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Research Article

Estimating greenhouse gas emissions from municipal solid waste management in Depok, Indonesia

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ABSTRACT

Almost every waste management step generates greenhouse gas (GHG) emissions; hence, it is imperative to design appropriate treatment methods from sources to disposal sites for reducing their environmental impact. In this study, to provide guidelines for developing a suitable waste management strategy for Depok, Indonesia, emissions from four waste management scenarios for the city are calculated. These scenarios involve treatments such as the application of Waste Treatment Unit (WTU), incinerator, anaerobic digester, composting, and landfill. The best scenario affords the treatment of 150 tons/day of municipal solid waste (MSW) via composting, 80 tons via WTU, and 500 tons/day via anaerobic digestion, and 390 tons/day, which are sent to a controlled landfill in Depok. This best scenario generates net GHG emissions of 202,800 kg CO_2-eq/day, accounting for 1900 kg CO_2-eq/day from transportation; 4 kg CO_2-eq/day from WTU; 25,700 kg CO_2-eq/day from composting; 46,200 kg CO_2-eq/day from anaerobic digestion; and 129,000 kg CO_2-eq/day from a controlled landfill. By contrast, the worst scenario corresponds to the city's current waste management approach, producing net GHG emissions of 299,602.6 kg CO_2-eq/day from the treatment of 600 tons/day of MSW via landfill, 70 tons/day via open burning, 60 tons/day via MRF, 340 tons/day via anaerobic digestion, and 40 tons/day via composting.

1. Introduction

Anthropogenic GHGs surely affect climate change; hence, GHGs have attracted research attention since the beginning of the 20th century [1–4]. The Intergovernmental Panel on Climate Change (IPCC) has stated that if action is not taken to prevent the continual increase of GHG emissions, the Earth's temperature will increase by 6.4 °C during the 21st century [5]. Electricity and land use sectors are the two largest contributors to GHGs, together accounting for ~50% of the anthropogenic GHG emissions [5]. Waste management accounts for ~5% of the GHG emissions [6].

Waste management can be described as managing the waste generated via storage, collection, transfer/transport, recycling, dumping, and landfill while simultaneously considering the costs and effects on human health and the environment [7]. Each waste management step generates GHGs. Waste management technologies, such as energy generation via landfill gas recovery, landfill bioreactors, aerobic composters, anaerobic digesters, incineration with energy recovery, refuse-derived fuel, and co-combustion in cement kilns, have been developed in several countries to curb GHG emissions in this sector. Policies such as the restriction of uncontrolled waste dumping sites in several developing countries; phase reduction of waste entering landfills in the European Union; incentives to generate energy via landfill gas recovery in the United Kingdom; and the requirement of landfill gas recovery at large landfill sites in the United States are also being introduced to achieve this goal [6].

In Indonesia, 60–70% of the generated waste is transported to landfills, while the remaining 30–40% ends up in rivers, burned, or independently managed by the community [8]. Such improper waste management can generate more GHGs than required. This study is conducted in Depok City (Fig. 1), a large Indonesian city that faces waste management issues. It is located around 20 km south of Jakarta (capital of Indonesia), with a population of ~2,106,100 and a population growth of 3.57% [9]. Owing to its proximity to Jakarta, Depok's population growth and waste generation are closely related to those of Jakarta. The population of Jakarta is ~10,177,924, which was growing at a rate of 1.20% in 2015 [10]. Depok generates an estimated 1120 tons of waste daily, 76.61% of which is organic (Table 1) [11]. The existing waste management facilities in Depok comprise one landfill known as the Cipayung Landfill, which covers 10.6 ha and can handle 55–58 garbage trucks per day, each with a capacity of up to 12 m^3 [11]. In addition, ~32 composting facilities and 500 Waste Treatment Units (WTUs) that apply manual sorting are located around the Depok City (Fig. 2). As Depok faces significant waste management issues, appropriate waste management needs to be applied to mitigate GHGs emissions. Therefore, this study aimed to develop scenarios that could serve as guidelines for Depok to manage its solid wastes, which in turn can reduce GHG emissions and enable it to adapt to future changes. Three scenarios and one existing waste management GHGs emission would be calculated. The produced methane (CH_4) and nitrogen dioxide (NO_2), based on their

