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Estimating Short-lived Climate Pollutions Emission from Waste Management System in Semarang – A Life Cycle and Material Flow Analysis

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ABSTRACT

The concept of short-lived climate pollutions (SLCPs) has been developed as part of global warming mitigation policies to identify the human-made atmospheric compounds that contribute to positive radioactive forcing. Numerous evident shows that there are those pollutants cause negative impact like climate change. Despite the extensive research in this area, the potential emissions of SLCPs from the waste management sector at the city level have not been thoroughly explored. This study aimed to reveal the material flow of domestic waste in Semarang City. The waste management system was assessed using a literature survey and the potential emissions of SLCPs from waste management were analysed from a life cycle assessment perspective. This study used emission quantification tool (EQT), developed by the Institute for Global Environmental Strategies (IGES), to calculate the greenhouse gas emissions from domestic solid waste management. While collecting data from existing literature, the author performed a MFA for the current conditions, which is based on the latest available data from 2022. The result showed that the current waste management system in Semarang City has several issues, such as a significant amount of unmanaged waste and the burning of waste, which contribute to high emissions of SLCPs. For the first time, this study demonstrated that by implementing advanced technologies such as incinerators and separating organic from inorganic waste, it is possible to achieve a substantial reduction in black carbon and methane emissions in Semarang City. These findings offer valuable insights for policymakers and contribute to the development of tailored waste management strategies that effectively mitigate SLCP emissions, setting a precedent for other urban areas facing similar challenges.

Keywords: short-lived climate pollutions, domestic waste, emission, life cycle assessment.

INTRODUCTION

Short-lived climate pollutions is what kinds of pollutant are identified, chiefly methane (CH_4) (Mathew et al., 2024), black carbon (Nakajima et al., 2020), hydrofluorocarbons (HDCs) (Ibarra-Yunez, 2022), and tropospheric ozone (O_3) (Nakata, 2019), remaining in the atmosphere for shorter periods that support the occurrence of climate change and global warming potential (Lin et al., 2022; Xiaopu et al., 2022), accounting for as much as 45% of the current global warming, and targeted initiatives to cut SLCP emissions could reduce the rate of global warming by 0.6 degrees Celsius by 2050 (Bessagnet et al., 2022). The concept of SLCPs has been developed as part of global warming mitigation policies to identify the human-made atmospheric compounds that contribute to positive radioactive forcing (Mathew et al., 2024). A myriad of evident shows that those pollutants cause breathing problems, heating the atmosphere, etc. (Ukaogo et al., 2020). With these circumstances, every molecules might foster the potential of warm the Earth faster than carbon dioxide. To address the impact of SLCPs, managing domestic waste effectively is crucial

(Premakumara et al., 2018). Implementing advanced technologies, such as incinerators, can significantly reduce black carbon emissions (Kurniawan et al., 2024; Woon et al., 2023). Additionally, separating organic from inorganic waste can help manage anaerobic decomposition in landfills, further reducing methane emissions (Liu et al., 2017). Proper waste management practices can therefore play a vital role in mitigating the effects of SLCPs on climate change (Morales et al., 2024).

Numerous researchers have conducted studies that implemented using life cycle assessment (LCA), material flow analysis (MFA), and calculation approach for waste management. In India, it had been evaluated on municipal solid waste management (MSWM) using LCA and considering four waste management scenarios including the current practice, 100% composting, 100% landfilling with energy recovery, and an integrated waste management approach (Rana et al., 2019). As a result, there were significant environmental benefits of adopting an integrated waste management strategy, which combines composting, recycling, and landfilling, in reducing greenhouse gas emissions, acidification, and eutrophication (Rana et al., 2019). Contrastingly, in Lebanon, chiefly in Tyre Caza, there was a research on waste sector using MFA resulting methane emissions from the waste sector accounting for 95% of GHG emissions, estimated at 11,000 metric tons of CO_2 equivalent per year, and black carbon emissions from open burning of waste accounting for 90% of SLCP emissions, estimated at 10 metric tons per year (Stege et al., 2022). Meanwhile, in China, the authority have promoted the integration of MSWM using Intergovernmental Panel on Climate Change (IPCC) methods with just below five disposal scenarios in Beijing; furthermore, a significant decrease on emission benefit of 70.82% was witnessed in every scenario (Xin et al., 2020). By adopting such integrated approaches, countries can not only mitigate the adverse environmental impacts of waste but also contribute to a more sustainable and resilient waste management system.

The novelty of this research lies in its focus on a city-specific analysis, providing a detailed understanding of SLCP emissions from municipal solid waste management in Semarang. This study bridged the knowledge gap by offering insights into the potential impact of waste management improvements on reducing SLCP emissions. The hypotheses guiding this research are that current waste management practices in Semarang significantly contribute to SLCP emissions, and that targeted interventions, such as enhanced waste segregation and the introduction of advanced waste treatment technologies, can effectively reduce these emissions.

The objectives of this study were threefold: first, to quantify the emissions of SLCPs from Semarang's waste management system using LCA and MFA methodologies; second, to determine the previously unknown data on the contributions of various waste management practices to SLCP emissions; and third, to develop actionable strategies that can effectively reduce these emissions. The study hypothesized that the current waste management practices in Semarang significantly contribute to SLCP emissions and that targeted interventions, such as enhanced waste segregation and advanced waste treatment technologies, can significantly mitigate these emissions. This research provides critical insights that can help policymakers in Semarang and other cities facing similar challenges to develop more effective waste management strategies. By offering a framework for reducing SLCP emissions, this study not only contributes to local environmental management efforts but also to broader global climate change mitigation initiatives. As urbanization continues to increase, the need for innovative and sustainable waste management solutions becomes ever more critical. This study underscores the importance of ongoing research and collaboration among stakeholders to address the complex issue of waste management and its impact on climate change.

Methods

On the basis of the conducted research, the author utilized an application named the Emission Quantification Tool (EQT), developed by the Institute for Global Environmental Strategies (IGES), to calculate the greenhouse gas emissions from domestic solid waste management. The required data included the population in specific years, the amount of waste generated, the amount of waste managed by the formal and informal sectors, and the amount of unmanaged waste. While collecting data from existing literature, the author performed a MFA for the current conditions, which is based on the latest available data from 2022. Subsequently, waste management scenarios for 2028 were developed, including both the business as usual (BAU) scenario and the government's target scenario (30:70) (Prihadi, 2018), despite the target being set for 2025. However, given the current data, significant improvements are still needed. Therefore, this target is used as the pessimistic scenario for 2028, and the reverse value represents the optimistic scenario for 2028. Additionally, data on waste composition, unmanaged waste composition, fuel consumption by transport equipment, and the calorific value of the fuel used by the transport equipment were considered. The collected data were used to create a mass balance, which was then input into the EQT application to estimate the greenhouse gas emissions from the current and projected waste management scenarios (Fig. 1). These data are presented in Table 1.

