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Case Report

Transition of greenhouse gas emission reduction from the management of municipal solid waste in Surabaya, Indonesia: Assessment on past and future prospective conditions

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ABSTRACT

The government of Indonesia is firmly committed to mitigate climate change in various sectors, including municipal solid waste (MSW) management. Several improvements have been made since the implementation of the national policy and strategy for MSW management. However, the impact of the changes on greenhouse gas (GHG) reduction has yet to be revealed. Within the life cycle assessment (LCA) framework, this study investigated the GHG emissions transition in Surabaya before and after the amelioration by taking 2020 as the baseline. Further prospective enhancement by following national policy guidance has also been assessed. The results indicate that the installment of the Waste to Energy (WtE) plant decreased emissions from 1,004,951.5 tons $CO_{2\text{-eq}}$ to 430,839.6 tons $CO_{2\text{-eq}}$. Recycling will provide further reduction of as much as 22.0 % whenever a 30 % recycling rate is reached. Meanwhile, RDF production with a capacity of 210 tons of waste/day will give 45.2 % additional emissions depletion. To achieve low-carbon MSW management, concern about waste separation needs to be anticipated by providing more Intermediate Treatment Facility (ITF) and shifting the waste collection method. Additionally, enforcement of related legislation systems and education for the community are indivisible.

1. Introduction

Efforts to mitigate climate change, a global environmental problem, have become a worldwide concern. The commitment to collectively combat this negative environmental phenomenon has been expressed in the Paris Agreement, a legally binding international treaty on climate change. Indonesia has ratified this convention and pledged to achieve an emission reduction target of as much as 29 % unconditionally and 41 % conditionally by 2030, as stated in the nationally determined contributions (NDCs). Lately, the target is increased to 31.89 % for unconditional emission reduction and 43.20 % for conditional reduction [1]. Based on the National Report on Greenhouse Gas (GHG) Inventory, the total emission of the country in 2019 was 1,866,552 Gg $CO_{2\text{-eq}}$. Among the contributing sectors, forestry and peatland were the top emission sources, which produced 924,853 Gg $CO_{2\text{-eq}}$. The energy was in second position, emitting 638,808 Gg $CO_{2\text{-eq}}$. Meanwhile, the waste sector was ranked number three, followed by agriculture and industrial processes and product utilization (IPPU), which contributed as much as 134,119 Gg $CO_{2\text{-eq}}$; 108,598 Gg $CO_{2\text{-eq}}$ and 60,175 Gg $CO_{2\text{-eq}}$ respectively [2]. Although nationally listed in third position with a 7.2 % contribution, emissions from the waste sector need special attention. Waste, more specifically municipal solid waste (MSW), emits not only carbon dioxide (CO_2) but also two other major greenhouse gases (GHG), which are methane (CH_4) and nitrous oxide (N_2O) [3]. These two gases have higher global warming potential (GWP) than carbon dioxide (CO_2). Methane (CH_4) has a GWP 28.5 times higher, while nitrous oxide (N_2O) is even much higher, 264.8 times higher than carbon dioxide (CO_2) [4]. The waste sector is reportedly the third largest producer of both gases globally [5]. Additionally, at the international level, in 2019, Indonesia was included in the top five MSW producers, putting the country as the

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second largest GHG emitter from the waste sector [6].

Based on that condition, an emissions reduction program for the waste sector is considered strategic and will significantly impact the achievement of national goals. In 2017, the Government of Indonesia launched Presidential Decree No. 97/2017 about the National Policy and Strategy for Municipal Solid Waste Management. This guidance focuses on achieving a higher collection and reduction rate, as high as 70 % and 30 % by 2025 [7]. Efforts to increase collection rate are intended to prevent unmanaged waste disposal practices such as open burning, illegal or wild dumps, and ejection to the ocean. Expanding coverage of waste collection services will lessen unfavorable impacts on the environment, including those caused by GHG emissions. Reduction is a crucial initiative; according to the decree, the reduction program can be implemented by following the 3R concept: limiting waste quantity at the source, reusing, and recycling. The success level of this action will determine the magnitude of the MSW management system and, more importantly, energy and natural resources savings. The higher waste reduction rate will positively contribute to the GHG mitigation plan. To accelerate the execution of the National Policy and Strategy, the Government of Indonesia has committed to build energy plants in 12 cities and prepared a road map for waste reduction [8,9]. Additionally, the government supports initiatives to convert waste into valuable materials, such as composting, biogas production, and refuse-derived fuel (RDF).