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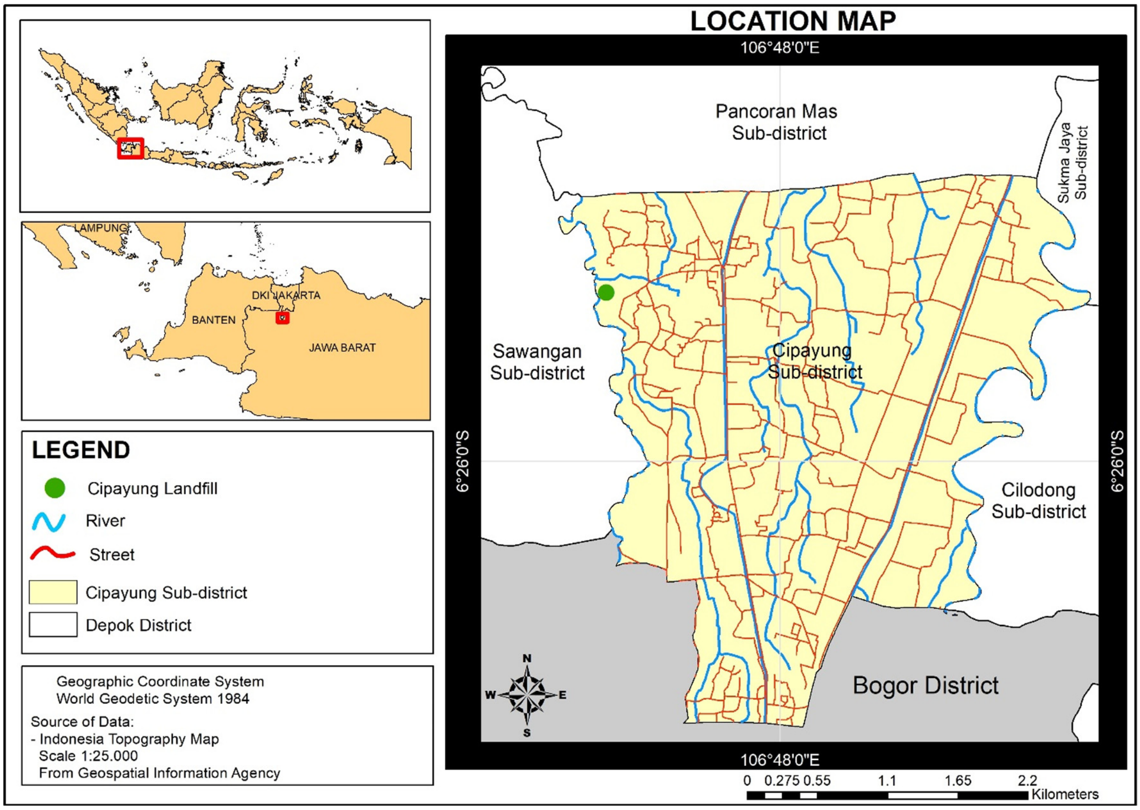

Fig. 1. The location of Depok City relative to Jakarta and Cipayung landfill.

global warming potential (GWP) were assumed to be equivalent to 25 kg CO_2-eq/kg CH_4 and 298 kg CO_2-eq/kg N_2O, respectively.

In this study, the waste management considered in the scenarios included biological treatment using an anaerobic digester and windrow composting; thermal treatment via incineration; and landfill as the final disposal. Anaerobic digestion and composting are extremely common biological treatments employed in developed and developing countries [6]. Anaerobic digesters treat waste anaerobically and are more suitable for wet waste, while composting is an aerobic process and suitable for drier organic feedstock. Anaerobic digestion also produces biogas for energy (CH_4 and CO_2) and biosolids for use as fertilizers (depending on the quality). In Indonesia, composting can be a more sustainable approach due to its more labor-intensive and less mechanical characteristics. In this study, owing to its simplicity and low implementation cost, windrow composting was more suitable for use in Depok's communities [12,13].

In countries that have limited space for landfill sites or those that find it difficult to find areas for landfills, thermal treatment, including incinerators, pyrolysis, and gasification, is becoming an alternative to landfills; however, these treatments must be equipped with advanced air pollution control devices to meet the strict environmental controls imposed by governments. Hence, the cost of such treatment can be high, depending on the plant scale and gas treatment used. In addition, as the land required for landfill is reduced, incinerators can produce useful heat or electricity [6,14].

For several years, landfills have become the oldest, unavoidable option for managing wastes. For decades, landfills, which constitute the final disposal step of municipal solid waste (MSW), are well known to lead to the pollution of all environmental components. One method to reduce the negative environmental impact of landfills is to propose their use as a bioreactor. Several benefits can be achieved, including waste stabilization, pathogen elimination, and biogas production for energy, as well as useful end products such as fertilizers and soil conditioners, depending on the quality [15,16].

Table 1
Composition of Depok's waste.

No.	Waste component	Waste mass (tons)	Percentage (%)
1	Food waste	817.3	72.96
2	Green waste	40.9	3.65
3	Paper	79.2	7.07
4	Plastic	40.0	3.57
5	Metal	15.3	1.37
6	Textile	27.0	2.41
7	Rubber/Leather	13.9	1.24
8	Glass	14.0	1.25
9	Others	72.6	6.48
	Total	1120.2	100

2. Material and methods

2.1. Waste management strategies

In this study, four waste management scenarios were considered, with the first being the default and current waste management applied in Depok, while the other three scenarios were designed. These scenarios were developed on the basis of the waste composition and available affordable technologies. Table 2 summarizes the detailed processes and amounts of waste handled by each process. Fig. 3 show the system boundary of the developed scenarios. As the existing condition, the first scenario send more than 50% of the waste directly to landfill, while more than 40% was treated by composting, anaerobic digestion, and WTU to recover the remaining value. Around 7% is handled improperly either by open burning or dumping into the river.

