	kCal
	Diesel	7.77E+00	l	Fluff RDF	2.88E+06	kCal
	Electricity	1.61E-03	kWh	CO_2	1.27E+01	t
	Ecoenzym	2.24E+04	mL	CH_4	2.52E-02	t
				N_2O	1.02E-04	t
				Wastewater	2.92E+01	kg
SC-4: RDF. Pellet. and Unmanaged Solid Waste	Solid waste	1.00E+00	t	Fluff RDF	9.80E+01	kg
	Diesel	2.00E+00	l	Biomass	1.53E+01	kg
	Electricity	7.81E+00	kWh	Unmanaged waste	8.09E+02	kg
				CO_2	5.55E+07	kg
				N_2O	1.89E-02	kg
				CH_4	1.82E-01	kg
				Cd	1.60E-02	kg
				Cr	9.32E-02	kg
				Cu	1.84E-01	kg
				Fe	7.87E+00	kg
				Ni	1.78E-02	kg
				Pb	1.52E-01	kg
				Zn	7.35E+00	kg
				SiO_2	1.99E-02	kg
				Ca	1.42E+02	kg
				Mg	2.68E-02	kg
				K	1.12E+01	kg
				Na	8.91E+00	kg
				Abu	4.04E+01	kg
				CO_2	1.26E+03	kg

Scenario	Input	Unit	Output		Unit
			CH_4	1.71E-09	kg
			N_2O	2.06E-10	kg
			CO_2	2.55E-05	kg
			CH_4. landfill	3.19E+00	kg
			Waste water	5.13E+01	kg

Life cycle impact assessment (LCIA)

The inventory data is still unable to show the potential impact value of some types of waste management. The LCIA stage aims to convert values derived from inventory data into impact values, particularly from the use of resources and emissions charged to the environment. In this study, the CML-1A Baseline and ILCD 2011 Midpoint+ methods were employed. This method can generate environmental impact categories, including Global Warming Potential (GWP), Acidification Potential (ADP), Eutrophication Potential (EP), Human Toxicity Potential (HTP), and Land Use Potential (LUP). The selection of impact categories was based on important issues that typically result from waste management and analysis of several inventory data (Table 1). Normalization was utilized to determine which impact categories are the most important to be discussed and become the main review in comparing the most environmentally friendly waste management scenarios, which will be further discussed in the interpretation section.

Interpretation

Interpretation is the final stage of this LCA study. Identifying key issues across various impact categories is necessary to establish the most appropriate environmental improvement priorities. The identification of important issues was determined based on the normalization results. The three most relevant impact categories for discussing significant issues, based on the normalization and weighting results, highlight some inventories that have the greatest influence on the impact value. Interpretation was carried out for the impacts related to Global Warming Potential (GWP), Acidification Potential (ADP), Eutrophication Potential (EP), Human Toxicity Potential (HTP), and Land Use Potential (LUP).

RESULTS AND DISCUSSION

Environmental impact of BAU scenario

Concerning the selection of the most appropriate scenario to be applied for waste management in Sleman Regency, it has been discussed previously that there are 3 alternative scenarios. According to the field data collected, which are summarized in Table 1 about data inventory, the amount of waste generated in Sleman Regency was the same at approximately 38,333.2 tons.y-1. However, only about 19% of waste was managed by the Regional Government in the existing condition. Meanwhile, the impact category results for each scenario are summarized in Table 2 below.

Table 2. Summary of potential environmental impact value of BAU scenario

Impact Category	Impact Assessment	Unit
Global Warming Potential	4.90E+03	kg CO_2 eq.
Acidification Potential	2.78E-03	kg SO_2 eq.
Eutrophication Potential	4.92E-02	kg PO_4 eq.
Human Toxicity Potential	2.06E+01	kg 1,4-DB eq.
Land Use	4.71E-08	kg C deficit eq.

Table 2 and Fig 4 exhibits that waste management activities, from collection to open dumping (BAU), have the potential to generate environmental impacts such as Global Warming Potential, Acidification Potential, Eutrophication Potential, Human Toxicity, and Land Use. This impact value is derived from both direct emissions and indirect emissions. For the Global Warming Potential (GWP) measured in kg CO2 eq, it is evident that the open dumping stage has the greatest influence on the magnitude of the impact value. This is because open dumping generates a significant amount of gases from waste decomposition, such as CH4. The majority of these gases are produced from the decomposition of organic waste, which is the most dominant among other types of waste. The Acidification Potential (ADP) impact was calculated in kg SO2 eq. The largest ADP impact value comes from the waste transportation process to the landfill site (TPA).