Data collection

The waste management scenario in the region is characterized by a significant gap between waste generation and handling represented in Table 3. In 2022, the population of approximately 1,659.975 (Ubajani, 2023a) generated 1,182.29 tonnes of waste per day, while only 852.41 tonnes were handled (Ubajani, 2023b). This indicates

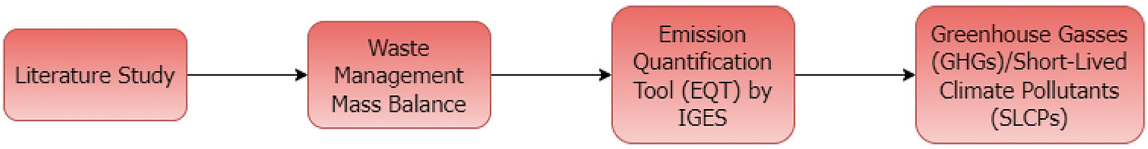

Figure 1. Research framework

Table 1. Data inventory

Data	Information	Reference
1,659.975	Population in 2022	(Ubajani, 2023a)
1. 1,182.29 tonnes/day 2. 852.41 tonnes/day	1. Total waste generation in 2022 2. Waste handled	(2022)
In Table 2.	Waste composition	(Ubajani, 2023b)
0.817 kg CO_2-eq/kWh	GHG emission factor for grid electricity production	(2021)
42.66 MJ/L	Net calorific value of Diesel	(Sommeng, 2018)
Burned waste: 11.26% Unburned waste: 1.99%	Uncollected waste (burned waste and unburned waste)	(Ramadan et al., 2022); (Ramadan et al., 2023)
0.57 tonnes/day	Reduce of the total waste transported to the landfill by CdMRF	(2021; Ramadan et al., 2019)
Composting: 0.11% Segregation: 0.07%	Reduced waste of waste generation by Integrated Temporary Waste Storages (ITWS)	(2021)
7.44 tonnes/day	Reduced waste by scavengers in landfill	(2021)
15.25 tonnes/day	Waste trader capacity	(Samadikun et al., 2020)
Target in 2025, Reduced: 30% Handled: 70%	Scenario I	(Prihadi, 2018)
5.53 tonnes/day	Maximum capacity of waste bank (Scenario I)	(Ramadan et al., 2019)
Composting: 2.80 tonnes/day Segregation: 1.37 tonnes/day	Maximum capacity of integrated temporary waste storages (Scenario I)	(2021)
1. Arm-roll truck: 347.9 L/day Dump truck: 1,222.87 L/day Excavator: 300 L/day 2. Paper and cardboards: 16% Plastics: 57% Metal: 16% Glass: 11%	1. Fuel consumption 2. Composition of recyclables collected by the informal sector	(2021)
Paper and Cardboards: 67.5% Plastics: 20.84% Metal: 4.99% Glass: 6.68%	Composition of recyclables collected by the city	(Ramadan et al., 2019)
1. 200 kg/m^3 2. Arm-roll truck 6 m^3: 170 units Dump truck 8 m^3: 41 units	1. Waste density 2. Quantity and capacity of transportation	(Ramadan et al., 2024)
Fuel for excavator: 300 L/day	Fuel consumption of excavator in 2018	(2021)

that about 330 tonnes of waste are not handled or disposed of properly every day. Furthermore, the waste composition data reveals that plastics account for the majority of the waste (57%), followed by paper and cardboards (16%), metals (16%), and glass (11%) (Ubajani, 2023b). This is consistent with the global trend of increasing plastic waste (Sommeng, 2018). The high percentage of plastics in the waste stream is a concern, as it can lead to environmental pollution and harm human health. To address this issue, the region has set a target to reduce waste by 30% and handle 70% of the total waste generated by 2025 (Prihadi, 2018). Achieving this target will require a comprehensive approach to waste management, involving both formal and informal sectors (Ramadan et al., 2022). The informal sector, which includes scavengers and waste traders, plays a crucial role in waste management in the region (Ramadan et al., 2024). In fact, scavengers have been shown to reduce waste by 7.44 tonnes per day (Ramadan et al., 2024). Additionally, waste traders have a capacity of 15.25 tonnes per day, which can help reduce waste generation. However, the informal sector faces several challenges, including lack of recognition and support from the government (Etim and Daramola, 2020). Therefore, it is essential to develop the policies and programs that support the informal sector as well as promote sustainable waste management practices (Tong et al., 2021). Table 2 are the data used to form the mass balance of waste management in Semarang City for the year 2022, as shown in Figure 2. These data were obtained from literature sources, such as data from the Ministry of Environment and Forestry on the SIPSN website, the Central Statistics Agency of Semarang City, journals on waste

Table 2. Waste compositions in Semarang City

Components	Composition (%)
Food waste	60.79
Plastics	17.20
Paper	10.18
Textile	4.94
Leather/rubber	1.00
Glass	1.79
Metal (aluminium + steel)	1.22
Others	2.88

