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Regional Case Study

Life Cycle Assessment to Compare the Environmental of Food Waste Management System in Semarang City

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Abstract

1.3 billion tons of the food produced for human consumption is wasted in the food supply chain as a result of a number of issues. A high proportion of food waste occurs during consumption, primarily influenced by consumer behavior. In Semarang City, Black Soldier Fly, incineration, and composting are alternatives to food waste management. This research aims to analyze alternative food waste management methods that yield reusable resources and materials because currently unknown which method has the smallest environmental impact. Life Cycle Assessment method can be used to examine the environmental impact of the food waste management system from every phase 1 ton food waste analyze. BSF has proven superior to composting, incineration and landfilling methods in analyzes of potential environmental impacts that reduce 90% environmental impact. Landfills cover a large area and the effect of global warming is significant until of 1.704E+03 CO2-eq, this issue needs more attention in the management of the generated CH4. Incineration needs to make advances in the method such as producing new resources and emissions so that can be reused because incineration impact eutrophication potential until 2.438E+00 PO_4^{3-}/kg. For reasons environmental concerns, efficient food waste management is crucial to realizing the Sustainable Development Goals.

Keywords: Food waste; life cycle assessment; semarang; sustainable development goals

1. Introduction

One to tree % (1.3 billion tons) of the food produced for human consumption is wasted in the food supply chain as a result of a number of issues (Ishangulyyev et al., 2019; Mesterházy et al., 2020). Food waste (FW) is uncommon among waste types because it will undergo a biological process, provided the appropriate waste management technology is used. A high proportion of Food Loss And Waste (FLW) occurs during consumption, primarily influenced by consumer behaviour, values, and attitudes. In managing FW, the USDA and EPA work together to achieve the target of point 12.3 with the UN's sustainable development goals (Babbitt et al., 2021; Omolayo et al., 2021). With this goal, USDA, and EPA directly process FW using the thermal method, composting for energy recovery, and economically powerful (Dalke et al., 2021). In various nations, food residue is processed in landfilling, thermal method (incineration), anaerobic digestion, and composting. This technological method for FW management can generate emissions with negative environmental implications, in addition to emissions from the use of fuels such as diesel, which can limit the potential for nutrient and energy recovery through alternative treatments (Ryen & Babbitt, 2022). Although this method optimizes food refuse while regenerating energy and resources, it impacts the environment in various ways at an additional cost (Ambaye et al., 2021; Onyeaka et al., 2023). In the city of Semarang, however Black Soldier Fly (BSF), incineration, and composting are alternatives to landfilling when it comes to FW (Budihardjo et al., 2023; Budihardjo et al., 2021).

The findings of this study can serve as a catalyst for public organizations and neighborhood businesses to implement circular procurement practices in Semarang City. This entails sourcing goods and services with an emphasis on robustness, recyclable materials, and reuse. Because of that, this study aims to analyze alternative FW management methods that produce resources and materials that can be reused because it is currently unknown which method has the smallest environmental impact and to compare the sustainability aspects of FW management, so that it can be considered in expanding the application of waste management food in Semarang City. Potential environmental impacts can be analysed using various methods, one of which is life cycle assessment (LCA), where with this method estimates the potential environmental impacts of inputs, outputs and emissions generated during the life cycle. LCA is a systematic evaluation of the potential environmental impact of each analyzed life cycle stage. ISO standards make reference to LCA methodology aims to increase transparency when using LCA methodology and improve comparability between LCA studies (ISO, 2016a; ISO, 2016b). In contrast to product LCA models, which only study the life cycle of a single product from extraction to end-of-life, the waste LCA model enables users to evaluate heterogeneous material flows incorporating distinct waste components.