Despite the ardent efforts to increase MSW management performance in the country, few studies discussed the correlation between MSW management and the potential reduction of GHG emissions. In 2012, Gunamantha and Sarto evaluated several options for MSW treatment for energy in the KARTAMANTUL region of Yogyakarta. The study found that implementing the gasification process provided the highest avoided emission, as much as −515.46 Kg $CO_{2\text{-eq}}$ per ton of waste [10]. Kristanto and Koven [11] calculated the potential GHG emission from existing MSW management in Depok, Indonesia, generating 1120 tons of MSW daily. Four scenarios that are being developed based on the distribution of waste amount in several treatment units (waste treatment unit (WTU)/material recovery facility (MRF), composting, anaerobic digester, controlled landfill, and incinerator) have been assessed. Based on the existing condition, this study concluded that the minimum net GHG emission of 202,800 Kg $CO_{2\text{-eq}}$ per day would be obtained by optimizing the anaerobic digestion process, accompanied by composting, WTU/MRF, and controlled landfill with energy utilization. Similar to this study, the development of a low-emissions solid waste management strategy for East Jakarta, Indonesia, has been conducted by Sekarsari et al. [12]. This study compared the produced GHG emissions from biological treatment (composting, anaerobic digester, and black soldier flies/BSF) and thermal process (incineration). It was noted that both options produced a similar amount of GHG emissions savings. However, the role of recycling needs to be considered due to its significant contribution. Another study was conducted in Semarang to determine strategies for reducing GHG emissions from MSW management. Unlike the earlier studies, this research used a Strength – Weakness – Opportunity – Threat (SWOT) analysis to assess existing MSW management to mitigate GHG emissions, followed by a quantitative strategic planning matrix (QSPM) to determine strategies prioritization. The study revealed that a decentralized waste management system and optimizing the performance of existing waste facilities were essential to reduce emissions. By taking ten-year period, quantitative analysis with Intergovernmental Panel on Climate Change (IPCC) guidance provided information that total GHG emissions will reduce from 349.75 to 339.02 Gg $CO_{2\text{-eq}}$ whenever the waste generation increases from 426.36 to 462.99 Gg from 2021 to 2030 [13]. Although some existing studies described the amount of GHG production as a consequence of MSW management options, the use of national policy and strategy as a basis to develop scenarios is less considered. The development of MSW management may differ from one to another city or region; however, the adoption is essential to support national target accomplishment.

Many scientific papers have used life cycle assessment (LCA) to analyze the potential environmental impacts of MSW management. LCA can quantify the total environmental impacts. Thus, it will be beneficial to evaluate an existing MSW management, compare different MSW management strategies or technologies, and predict the possible future of MSW management performance [14,15]. However, it was advised that the LCA study should include the evolution of MSW management rather than focus only on specific process optimization [16]. Hence, the results of the LCA application enable policymakers to devise sustainable MSW management and/or to look for any improvement opportunities for the existing system. Despite the popularity, it was observed that since 2013, 178 out of the total countries in the world have yet to produce scientific manuscripts of LCA studies on MSW management [17]. Indonesia was categorized as a country with minimum (0–5) LCA studies in MSW management [6,18]. This condition is irrelevant to the country's position regarding the rank of global MSW producers and GHG emitters from the waste sector, as mentioned previously.

Based on the identified gap, this study attempts to assess the impact of the improved MSW management as guided by national strategy on GHG emissions production. The quantified GHG emissions will be evaluated and compared to the baseline scenario, representing the previous waste management practice. Since the target accomplishment will be due in 2025, a future scenario is also developed considering the national target values and potential new treatment. Surabaya, the capital of East Java Province, was selected as the study area. The city has experienced significant transformation in MSW management since establishing national guidance. The results of this study dispense information on the impact of improved MSW management on GHG emissions reduction. Assessment of the future condition by considering several treatments and target values will help policymakers map the area of prioritization for further MSW management improvement. Thus, this finding may be a reference for developing MSW management to reduce GHG emissions in similar cities.

2. Methodology

2.1. Study area

Surabaya (7° 16′ S and 112° 43' E) is one of the vital cities in Indonesia, covering an area of 350.54 km^2 with a total population of 2,874,314 in 2020 [19]. In the same year, the city generated 811,255.10 tons of MSW [20]. The municipality provides intermediate treatment facilities (ITF) and a final disposal site to manage the MSW. ITF is a station that may serve different activities, such as separation, compaction, and waste conversion. Until 2020, there were a total of 35 units of ITFs comprising 26 composting houses and 9 TPS3Rs (Tempat Pengolahan Sampah 3R, a waste treatment station with a 3R concept) distributed in the city area as illustrated in Fig. 1. The composting house receives organic waste, mainly garden waste, and converts it into compost. Meanwhile, in TPS3R, more treatments can be found since the station collects MSW from the surrounding area. Surabaya has one final disposal site in Benowo (−7.21328; 112.63184), about 24.5 Km northwest of the city center. This final disposal site has a total area of 37.4 Ha and is operated based on a sanitary landfill concept. Although some facilities have existed, MSW management in Surabaya still dramatically depends on landfills. Based on 2020 data, as shown in the mass balance in Fig. 2, about 76.51 % of waste was sent to the final disposal site. Of that amount, 74.64 % was from direct disposal practice, while the remaining was residues from ITFs. Portions of convertible waste in the ITFs were relatively low, only 0.44 % recyclable and 3.85 % compost, while 22.5 % of the generated MSW is digested anaerobically in the landfill area. In May 2021, there was a vast improvement in MSW management in Surabaya since the waste-to-energy (WtE) plant was officially operated. This first WtE plant in Indonesia has a capacity of 1000 tons of waste per day to produce electricity up to 12 MW.