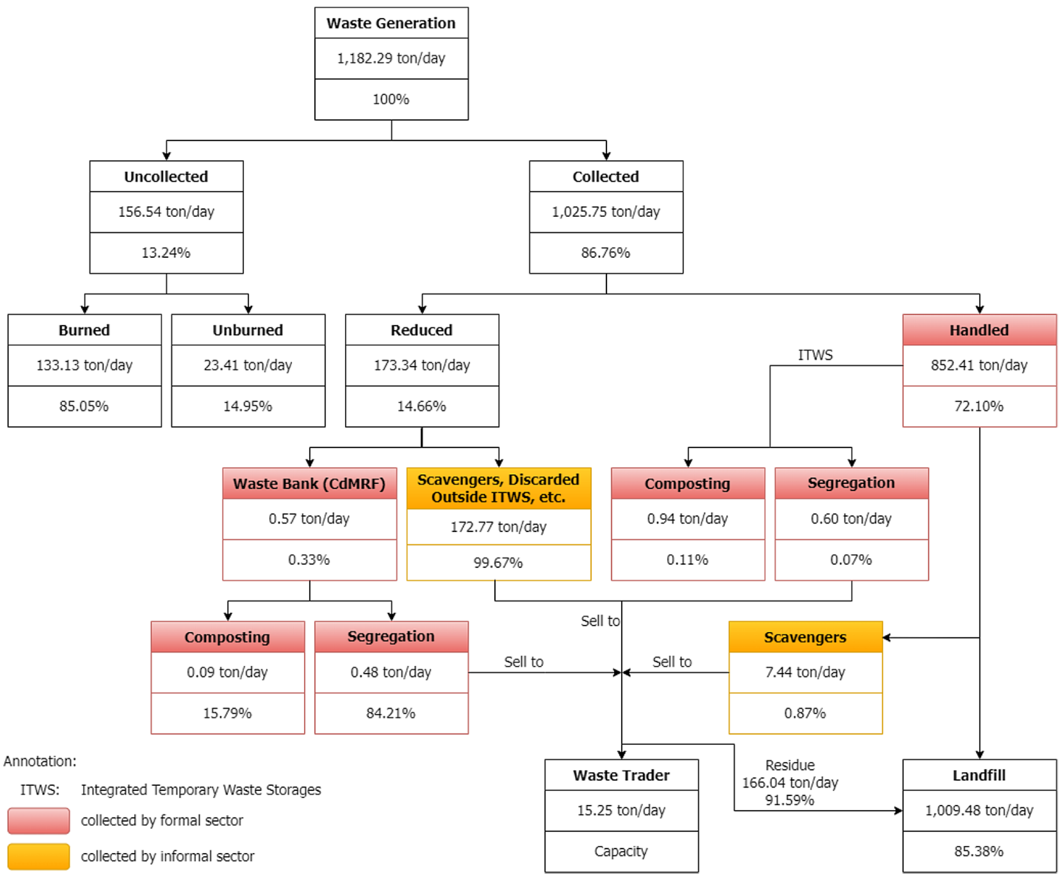

Figure 2. Current waste management in 2022

Table 3. Scenario comparison

Waste management	Current	BAU	Scenario I	Scenario II	Annotation
Uncollected	13.24%	13.24%	0	0	
Reduced	14.66%	14.66%	30%	70%	
Waste Bank	✓	✓	↑	↑	Seen from quantity
Scavenger, discarded outside ITWS, etc.	✓	✓	↑	↑	Seen from quantity
Handled	72.10%	72.10%	70%	30%	
Composting	✓	✓	↑	↑	Seen from quantity
Segregation	✓	✓	↑	↑	Seen from quantity
To Landfill without residue	843.44	899.74	870.74	363.71	ton/day

management in Semarang City, and other sources to complement the calculation of greenhouse gas emissions. The integration of these diverse data sources ensures a comprehensive and accurate representation of waste management practices and their environmental impact in Semarang City. By using the EQT application, the study not only quantifies current greenhouse gas emissions but also projects potential future scenarios, enabling policymakers to make informed decisions. This approach highlights the importance of adopting an integrated waste management strategy that prioritizes sustainability and efficiency. Further analysis and discussion are necessary to explore the implications of different waste management strategies on greenhouse gas emissions. This includes assessing the effectiveness of various waste treatment technologies and their potential to mitigate environmental impact. Additionally, the study emphasized the need for continuous monitoring and data collection to update as well as refine the mass balance and emission estimates regularly.

Data collection for developing an action plan for SLCPs reduction and achieving reduction targets

To develop a comprehensive understanding of waste management in Semarang City, it is essential to collect population data for the specified year from reliable sources such as the Central Statistics Agency of Semarang City. This data is critical for estimating the volume of waste generated and understanding the demographic factors influencing waste production. Detailed annual waste generation data, including its composition specifically the proportions of organic, recyclable, and non-recyclable waste must be obtained. Valuable insights into waste generation patterns can be sourced from the Ministry of Environment and Forestry SIPSN website, academic journals, and local government reports. Moreover, it is important to gather data on current waste management practices, including the quantities of waste managed by formal and informal sectors and the amount of unmanaged waste. This data is crucial for evaluating the efficiency of existing systems and identifying the areas that need improvement. Meanwhile, the information on the fuel consumption of waste collection and transportation vehicles, including the calorific value of the fuel used, is necessary for calculating greenhouse gas emissions associated with waste transportation. Establishing a baseline for current waste management practices and projecting future scenarios is vital. This process involves creating a mass balance for the current year and developing scenarios for future years based on different assumptions, such as BAU and target scenarios. Emission factors for various waste treatment processes, including composting, recycling, landfilling, and incineration, must be included in the analysis. These factors are essential for estimating the potential emissions of greenhouse gases and SLCPs from different waste management scenarios.

Data analysis

Material flow analysis

On the basis of data, a mass balance was created using the collected data. The purpose of this mass balance is to adjust and integrate the collected data into a coherent framework. This data was then input into the EQT application, customized to meet the specific data requirements of EQT. The data entered into EQT included basic information, the amounts of waste collected and uncollected, the composition of generated waste, waste utilization, energy consumption data, the total amount of fossil fuel used in transportation, as well as data on composting, anaerobic digestion, recycling, mechanical-biological treatment (MBT), incineration, mixed waste landfilling, and uncollected waste. However, data for the processes of composting, anaerobic digestion, and MBT were not included due to their unavailability. The mass balance and EQT analysis revealed that waste management in Semarang City involves a comprehensive approach, covering all stages from upstream to downstream, including transportation, reduction, and disposal in landfills. The formal sector is responsible for transporting waste to landfills. However, before reaching the landfill, waste is processed through sorting at reuse, reduce and recycle waste management site facilities. The informal sector contributes to reducing inorganic waste through scavenging activities, while the formal sector also facilitates waste reduction through waste banks. The mass balance of waste management in Semarang City for the year 2022 serves as the basis for developing the waste management scenarios for the year 2028, approximately 5–6 years into the future. Comparisons of the proposed scenarios and the corresponding mass balances can be seen in in Figure 3, Figure 4, and Figure 5.

Selection of current, BAU, Scenario 1, and Scenario 2

By establishing the mass balance from current conditions and scenarios, this study created a comparison table to clearly illustrate the differences between each mass balance. Table 3 indicates that the conditions in both the current scenario and the BAU scenario are the same. However, the waste generation in the BAU scenario is larger because it is projected for the year 2028. It is estimated that the population and waste generation will increase, resulting in more waste going to the landfill compared to the current scenario. On the basis of the population in 2022, with an average growth rate of 0.46% over the last 10 years, and an average waste generation of 0.71 kg/person/day, this study chose the arithmetic projection method, rather than the geometric or exponential methods because it produces a goodness of fit value closer to 1. The projected population of Semarang City in 2028 is 1,775.356. The Mayor of Semarang's Regulation No. 79 of 2018 on Regional Policies and Strategies for Managing

