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Regional Case Study

Assessing the Environmental and Health Impacts of Thermal Waste and Landfill-Based Waste Management

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Abstract
According to Presidential Regulation No. 35 of 2018, which focuses on accelerating the development of waste-to-energy projects, Denpasar City in Bali has been identified as one of the key Indonesian cities for implementing these projects. The daily waste generation in Denpasar City is estimated at 750 tons. The city's sanitation strategy outlines that 20% of this waste will be reduced at its source, while the remaining 80% is managed at the final treatment site. This study employs the Life Cycle Analysis (LCA) approach to evaluate the environmental impacts of traditional landfilling and various thermal waste treatment methods. The findings reveal that gasification (Scenario 2) has the lowest Global Warming Potential (GWP), with 779,759 kg CO_2 equivalent emitted, indicating its superiority in reducing greenhouse gases. In contrast, landfilling (Scenario 1) is the least favorable, with a GWP of 2,885,770 kg CO_2 equivalent and a significant cancer risk due to hexavalent chromium emissions estimated at 1,634,050 kg equivalent. These results underscore the health and environmental hazards of landfilling. Further, the study delves into each treatment scenario's impact on acidification, eutrophication, global warming potential, and photochemical oxidation.

Keywords: Denpasar City; impact scenario; LCA; thermal; waste to energy

1. Introduction

Based on the National Waste Management Information System (SIPSN), the waste generation rate in Denpasar reached 750 tons per day in 2018, as reported by (Kementerian Lingkungan Hidup dan Kehutanan, 2021). The heating value of waste in Denpasar has met the minimum standard required for Refuse-Derived Fuel (RDF) (Qonitan et al., 2021). In line with the Presidential Regulation (PERPRES) Number 35 of 2018, which aims to accelerate the development of waste-to-energy (WtE) projects, Denpasar is mandated to convert its waste into energy (Qodriyatun, 2021). The city has set a waste reduction target of 20% as outlined by the Denpasar City Working Group (Pemerintah Kota Denpasar, 2013), achievable through reduction, reuse, and recycling activities from the source to the waste transfer station (TPS). However, these measures have been insufficient in addressing the issue of land scarcity for landfilling processes.

This predicament necessitates a breakthrough in waste management technology, with one potential solution being the adoption of waste-to-energy (WtE) technology (Raksasat et al., 2021; Suryawan et al., 2023; Suryawan & Lee, 2023). Regarding WtE adoption, Indonesia's efforts have primarily focused on tapping into landfill gas (Budiarto et al., 2021; Kurniawan et al., 2022). As organic waste decomposes anaerobically within landfills, it produces biogas, a mixture of methane and carbon dioxide (Atabani et al., 2019; Binaghi et al., 2007; Kim & Oh, 2011; Martins das Neves et al., 2009). This gas is a potent greenhouse emitter if released unchecked into the atmosphere, but it can be harvested as a valuable energy resource (Yodi et al., 2020). Specialized infrastructure is installed in landfills to collect this gas, which involves a network of pipes, wells, and flares (Siddiqui et al., 2022; Vakylabad & Moravvej, 2023). Once captured, the landfill gas can be used to generate electricity or heat (Batool et al., 2020; Kaur et al., 2023). For instance, it can be burned in a gas engine to produce electricity or cleaned and used directly for cooking or heating (Banaget et al., 2020). Even though other WtE technologies like pyrolysis, gasification, and incineration have been acknowledged for their energy-producing potential and their role in reducing waste volume (Roy et al., 2022), their deployment in Indonesia is not as widespread (Sari et al., 2023, 2024; Sarwono et al., 2021; Suryawan et al., 2022). Pyrolysis thermally breaks down waste without oxygen to produce syngas and solid char (Sari et al., 2023, 2024). Gasification uses limited oxygen to convert organic materials into a synthesis gas, which can then be used for power generation or as a chemical feedstock (AlNouss et al., 2020; dos Santos & Alencar, 2020). Incineration burns waste to produce steam that can drive turbines to generate electricity (Zahedi et al., 2022). Applying these more complex WtE processes in Indonesia faces challenges such as high initial investment costs, technical complexity, and the need for robust environmental safeguarding measures. Nevertheless, the interest in these technologies is growing, with the potential for future expansion to help Indonesia manage its waste problems more sustainably and with added energy production benefits.

The Suwung landfill in Denpasar City currently employs an open dumping method for waste disposal (Dana & Saraswati, 2022; Handriyani et al., 2020; Septiariva & Suryawan, 2021), a conventional technique favored in many parts of Indonesia because of its low operational costs. Open dumping involves waste disposal in a designated area without treatment or containment measures to prevent environmental contamination (Siddiqua et al., 2022). Despite its cost-effectiveness, open dumping has several significant environmental drawbacks. One of the primary issues is the risk of water and soil contamination through leachate production (Siddiqua et al., 2022). This liquid percolates through the waste material and can carry harmful substances into the environment (Ma et al., 2022).