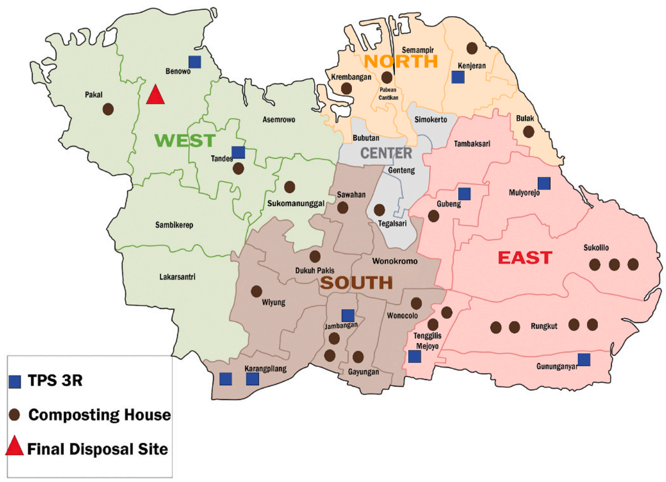

Fig. 1. The distribution of ITFs in Surabaya City.

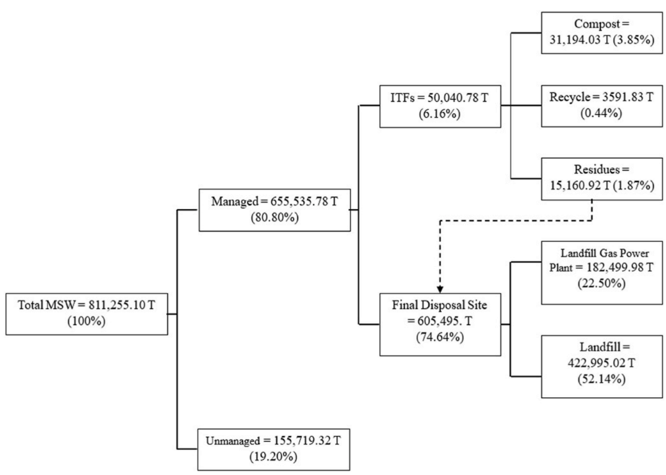

Fig. 2. Mass balance of MSW in Surabaya City (2020).

2.2. System definition

This study was intended to calculate and collate the GHG emission from three different conditions, namely before and after the operation of the WtE plant, and future possible developments as guided by national policy and strategy by considering the recycling rate and RDF production. The total amount of MSW in 2020 was used as the functional unit so that all scenarios' GHG emissions were comparable and each treatment's contribution could be analyzed. GHG emissions from the involved processes were calculated following the IPCC 2006 guidance [21], and total emissions were expressed as carbon dioxide equivalent ($CO_{2\text{-eq}}$). Emissions from transportation were excluded due to their minimum contribution compared to those from other MSW treatments [18,22–25]. In addition, the exclusion will enable an equitable comparison of GHG emissions from the MSW treatments as suggested by national policy and strategy. However, the emissions calculation from transportation is still needed to provide information on total GHG emissions from the selected MSW management strategy. This part will be conducted in the succeeding phase of this research.

2.3. Description of scenarios

Three scenarios have been developed according to the evolution and possible improvements in the MSW management system of Surabaya City. The elaboration of each scenario is provided in the following section.

2.3.1. Scenario 1 (S-1)

Scenario 1 (S-1) reflects the situation of MSW management in the year 2020 as described in Fig. 1. At that time, there were three types of treatment, which were composting and recycling with a meager rate, 3.85 % and 0.44 % from the total waste generation and landfill gas power plant (LFG) that received 22.50 % of the total waste (S-1.1). The collected gas from the anaerobic decomposition unit was converted into electricity with an efficiency of 30 % [3]. Since it is difficult to find data on the proportion of unmanaged waste distribution, it is assumed that the amount scattered, openly burned, and dumped illegally is equal. A sub-scenario without landfill gas treatment is provided to evaluate the performance of bioprocess intervention (S-1.0).