In recent years, LCA has emerged as a powerful instrument for influencing rules and policies pertaining to waste management. Decisions about waste management techniques and infrastructure investments are aided by LCA results made by governments and organizations (Syafrudin et al., 2023). To make sure that environmental restrictions are effective, policymakers can match their goals with real-world data. By incorporating LCA into policymaking processes, more environmentally friendly methods of garbage disposal can be implemented on a societal scale (Budihardjo et al., 2023). Although LCA is primarily concerned with environmental effects, the necessity of including social and economic factors in waste management evaluations is becoming increasingly apparent. These more inclusive sustainability frameworks recognize the wide-ranging social and economic effects of waste management choices. Therefore, modern LCAs are delving into the social and economic aspects of waste management techniques, with an eye toward gaining a more holistic comprehension of sustainability that takes into account community health and economic viability (Simons et al., 2023). The software Simapro is utilized to calculate and estimate the prospective environmental impact of each scenario. Comparison of alternative FW management systems yields the optimal waste management scenario from a number of perspectives, so that FW management in Semarang City is sustainable.

2. Methods

Goal and scope stages aim to limit the scope of the life cycle to be analyzed, and determine the functional unit (FU). Goals and Scope, serve to limit the amount of the life cycle that needs to be looked at, define research goals, and set up functional units that will be used as the base for all furthered data collection, modeling, and evaluating. The LCA framework in the ISO standard makes sure that the study is focused, clear, and in line with its goals by clearly defining its purpose and scope. In this study, FU is 1 ton of FW serves as the basis for estimating the possible environmental impact of each waste management strategy adopted in the city of Semarang, FU indicates the quantity of waste that will be treated as a result of the management method. System boundaries for each FW processing cycle scenario (gate to gate) base on Semarang City existing, system boundary includes three outputs: compost, air emissions, and animal feed. The environmental assessment has been conducted according to the LCA principles. As specified by ISO 14040, the stages of goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and life cycle interpretation were implemented (ISO, 2006). Goal and scope, LCI, LCIA and life-cycle interpretation of impact results are the four major phases in LCA. Inventory data in LCA must be thoroughly explained in order to maintain transparency and reliability. First, the data must reflect its relevance, currency, and geographic scope, taking into account regional differences in processes and technologies. In addition, the sources of these analyses using secondary data must be disclosed, as well as any adjustments or transformations made to adapt the data to the particular LCA context. To collect data, LCA must describe how the collected information is organized and structured, typically in the form of an exhaustive inventory table listing all inputs and outputs associated with the product or process being evaluated. In addition, appropriate documentation of inventory data and sources is essential for traceability and reproducibility, and the data should be reviewed and validated by specialists or interested parties to ensure accuracy and completeness. Compliance with internationally recognized LCA standards and guidelines, such as ISO 14044, can improve the rigor and uniformity of the entire LCA process. For this analysis we used the CML IA Baseline method, but only chose three impact analysis indicators, namely Global Warming Potential (GWP), AP (Acidification Potential), and Eutrophication Potential (EP) will be analyzed and compared to each alternative method of FW management utilizing the LCA technique. The choice of this impact category is due to its alignment with specific environmental issues relevant to the product, process or system being evaluated. Where, each management must be in accordance with the waste products produced and the products sold (Omolayo et al., 2021). SimaPro software, and Eco invent 3.1 database as background data. Each material input conforms to the current conditions at the Jatibarang landfill and Semarang State University's. **Figure 1 a-d** depicts the primary processes involved in the system scenario.