Furthermore, landfills like Suwung generate methane and carbon dioxide emissions from the decomposition of organic waste. These are potent greenhouse gases that contribute to climate change, and methane, in particular, poses a risk of flammability (Cristello et al., 2023). In addition to the risk of fires, human exposure to volatile chemicals is a concern, as these can be harmful if inhaled or ingested. Residents near open dumps also often have to contend with unpleasant odors (Etea et al., 2021). After a landfill is closed, ongoing monitoring and remediation efforts are required to mitigate these environmental hazards (Tenodi et al., 2020). Given these concerns, there is a clear need for alternative waste processing technologies to reduce reliance on landfills and provide enhanced energy recovery options. Thermal processing technologies like incineration, gasification, and pyrolysis offer different methods for managing waste. To select the most appropriate thermal treatment option, thoroughly analyzing each method across various dimensions is essential. The LCA method is utilized to achieve this. LCA is a comprehensive approach designed to quantify the environmental impacts of each waste management strategy, covering aspects such as acidification, eutrophication, global warming potential, and photochemical oxidation. This holistic analysis helps identify the most environmentally sustainable option for waste treatment. This study leverages the LCA methodology to address the environmental concerns of waste management in Denpasar City. This comprehensive approach evaluates the potential environmental impacts of different waste management practices throughout the life cycle. LCA assesses the full range of environmental effects for each waste management scenario, including acidification, eutrophication, global warming potential, and photochemical oxidation (Abdulkareem et al., 2021; Colón et al., 2010; Suryawan et al., 2021; Wei et al., 2023). The application of LCA in this study served a dual purpose. First, it assesses the environmental burdens of the city's current waste disposal methods, notably the open dumping practice at the Suwung Landfill. Second, it examines the viability and environmental performance of alternative waste processing technologies, particularly thermal treatment options, such as incineration, gasification, and pyrolysis. By conducting an LCA, the research aims to identify and quantify the environmental impacts of the various waste management scenarios operating in Denpasar City. This analysis is integral to formulating strategies that could considerably reduce these impacts. The ultimate goal is to provide a foundation for Denpasar to transition towards more sustainable waste management practices that align with environmental conservation goals and policy directives. Through LCA, the study contributes valuable insights into the lifecycle impacts of waste management systems, aiding in developing more effective and sustainable waste management solutions for the city.

2. Methods

2.1. Goal and Scope

In the Goal and Scope phase of the Life Cycle Assessment (LCA), the researcher meticulously outlines the objectives and boundaries of the study. This crucial step involves defining the input and output parameters of the inventory data, which is essential for facilitating a comprehensive comparison between the waste management systems under analysis. Specifically, this study aims to construct a robust database that can support the implementation of Presidential Regulation (PERPRES) No. 35 of 2018. This regulation is pivotal for accelerating the development of waste-to-energy projects in Indonesia, with a particular focus on enhancing sustainable waste management practices. By establishing a clear goal and scope, this study aims to provide valuable insights and data that can inform policy decisions, guide the effective implementation of waste-to-energy initiatives, and ultimately contribute to the broader objective of sustainable environmental management within and beyond the context of Denpasar City. This detailed approach ensures that the research aligns with specific policy frameworks and addresses the critical need for data-driven waste management and energy recovery strategies.

2.2. Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) phase is crucial in Life Cycle Assessment (LCA) studies as it focuses on identifying and quantifying the flows of materials, energy, and emissions associated with a particular system. The core objective of LCI is to model the system's inflows and outflows, providing a detailed mapping of how resources are consumed and how emissions are generated throughout the lifecycle of the system being observed.

A specific mathematical approach is employed to accurately capture the input and output inventory values, represented by Equation 1. This equation calculates the emissions inventory for each waste treatment scenario by multiplying the activity level of a given process by its corresponding emission factor (Chairani et al., 2021; Noviarini et al., 2022). This method allows for a precise estimation of emissions released into the environment, thereby facilitating a comprehensive analysis of the environmental impact of different waste management practices following equation (1) (Chairani et al., 2021; Noviarini et al., 2022):

$$\text{Inventory} = \text{Activity} \times \text{Emission Factor} \quad (1)$$

Additionally, to assess the potential environmental impact of leachate, a liquid that drains or 'leaches' from a landfill, a theoretical calculation is performed using the rational method, as shown in Equation 2. This equation calculates the discharge of leachate based on several factors, including the drainage rate (C), the maximum rainfall intensity (m/hours) (I), and the area of flow (km^2)(A) (Rachman et al., 2014). The discharge of leachate (D) is thus determined, providing valuable insights into the potential for water pollution from landfill sites following equation (2) (Rachman et al., 2014).

$$D = 0.278\ C.\ I.A\ (m^3/sec) \quad (2)$$

Table 1. Input and output factors used in the LCI for thermal waste management.

Input/Output	Unit	Pyrolysis	Incineration	Gasification
Operational Electricity	kWh/ton	339,3[1]	339,3[1]	77,8[1]
Electricity production	kWh/ton	685[1]	685[1]	554[1]
Solid residual	kg/ton	-	180[1]	120[1]
Char	kg/ton	150[2]	-	-
Pyrolysis oil	kg/ton	51[3]	-	-

Source: [1] (Zaman, 2010), [2] (Cherubini et al., 2009), [3] (Chen et al., 2014)