2.3.2. Scenario 2 (S-2)

S-2 is designed based on the operation of the WtE plant in the final disposal site. A unit of gasification with a capacity of 1000 tons of waste per day was operated in 2021 to produce electricity with an efficiency of 15 %. The national emission factor for electricity generation, the JAMALI (Jawa – Madura – Bali) grid, was selected to calculate the emission and avoided-emission from the thermal plant. The value of this emission factor is 0.87 Kg $CO_{2\text{-eq}}$/kWh [26]. Except for the WtE implementation, other waste treatments in S-2 are set similarly to S-1.

2.3.3. Scenario 3 (S-3)

S-3 displays the possible improvements in the MSW management system of Surabaya City based on the national guidance. Background information for this scenario is referred to as S-2. However, several sub-scenarios have been made to focus on the increasing recycling rate for recyclable materials and the conversion rate for organic biowaste. In addition, one sub-scenario to evaluate the impact of RDF production on reducing GHG emissions from MSW management is also created. Sub-scenarios for S-3 are :

- S-3.1.: In this scenario, the recycling rate is set at 30 %, as targeted by national guidance. Referring to the mass balance of MSW in 2020, the recycling rate was meager, with 1.62 % of the total recyclable (or 0.44 % of the total waste generated). Recyclable items include paper, plastic, glass, metals, aluminum, and textiles.
- S-3.2.: Another setting of 30 % is made for organic biowaste (food waste and garden waste) conversion through the composting process. In the initial condition (2020 – baseline), only 6 % of organic biowaste (or 3.85 % of the total waste generated) was converted to compost.
- S-3.3.: This scenario tests the GHG emissions reduction if 12.5 % of the remaining waste (after subtracted by the portion of recyclable waste), about 76,421.24 tons/year (210 tons/day), is converted to RDF. This amount corresponds to the need for RDF as co-fuel in one cement industry in Tuban City, about 16 km from Surabaya. Solusi Bangun Indonesia (SBI), a member of the Cement Indonesia Group, is a pioneer in utilizing RDF as a co-fuel in its production process. Based on RDF off-taker analysis by GIZ, two plants in Tuban need RDF to supply as much as 91.3 tons/day [27].

2.4. Data inventory

This study's MSW modeling information was obtained from published sources such as governmental platforms, project reports, scientific papers, interviews, and direct measurements in the field. Waste composition data is crucial to determine MSW management. Data for the same year of reference was used in the calculation. However, updated information from field measurements to anticipate post-pandemic COVID-19 was also utilized for sensitivity analysis (Table 1). Field measurements referred to the standard test method for the determination of the composition of unprocessed municipal solid waste (ASTM

Table 1
Waste composition in final disposal site and ITFs of Surabaya city (%).

Waste Composition	2020	2024	
	Final Disposal Site	Final Disposal Site	Average from 9 ITF locations
Food Waste	38.77	34.48	37.94
Garden Waste	21.08	19.09	11.20
Plastics	13.31	16.51	17.44
		0.90	2.39
- **PET**		0.86	2.05
- **PP**		0.41	0.79
- **PS**		0.2	0.34
- **PVC**		1.05	1.49
- **HDPE**		13.09	10.38
- **LDPE**			
Papers	4.18	5.89	9.49
		0.23	1.07
- **White paper**		4.47	6.71
- **Cardboard**		1.19	1.71
- **Tissue paper**			
Textiles	3.83	3.46	2.32
Rubber, Leather	0.58	1.54	0.37
Wood	4.53	1.52	0.88
Diapers	10.87	9.77	9.45
Glass	0.76	1.01	1.37
Aluminium	0.12	0.26	0.75
Metals	0.7	0.14	0.07
Others	1.19	6.33	9.40

D5231-92). Meanwhile, emission factors for the involved processes were mainly adopted from the study of Prognos – Ifeu -INFU [28], as presented in Table 2. The calculation of these emission factors followed the international protocol and can be compared to other studies [29,30]. Some of the background data were referred to the IPCC guidance for composting and anaerobic digestion and Breeze [31] and Silva et al. [32] for RDF production.

3. Results and discussion

The results of GHG calculation within the LCA framework for MSW management of Surabaya City, accompanied by correlated discussions, are presented in the following section. The presentation is divided into two sections, which are (i) GHG emissions of past MSW management (pre and post 2020) and (ii) GHG emissions of MSW management in future scenarios. In addition, sections to elaborate on the sensitivity analysis results and proposed MSW management for Surabaya City are also given.

3.1. GHG emission of past MSW management (pre and post-2020)

The transition of GHG emissions before and after the installation of advanced MSW technology in Surabaya City is displayed in Fig. 3.

Table 2
Emission factors for waste processing in Surabaya City (Kg $CO_{2\text{-eq}}$/ton waste).

