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Technological and Environmental Evaluation of Incinerator Systems for Sustainable Waste-to-Energy Solutions in Denpasar City

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ABSTRACT

The rapid urbanization and tourism growth in Denpasar City, Bali, have led to increasing waste management challenges. Currently, only 22% of the daily 850 tons of waste is managed at the source, with the rest transported to landfills. This study aims to evaluate the implementation of Waste-to-Energy (WES) incineration systems as a potential solution to both waste disposal and energy production. The research uses a quantitative method involving primary data collection through interviews and secondary data from existing documentation. Three incinerator designs were analyzed based on parameters like energy efficiency, emissions, and environmental impact. The results show that the third incinerator system delivers the highest power output at 445.67 KW, although it also produces moderate pollutant emissions. The second design system, however, strikes a better balance, offering both lower emissions and effective power generation, making it the most environmentally favorable option. The study contributes to the growing body of research on WES technology, highlighting the need for advanced design optimization to minimize environmental impacts while maximizing energy output.

INTRODUCTION

Waste remains a challenging issue to address, especially in large cities, where it can cause environmental problems if not resolved effectively (Abdel-Shafy & Mansour, 2018; Gutberlet, 2018; Maalouf & Agamuthu, 2023). The increase in urbanization and population growth worldwide has had a significant impact on waste management issues in many cities (Papargyropoulou & Z, 2014; Vij, 2012; Wikurendra et al., 2024), including Denpasar City, located in Bali Province, Indonesia. As one of the world's tourist destinations, Denpasar City faces waste management challenges not only from the local population but also from the ever-increasing flow of tourists each year. This places substantial pressure on existing waste management infrastructure and leads to serious environmental issues such as air, water, and soil pollution, as well as economic and social losses. With rapid economic growth and lifestyle changes brought about by globalization, the consumption of goods and products has increased significantly, consequently increasing the volume of waste generated (Clarke et al., 1999; Ferronato & Torretta, 2019; Ghimire & Ariya, 2020; Pérez-Villarejo et al., 2020; Wu et al., 2017; L. Zhang et al., 2022). Denpasar City is estimated to produce approximately 1200 tons of waste per day (Pertiwi & Purbadharmaja, 2021). The ineffectiveness of waste management regulations in Denpasar stems from internal challenges, such as inadequate resources and budget constraints, and external issues, including limited government and private sector support, insufficient community participation, and financial assistance (Purwanto, 2024).

Waste has become a complex and multifaceted social phenomenon, not only as a technical issue but also as a social, economic, and environmental issue

(Haryanti et al., 2023; Lu et al., 2024; Vergara & Tchobanoglous, 2012). Ineffective waste management can result in environmental pollution, economic losses, public health threats, and social and psychological damages (Fatima et al., 2019; Maalouf & Agamuthu, 2023; Mahajan & Vakharia, 2016; Rahmadyanti & Dzakiyati, 2021; Salvia et al., 2021; Wondimu, 2020). Waste issues are also a major aspect of global climate change, as poor waste management can lead to greenhouse gas emissions and accelerate climate change (Abbass et al., 2022; Ashshidiqi et al., 2020; Attiogbe et al., 2019; Mønster et al., 2019; Z. Zhang et al., 2024). Environmental pollution caused by open waste burning or waste dumped into landfills without adequate processing can threaten public health and damage local ecosystems (Ferronato & Torretta, 2019; Kibria et al., 2023; Kumar et al., 2021; Njoku et al., 2019; Pathak et al., 2023). Additionally, poorly managed waste piles create unsightly views and reduce the attractiveness of tourist areas. The increasing volume of waste, along with population growth, necessitates anticipatory programs. Various efforts have been made, including independent bodies such as waste banks, temporary waste storage sites, and waste banks' landfills (Gunamantha et al., 2023; Saitullah, 2022; Sulistiyani & Dahlia, 2024; Tarmizi & Surtikanti, 2023). Cooperation programs between the government and the private sector, such as waste-to-energy solutions (WES), are also potential solutions for converting waste into electricity (Bosmans & Helsen, 2010; Gad et al., 2024; Khawaja et al., 2024; Sharma et al., 2021; Suryawan et al., 2023).