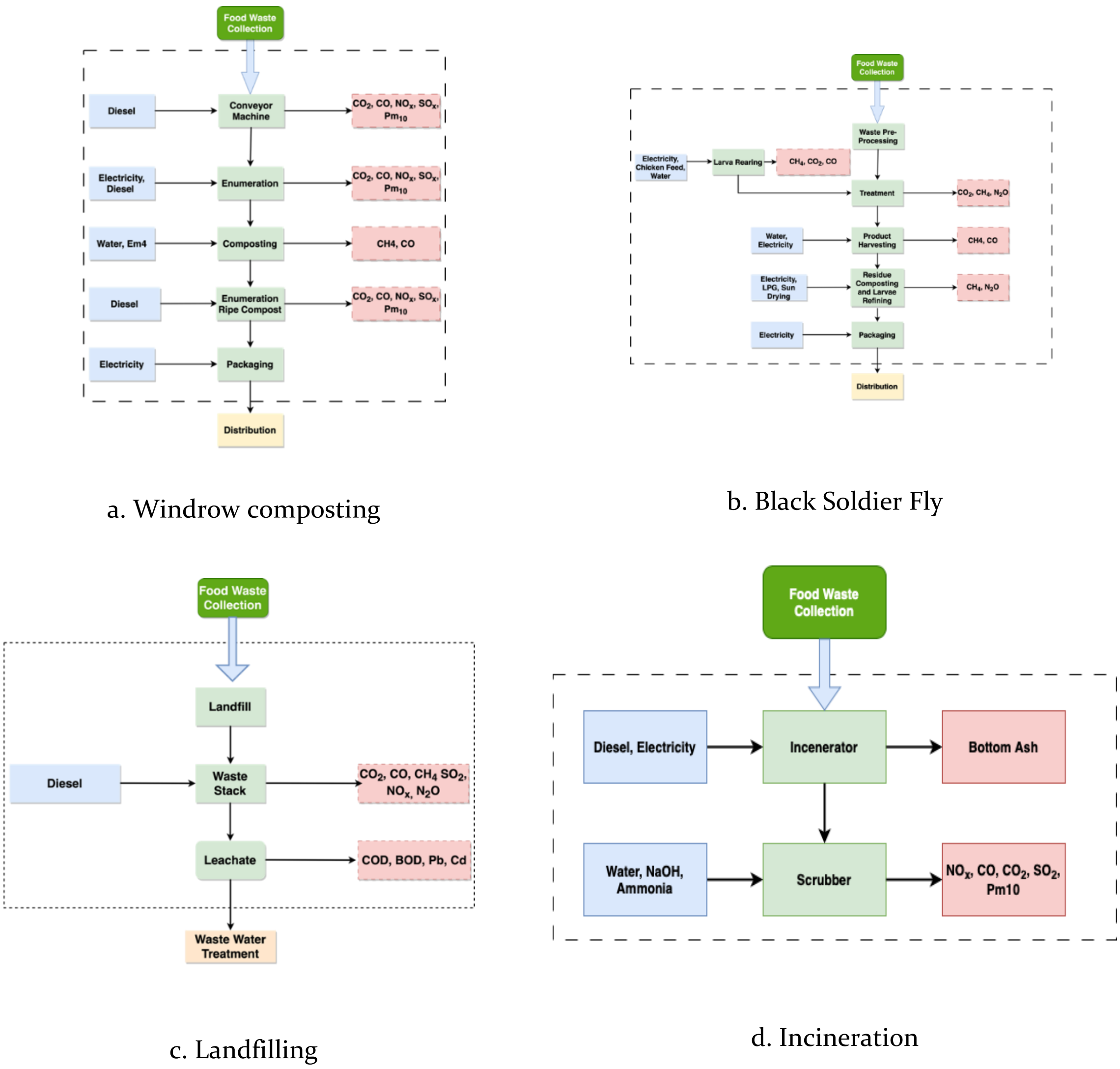

Figure 1. Flowchart showing the main processes involved in the four-system food waste management, a: windrow composting, b: Black soldier fly, c: Landfilling, and d: Incineration

3. Result and Discussion

3.1. Life cycle assessment

GWP is frequently used as a multiplier to convert emissions of different greenhouse gases into values that may be consistently compared. This enables a direct comparison of greenhouse gas emissions based on their ability to cause global warming. In the meanwhile, EP is used in this research since it can take into account the effects of waste produced on the aquatic ecosystem, which can include a decline in water quality or a decrease in oxygen levels. For AP analyses, it is important to take into account gas emissions that cause acid production as well as their propensity to interact with water and intensify acidification. These three potential environmental impacts analyze can become a crucial foundation in improving the established technology

3.2. Goal and Scope

The primary objective is to compare these processes from beginning to end, i.e., from when the organic material first enters the system to when the product departs the processing process. In describing the scope of this analysis, give close attention to the system boundaries that encompass the initial to final phases of each waste management technique. All methods utilize the same functional (1 ton FW) to enable for a fair comparison. Identify relevant environmental parameters, including CO2, CH4, NOx, PM10, etc., as well as the energy consumption and water emissions associated with each method.