Waste processing	Emission factor
Recycling	−820
	−414
- **Papers (mixed)**	−480
- **Plastics (mixed)**	−11100
- **Glass**	−2025
- **Metals (Al)**	−2818
- **Metals (Fe)**	
- **Textiles**	
Composting	−8
Anaerobic digestion	−100
Landfilling	1704.2
Landfilling with gas collection and electricity production	1003.9
Thermal - Gasification	38.2
RDF production	−368.9

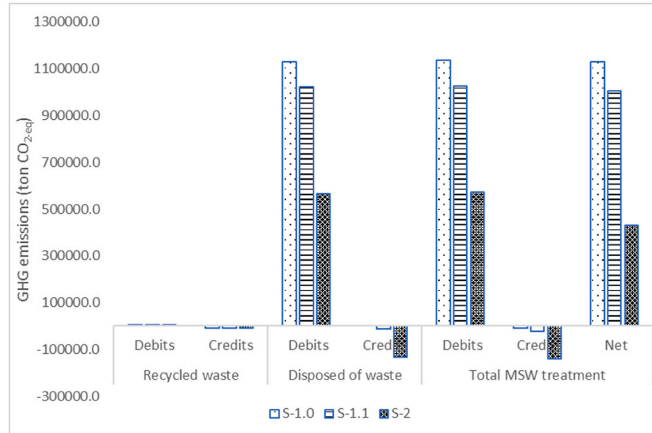

Fig. 3. GHG emissions of past MSW management (S-1 and S-2).

Notably, the interventions significantly impact the reduction of GHG from MSW management. Before the installation of the landfill with gas collection in 2015, the landfill was the only solution to manage the MSW of the city, which resulted in 1,128,516.1 tons $CO_{2\text{-eq}}$ of GHG(S-1.0). The LFG operation decreased the emissions to 1,004,951.5 tons $CO_{2\text{-eq}}$ (S-1.1). Further abatement of as high as 57.1 % was obtained after thermal technology, gasification, was officially involved in the treatment process in mid-2021 (S-2). Many researchers reported the dominant contribution of landfills in releasing GHG emissions. A big pile of MSW enables anaerobic microorganisms to decompose organic substances, which leads to massive CH_4 production [33]. The amount of landfill gas per ton waste in the final disposal site of Surabaya City was 1.39 tons $CO_{2\text{-eq}}$, compatible with those reported for Rome, Italy (1.31 tons $CO_{2\text{-eq}}$) and Sakarya, Turkey (1.84 tons $CO_{2\text{-eq}}$) [13,34]. Improvement by providing LFG collection in the landfill area was suggested to reduce emissions. In this case, the obtained reduction of as much as 123,564.6 tons $CO_{2\text{-eq}}$ is relevant to the result in eThekwini municipality, South Africa, which had 148,583.0 tons $CO_{2\text{-eq}}$ emissions saving for 1.38 times higher amount of waste[35]. The production rate of landfill gas may vary from one location to another since it is strongly dependent on several factors. Scarlat et al. [36], reported that biological decomposition in landfill areas is determined by temperature, precipitation rate (water content), storage time, cover material, the design of the landfill, and its operational parameters. The operation of the WtE plant reduced the net GHG emissions significantly to 430,839.6 tons $CO_{2\text{-eq}}$. The involvement of thermal technology in MSW management has been widely reported to successfully lessen the waste volume and GHG emissions if combined with a power generation system [6]. Gasification, a thermochemical process that limits oxygen in the combustion reaction, was selected as it provides numerous benefits, mainly on syngas production and better prevention of air pollution [37]. In this study, the operation of this plant cut down the emission of as much as 454,158.2 tons $CO_{2\text{-eq}}$ from diverting 1000 tons of waste per day in landfills into the thermochemical reactor. Another portion of −119,953.7 tons $CO_{2\text{-eq}}$ was saved due to electricity production. Although the technology development has significantly impacted the mitigation effort, the contribution from recycling, an upstream MSW management approach, seemed negligible. In 2020, recycling and composting only provided emission savings as much as −7715.5 tons $CO_{2\text{-eq}}$.

3.2. GHG emissions of MSW management in future scenarios

Scenario 3 elaborates on the potential further reduction of GHG emissions from several efforts guided by national policy. As displayed in Fig. 4., in S-3.1., when the recycling rate becomes 30 %, the net total GHG emissions from MSW management of Surabaya decreases from 430,839.6 tons $CO_{2\text{-eq}}$ (S-2) to 336,297.4 tons $CO_{2\text{-eq}}$. Another reduction