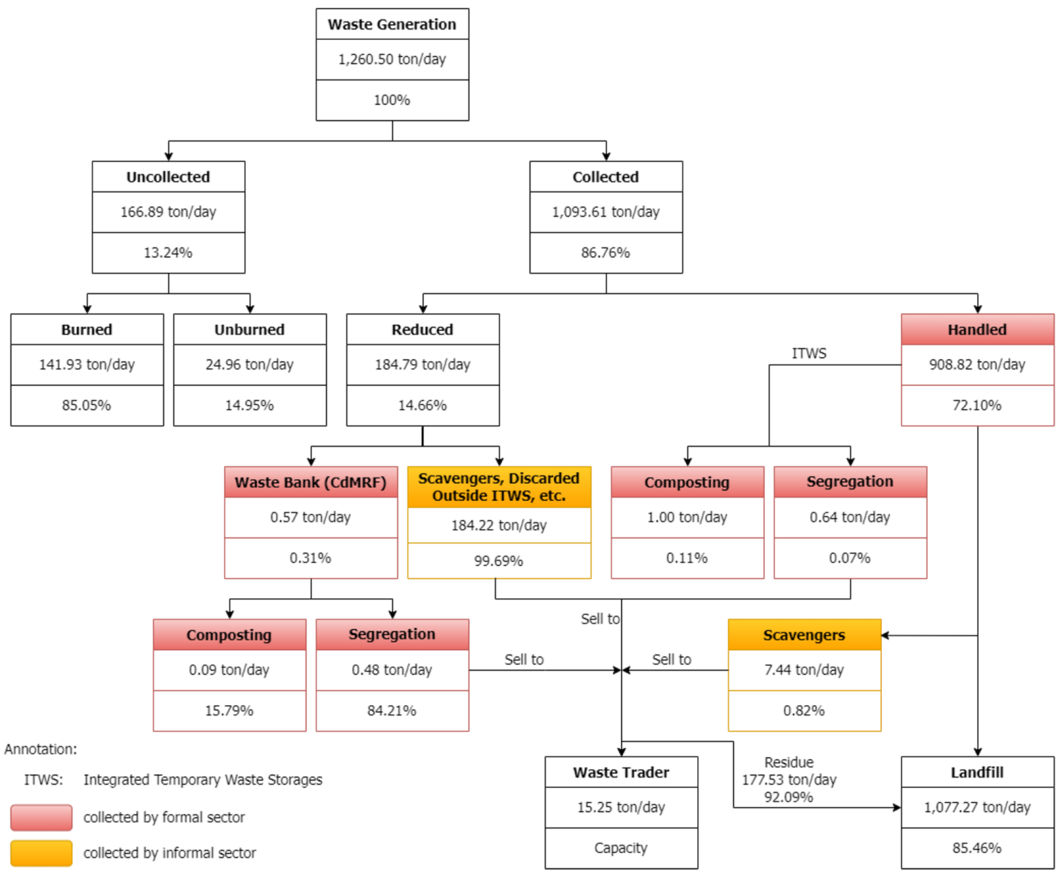

Figure 3. Business as usual (BAU) 2028

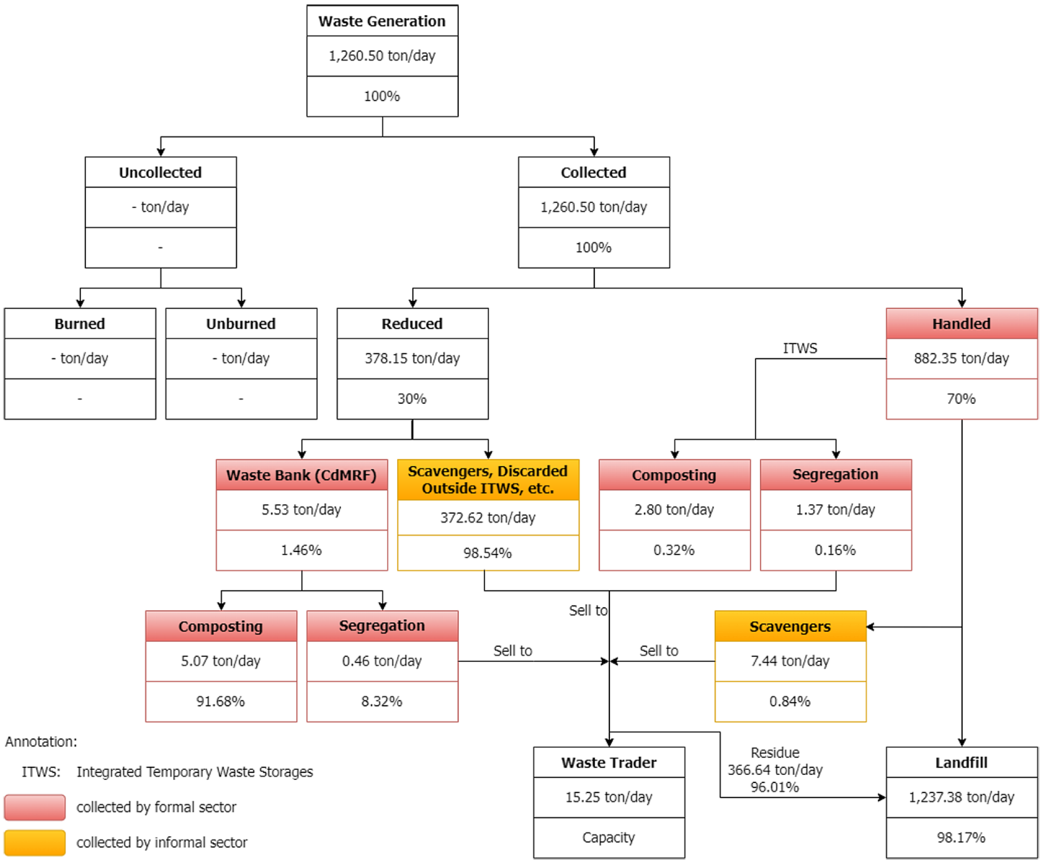

Figure 4. Scenario I 2028

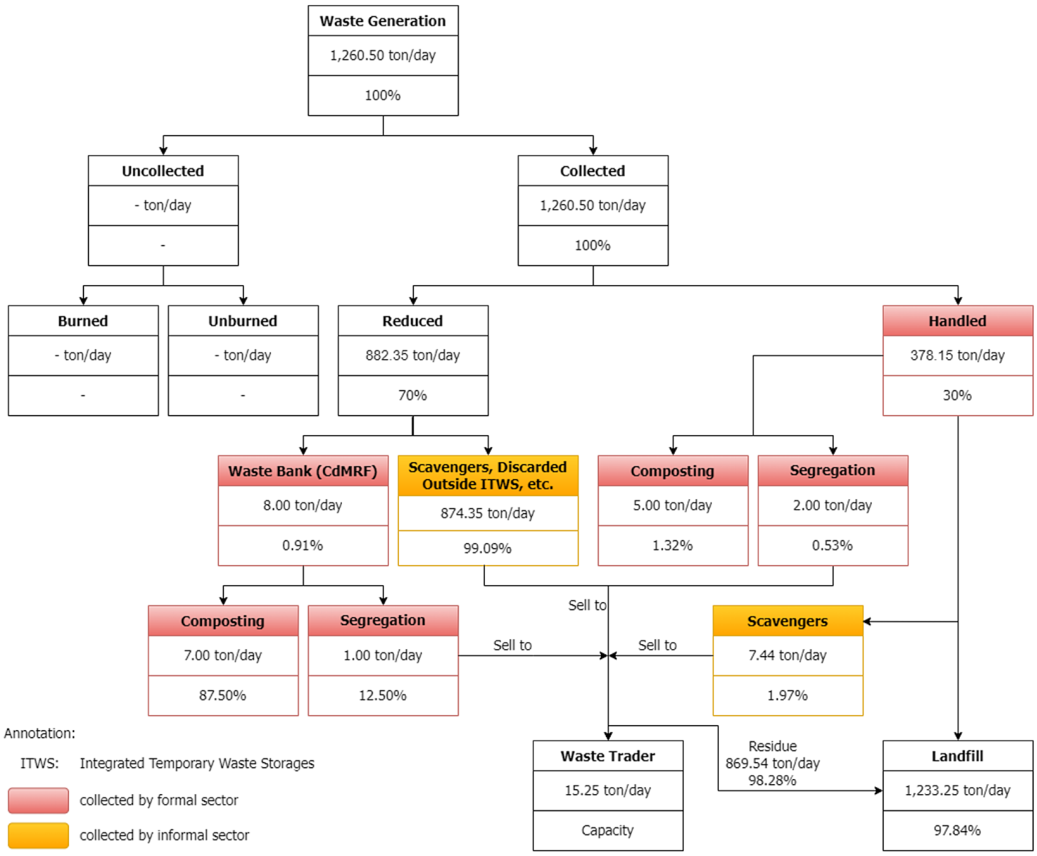

Figure 5. Scenario II 2028

Household Waste and Similar Waste sets a target of 30% waste reduction and 70% waste handling by 2025. On the basis of these targets and the results of the mass balance in the current scenario, Scenario I is designed as a pessimistic scenario, assuming that the targets for 2025 will not be met and will therefore need to be extended. However, to achieve the objectives of this scenario, the existing facilities and waste reduction capabilities must be maximized. Consequently, indicators for waste banks, scavengers, composting, and segregation point upwards, indicating an increase. Conversely, Scenario II is categorized as an optimistic scenario, assuming the opposite outcomes of the pessimistic scenario. In this scenario, waste reduction values are expected to increase significantly due to the growing waste generation and high targets that must be met. This requires maximum efforts, such as fully operational waste banks, no inactive facilities, and increased capacity of existing facilities. Additionally, optimizing waste collection routes to enhance fuel efficiency is essential. These measures are crucial to meeting the expected targets and addressing the challenges effectively.

The utilization of EQT (LCA)

With these circumstances on establishing the mass balance and comparing the scenarios, the data were entered into the EQT application to calculate the greenhouse gas emissions for each scenario. EQT is an Excel-based tool consisting of several sheets: home, introduction, key data, transportation, composting, anaerobic digestion (AD), recycling, MBT, incineration, mixed waste landfilling, open burning and landfill fire, uncollected waste, summary, and user guide. Data were input into the Key Data, transportation, recycling, mixed waste landfilling, and uncollected waste sheets, and the results were reviewed on the summary sheet.

For the transportation data, the scenario I estimated the fuel consumption of transport vehicles for 2028. This estimation was based on literature, regarding fuel consumption and the quantity of waste transported, including the number of trips required. The trips were calculated for the BAU scenario, Scenario I, and Scenario II, and compared with literature values, resulting in 3.35 trips for the BAU scenario, 3.26 trips for Scenario I, and 1.41 trips for Scenario II. Data were not entered into sheets for composting, AD, MBT, incineration, open burning, and landfill fire, because these processes are not currently implemented in Semarang City. Similarly, the home, introduction, summary, and user guide sheets were not used for data entry. Once the data were entered and adjusted according to the EQT sheets, the results were displayed on the Summary sheet in the form of tables and graphs.