The WES program is relatively new in Indonesia, with implementation beginning in cities like Surabaya, Jakarta, and Semarang (Hermansyah et al., 2024). WES promises to address waste issues while generating electricity that can be utilized. WES uses modern technology to convert waste into energy, thereby potentially reducing environmental pollution caused by open waste burning and decreasing dependency on non-environmentally friendly conventional energy sources (Nur et al., 2023; Rayesa et al., 2022). WES employs modern technologies, such as incinerators or pyrolysis reactors, to convert waste into electrical or thermal energy to meet local electricity needs. Implementing WES is not easy, requiring careful attention to selecting the right technology according to local waste characteristics and environmental conditions. Incinerator technology in WES can process waste with high energy efficiency and significantly reduce waste volume (Amanda Siregar Wildan Al Kautsar Anky et al., 2023; Winanti et al., 2022). However, its use also raises concerns about air pollutant emissions and hazardous residues. Furthermore, WES implementation involves various other aspects, such as infrastructure planning, policy regulation, funding availability, and community support. Therefore, this study aims to analyze various alternative incinerator technology models for potential application in WES.

The incinerator technology considered includes three alternatives with added systems using emission control modules, air pollution control, and steam turbines. These three system alternatives can produce efficient and environmentally friendly electricity, with higher production rates and lower environmental pollution levels (Makwana et al., 2023; Quina et al., 2011; Stantec, 2011). Additionally, this study adopts an interdisciplinary approach, involving technical and environmental aspects in analyzing WES implementation with a focus on developing alternative incinerators in Denpasar City. This approach differs from previous studies that focused solely on either technical or environmental aspects. Furthermore, this study will conduct an in-depth analysis of waste types, chemical composition, calorific value, and other relevant factors. This approach provides a more comprehensive understanding of local waste, which may not have been addressed in previous studies.

MATERIALS AND METHODS

The research will focus on the Suwung Landfill (Figure 1). Suwung Landfill is the largest waste disposal site in Bali, covering an area of approximately 32.48 hectares, and has been operational since 1986. Suwung Landfill receives about 1,800 tons of wet waste or 650 tons of dry waste from Denpasar City, Badung Regency, Tabanan, and Gianyar.

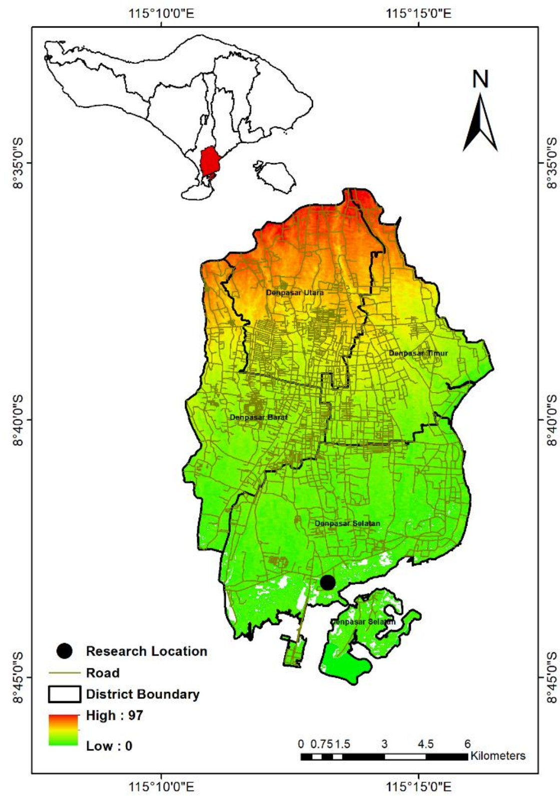

Figure 1. Research Location

The methods used to achieve the objectives of this study are quantitative. This research will examine waste characteristics, followed by an analysis of waste selection by segregating organic and non-organic waste. These two treatments will be compared based on consolidation time, safety factors, and their environmental impact. Primary data collection will be conducted through interviews. Interviews are a method of data collection carried out through verbal communication in structured, semi-structured, and unstructured forms. The sample determination will use purposive sampling techniques. This technique is used to ensure that the data obtained is from experts who understand public and stakeholder perceptions regarding waste issues in Denpasar City and green construction. Secondary data will be collected using the documentation method. Documentation involves collecting existing data, such as basic documents for the establishment of WES plants. Documents to be collected in this study include waste characteristics data, turbine type properties data, and generator type properties data.