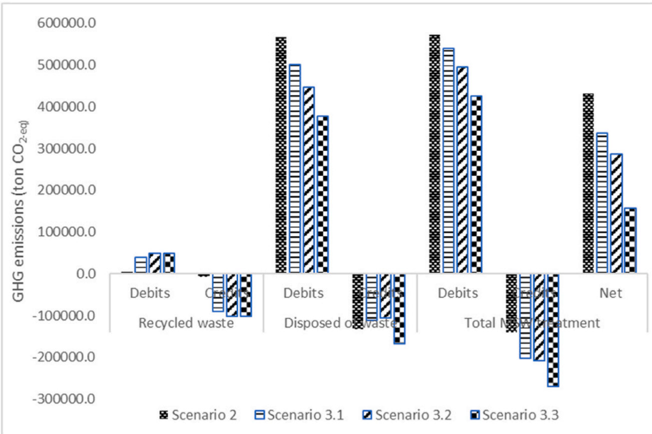

Fig. 4. GHG emissions for future scenario (S-3).

of 50,052.9 tons $CO_{2\text{-}eq}$ is achieved whenever a 30 % composting rate (for food and garden waste) is applied (S-3.2). Further curtailing of 129,334.1 tons $CO_{2\text{-}eq}$ due to RDF production will be secured, making the total GHG emissions 156,910.4 tons $CO_{2\text{-}eq}$ (S-3.3). By using the condition in 2020 as a baseline (S-2), the most significant contribution to supplemental emission decline is provided by RDF production (45.2 %), followed by recycling (22.0 %) and composting (14.9 %). All three treatments share similar characteristics of the feedstocks. RDF consists of about 50 %–80 % of paper and plastic, while the remaining fractions are organics, wood, and textiles [38]. Most of the components also belong to the group of recyclable materials. As for composting, the process needs rich organic materials, including proteins and minerals. Considering that condition, separation is the essential activity that should be embedded in the MSW management framework. The separation will ensure more homogeneity of raw materials quality, not only for those three proposed improvements but also for landfill gas and thermal power plants. Thus, the quality of secondary products can be maintained.

3.3. Sensitivity analysis

Sensitivity analysis was conducted by introducing the new waste composition data from field measurement (Table 1) into S-3.3. The results, as displayed in Fig. 5 and Fig. 6., indicate that the different data affect the calculation of GHG emissions. Total emissions from MSW management shift from 156,910.4 tons $CO_{2\text{-}eq}$ to 149,715.2 tons $CO_{2\text{-}eq}$ (Fig. 5). Among the proposed treatments, recycling appears to be the most sensitive regarding providing GHG emissions credits. The waste

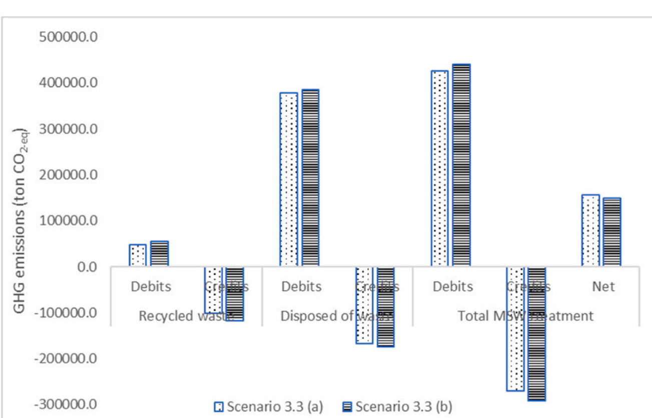

Fig. 5. Comparison between calculated GHG emissions for different waste composition data (a) 2020; (b) 2024.

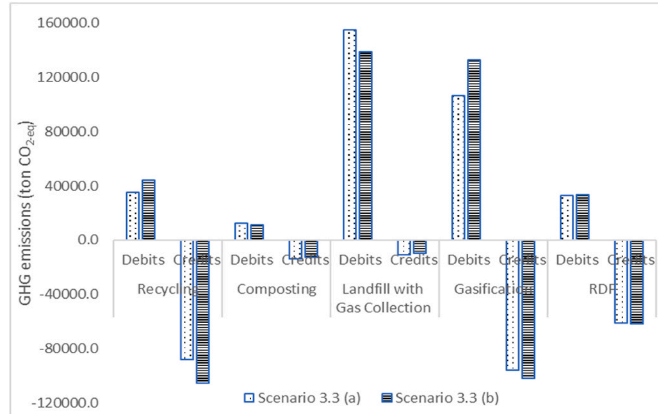

Fig. 6. Comparison between calculated GHG emissions in each treatment for different waste composition data (a) 2020; (b) 2024.

composition data for 2024 presents a percentage increment for almost all recyclable materials except for metals. The overall emissions savings from recycling rise to −105,448.2 tons $CO_{2\text{-}eq}$ or 20 % higher compared to one with previous waste composition data (Fig. 6). On the contrary, composting and anaerobic digestion in the landfill area experience diminution both in debits and credits due to the drop in organic waste composition. The increase in GHG savings from recycling is determined by the fewer natural resources extracted and the less energy used. Because of its positive environmental impacts, recycling must be prioritized to tackle the solid waste problem [39]. As for the Surabaya case, concern about securing plastics, papers, and textiles as recyclable materials should be prioritized due to their amount and avoided emission potential. Additionally, using rubber waste for green supplementary material (e.g., for aggregate in concrete production) will potentially bring further environmental benefits [40].