3.3. Life cycle inventory

Results of LCA study directly depend on LCI, which is a crucial component (Lai & Beylot, 2023; Leal Filho et al., 2023). In this study, the LCI was carefully selected based on previous research to justify the conditions and describe the situation to be properly evaluated, in this stage covering emissions, material inputs and generated outputs. The obtained LCI findings are detailed in Table 1.

Table 1. Inventory of treatment processes of food waste

Input & Emission	Material and Substances	Windrow Composting	Landfilling	Incineration	BSF
Input material	Diesel	7.7 L/t FW	8 L/t FW	10 L/t FW	-
	Ammonia	-	-	0.4 kg/t FW	-
	Water	38.9 L	-	15 L	669 L
	Electricity	1.33 kWh	-	80 kWh	7.45 kWh
	Chicken Feed	-	-	-	3.1kg
	LPG	-	-	-	3 kg
	EM_4	2 L	-	-	-
Emission to Air	CO_2	26.7 kg/t FW	65 kg/t FW	-	-
	CO	1.5 kg/t FW	185 kg/t FW	0.22 kg/t FW	-
	CH_4	8.93 kg/t FW	61.29 kg/t FW	6.4 g/t FW	631 g/t
	NO_x	0.753419 kg/t FW	0.753419 kg/t FW	0.27 kg/t FW	-
	NaOH			0.5 kg/t FW	
	N_2O	0.00728 kg/t FW	0.00728 kg/t FW	-	65 g/t
	SO_2	-	37 kg/t FW	5.8 g/t FW	-
	Pm_{10}	0.00846 kg/t FW	-	0.063 kg/t FW	-

	Hydrocarbon (unspecified)	1.05 kg/t FW	-	-	-
	SO_X	2.55 kg/t FW	-	-	-
	Ammonia	-	-	6.8 g/t FW	-
Emissions to Water	COD	-	2717 mg/L	-	-
	BOD	-	1395 mg/L	-	-
	Pb	-	1.05 mg/L	-	-
	Cd	-	0.862 mg/L	-	-
	TSS	-	405 mg/L	-	-

Source: Window Composting (Ouedraogo et al., 2021; Recycled Organics Unit, 2006), Landfilling (Ouedraogo et al., 2021; Slorach et al., 2019), Incineration (Nofiyanto et al., 2019; Slorach et al., 2019), BSF (Mertenat et al., 2019)

3.4. Life cycle interpretation

The results of the LCIA for 1 ton of FW management are shown in **Figure 2**. AP, EP, and GWP are the three environmental impacts that are combined in this study.