The incinerator system analysis includes thermal efficiency, heat rate, calorific value, and energy production generated, as well as the potential environmental impacts. The selection of an environmentally friendly incinerator system model will be carried out using a weighting matrix between incinerator system parameters and environmental impact parameters.

RESULTS AND DISCUSSION

Denpasar City is estimated to generate at least 850 tons of waste daily. However, source-based waste management in Denpasar has not achieved optimal performance, processing only 22 percent of the waste at its source, with the remainder being transported to the landfill. According to data from the Denpasar City Regional Government Work Plan, the volume of waste directed to the Suwung landfill was 1,195,939 m³, originating from both Denpasar City and parts of Badung Regency. The following provides monthly data on the volume of waste transported to the Suwung landfill from January 2020 to December 2023.

The development planning of the Incinerator system at the Suwung WES, with a maximum capacity of 550 KW, will be carried out at the Suwung Landfill, Suwung Kauh Village, South Denpasar District. The geographical position of the WES plant is located at coordinates 8°43'23.9" South Latitude and 115°13'16.7" East Longitude. The feasibility study for the development planning is conducted by analyzing several parameters at the site plan location. The selection of the development site located at Suwung Landfill is based on the following considerations:

1. Adequate land area of 2.2 hectares for the plant.
2. Availability of water supply due to proximity to the coast.
3. Proximity to the fuel source, which is waste.
4. Proximity to consumers who require a large and increasing amount of electricity, especially in Denpasar City

First Incinerator Design System

The basic system utilizes an emission control system that generates a generator output of 114.67 KW, which includes the input of the feeder facilities and its accessories (Figure 2). These facilities play a crucial role in the operational continuity of the unit, as the sorting of waste types entering the combustion chamber and compliance with design conditions are necessary during the incinerator operation.

The combustion chamber (furnace) is designed to facilitate the conversion of combustion gas heat to water pipes, where the heat from the gas generates steam that will eventually produce electricity through conversion to a turbine and generator. The temperature in the incinerator combustion chamber can reach approximately 1100°C.

Before the gas is released, a heat exchanger unit (fin fan/heat exchanger) is required to absorb heat from the gas, which serves as a preheater for the boiler feedwater. This cooling system can reduce the exhaust gas temperature from around 800°C – 900°C to approximately 300°C – 450°C. Further, through a heat exchanger for air preheating, the exhaust gas temperature can be reduced to 200°C, which will be released into the air through a chimney. The output of the first emission control system design produces an electrical output of 114.67 KW from the emission control system.