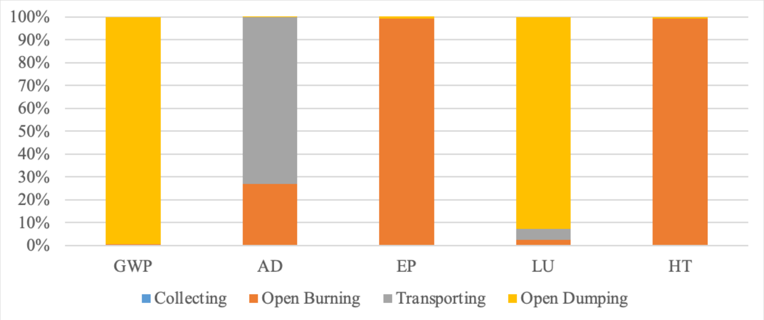

Figure 4. The primary contributor to environmental impacts in the BAU Scenario

During the waste transportation process, indirect emissions or background data from fuel consumption are produced. Consequently, the impact value increases with higher fuel usage. The amount of fuel used depends on the amount of waste transported to the landfill. Concerning the Eutrophication Potential (EP) impact, it was calculated in units of kg PO4 eq. The results suggest that the largest contributor to the impact is indirect emissions from burning waste of unmanaged waste. This also applies to the potential impact of Human toxicity (HTP). In terms of Land Use Potential (LUP), the largest contribution of impacts is generated from open dumping of waste in landfills. These results indicates that the two most significant contributors of impact are emissions from the open dumping process and the transportation of waste to landfills.

Comparison between BAU scenario and other scenarios

The results of the input and output inventory serves as foundation for determining the value of potential impacts, particularly those related to the use of resources and emissions released to the environment. The analysis of impact normalization using the World 2000-CML-IA-Baseline method revealed that the most significant impacts on waste management were Global Warming Potential, Acidification, Eutrophication, and

Human Toxicity.

After comparing the three scenarios, it was found that Scenario 3 yielded the lowest impact value among the others (Fig.5). Scenario 1 generated the highest impact value for the GWP category. Scenario 2 had the highest impact value for the ADP and LUP categories. Meanwhile, Scenario 4 recorded the highest impact value for the EP and HTP categories.

Comparison of the impact contributions of the four scenarios at the midpoint level

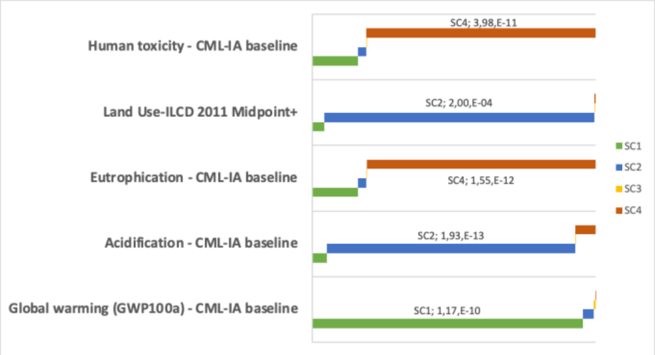

Figure 5. Comparison of impacts of normalized waste management scenarios

Global warming potential (kg CO_2 eq.).

Global Warming Potential (GWP) refers to an environmental impact caused by the release of greenhouse gases, which contributes to the increase in Earth's temperature (Muralikrishna & Manickam, 2017). Some emissions such as CO_2, CH4, and NO2 are classified in the GWP impact category (EPA, 2024). The composition of waste was dominated by those containing Degradable Organic Carbon. According to the approach utilizing Equations 2 and 6, the DOC content in waste leads to the formation of CH_4 gas as a result of the decomposition process, which in turn contributes to the GWP impact value. CH_4 emissions become an impact hotspot for Scenario 1, Scenario 4, and Scenario 2 as a result of open dumping in waste management. SO_2 and NOX emissions mostly come from indirect emissions due to the use of fossil fuels. Fossil CH_4 emissions also contribute to the impacts in Scenarios 2 and 3 as direct emissions from fuel use, even though they are not dominant. Fuel use during the production process of pellet and RDF (collection, sorting, and shredding) generates direct emissions that cause GWP impacts (Fig. 6a)

Acidification Potential (kg SO_2 eq.).