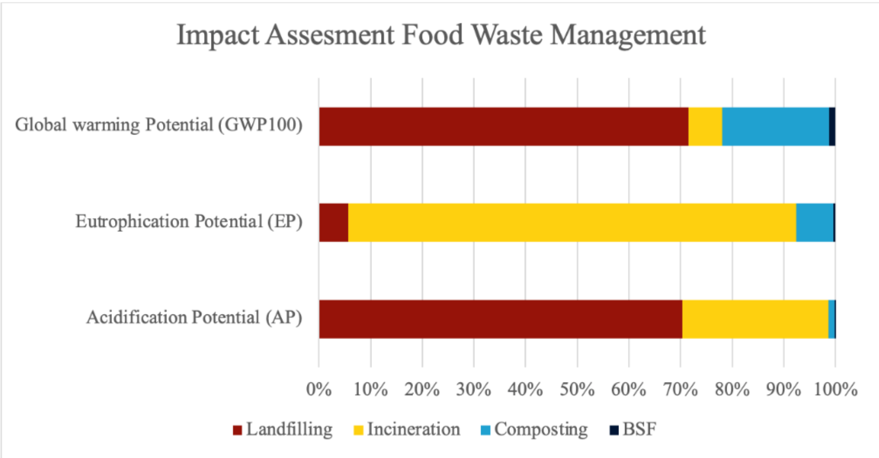

Figure 2. Representation of environmental impact from food waste management

3.4.1 Global warming potential

GWP in terms of equivalent CO_2 units, the effect of greenhouse gases is compared to the GWP of carbon dioxide over a 100-year time horizon (Szczęśniak & Stefaniak, 2022; Zieger et al., 2020). The results of the analysis show that landfilling has the highest GWP of 1.704E+03 CO2-eq which accounts for 70% of the impact of the four FW treatments in Semarang City, mainly due to untreated methane emissions from FW unmanaged in landfills. Among waste management methods, landfilling is associated with the highest GWP, predominantly due to the unusual manner in which organic waste decomposes in landfills. Food waste and other organic materials endure anaerobic decomposition in an oxygen-deficient environment. This process generates vast quantities of CH_4, a potent greenhouse gas with a significantly higher heat-trapping potential than carbon dioxide CO_2. While the Windrow composting method has the highest GWP value after landfill as much as 1,503E+02 CO2-eq or as much as 19% of the four different methods. Like the composting approach that exposes FW to the open air for twenty-one days during the composting stage, composting is the second highest source of GWP emissions (Kumar et al., 2023; Kumar et al., 2021; Kumar et al., 2022). Because the materials and energy used are minimal, BSF has the lowest GWP emissions, and the results have no significant impact on the environment that impact 3,061E+01 CO2-eq. As for the incineration method, the use of wet scrubbers before the exhaust gases are released into the atmosphere makes incineration the second recommended method for managing FW because it only contributes 9% or 1,530E+02 CO2-eq of the total emissions. Due to the use of modern technology and stringent emission regulations, incineration typically produces a lower GWP than landfilling. This is due to the fact that the incineration process converts waste's organic carbon into CO_2 and not methane. CO_2 is a greenhouse gas, but its heat-trapping capacity is lower than that of methane, and it disperses more rapidly in the atmosphere. In addition, an efficient incineration process includes measures to capture the majority of CO_2 emissions via combustion controls and air pollution control devices, such as exhaust gas scrubbers.

GWP demonstrates the total carbon equivalent emissions associated with the complete life cycle of food waste management by landfilling. GWP hotspots are frequently associated with life cycle stages where substantial greenhouse gas emissions occur. In the case of landfilling, for instance, the decomposition of food waste produces unprocessed methane gas, which has a significant impact on the environment. Landfilling is the least recommended option for managing FW because of its potential for outstanding environmental effects. Methane is especially worrisome because its heat-trapping capability is astonishingly 84 times larger than CO_2's over a very short time period (usually estimated as 20 years). Methane contributes greatly to global warming and the greenhouse effect because it is so effective at absorbing and holding heat in the Earth's atmosphere on a molecular level. It is now evident why organic waste, including food waste, should not be disposed of in landfills (Farghali et al., 2022; Nunes et al., 2020). Alternative waste management systems that prioritize reducing methane emissions are urgently needed due to the combination of the potential for methane emissions and methane's high GWP.

3.4.2 Eutrophication potential

Eutrophication potential for each eutrophying emissions into air, water, and soil is generally measured as PO_4^{3-}/kg emission (Wahyono et al., 2022). The data shows that incineration is the most significant EP contributor among all FW management techniques of 2.438E+00 PO_4^{3-}/kg or 90%. In addition, the use of ammonia in incineration has a relatively high impact on the environment. While the impact of EP from the FW management method comes from the use of diesel fuel in each process used by heavy equipment as well as shreds machines and conveyors. Then the BSF method has the lowest potential impact of all methods of 2.003E-1 or 1%. Sulfur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3) are anthropogenic emissions that are created in the exhaust gas from scrubbers due to combustion, the use of diesel, and the use of ammonia to reduce NO_x emissions (Larki et al., 2023; Shelyapina et al., 2020). These emissions cause air pollution, acid rain, and health issues, and they come from combustion processes and the disposal of gas. Efficient scrubber systems are crucial in reducing these pollutants, which demonstrates concern for better environmental performance. Scrubber technology, which is meant to catch emissions and neutralize or transform them into less toxic molecules, is an effective method for lowering emissions. By decreasing air pollution and its effects on human health and the natural world, this preventative strategy boosts environmental performance. The main hotspots in EP for incineration methods are NO_x emissions from combustion products and the significant use of electricity generated and used during the combustion process. NO_x is a nitrogen precursor that can contribute to increased nitrogen levels in the environment. When NO_x reaches waters, especially in the form of acid rain, it can increase the nitrogen content in the water, trigger eutrophication, and have a negative impact on aquatic ecosystems.