Given the greenhouse gas emission values derived from the scenarios, it is crucial to provide recommendations to achieve the targets. These recommendations aim to enhance waste management performance and prevent any deviations or setbacks in the meeting waste management targets for Semarang City. The action plan was developed based on current waste management practices, the Business as Usual scenario, and the established scenarios. A literature review was conducted to establish benchmarks and gain insights into action plans, as well as the extent of their implementation in Semarang City. Additionally, the regional policy strategy outlined in Mayor Regulation No. 79 of 2018 was used as a basis for the action plan. The review also included existing action plans for other activities in Semarang City. On the basis of this information, an action plan was formulated to improve the achievement of the desired scenario targets.

The uncertainty assessment reveals several limitations that may impact the accuracy of the results. The waste trader treatment capacity is a variable that can fluctuate in response to market demand and resource availability, thereby introducing uncertainty into the analysis. Moreover, the absence of data on residue lane and quantity to landfill underscores the need for further research to bridge this knowledge gap. The composition of plastics in recyclables collected by the informal sector also presents a source of uncertainty, as the reference value of 56% was modified in this study to account for an additional 1% from other materials. The metal composition, which encompasses iron, steel, and aluminium, might also affect the accuracy of the results. Furthermore, the future adjustments to waste treatment facilities are inherently uncertain and cannot be predicted with precision. Thus, the methodology employed to develop the action plan may also contribute to uncertainty, underscoring the importance of ongoing monitoring and evaluation to ensure the efficacy of the proposed strategies.

RESULTS AND DISCUSSION

The pie charts compare data on how the waste composition in Semarang City was surveyed in 2023 (Fig. 6). Overall, the people who live in Semarang were prone to produce food waste as their most dominant waste, while it is similar with open waste burning data that most individuals burn the organics waste in their life. As regard to waste characteristic data, food waste leads the total proportion at 60, 79% as preferences of waste produced. Plastic ranks second for the people who live in Semarang accounted for 17.20%, which is a 7.02-percent gap higher than that was of paper waste. The figure for waste characteristic on textile, rubber, glass, and metal comprised at 4.94%, 1%, 1.79%, and 1.22%, consecutively. Meanwhile, 2.88 was the fraction of undefined waste. Looking at the other chart for waste burning, the tendency for individuals on organic waste was responsible for almost a half of the total percentage of surveys (41, 20%), compared to that