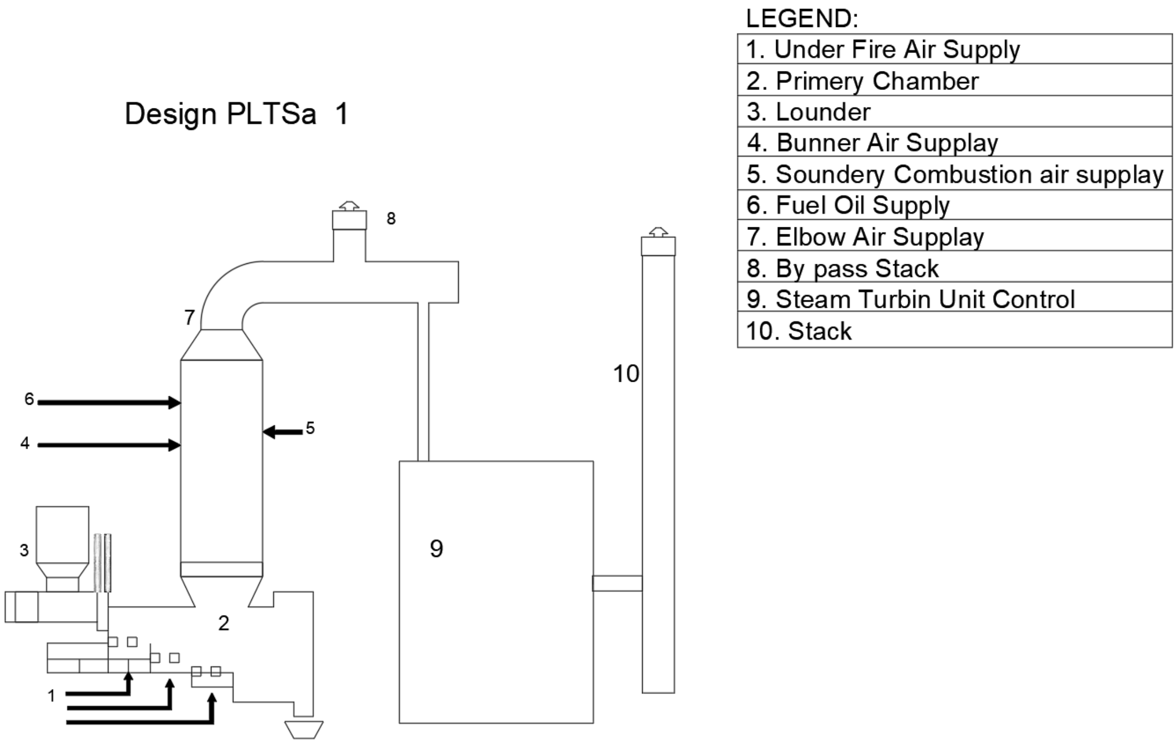

Figure 2. First Incinerator Design System

Second Incinerator Design System

The basic system incorporates an APC (Air Pollution Control) system (Figure 3), capable of generating an output of 223.87 KW. The feeder facilities and their accessories are vital for the operational continuity of the unit, as waste must be sorted before incineration to comply with the incinerator's design specifications.

The combustion chamber (furnace) is engineered to convert the heat from combustion gases into water pipes. The heat from these gases generates steam, which subsequently produces electricity by driving a turbine and generator. The temperature within the incinerator combustion chamber can reach approximately 1100°C.

Before the gas is released, a heat exchanger unit (fin fan/heat exchanger) is needed to absorb heat from the gas, acting as a preheater for the boiler feedwater. This cooling system can reduce the exhaust gas temperature from approximately 800°C – 900°C to around 300°C – 450°C. Additionally, using a heat exchanger for air preheating, the exhaust gas temperature can be further reduced to 200°C before being released into the atmosphere through a chimney. The second emission control system design yields an electrical output of 223.87 KW.