The calculation of rainfall intensity commonly employs the Mononobe Method (Kistiawan & Irawan, 2023; Susilowati et al., 2022; Winardi et al., 2022), a widely recognized approach. According to this method, rain intensity (I) is calculated using equation 3, which considers the maximum rainfall over 24 hours and the duration of rainfall in terms of days. The equation is structured as follow equation (3):

$$I = (R_{max}/24) \cdot (24(t/60)) \quad (3)$$

In the equation under discussion, several key variables were defined to understand the dynamics of rainfall and its contribution to leachate generation. The variable 'I' represents the rainfall intensity and is measured in mm/day, quantifying how much rain falls over a specific area in a day. 'Rmax' represents the maximum amount of rainfall received, recorded in mm, indicating the highest rainfall event expected or observed. The variable 't' denotes the duration of the rainfall event, expressed in days, and provides insight into the duration of a particular rainfall event. Notably, it is estimated that 20-30% of the maximum rainfall amount (Rmax) is expected to transform into leachate. This estimation underscores the importance of accurately calculating rainfall intensity and understanding its impact on leachate generation, as it highlights a significant portion of rainfall that contributes to leachate production from landfill sites.Furthermore, the pollution load (L) is determined by the concentration of pollutants in the water (*C*) and the volume of water discharge containing these pollutants (Q). The formula for calculating the pollutant load is presented in equation (4) (Reckhow & Chapra, 1983):

$$L = C \cdot Q \quad (4)$$

The water quality analysis from landfill waste treatment in Denpasar indicated the presence of various pollutants. The parameters tested included Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Dissolved Oxygen (DO), as well as concentrations of phosphate, nitrate, nitrite, ammonia, iron, chloride, sulfate, hydrogen sulfide, and phenol (Arbain et al., 2009). Each parameter was reported in, each displaying a range of concentrations indicative of the degree of pollution in the water. The study provides crucial data for the LCIA of the environmental impact of waterborne pollutants originating from landfill sites.

2.3. Life Cycle Impact Assessment

In the Life Cycle Impact Assessment (LCIA) phase, the Life Cycle Inventory (LCI) analysis data are evaluated to ascertain their environmental impacts. This evaluation involves classifying LCI data into various impact categories and aggregating this information to generate indicators for each category. These indicators quantify the potential environmental impacts within these categories and offer insights into how different elements contribute to environmental degradation.

For this study, the collected data were analyzed using the OpenLCA software version 1.9. This software facilitates the mathematical calculation of chemicals released during the waste treatment process, allowing for the quantification of their environmental impacts. The methodology applied in OpenLCA 1.9 for this research is based on Environmental Product Declarations (EPD) 2013 and the Building for Environmental and Economic Sustainability + (BEES+). As referenced in the literature, these frameworks have previously been utilized in waste treatment research, indicating their effectiveness in assessing environmental impacts in similar contexts.

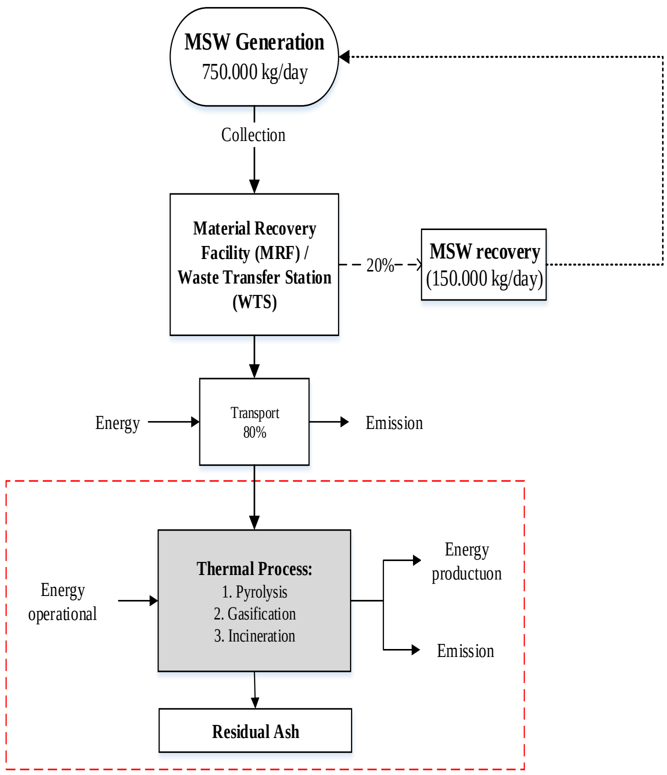
2.4. Interpretation

The final stage of the LCA process is interpretation. This step involves a thorough evaluation of the findings from both the Life Cycle Inventory and the Impact Assessment phases. The aim is to contextualize these results within the defined scope of the study and to draw conclusions that can inform decision-making. Interpretation provides a comprehensive understanding of the system's environmental performance and,identifies areas for improvement and recommends strategies for mitigating adverse environmental impacts. Stakeholders can develop more sustainable practices and policies through careful analysis and thoughtful consideration of the LCA findings.