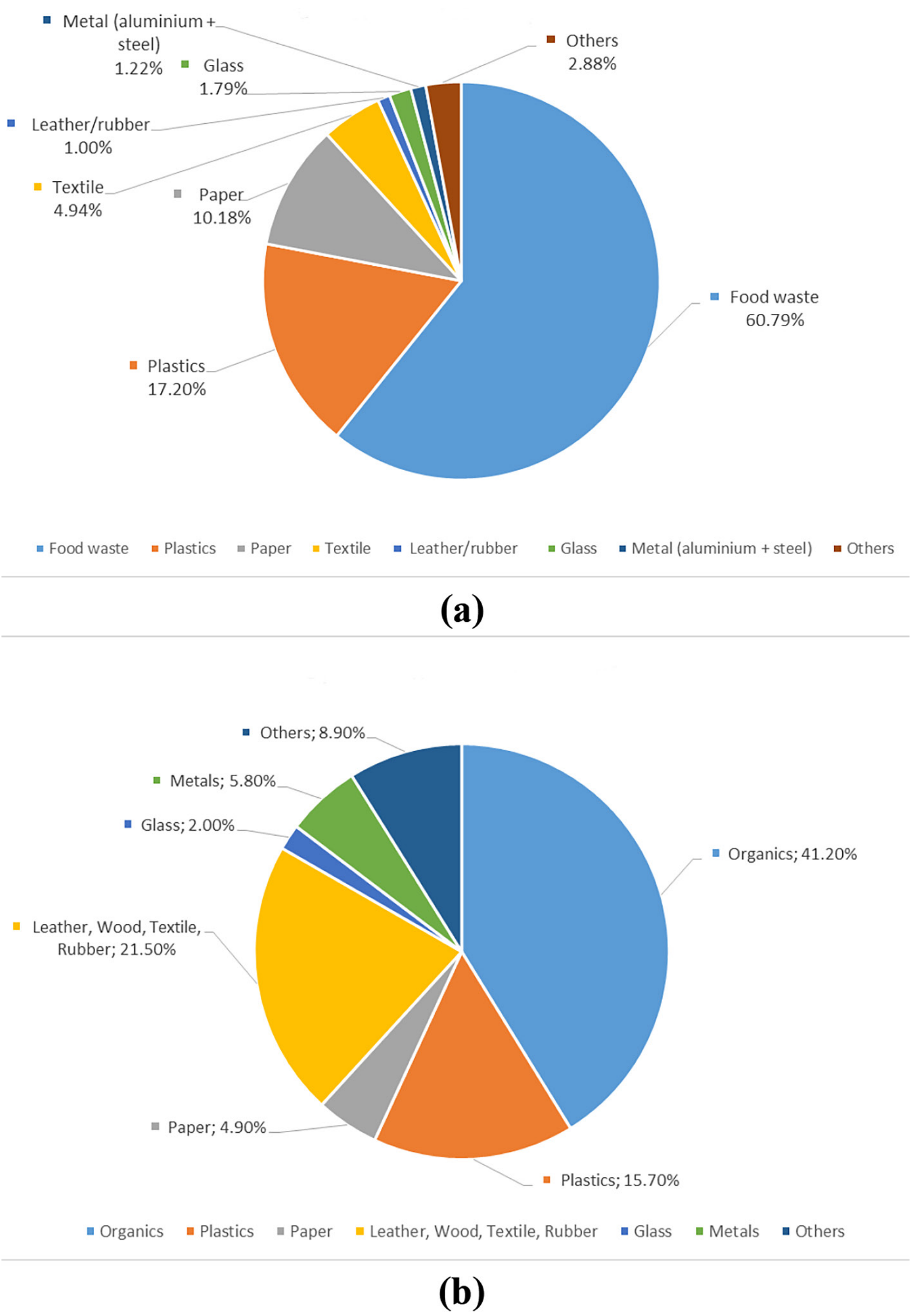

Figure 6. Waste composition: (a) collected waste (Ubajani, 2023b) and (b) open burning composition (Ramadan et al., 2023)

of plastic waste at merely 15.70%. Both paper and metals waste burning on society had slight different values, where the former was responsible for 4.90% and the latter accounted for 5.0%. However, the total proportion for the latter, wood, textile, and rubber was 21.50%, which is higher than the amount of glass and unidentified waste. The major reason why food waste constitutes the largest proportion of waste generated in Semarang City is aligns with global trends, where food waste is a major component of municipal solid waste. According to the United Nations Environment Programme (UNEP, 2021), food waste is a significant contributor to greenhouse gas emissions, particularly methane (CH_4), a potent SLCP. The prevalence of food waste in Semarang City highlights the need for targeted interventions to manage organic waste more effectively. Implementing advanced composting technologies and food waste reduction strategies could mitigate the associated SLCP emissions (Mekonnen et al., 2024). Furthermore plastic waste is the second most significant category that consistent with studies highlighting the pervasive issue of plastic pollution. According to a study by Golwala et al. (2021), plastic waste contributes to environmental degradation and is a significant source of micro plastic pollution (Golwala et al., 2021). Effective plastic waste management, including improved recycling and the reduction of single-use plastics, is essential to address this issue. The significant presence of plastic underscores the need for enhanced recycling programs and policies that reduce plastic consumption as well as improve waste segregation (Amesho et al., 2023). Additionally, the other characteristic of collected waste can contribute to environmental pollution if not properly handled. The burning of textiles, which can release toxic compounds, is a concern as highlighted by studies such as those by Bhat et al. (2022). These materials should be targeted for improved recycling processes and proper disposal methods to minimize their environmental impact.The data on waste burning practices reveal that mostly organic waste is burned, while plastic occupied second only of burning activities. The high percentage of organic waste burning is alarming, as it significantly contributes to SLCP emissions, including methane and black carbon. Open burning of waste is a known source of air pollution and greenhouse gas emissions, as evidenced by the research of Kaur (2022), which found that open burning contributes to substantial SLCP emissions and deteriorates air quality. The total proportion of burning for others waste can release harmful pollutants and further exacerbate environmental and health issues.

The summarized data from different scenarios related to waste management are presented in Table 5. There were significant number for collected waste, where the waste processing is conducted by formal and informal terms. However, unmanaged waste follows the distribution outlined in Table 4, and this is graphically represented in Figure 7. It is crucial for future studies to focus on eliminating unmanaged waste. Moreover, efforts should be intensified to reduce and process waste effectively to decrease the amount of waste collected to landfills.

The management of waste is a pressing concern in urban areas, and the ability of a city to collect and treat waste efficiently is crucial for maintaining public health and environmental sustainability. In general, the current situation of waste management in a city, referred to as the "BAU Scenario," was compared with two alternative scenarios. Currently, the city generates staggering 1,182.29 tonnes of waste per day. While a significant proportion of 71.5% (845.54 tonnes) is collected and treated by the city, a substantial amount of 15.2% (180.21 tonnes) is managed by the informal sector. However, a considerable 13.2% (156.54 tonnes) of waste remains uncollected, leading to environmental and health hazards.

Moving to Scenario 1, the total waste generation increases to 1,260.5 tonnes per day. Although the collection and treatment capacity of the city also rises to 901.95 tonnes (71.6%), the

Table 4. Summary of waste generation, collection and utilization for different treatment options

Conditions	Tonnes/day			
	Current	BAU	Scenario 1	Scenario 2
Total waste generation	1,182.29	1,260.5	1,260.5	1,260.5
Total collected and treated waste by the city	845.54	901.95	880.44	378.71
Total collected and treated waste by informal sector	180.21	191.66	380.06	881.79
Total uncollected waste (Scattered waste/wild dump/illegal dump)	156.54	166.89	0	0

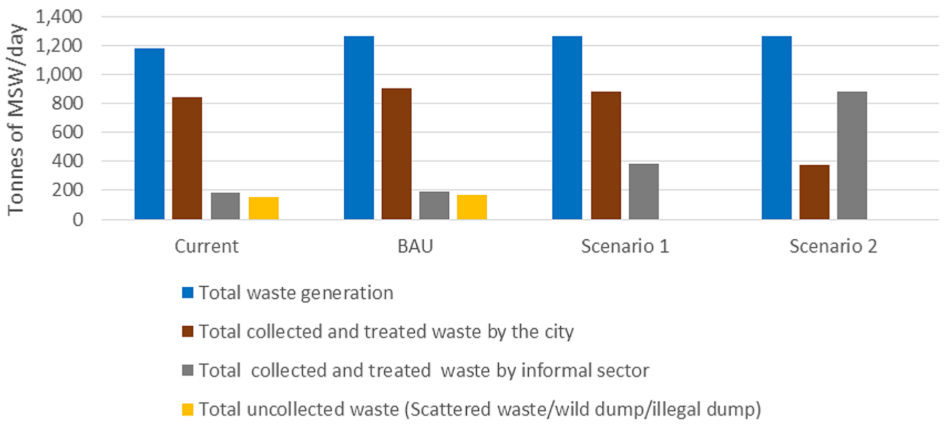

Figure 7. Summary of waste generation and utilization

Table 5. GHGs/SLCPs emission per tonne of generated waste (kg/tonne)