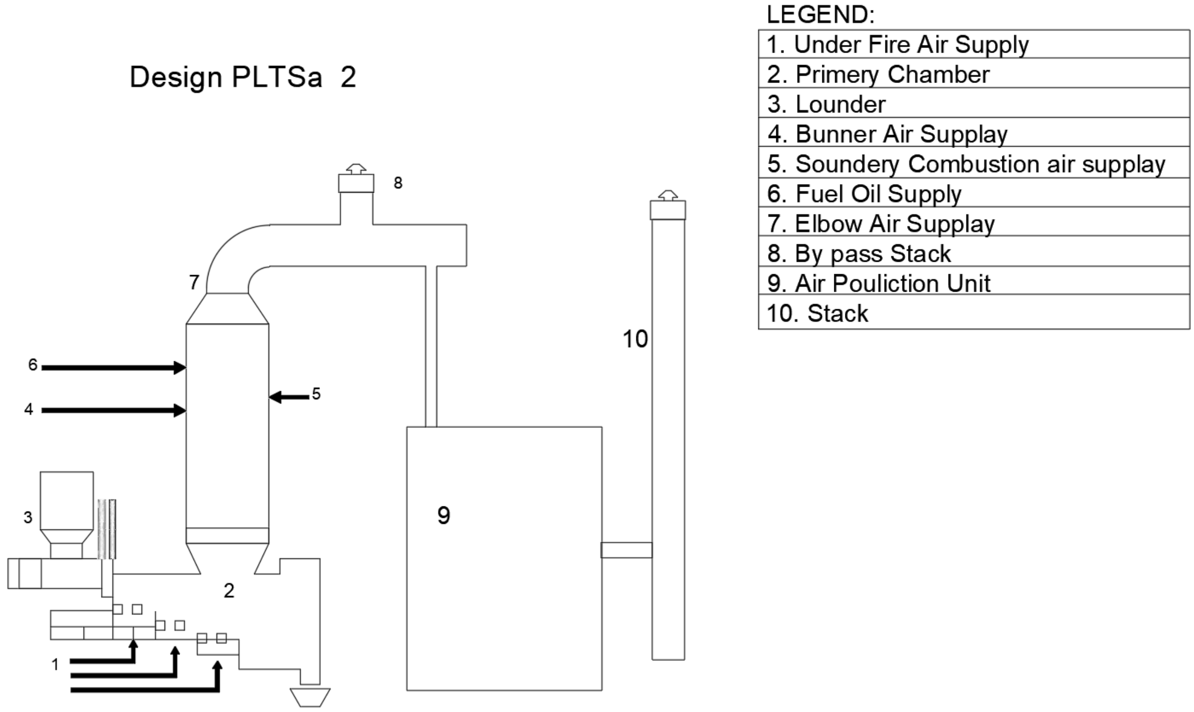

Figure 3. Second Incinerator Design System

Third Incinerator Design System

The basic system uses a steam turbine (Figure 4), which can produce a generator output of 445.67 KW. The feeder facilities and their accessories are crucial for the operational continuity of the unit, as waste needs to be sorted before incineration to meet the conditions specified in the incinerator design.

The combustion chamber (furnace) is designed to convert the heat from combustion gases into water pipes. The heat from these gases generates steam, which then produces electricity by driving a turbine and generator. The temperature in the incinerator combustion chamber can reach approximately 1100°C.

Before the gas is released, a heat exchanger unit (fin fan/heat exchanger) is required to absorb heat from the gas, serving as a preheater for the boiler feedwater. This cooling system can reduce the exhaust gas temperature from around 800°C – 900°C to approximately 300°C – 450°C. Additionally, using a heat exchanger for air preheating, the exhaust gas temperature can be further reduced to 200°C before being released into the atmosphere through a chimney. The third emission control system design yields an electrical output of 445.67 KW.

The calculation results of the incineration system include the analysis of the combustion process within the combustion chamber, the mass of steam generated, and the power produced (Table 1).

Based on the analysis results obtained from the three design systems, the output of the third design system generated the highest power, which is 445.67 KW. The installation of this system is very easy to execute, and the system placement is less complicated compared to the other systems.