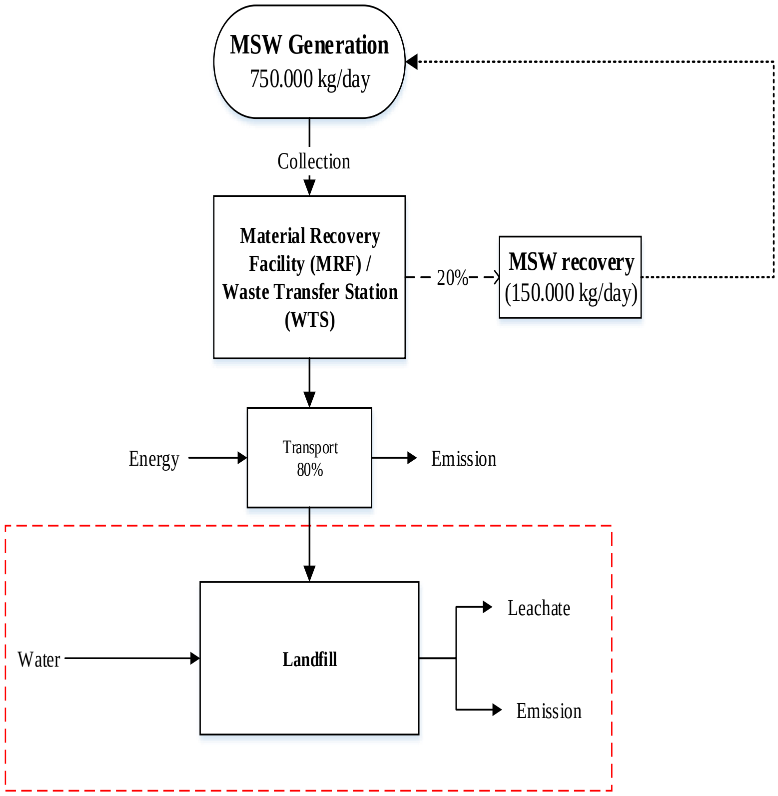
3. Result and Discussion

3.1. Goal and scope

Determining the goals and scope of this waste processing is based on 4 scenarios, whichDetermining the goals and scope of this waste processing is based on 4 scenarios: pyrolysis, incineration, gasification, and landfill processes. The thermal waste management scope is the energy needed for operations and waste generation that enters the processing unit as input. In contrast, the energy produced, solid residue, and emissions are released as the output (Figure 1). This thermal process applies to pyrolysis, incineration, and gasification processing scenarios. For landfills, the input of the treatment process was waste generation and rainwater discharge, while the output was pollutant load from leachate and emissions released by the landfill (Figure 2). The scope of this research is only on the gate-to-gate condition, that is, the waste entering each process without seeing the flow of the waste process from source to transport. Based on the waste management plan, Denpasar should be able to recover as much as 20% of the total waste heap. Therefore, in this research, the waste processed is 80% of the total waste heap.



Fiigure 1. Process chart and LCA scope of Denpasar waste processing using a thermal process.



Fiigure 2. Process chart and LCA scope of Denpasar waste processing with landfill processes.

3.2. Calculation of Lifecycle Inventory

In the life cycle inventory (LCI) calculation phase, the focus is on identifying the inputs and outputs established during the goal and scope phases of the research. The inputs were primarily derived from the quantities of waste and the thermal technology utilized. Furthermore, the scope of the emission inventory, pivotal for this study, is outlined in Table 5. The emission inventory plays a critical role not just as a foundational element for strategizing but also in assessing air quality conditions and the extent of environmental impacts, serving as a crucial component for the Life Cycle Assessment (LCA) analysis.

3.3. Lifecycle Impact Assessment

The Lifecycle Impact Assessment (LCIA) or the analysis stage focuses on the type and amount of value of each impact category that results from each product-making process (Abdulkareem et al., 2021; Colón et al., 2010; Suryawan et al., 2021; Wei et al., 2023). There are three main steps: characterization, normalization, and weighting (Roesch et al., 2020) 1. Determination of the category is conducted by selecting a category following the scope of research used. Classification was conducted by establishing inventory data supporting impact categories. Characteristics were determined by assessing the results of the impact category indicators. At the same time, normalization refers to the relative magnitude of each impact category of the product system analyzed in the study and weighting, a combination of the indicator results. This research assesses the impacts resulting from waste processing products based on data analysis using OpenLCA 1.9 Software with EPD 2013 and BEES+ databases.

Water discharge measurements were conducted using the rational method. The leachate discharge calculation first calculated the rain intensity derived from the rainfall distribution calculation. The equation used to get rainfall intensity follows equation 3, where the maximum daily rainfall is 32.27 mm. The area of the Suwung landfill is 40 ha with centralized rain time set under Government Regulation of Ministry of Public Works Number 3 in the Year 2013, which is 4 hours. The average discharge calculation assumes that a maximum of 25% of rainfall turns into leachate. Average leachate discharge of 17051.9

m^3/day. Based on Equation 4, each pollutant load will be obtained during the leachate operation. Specific pollutant loads for each parameter are shown in Table 2.

Table 2. The output value of pollutant load by leachate from Landfill Operations

Parameter	Unit	Specific pollutant loads (L)
BOD	kg/day	6889.0
COD	kg/day	14291.2
Phosphate	kg/day	1140.1
Nitrate	kg/day	1246.9
Nitrite	kg/day	25.6
NH3	kg/day	8976.3
Ferrum	kg/day	258.3
Sulfate	kg/day	6985.0
Phenol	kg/day	4300.1
CH_4 from BOD	kg/day	4133.4
CH_4 from COD	kg/day	3572.8

Table 4 provides environmental impact assessments from landfill operations, comparing waste management methods. The assessment includes acidification, where pyrolysis and gasification both show an impact of 470 kg of SO_2 equivalent; incineration doubles that impact, and landfilling presents the least at 402.33 kg SO_2 equivalent. Eutrophication impacts follow a similar trend, with pyrolysis and gasification equal at 76.1 kg of PO_4 equivalent, incineration again higher at 156 kg of PO_4 equivalent, and landfilling far exceeding the other methods at 4789.8 kg PO_4 equivalent. Global warming potential is measured as CO_2 equivalents over a 100-year period, where pyrolysis and incineration are identical at 879782 kg CO_2 equivalent, gasification is slightly lower, and landfilling has the highest impact at 2885770 kg CO_2 equivalent. For photochemical oxidation, pyrolysis and gasification again match at 3.9 kg C_2H_4 equivalent, incineration has the least impact at 1.5 kg C_2H_4 equivalent while landfilling stands significantly higher at 138.2 kg C_2H_4 equivalent.