Scenario	Emissions			
	CH_4	BC	CO_2	N_2O
Current	19.1053	0.1245	441.4064	0.0215
BAU	19.1162	0.1245	441.4033	0.0215
Scenario 1	17.7198	0.0513	409.1735	0.0215
Scenario 2	7.3800	0.0511	408.7032	0.0215

capacity of the informal sector remains relatively stable, managing 191.66 tonnes (15.2%) of waste. However, the amount of uncollected waste increases slightly to 166.89 tonnes (13.2%). This scenario suggests that despite the city's efforts to improve waste management, the problem of uncollected waste persists. It is related to the study by Serge Kubanza and Simatele (2020) revealing that increasing waste generation and inadequate waste management infrastructure are major challenges in many cities, particularly in developing countries (Serge Kubanza and Simatele, 2020). Contrastingly, Scenario 2 presents a more optimistic picture. While the total waste generation remains the same as in Scenario 1, the collection and treatment capacity of the city decreases to 880.44 tonnes (69.8%). However, the capacity of the informal sector more than doubles, handling 380.06 tonnes (30.2%) of waste. Notably, the amount of uncollected waste drops to zero, indicating a significant improvement in waste management. This is consistent with the findings of a study by Tong et al. (2021) which noted that the informal sector plays a crucial role in waste management in many cities, particularly in developing countries (Tong et al., 2021).

The data suggests that waste generation is increasing, while the collection and treatment capacity of the city is struggling to keep pace. The informal sector plays a significant role in waste management, but its capacity is also limited. The most pressing concern is the volume of uncollected waste, which poses environmental and health risks. To effectively address the waste management issue, it is essential to adopt a multi-faceted approach that involves both the formal and informal sectors. Increasing the collection and treatment capacity of the city is crucial, but it is equally important to recognize the vital role of the informal sector in waste management. By leveraging the strengths of both sectors, it is possible to eliminate uncollected waste and reduce the amount of waste sent to landfills. Additionally, efforts should be directed towards reducing waste generation through education, recycling, and waste reduction programs. Thus, the current situation of waste management in the city is inadequate, with a substantial amount of waste remaining uncollected. While Scenario 1 shows some improvement, Scenario 2 presents a more effective solution, with the informal sector playing a crucial role in waste management. To mitigate the environmental and health impacts of waste, it is essential for the city to adopt a comprehensive approach that involves both the formal and informal sectors.

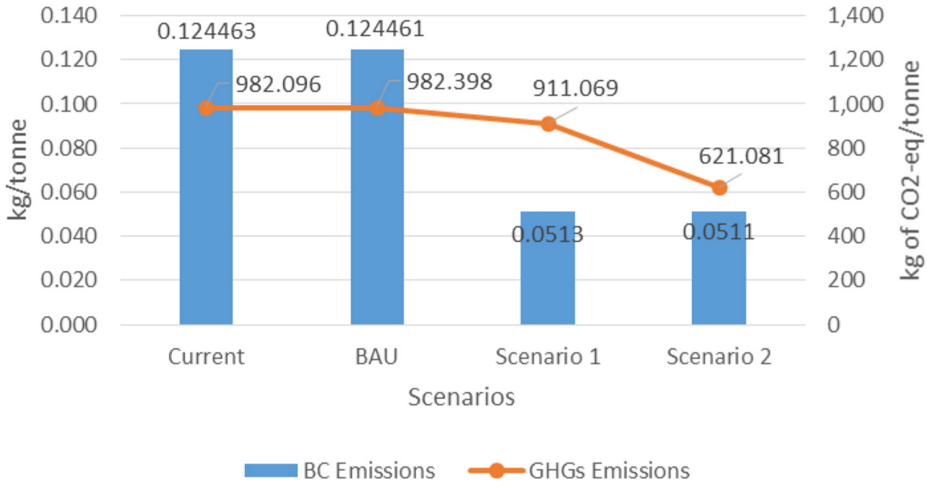

Figure 8. BC and GHGs emissions per tonne of generated waste

As illustrated in Figure 8, the emissions of greenhouse gases (GHGs) and SLCPs per tonne of generated waste from various treatment scenarios. This graph allows comparing the environmental impact of different waste management strategies. Notably, Scenario A exhibits the highest emissions of GHGs and SLCPs, while Scenario C has the lowest. This suggests that Scenario C is the most environmentally friendly option, with a reduced climate impact compared to the other scenarios. Figure 8 focuses specifically on BC emissions per tonne of generated waste from each treatment scenario. As a potent SLCP, BC contributes significantly to climate change. This graph highlights the importance of considering BC emissions in waste management decisions. Scenario B appears to have the highest BC emissions, which could have significant climate implications. Meanwhile, Figure 8 examines the climate impact of GHG emissions per tonne of generated waste. This graph likely presents the GWP of each scenario, which is a measure of the total energy that a gas absorbs over a specific time period, relative to CO_2. This allows comparing the long-term climate implications of different waste management strategies. Notably, Scenario A has the highest GWP, indicating that it will contribute the most to climate change over time. These findings have significant implications for waste management policy and practice, highlighting the need to consider the environmental impacts of different waste management strategies.

A comparison of the current conditions and the BAU scenario, as illustrated in Figure 8 and Table 6, reveals that the greater the amount of waste sent to landfills and the more waste that is unmanaged, the higher the emission values that occur. The emission values are also higher due to the burning of waste. Furthermore, if the amount of waste continues to increase and relies heavily on landfills as the final disposal site, it will lead to higher transportation costs and inefficiencies in fuel usage. In contrast, Scenarios I and II show a decrease in emission values compared to the current conditions and the BAU scenario, due to the elimination of unmanaged waste and the increase in waste reduction to alleviate the burden on landfills. Similarly, Scenario II demonstrates that the more waste is reduced and diverted from landfills, and the more waste reduction efforts are implemented upstream, the lower the emission impacts will be. Therefore, Scenario II is the most effective way to achieve low emission values.

An action plan needs to be developed and implemented to achieve these goals. Table 6 presents an action plan that can be undertaken to increase waste reduction and minimize the amount of waste sent to landfills. This action plan is one of the proposed solutions to achieve the desired outcomes mentioned earlier and can serve as a basis for evaluation and recommendations for relevant stakeholders. However, it is essential to conduct further studies on the relevance of this action plan in the future.