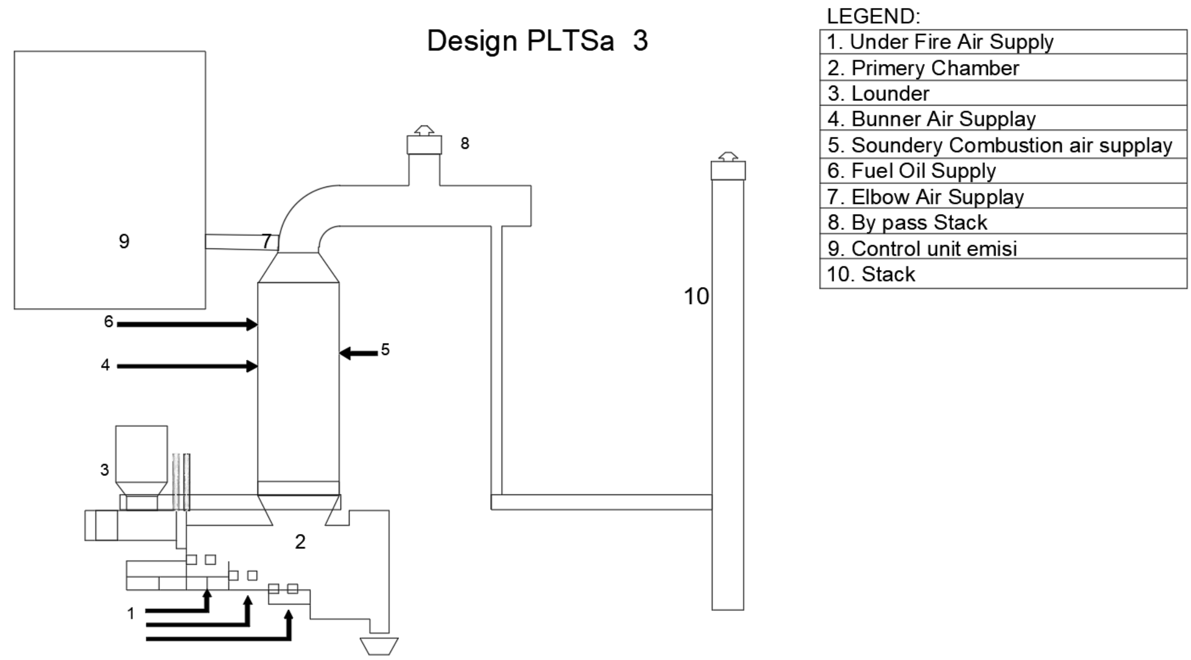

Figure 4. Third Incinerator Design System

The calculation results of the incineration system include the analysis of the combustion process within the combustion chamber, the mass of steam generated, and the power produced (Table 1). Based on the analysis results obtained from the three design systems, the output of the third design system generated the highest power, which is 445.67 KW. The installation of this system is very easy to execute, and the system placement is less complicated compared to the other systems.

Table 1. The Analysis Results of the Electrical Power Generated by Each Incinerator System

Parameter	First Incinerator Design System	Second Incinerator Design System	Third Incinerator Design System
Combustion heat in the combustion chamber (kJ/hour)	2137.25	2137.25	2137.25
Heat rate released from the incinerator (kJ/hour)	1.71×10^6	2.83×10^6	4.92×10^6
Steam mass flow rate (kg/hour)	680.71	792.82	945.72
Steam turbine performance (kJ/kg)	1963.78	2456.88	4756.67
Power generated by the generator (kW)	114.67	223.87	445.67

Environmental Feasibility

A simulation of the impact of constructing an incinerator on the development of a Waste-to-Energy System (WES) at the Suwung landfill was conducted with the aid of Life Cycle Assessment (LCA). To evaluate the potential of waste as a fuel for electricity generation, its environmental viability must first be assessed. According to the simulation results, which were carried out using the CML IA baseline method, the outcomes are presented in Table 2.

The results of the LCA simulation, which was used to assess the environmental impact of waste incineration to produce 445.67 MW of electricity, are presented below. The following are the air emissions from waste incineration to generate 445.67 MW of electricity (Table 3).