Ecotoxicity measurements indicate the potential harm to ecosystems, with pyrolysis generating 6182600 g 2,4-D equivalent and incineration less at 4493870 g 2,4-D equivalent. Gasification and landfill operations show similar values in this category. Human health impacts are also considered, with cancer risks measured in grams of C_6H_6 equivalent and non-cancer criteria air pollutants measured in microDALYs. Pyrolysis and gasification report identical figures for cancer risks, and incineration is slightly lower, but landfilling reveals a staggering potential impact. Non-cancer impacts follow the same pattern, with landfilling showing the highest risk.

Table 4. Output values of environmental impact assessments from Landfill Operations

Impact category	Method	Unit	Pyrolysis	Incineration	Gasification	Landfill
Acidification	EPD 2013	kg SO_2 eq	470	911	470	402.33
Eutrophication	EPD 2013	kg PO_4 eq	76.1	156	76.1	4789.8
Global warming (GWP 100a)	EPD 2013	kg CO_2 eq	879782	879782	779759	2885770
Photochemical oxidation	EPD 2013	kg C_2H_4 eq	3.9	1.5	3.9	138.2
Ecotoxicity	BEES+	g 2.4-D eq	6182600	4493870	6182600	2183390
HH cancer	BEES+	g C_6H_6 eq	149940	12898.1	149940	1634050000

HH criteria air pollutants	BEES+	microDALYs	2248.1	4398	2248.1	1862.1
HH noncancer	BEES+	g C_7H_7 eq	1034550000	743465000	1034550000	281792000
Smog	BEES+	g No_x eq	727144	1489390	727144	716138

Normalization in LCA is a crucial procedure that translates the impact assessment results across varied categories into a unified metric. This essential step ensures a coherent and all-encompassing comparison across the diverse environmental impact categories identified during the assessment process. By standardizing the data, researchers are empowered to efficiently assess and compare the relative importance of each impact category, thus streamlining the analysis of environmental impacts associated with the system or product under review. In this study, environmental impact data was normalized using two separate databases: the Environmental Product Declarations (EPD) for 2013 and the Building for Environmental and Economic Sustainability (BEES+). The standardized outcomes of the environmental impact data, referencing the EPD 2013 database, are depicted in a graphical format in Figure 3. This illustration provides an immediate visual understanding of the scale of environmental impacts across various categories, aligned with the standards and metrics established in the EPD 2013 database.

Similarly, the normalization of environmental impacts based on the BEES+ database is depicted in Figure 4. This figure offers a parallel view of the environmental impacts when analyzed through the lens of the BEES+ database, which may incorporate different weighting and assessment criteria. By presenting the normalized results from both databases, the study provides a dual perspective on the environmental impacts, enriching the analysis and offering a comprehensive overview of the potential environmental implications of the system or product under investigation. This dual-database approach ensures a robust and versatile analysis, accommodates varied assessment standards, and enhances the interpretability of LCA results.