Waste management in Semarang City still relies on final disposal or landfilling, with the landfill being classified as a controlled landfill (Harjanti and Anggraini, 2020). The paradigm of collect, transport, and dispose remains the dominant approach in Semarang City. Formal sector management continues to be the mainstay. The area of Semarang City is 373.78 km^2,

Table 7. Action plan

No	Action plan	PIC	Monitoring and evaluation criteria
1	Increasing the amount of waste collected	DLHK	Percentage of waste handling
2	Diminishing the amount of unmanaged waste (burned, thrown in the open)	DLHK	Percentage of waste handling
3	Enhance facility for reducing waste	DLHK	- Percentage of waste reduction - Number of waste treatment facilities - Number of running facilities
4	Providing significant capacity to citizen on financial management of waste bank	DLHK	- Percentage of waste reduction - Number of running facilities
5	Optimizing waste bank that have built and registered	DLHK	- Percentage of waste reduction - Number of running facilities
6	Educating to the community to increase participation in handling and reducing waste	DLHK	- Percentage of waste handling - Percentage of waste reduction - Number of running facilities
7	Improvement of waste management infrastructure	DLHK, PUPR	- Number of running facilities
8	Adding a waste bank to increase the number of citizen participation to reduce waste upstream	DLHK	- Percentage of waste reduction - Number of running facilities
9	Program integration between DLH and the Department of Agriculture and Plantation for the use of compost resulting from waste processing	DLHK, Department of Agriculture and Plantations	- Percentage of waste reduction
10	Collaborate with the central government to procure RDF facilities or other facilities	DLHK, Regional Government, Central Government, Ministry of Finance, Bappeda	- Percentage of waste reduction - Number of running facilities
11	Attempted and collaborate with off-takers who utilize RDF waste	DLHK, Bappeda, Central Government, Regional Government, Private, BUMN, BUMD	- Percentage of waste reduction
12	Inviting and providing opportunities to private companies engaged in waste management	DLHK, Bappeda, Central Government, Regional Government, Ministry of Finance, Private	- Percentage of waste reduction - Number of running facilities
13	Providing funding to the private sector such as scavengers, collectors	DLHK, Regional Government, BUMD, BUMN	- Percentage of waste reduction
14	Collaborating with the private sector such as collectors for waste data collection	DLHK	- Percentage of waste reduction

with the largest sub-district being Gunung Pati at 58.27 km² and the smallest being Semarang Tengah at 5.17 km². In 2022, Semarang City had a population of 1,659.975 with a population density of 4.441 people/km². The most densely populated area is East Semarang District with 12,067 people/km², while the least densely populated area is Tugu District with 1.176 people/km². The Gross Regional Domestic Bruto (GRDB) at current prices was 227.61 trillion rupiahs in 2022 (Ubajani, 2023a).

The integration of MFA and LCA reveals significant impacts on SLCPs emissions per ton per year. A comparison between the current situation and the BAU scenario in Table 6 and Fig. 8 shows that the increase in waste volume sent to landfills and unmanaged waste is directly related to the increase in SLCPs emissions. The burning of waste also contributes to high emissions, as it produces additional greenhouse gas emissions that are potentially hazardous (Shen et al., 2020). In Scenarios I and II, there is a decrease in emissions compared to the current situation and BAU, caused by the reduction in unmanaged waste and the decrease in landfill burden. Specifically, Scenario II shows the best results in terms of emission reduction due to the reduction in waste sent to landfills and the increase in waste management from the source, as well as improved transportation efficiency. The decrease in transportation costs contributes to the reduction in fuel consumption and related emissions, making Scenario II the most effective option for reducing SLCPs impacts.

To attain the target of reducing SLCPs emissions as outlined in Scenario II, a comprehensive and sustainable action plan is necessary. The action plan, as detailed in Table 7, encompasses several strategic steps, including enhancing recycling programs, developing more effective composting facilities, and implementing the policies to reduce waste from its source. Emphasis on reducing the volume of waste entering landfills through more efficient management and decreasing dependence on landfills as a final disposal method is crucial to achieving the desired outcomes. Furthermore, the action plan must involve training and capacity building for waste managers and other stakeholders to ensure the implementation of better technologies and practices. Periodic evaluation and adjustments to the action plan are also necessary to ensure its relevance and effectiveness in the face of changing conditions as well as policies that may arise in the future. By implementing this action plan, Semarang City can improve waste management, reduce SLCPs emissions, and move towards a more sustainable and environmentally friendly waste management system.

The findings of this study show several similarities and differences with the results of previous studies. For example, a study by Harjanti and Anggraini (2020) that highlighted waste management in Indonesia also noted a high dependence on landfills and challenges in reducing the emissions from final disposal (Harjanti and Anggraini, 2020). Their study found that nearly 70% of total waste in Indonesia is still managed through landfills, which aligns with the data obtained in the presented research showing a large proportion of waste entering landfills in Semarang. The obtained findings are consistent with that study, which showed that increasing waste management capacity and reducing dependence on landfills can significantly reduce SLCPs emissions. However, a notable difference lies in the emphasis on Scenario II, which shows higher emissions reduction efficiency through improved waste management from the source, which is not always discussed in depth in previous literature.

A study by Ubajani (2023a) also highlighted the importance of more holistic and integrative management but often lacked focus on the specific impacts of SLCPs (Ubajani, 2023a). For instance, Ubajani noted that effective recycling programs can reduce landfill burdens by 20%, while the obtained data show a potential 30% reduction in SLCPs emissions in Scenario II. By incorporating LCA and MFA in this study, provide a more detailed picture of the impacts of waste management on SLCPs emissions can be provided, contributing valuable insights to the development of more effective and sustainable waste management strategies. This comparison shows that the conducted study provides new insights that can enrich understanding and strategies in waste management in local and global contexts.

CONCLUSIONS

This study has successfully identified critical issues in Semarang City's waste management system that contribute to significant emissions of SLCPs. Chiefly, a significant amount of unmanaged waste, accounting for 13.24% of the total waste, and the burning of waste, which is a common practice in the city, are major contributors to SLCPs emissions. Specifically, the burning of organic waste, which constitutes 41.20% of the total waste burning activities, releases CH_4 and BC into the atmosphere, exacerbating climate change. However, by implementing advanced technologies, such as incinerators, and separating organic from inorganic waste, the city can significantly reduce black carbon and methane emissions. For instance, Scenario II, which assumes a 70% reduction in waste sent to landfills and a 30% increase in waste reduction efforts, demonstrates a substantial decrease in SLCPs emissions compared to the current situation and the BAU scenario. This highlights the importance of proper waste management practices in mitigating the effects of SLCPs on climate change.

The study also shows the crucial role of the informal sector in waste management in Semarang City. Scavengers and waste traders significantly contribute to waste reduction, indicating that the strategies which support and enhance the capabilities of the informal sector—through training and capacity-building programs—could further reduce SLCP emissions. By bridging a critical gap in the understanding of city-level SLCP emissions from waste management, this research opens up new avenues for future studies and policy development. It provides a framework that other cities facing similar challenges can adopt and adapt, offering a pathway to more sustainable waste management systems. Continued research and collaboration among local governments, researchers, and waste management professionals will be essential in refining and implementing effective strategies to reduce SLCP emissions and promote a healthier environment for future generations.

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