Table 2. Environmental Impact Categories

Impact category	Reference unit	First Incinerator Design System	Second Incinerator Design System	Third Incinerator Design System
Abiotic depletion	kg Sb eq	8.43×10^{-4}	6.32×10^{-4}	6.32×10^{-4}
Abiotic depletion (fossil fuels)	MJ	1.76×10^{3}	1.32×10^{3}	1.32×10^{3}
Acidification	kg SO2 eq	6.17×10^{5}	3.41	4.62×10^{5}
Eutrophication	kg PO4--- eq	1.29×10^{5}	3.43×10^{-1}	9.70×10^{4}
Fresh water aquatic ecotox.	kg 1.4-DB eq	1.27	9.53×10^{-1}	9.53×10^{-1}
Global warming (GWP100a)	kg CO2 eq	1.42×10^{5}	5.73×10^{2}	1.06×10^{5}
Human toxicity	kg 1.4-DB eq	1.68×10^{7}	1.26×10^{6}	9.69×10^{6}
Marine aquatic ecotoxicity	kg 1.4-DB eq	1.20×10^{5}	8.98×10^{4}	8.98×10^{4}
Ozone layer depletion (ODP)	kg CFC-11 eq	4.64×10^{-5}	3.48×10^{-5}	3.48×10^{-5}
Photochemical oxidation	kg C2H4 eq	-2.24×10^{-1}	-1.68×10^{-1}	-1.68×10^{-1}
Terrestrial ecotoxicity	kg 1.4-DB eq	3.58×10^{-1}	2.68×10^{-1}	2.68×10^{-1}

Table 3. Reduction of Air Emissions

Impact category	Reference unit	First Incinerator Design System	Second Incinerator Design System	Third Incinerator Design System
Carbon dioxide	Kg	1236.35	252.26	881.36
Carbon disulfide	Kg	7.99×10^{-9}	5.99×10^{-9}	5.99×10^{-9}
Carbon monoxide	Kg	5.83	0.62	0.93
Methane	Kg	3.45	1.09	1.18
Nitrogen dioxide	Kg	1.10	0.83	0.83
Nitrogen monoxide	Kg	1.00	0.75	0.75
Sulfur dioxide	Kg	7.52	1.89	4.00
Hydrogen	Kg	0.19	0.07	0.07
Particulate	Kg	2.24	1.68	1.68

The environmental impact assessment based on the Life Cycle Assessment (LCA) for three incinerator design systems reveals distinct variations across several impact categories. In terms of abiotic depletion, the first design system exhibits a higher depletion of non-renewable resources, measured at 8.43×10^{-4} kg Sb eq, compared to the second and third systems, both at 6.32×10^{-4} kg Sb eq. This suggests that the second and third systems are more resource-efficient. Similarly, for abiotic depletion of fossil fuels, the first system consumes 1.76×10^{3} MJ, higher than the 1.32×10^{3} MJ consumed by the other two systems, indicating a less sustainable approach to energy use. The acidification potential, however, presents a stark contrast: the first system generates a significantly higher impact at 6.17×10^{5} kg SO_2 eq, which is markedly larger than the second and third systems at 3.41 kg SO_2 eq and 4.62×10^{5} kg SO_2 eq, respectively. This highlights a need for optimization in the first system to mitigate air pollution. Additionally, in eutrophication potential, the first system again leads with 1.29×10^{5} kg PO_4 eq, which could result in more severe nutrient pollution compared to the second and third systems, which register 3.43×10^{-1} kg PO_4 eq and 9.70×10^{4} kg PO_4 eq.

In terms of other environmental impact categories, the first incinerator design also performs worse in freshwater aquatic ecotoxicity, with an impact of 1.27 kg 1.4-DB eq, while the second and third systems show a lower and identical value of 9.53×10^{-1} kg 1.4-DB eq, suggesting less potential harm to freshwater ecosystems. The most striking difference, however, is observed in the global warming potential (GWP100a), where the first system generates 1.42 × 10^5 kg CO_2 eq, far exceeding the second system's 5.73 × 10^2 kg CO_2 eq and the third system's 1.06 × 10^5 kg CO_2 eq, indicating that the first system has a far larger carbon footprint. In terms of human toxicity, the first system also stands out with 1.68 × 10^7 kg 1.4-DB eq, compared to the significantly lower values in the second and third systems. Across categories such as marine aquatic ecotoxicity, ozone layer depletion, and photochemical oxidation, the first system consistently shows a higher environmental burden. These results underline the importance of carefully considering and optimizing design choices in incinerator systems to minimize environmental harm.