3.4. Low carbon MSW management for Surabaya City

Based on the above results, it is confirmed that installing an LFG power plant and gasification in the landfill area significantly contribute to the reduction of GHG emissions. However, further improvement is still possible following the national policy and strategy to bring more environmental benefits. Following the waste hierarchy concept, recycling is the foremost alternative that needs to be prioritized. The increase in the recycling rate in MSW management of Surabaya will inflate the GHG emissions reduction, confirming similar studies in other regions [41–44]. Although it seems too ambitious to achieve a 30 % recycling rate by 2025, consistent steps must be conducted to build a recycling system in the city. These involve providing facilities for effective and optimal waste separation, building a networking platform among stakeholders, and standardizing prices for collectible materials and quality for secondary products.

Like other metropolitan cities in Indonesia, Surabaya applies a decentralized system for MSW management. A decentralized system is intended to cover the service area optimally. The service area is divided into several clusters, and each cluster will have one or more ITF(s) to collect MSW from the surrounding area. As mentioned previously, some critical activities for MSW processing are conducted in the ITF to lessen the amount of waste that will be sent to the final disposal site; hence, the role of the ITF is essential. ITFs, in this case, referred to as TPS3R, can support recycling programs effectively. Until 2023, there are 10 TPS3Rs with a total capacity of 29,565 tons of waste per year; however, these stations still operate at 57 % of their maximum performance. The provision of separation facilities, mainly belt conveyors and compactor or baler for packing the recovered materials, just like in 2 TPS3Rs (Super Depo Sutorejo and PDU Jambangan), needs to be replicated in the other TPS3Rs. Besides equipping the facility with segregation tools, adding the number of ITF/TPS3R is another issue in anticipating the amount of waste to be recycled. A calculation to estimate the number of ITF/TPS3R to support the achievement of a 30 % recycling rate is conducted with results as shown in Table 3. A number of 35-equipped unit ITFs/TPS3Rs with a capacity of 20 tons/day is needed to ensure the recycling program's success until 2035. The importance of ITF/TPS3R/MRF in supporting sustainable MSW management in Surabaya was also reported by Muhamad et al. [45].