Acidification Potential (AP) is an impact that can produce acid rain. Emissions classified under AP are sulfur dioxide (SO_2), nitrogen oxide (NOx), nitrogen monoxide (NO), and several others (Dincer & Abu-Rayash, 2020). Some emissions such as SO_2 and NOx are impact hotspots. One of the consequences of the open burning of waste is the production of ash from combustion. Additionally, emissions generated from fossil fuels during the production process are considered indirect emissions (Fig. 6b).

Eutrophication Potential (kg PO_4 eq.).

Eutrophication Potential (EP) generally occurs due to an increase in nutrient levels in the water caused by nitrogen and phosphorus, leading to an increase in phytoplankton productivity (Banar et al., 2009). In the BAU scenario and Scenario 4, the impact value is attributed to PO_4 produced from ash generated by burning waste and released into the environment. Meanwhile, when all waste is disposed of in landfills (Scenario 2), several other emissions, including NO_3, COD, NOx, N_2O, and Phosphorus, contribute almost equally. In Scenario 3, the largest contribution comes from N_2O emissions resulting from the use of fossil fuels during waste collection and the production of pellets and RDF (Fig. 6c).

Human Toxicity Potential (kg 1.4-DB eq.).

Human toxicity refers to the adverse effect on humans due to the toxicity of chemicals released into the environment (Mio et al., 2022). Waste combustion activities produce several metals that can be released into the environment (Scenario 1 and Scenario 4) such as Pb, Br, and Mb, which are emitted into the air or contained in the combustion ash. Meanwhile, in scenario 2, leachate from open landfilling has the potential to release several metals that can lead to human toxicity impacts. As for Scenario 3, the impact hotspot arises from utilizing ecoenzyme in biomass pellets production, with the actual impact value stemming from the background data of ecoenzyme production (Fig. 6d).

Land Use Potential (kg C deficit).

Land use is an impact caused by land intervention due to land conversion, including occupation (Vidal-Legaz et al., 2016). Land occupancy from scenarios with open waste disposal (Scenarios 1, 2, and 4) is the impact hotspot. This suggests that without waste treatment, land use impacts will increase. As for Scenario 3, the reliance on ecoenzymes in the production of biomass pellets requires land transformation to ensure the availability of raw materials (Fig. 6e).

Sensitivity analysis

Several researchers have employed sensitivity analysis to assess the significance of variables in generating impacts. In this case, the scenario of converting waste into biomass pellets and RDF is the best scenario in terms of the lowest impact value. However, the contribution analysis reveals that fuel use in waste collection and the production of pellets and RDF results in hotspots. Therefore, determining possible steps when the scenario is implemented is necessary. The use of fuel in waste collection depends on the amount of waste transported.

The sensitivity analysis results (Table 3) exhibit a decrease in the GWP and EP impact values when scenario 3 was implemented with waste reduction at the beginning of the collection. The lower amount of waste leads to lower fuel use, resulting in lower potential impact values across all five impact categories. The reduction of waste fuel use depends on the amount of waste managed. When the waste entering the transfer station or transfer depot is less than that in the initial scenario, the fuel required for waste transportation and segregation will also be significantly reduced.

Limitations of the study

This research is a prediction of the potential impacts of several waste management options that can be implemented in Sleman Regency using LCA. The limitation of this research was the lack of secondary data related to ecoenzyme production. To overcome this, vinasse data from Global libraries (GLO) were used. LCA analysis can help to determine environmentally friendly management scenarios in waste management that are relative rather than absolute.