The analysis of air emissions reductions from three different incinerator design systems, as shown in Table 3, highlights significant variations across key pollutants. The first incinerator design system exhibits the highest carbon dioxide emissions at 1236.35 kg, far exceeding the 252.26 kg from the second system and the 881.36 kg from the third. This suggests that the first system is less efficient in mitigating CO_2 emissions. Similarly, the emissions of carbon monoxide (CO) are substantially higher in the first system at 5.83 kg, compared to 0.62 kg in the second and 0.93 kg in the third, indicating that the first system may contribute more to air quality degradation through incomplete combustion. For methane (CH_4), which is a potent greenhouse gas, the first system again shows a higher value of 3.45 kg, as opposed to the 1.09 kg and 1.18 kg emitted by the second and third systems, respectively. In terms of nitrogen oxides (NO_2 and NO), which contribute to acid rain and smog, the first system also performs worse, emitting 1.10 kg and 1.00 kg of NO_2 and NO, respectively, while the second and third systems are lower at 0.83 kg and 0.75 kg each. Additionally, sulfur dioxide (SO_2), a major contributor to respiratory problems and acidification, is emitted at 7.52 kg by the first system, significantly higher than the 1.89 kg from the second and 4.00 kg from the third system. Finally, the emissions of particulate matter are highest in the first system at 2.24 kg, compared to 1.68 kg in both the second and third systems. These findings suggest that while the first incinerator design is less effective at reducing harmful air emissions, the second design system demonstrates the best overall performance in minimizing pollutants across several categories.

Recent studies on WES incineration systems further support the findings related to environmental impacts. Research emphasizes that incineration, while an effective solution for reducing waste volumes, presents significant challenges in terms of emissions, particularly global warming potential (GWP) and acidification. A study conducted in Southeast Asia found that incineration can contribute up to 41% reduction in CO_2 emissions if optimized properly, but still exhibits high impacts in categories like terrestrial ecotoxicity and eutrophication, which align with the results seen in the first design system in Table 2 (Bianco et al., 2021; Kwon et al., 2024). Moreover, effective policy frameworks, such as those implemented in South Korea, have demonstrated that integrating incineration with strict emissions controls and energy recovery incentives can substantially mitigate environmental burdens. South Korean facilities, for instance, have succeeded in reducing nitrogen oxide (NOx) emissions, a key contributor to acidification, and extended landfill lifespans through energy recovery from incineration (Kwon et al., 2024).

Further research underscores the potential for WES incineration to meet renewable energy targets while simultaneously addressing waste management concerns. In Indonesia, for example, WES incineration was projected to contribute to 3.72% of the country's renewable energy mix by 2025. However, the study highlighted that without stringent environmental controls, the incineration process could still lead to significant air pollution, particularly through emissions of greenhouse gases and acidification agents, which is consistent with the higher GWP and acidification potential seen in certain incinerator designs (Di Maria & Micale, 2015; Zeng et al., 2024). These findings emphasize the need for comprehensive life cycle assessments and policy integration to ensure that incineration systems are both environmentally and economically viable in the long term. On the other hand, these findings reinforce the need for continuous technological improvements and policy incentives to drive the adoption of cleaner incineration systems globally.

CONCLUSION

The waste-to-energy (WES) incineration systems analyzed in this study demonstrate varying levels of performance across key environmental impact and energy generation metrics. The third incinerator design system stands out with the highest energy output of 445.67 KW, surpassing both the first and second systems. However, this system also shows moderate carbon dioxide and other pollutant emissions. The first incinerator design system performs the worst in terms of environmental sustainability, with higher emissions across multiple categories, including CO_2, sulfur dioxide, and particulate matter. In contrast, the second design system achieves a balance between emissions control and energy generation, making it the most environmentally favorable choice. The findings underscore the critical role of design optimization in reducing environmental impacts while improving energy efficiency.

For future research, it is advisable to focus on improving waste-to-energy (WES) incineration system designs, particularly in terms of enhancing emission control mechanisms to minimize air pollutants. Investigating newer technologies like advanced filtration and gas treatment systems could yield better environmental outcomes. Additionally, exploring the integration of renewable energy sources alongside incineration might further reduce carbon footprints and improve system efficiency.

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