Although it has higher net emissions compared to anaerobic digestion [16,46,47], composting is considered bio-treatment that is more applicable in the ITFs (TPS3R and composting house). This is mainly due to the anaerobic decomposition process's instability, which requires a more advanced control system to ensure complete biodegradation [48]. The open windrow technique is a simple composting treatment successfully applied on a small scale, including in TPS3R and composting houses. However, it should be carefully noted that the GHG emissions reduction from this process will occur if only the product is used for chemical fertilizer substitution [49,50]. Therefore, mapping the off-taker of composting products is important, especially when expecting the increasing amount of waste to be treated. Together with that, a more considerable scale implementation of alternative bio-process, in this case, black soldier fly (BSF) farming, could be taken into account since this treatment offers less GHG emissions if compared to composting [51]. Direct emissions from BSF were reported as much as 0.4 g CH_4/ton waste and 8.6 g N_2O/ton waste [52]. These values are much lower compared to the emission production from composting. Boldrin et al. (2009) mentioned that the emissions from composting were 30–6800 g CH_4/ton waste and 7.5–252 g N_2O/ton waste [49]. Meanwhile, the UNFCC reported that the emission values of 2000 g CH_4/ton waste and 200 g N_2O/ton waste were from composting [53]. BSF's overall global warming potential was identified as high as 35 Kg $CO_{2\text{-eq}}$, while composting emitted 111 Kg $CO_{2\text{-eq}}$ per ton of biowaste [52]. Small-scale initiatives for this treatment have been started in TPS3R in Surabaya [54]. RDF production poses a reduction in GHG emissions and natural resource extraction. This is a potential treatment to aid a successful emissions minimization program from the waste sector in Surabaya. The availability of potential off-takers (e.g., cement industry, power plant, and heavy industries like paper, fertilizer and steel manufacturers) near the city is an advantage for establishing the plant. However, despite the technical adjustments that may be needed by the RDF users (e.g., modification of the feeding system in the kiln or boiler and installation of air pollution control) [27], the main challenge is to ensure the stability of RDF quality made from solid waste.In order to support the proposed treatments mentioned above, a compelling collection system must be established. Currently, the municipality provides transfer stations where the mixed collected waste will be sent to ITFs or the final disposal site. Transfer from waste sources to the waste collection points is conducted by residential management or individually. In this part, leakage potential exists due to the resistance to pay retribution fees and distance barriers leading to undesirable disposal practices. A source collection system (door-to-door) can be considered to replace the existing system since this approach enables source segregation activity and avoids illegal waste treatment (e.g., open burning, open dumping, and inappropriate discharge). Source segregation will complement the separation process in ITF/TPS3R, resulting in a higher recycling rate, as confirmed by the study in Florence, Italy and Lebanon [55,56]. Furthermore, a study in Hangzhou, China, and Bari, Italia, explained that source collection positively affected the GHG emissions reduction from integrated MSW treatment [16,57]. In Surabaya's case, it will help maintain the consistency of waste feedstock in the LFG and gasification plant, composting process, and the proposed RDF plant. However, as mentioned by the studies above, the door-to-door collection method requires higher financial support than the curbside method. Currently, budget allocation for MSW management system in Indonesia is considered low. It was reported that for urban areas, including big cities, the average allocation was only 1.2 % of the regional revenue and expenditure budget [58]. Hence, anticipation for budget adjustment, including the potential shifting of waste collection method, is needed along with the ongoing reformation of the MSW management system.Besides technical arrangements, official directions to support the implementation of those proposed improvements by national regulations need to be anticipated. These may include procedure on recyclable materials flow and pricing (involving waste collector – municipality/informal sector and recycling company), standardization on price and quality of secondary products (adding to the existing ones, Standard National Indonesia/SNI-19-7030-2004 for compost and SNI-8424:2023 for PET recycling) and reformation of waste retribution fee as well as tax deduction mechanism for the users of secondary products from waste. Community participation in waste management system is another crucial issue that should be addressed. Surabaya has a best practice of community-based waste management action through a unit called the waste bank. The waste bank is a management system that facilitates community participation in separation and recycling activities by offering economic compensation. Waste banks provide a price list for every exchangeable recyclable material. A waste bank customer can exchange recyclable materials with some amount of money in cash or deposit the values as in regular banks [44]. Based on 2023 data, there were 658 waste banks in Surabaya. This system received as much as 2026.645 tons of recyclable materials [20]. Although the sorption capacity is still minimal compared to the total amount of recyclable materials, the enhancement of this public participation system will contribute to determining the success of increasing the recycling rate. The combination of a community participation program and the provision of a recycling unit (TPS3R) is essential, as also identified in the Balikpapan case [59]. Thus, continual education programs to build community awareness and participation in reducing and separating waste are inseparable from attaining low-carbon MSW management for Surabaya City.

Table 3
Estimation on the unit of ITF/TPS3R needed to support a 30 % recycling rate program.

	2020	2025	2030	2035
Population	2,874,314	2,931,611	2,965,388	2,977,001
Total generated waste (ton)	811,255.1	827,426.8	836,960.1	840,240.6
Total amount of waste entering the ITFs/TPS3Rs (ton)	243,376.5	248,228.0	251,088.0	252,072.2
Amount of ITFs/TPS3Rs		34	34	35

Note: population projection follows official data from Surabaya Statistic Bureau [38].

4. Conclusions

An assessment has been conducted to evaluate the effectiveness of national guidance and strategy for MSW management on GHG emissions reduction in Surabaya. The installation of the WtE plant has successfully brought the emissions downward by as much as 57.1 % from the condition when the LFG power plant was already operated. Further prospective descent can be obtained by increasing the recycling rate and operating the RDF production plant as the national policy mandates. Future scenarios reveal that another 22.0 % reduction is secured whenever a 30 % recycling rate is achieved. Meanwhile, RDF production contributes to a 45.2 % reduction in GHG emissions following achieving a 30 % rate for recycling and composting. Low-carbon MSW management of Surabaya can be performed by anticipating technical and non-technical aspects. Based on the sensitivity analysis, recycling should be prioritized and backed up by an effective segregation process. Waste separation is a crucial issue, and this activity's success will positively affect the implementation of existing and proposed waste treatments. To achieve that success, activities under municipality authority, like building more TPS3R and shifting the collection method to the door-to-door system, could be considered. As important as it is, public participation shall be included in the MSW management program. Additionally, establishing governmental regulation, especially on recycling programs, will foster the achievement of the expected low-carbon MSW management. The findings of this study open the opportunity for future prospective research. The impact of different collection methods on the recycling rate and its economic consequences should be further explored.

CRediT authorship contribution statement

Yunus Fransiscus Liem: Writing – review & editing, Writing – original draft, Investigation, Data curation, Conceptualization. **Aulia Ulfah Farahdiba:** Writing – review & editing, Investigation. **I.D.A.A. Warmadewanthi:** Writing – review & editing, Supervision. **Joni Hermana:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cscee.2024.100995.

Data availability

Data will be made available on request.

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