3.4.3 Acidification potential

Acidification potential for each acidification emission is expressed as kg SO_2 eq (Burchart et al., 2023). AP is associated with the acid deposition of contaminants that acidify soil, groundwater, surface waters, biological organisms, ecosystems, and substances. SO_2, and NO_x are the principal acidifying pollutants (Whelan et al., 2022; Yadav et al., 2020; Yadav & Samadder, 2018). According to research results, landfilling and incineration methods are the biggest contributors to AP where each contributes emissions of 4.506E+01 kg SO_2 eq and 1.810E+01 kg SO_2 eq. Anaerobic decomposition of organic waste contributes to high AP in landfills by producing CH_4, a powerful greenhouse gas. Acid rain is exacerbated when methane reacts with oxygen in the air, producing sulfuric acid (H_2SO_4) and nitric acid (HNO_3). When ammonia (NH_3) is released during decomposition, it can be oxidized in the air and help produce nitric acid (HNO_3)(Mor & Ravindra, 2023; Zhang et al., 2023). Furthermore, gas emissions like NOx during waste incineration are mostly related to incineration hotspots in AP. In addition to producing NOx emissions, burning trash at high temperatures also contributes to incineration's high AP (Cho et al., 2020). HNO_3, a byproduct of the reaction of nitrogen oxides (NOx) with water and other chemicals in the atmosphere, is a contributor to acid rain. Whereas the two composting and BSF methods have very small potential environmental impacts in this potential impact analysis.

3.5 Recommendation food waste management

According to the FW management hierarchy, it is seen that preventing edible FW is better than treating or taking advantage(Lombardi & Costantino, 2021; Lombardi et al., 2021). Analysis of the three impact categories, BSF is the most environmentally friendly method compared to composting and burning. These results are the same as research which shows BSF management has three times lower emissions than management using the composting method (Mertenat et al., 2019). Whereas the landfilling method is the last choice in managing FW because landfilling can produce methane gas without management, which makes the potential environmental impact up to 80-95% higher than the three methods analyzed. When economic costs are taken into account, BSF is the most profitable alternative method, better than the output produced by the composting method. While incineration produces only bottom ash, which requires additional management to convert into reusable concrete, it does impact investment. Whereas the landfilling method requires a relatively very high investment compared to incineration, because it includes the construction of a methane gas catcher, the addition of heavy equipment used and landfill cover soil. In accordance with the development of technology policies and applications, there are various alternative methods of FW management. However, prevention is recommended as the first choice option, but analysis of this method is rare. However, from this analysis the BSF method is a method that needs to be widely applied, followed by composting while incineration and landfilling require sustainable implications and higher investment to produce new resources that can be used. Composting is showing promise as an environmentally friendly and resource-efficient way to manage food and organic waste, improving soil quality and lowering the need for landfills, according to a different study. Furthermore, the BSF approach was assessed and discovered to be a viable choice for reducing food waste because of its capacity to transform organic matter into useful resources like compost and insect protein (Mertenat et al., 2019). Nonetheless, this study also highlights how technology, emission control, and trash sorting procedures all play a significant role in the environmental effects of landfilling waste. Incineration can aid in energy recovery and lower greenhouse gas emissions if done so with the use of contemporary, effective technology and stringent emission controls. Even while landfilling has a longer-term negative influence on the environment, it can still be done in an environmentally responsible manner if leachate and methane emissions are controlled (Budihardjo et al., 2023).