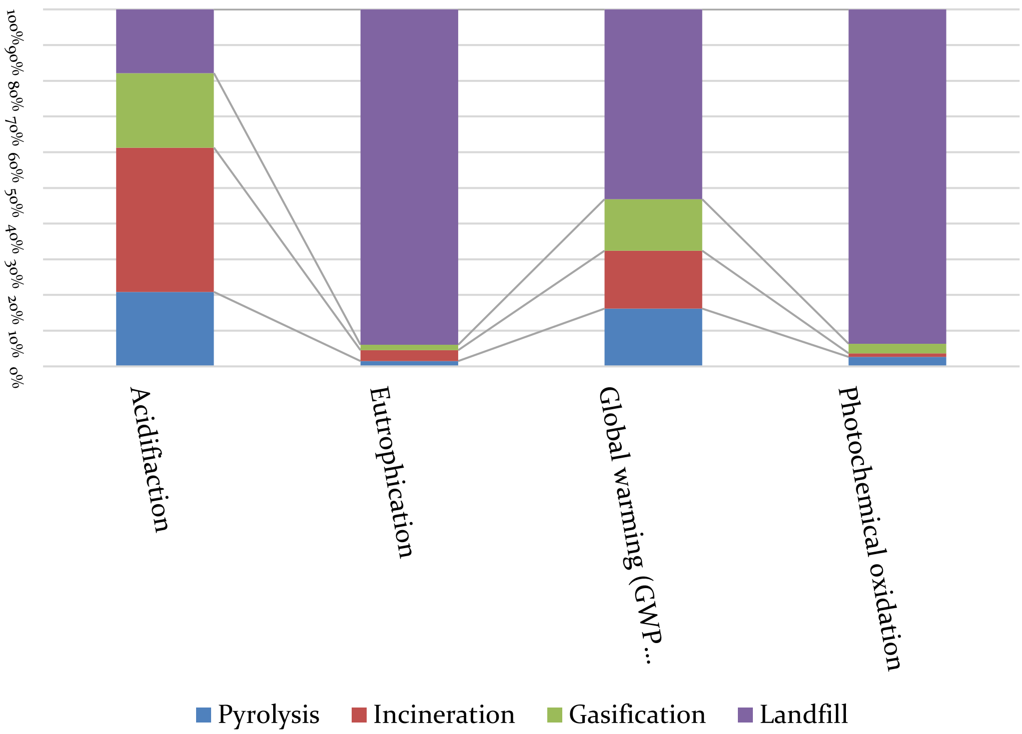


Figure 3. Normalization of environmental impact data, based on Denpasar waste management EPD 2013 database

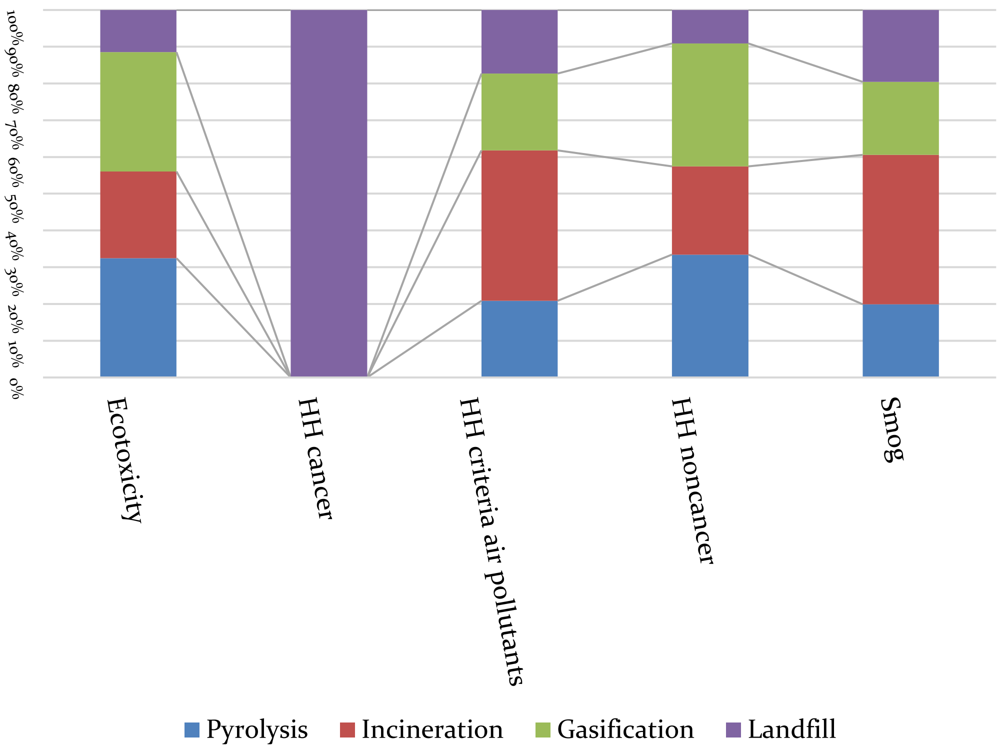


Figure 4. Normalization of environmental impact data, based on Denpasar waste management BEES+ database

Acidification, HH criteria air pollutants, and smog are the highest impacts that can be caused by treatment with incineration compared to other treatments. Acidification is the forming process of hydrogen ions due to SO_4, NO_x, and NH_3. Acidification can damage the quality of the environment because of emissions from acidified gas released into the air (Van Haaren et al., 2010)). The incinerator waste processing scenario showed the worst performance if the environmental performance was focused on potential acidification indicators. According to previous research, gasification is one of the best treatment processes with minimal impact on acidification (Gunamantha, 2011)—NOx, SOx, and particulates cause HH criteria air pollutants. Incinerator technology can cause the highest reduction in air quality. The particulate components of the incinerator play an essential role in decreasing air quality. The research mentioned that the particulate component influences the chemical composition of the incinerator treatment (Yang et al., 2016).

Waste treatment using gasification and pyrolysis has the same tendency, which has a more significant impact on ecotoxicity and HH non-cancer than other waste treatments. The ecotoxicity in the BEES+ method equated to 2.4-D (2.4-dichlophenoxyacetic acid) eq. The 2.4-D compound is deadly in water medium oil and water material cells (Li et al., 2017). HH non-cancer in gasification and pyrolysis waste treatment shows the impact value of 1,034,550,000 g C_7H_7 eq. Previous research mentions that the impact of HH non-cancer on waste management with a landfill system does not exist (Rifai et al., 2016).

Waste management through landfilling is identified as having the most significant environmental impact, particularly in eutrophication, global warming, photochemical oxidation, and HH cancer risks. This waste treatment method has the highest potential impact among the evaluated options. The analysis, as depicted in Figures 5 and 6, highlights that for the impact categories of eutrophication, photochemical oxidation, and HH cancer, landfilling's contribution to these environmental burdens is exceedingly high, with the percentage of impact in each category surpassing 95%.