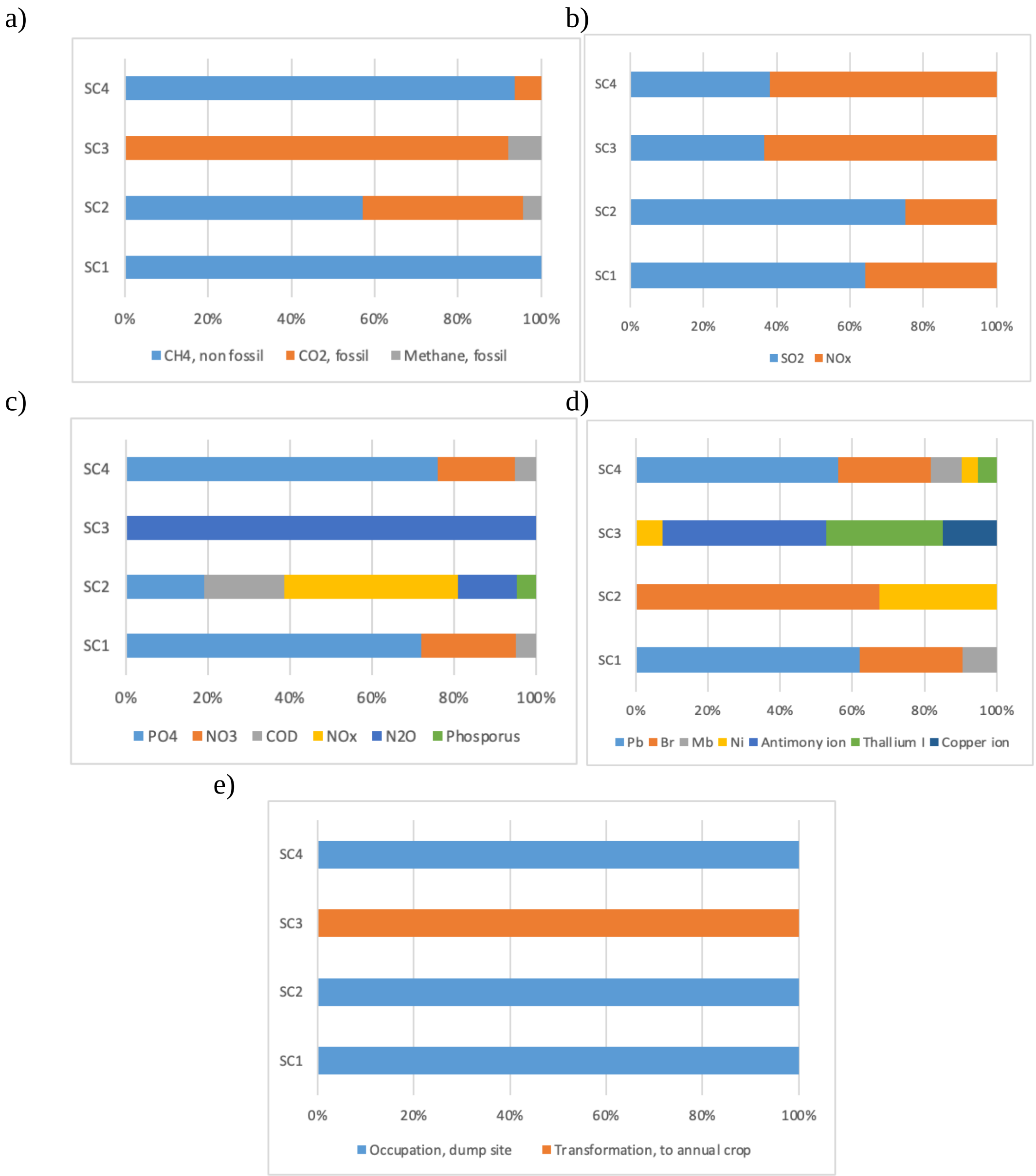

Figure 6. Impact contributor: a) GWP ; b) ADP; c) EP; d)HTP; dan e) LUP

CONCLUSION

According to the LCA results, the environmental impact generated from the existing scenario is not the most effective scenario for waste management. The impact value is caused by direct emissions from waste and fuel use. Emissions from waste may be released into the atmosphere, leading to GWP impacts. Meanwhile, the use of fossil fuels contributes to ADP, EP, and HTP impacts. Additionally, EOP with open dumping operation causes LUP impact. Enhancing the usability of waste for producing biomass pellets and RDF could significantly reduce the potential impact for every 1 ton of waste managed. GWP value decreased from 4.90E+03 to 37.87 kg CO_2 eq. (-99.20%), ADP value from 2.78E-03 to 2.96E-06 kg SO2 eq. (-99.9%), EP value from 4.92E-02 to 7.59 kg PO4-eq. (-99.8%), HTP value from 2.06E+01 to 3.70E-04 kg 1.4 DB eq. (-100%), and LUP value from 4.71 to

2.11E-03 kg C deficit eq. (-100%). Furthermore, processing waste into biomass pellets and RDF, along with waste reduction, could decrease GWP (-10.11%) and EP (-3.43%) for every 1 ton of waste managed. The results of this LCA study can serve as a consideration for stakeholders in Sleman Regency in determining waste management with lower environmental impact. Particularly, it is important to focus on waste reduction from the upstream by ensuring that supporting facilities, such as waste storage to waste transportation, as well as technological readiness for waste processing, are well-considered. Finally, further studies on the techno-economics of the WTE option is necessary to evaluate the economic perspective of waste management that have lower environmental impact.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest related to this study.

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