The Sustainable Development Goals (SDGs) are dependent on resolving pressing issues like FW management (Chaerani et al., 2023; Kastrinos & Weber, 2020). Not only is FW management an environmental issue, but it also has serious consequences for many facets of human existence and the success of the SDGs as a whole (Sharma et al., 2021; Sharma et al., 2023). SDG 2, "Zero Hunger," is one of the SDGs that has strong ties to FW management. To get there, we need to drastically cut down on wasted food. (Costa et al., 2022) To accomplish this, only purchase what will be consumed and store food safely. In addition, a major step towards achieving SDG 2 is providing funding for food programmers that redistribute surplus food to those in need (Chandan et al., 2023). Goal 12 of the Sustainable Development Agenda, "Responsible Consumption and Production," thus stresses the significance of sustainable farming practices that lessen the amount of wasted food while increasing crop yields (Chen et al., 2023). Achieving SDG 12 also requires encouraging more sustainable consumption patterns, such as a plant-based diet and the reduction of excessive meat consumption. An additional SDG that is affected by FW management is SDG 13, "Climate Action." We can help the worldwide effort to prevent climate change by lowering emissions of greenhouse gases caused by the decomposition of organic waste in landfills (Ilango et al., 2023). Third of the Sustainable Development Goals is "Good Health and Well-being," which deals with health issues. Diseases caused by improperly managed FW can be avoided by encouraging good food hygiene and processing practices. Awareness can also be increased by spreading data on the dangers of eating stale or otherwise compromised food. For SDG 17 to be realized, "Partnerships for the Goals," there must be effective cooperation between governments, NGOs, and the corporate sector. By working together, we can create a system to control FW that will last for the long haul. In order to help developing countries achieve sustainable FW management, it is essential to share knowledge and technology with them (Stott & Murphy, 2020).

4. Conclusions

BSF and composting have proven superior to landfilling and incineration and stockpiling methods in various analyzes of potential environmental impacts. Because landfills cover a large area and have a significant GWP until 1.704E+03 CO2-eq and AP that impact until 4.506E+01 kg SO_2 eq, this issue requires more attention in managing the gas produced. Whereas incineration needs to make progress in methods such as generating new resources and emissions so they can be reused because still impact GWP. Moreover, still impact on AP that impact until 2.438E+00 PO_4^{3-}/kg or 90% that compared to any other management. Based on the results of this analysis, alternative FW management is suggested using the composting and BSF methods because they have more significant benefits in reducing environmental impacts and have higher sustainability potential in terms of environmental impacts. Additional analysis of economic aspects can be added as a further analysis to determine the economic potential resulting from each method applied. Alignment with the SDGs is also necessary for the successful implementation of FW management. This involves not only playing a crucial part in attaining a number of SDGs, but also in reducing FW and minimizing environmental impacts. Contributing to SDG 2, "Zero Hunger," which aims to ensure sufficient and high-quality food availability for all, through reducing FW and encouraging sustainable agriculture practices. Prudent FW management supports SDG 12's principle of responsible consumption and production of food.

The LCA of FW management methods is highly relevant to the global fight against climate change and correlates with a number of SDGs. The results of the LCA shed light on the environmental impacts of various food waste management techniques, thereby shedding crucial light on the decisions we make to reduce emissions and safeguard the environment. By reducing the greenhouse gas emissions caused by improper food waste disposal, we directly contribute to Sustainable Development Goal 13, "Climate Action." This is consistent with international efforts to mitigate climate change and limit its negative effects on our planet. In addition, the appropriate management of food waste contributes to the achievement of SDG 3, "Good Health and Well-Being," by preventing diseases that can result from unsanitary waste disposal methods. The 8 Sustainable Development Goal, "Decent Work and Economic Growth," is aided by advanced waste reduction strategies and the creation of new employment in the sector of sustainable waste management. This shows that environmentally responsible practices can also promote economic growth and prosperity. SDG 17, "Partnerships for the Goals," highlights the significance of collaborative efforts among stakeholders in establishing a sustainable system for managing food waste. The LCA results serve as a valuable resource for policymakers, businesses, and communities to make informed decisions toward a more sustainable future.

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