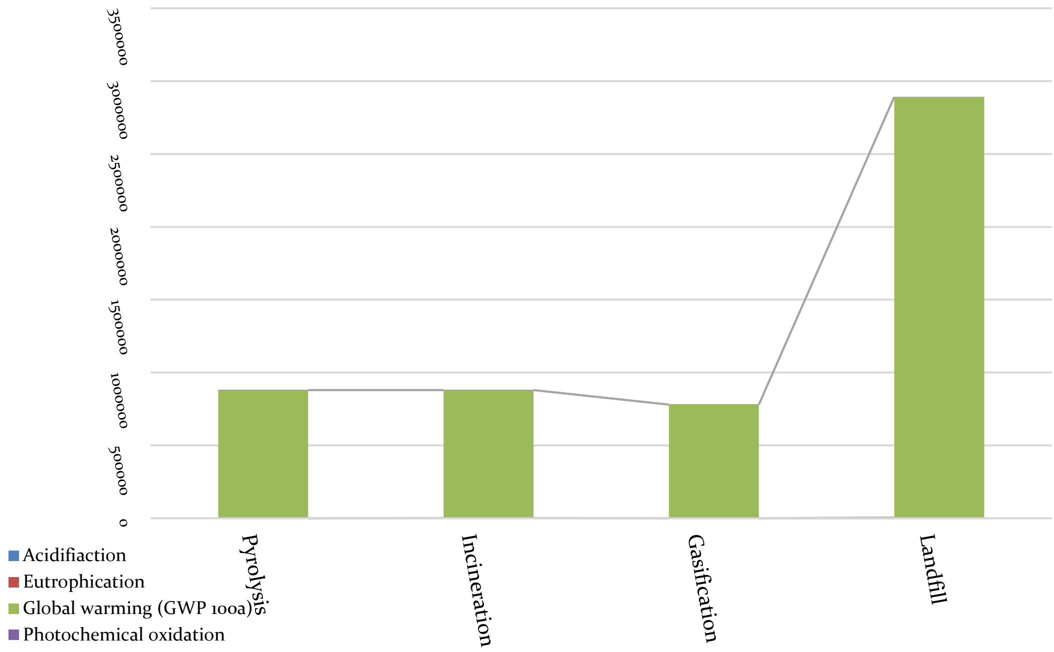


Figure 5. Weighting data on environmental impact is based on the Denpasar Waste Management EPD 2013 database.

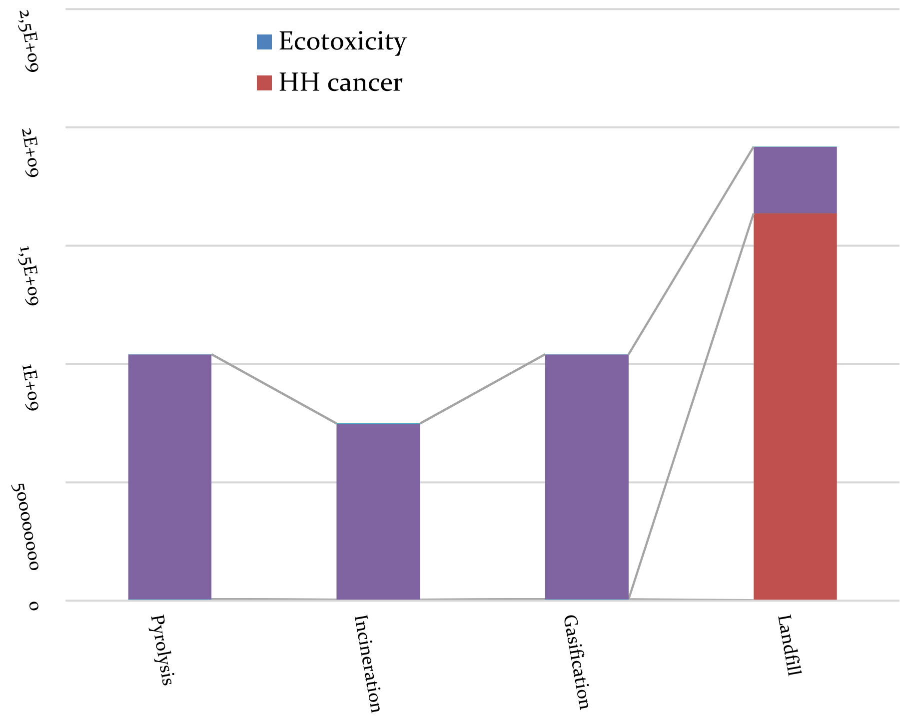


Figure 6. Weighting data on environmental impact is based on the Denpasar waste management BEES+ database.

Emissions and the quality of leachate water cause eutrophication in landfill waste management. NO_x emissions and the leachate quality contain a large amount of ammonia, phosphate, COD, nitrate, and nitrite, which can contribute to the impact of eutrophication on landfill waste management. Leachate, produced from the degradation and infiltration of water in waste, will form these pollutants. Research has shown that leachate runoff into solid waste can cause eutrophication (Sharifi et al. 2017). Eutrophication in water bodies can cause environmental disturbances such as soaring algae growth and the death of biota. In addition, recent research has mentioned that the conditions of the waters around landfills are categorized as heavily polluted (Septiariva & Suryawan, 2021).

Emissions from giant landfill biodigesters and anaerobic degradation processes in leachate water can contribute to CH_4 emissions. CH_4 and SO_x that accumulate in these emissions also have the potential to affect global warming. Global warming resulting from the anaerobic degradation process produces CO_2 and CH_4. CH_4 produced at the methanogenesis stage can reach the same value as CO_2 production. Research from the Indonesian Ministry of the Environment said CH_4 could cause 20-30 times the effect of global warming compared to CO_2 (Twidyawati et al., 2021). The gasification process shows the most negligible impact of global warming, $7.8 x 10^5$ kg CO_{2eq}. Compared to previous research, waste processing with gasification in this research is lower than other research, which is 5.8×10^4 ton CO_{2-eq} (You et al., 2017). Previous research has shown that the contribution of emissions from landfill operations is significant anthropogenic CH_4 emissions (Du et al., 2017; Wang et al., 2020). Besides global warming, CH_4 is also a major contributor to the effects of photochemical oxidation. Photochemical oxidation is a primary natural mechanism for removing tropospheric CH_4 (Helen et al., 2018).

The impact that can be considered the most important is the impact of HH cancer from the landfill's operation. HH cancer can be caused by the quality of wastewater containing phenols and emissions from landfills, which contain cadmium, arsenic, chloroethene, nickel, and benzene. Phenol in leachate is the biggest component contributing to the impact of HH cancer, which is 380,000 times from benzene. Phenol concentrations in human urine are used as biological indicators of benzene exposure; urine phenol concentrations indicate a higher degree of benzene poisoning (Kirkeleit et al., 2008). Continuous exposure to benzene will certainly affect health. Constant exposure to benzene causes symptoms and signs of chronic poisoning, such as headaches, dizziness, nausea, vomiting, slow reaction, and paleness due to anemia, which is often accompanied by bleeding under the skin and mucosa (Setiowati, 2017). Benzene solid waste is found in plastic waste such as polystyrene(Karmore & Madras, 2000))/ This compound can also be obtained from leachate as a volatile organic compound due to aromatic compounds or petroleum products in the waste (Jayawardhana et al., 2019; Sizirici & Tansel, 2010).

Weighting is the stage in which all the assessed impacts will be compared and simplified equally. Weighting results based on the EPD 2013 and BEES + methods can be seen in Figures 5 and 6. The result of weighting shows that the most significant environmental impact can be caused by waste management with landfill methods, where the most likely impacts are global warming and HH cancer. Waste management with an incinerator is the easiest and fastest way to destroy the volume and amount of waste. Whether smooth or not the combustion process depends on the physical and chemical properties of the waste, these conditions ultimately require complex calculations and accuracy. From the impact of human health, the incineration method is the best choice, whereas if seen from the environmental impact the gasification method is the best. From weighing the landfill process to the technology with the most significant impact, processing with this technology is not recommended.

Based on the impact analysis results, the technologies with the lowest impact are incineration and gasification. However, incineration technology tends to produce non-cancerous effects that are not too large. Based on data from Denpasar in Numeral 2019, the city's electricity consumption can reach 1423518963 kWh. Compared with electricity production for each waste treatment and thermal gasification technology, it can supply around 10.6% of the electricity service in Denpasar. Partha stated that the electric power prediction generated from the gasification process in Denpasar is 99,072 MWh or 6.9% of the total energy needs (Gede & Partha, 2010). In general, gasification planning requires pretreatment in the form of shredding to reduce the size of the waste that will enter the reactor. Besides, the drying process is also needed to get a higher heating value of already dry, so the process result selected is the gasification process. Gasification technology has also been used in the study of Klungkung (Legino et al., 2019), Depok

(Sarwono et al., 2021; Suryawan et al., 2022) and Semarang (Khuriati et al., 2018) waste management processes. The research also mentioned that gasification is an economically viable and environment-friendly biomass treatment(Udomsirichakorn & Salam, 2014). Based on the economic analysis of gasification shows the value of biomass cost of 0.03-0.07 USD/kg, while the cost to produce electricity is 0.09-0.16 USD/kWh (Susanto et al., 2018).

4. Conclusions

The conclusions drawn from the Life Cycle Assessment (LCA) analysis indicate that gasification emerges as the most environmentally favorable method among the evaluated waste treatment technologies. This technology has the lowest environmental impact and can generate approximately 415,500 kWh of electricity. The associated potential impact on global warming, measured as Global Warming Potential (GWP) over 100 years, is quantified at 779,759 kg of CO2 equivalent (CO2eq). This relatively lower GWP highlights gasification's efficiency in mitigating greenhouse gas emissions compared to other waste treatment options.

In contrast, landfilling, as a waste processing technology, is deemed less suitable due to its significantly higher contribution to global warming and potential human health impacts, particularly regarding cancer risk. The impact value associated with landfilling's contribution to global warming is alarmingly high, estimated at 2,885,770 kg of CO2 equivalent. Furthermore, the risk of cancer, represented through the hexavalent chromium equivalent (C6H6eq) indicator, is assessed at 1,634,050 kg, underscoring this method's substantial health and environmental risks. These findings underscore the necessity of transitioning towards more sustainable waste treatment solutions, such as gasification, which minimizes environmental and health impacts and contributes to generating renewable energy. The LCA results thus advocate for reevaluating current waste management practices, emphasizing the importance of adopting technologies that align with environmental sustainability and public health objectives.

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