To minimize the amount of improperly treated waste and reduce waste disposed in the landfill, the proposed scenarios (Scenarios 2, 3, and 4) increased the use of waste treatment such as composting, WTUs, anaerobic digestion, and incineration. The total amount of waste sent for composting

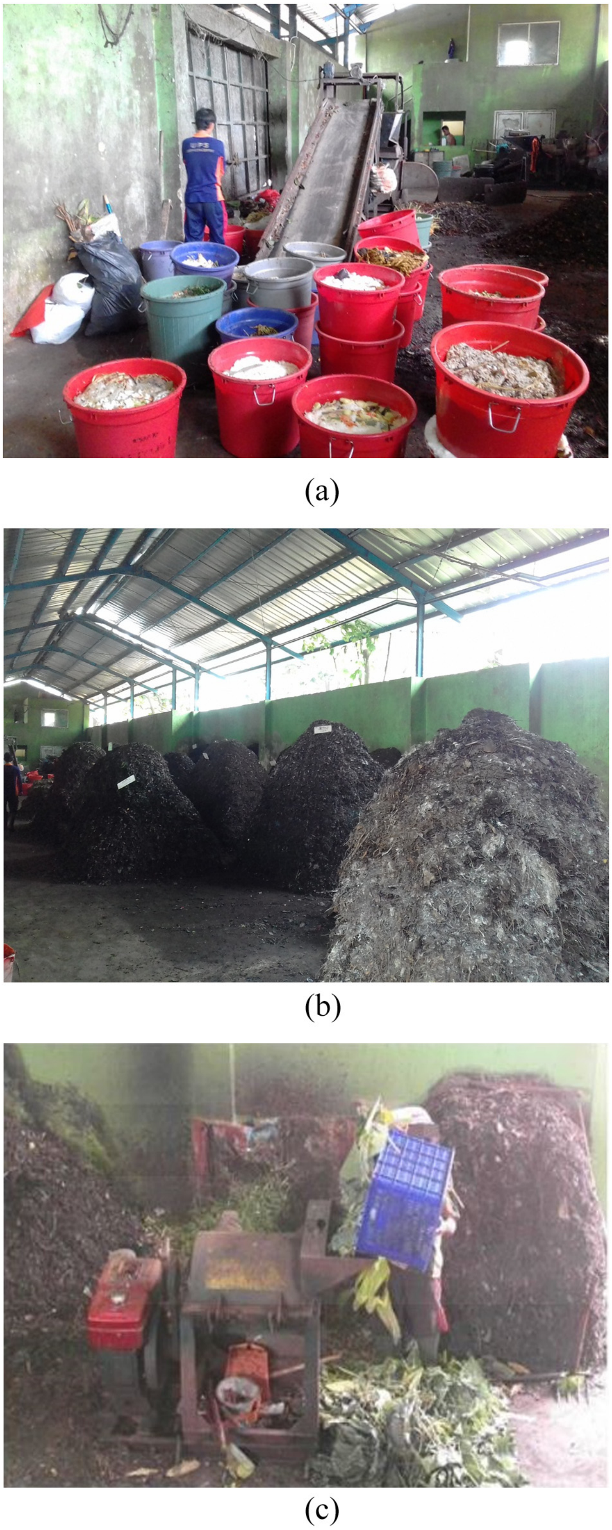

Fig. 2. Activities at Depok WTU facility (a) waste separation, (b) composting, and (c) shredding organic waste manually.

and anaerobic digestion cannot be more than 858.2 tons as it is the maximum amount of organic composition in the wastes (as the total amount of food and green waste). Due to significantly higher food waste content in the waste composition, anaerobic digester is utilized more than composting. Scenarios 3 and 4 also applied waste to energy, an alternative technology that converts non-recyclable material into thermal energy. Except for Scenario 1, all scenarios will not practice open burning and open dumping, as these practices are strictly prohibited under Depok Government Regulation No. 5 (2014).

2.2. Estimation method for emissions

In this study, emissions were estimated using a method developed by Chen & Lo [14] and the IPCC Guidelines for GHG inventories [14,15]. The GHG emissions produced by transporting solid waste were calculated using Eq. (1), while those produced by waste treatment (i.e., anaerobic digestion, incineration, controlled landfills, WTU, and composting) were calculated by Eq. (2). Table 3 summarizes the emission factors (EFs) used.

$$\text{Emissions} = \sum (EF_{trans} \cdot d \cdot \text{mass}) \tag{1}$$

$$\text{Emissions} = \sum (EF \cdot m) \tag{2}$$

where EF_{trans} is the fuel emission factor (kg of gas/ton/km); d is the distance (km); m is the mass of solid waste (tons); and EF is the emission factor (kg of gas/ton).

2.3. Emissions produced by waste transport

In all scenarios, at the beginning, waste was transported from its source to temporary waste treatment facilities, processed by different treatment methods, and finally disposed of at the Cipayung Landfill, as well as the ash from the incinerator facility. The average distance between facilities was 20 km. Table 3 summarizes the GHG EFs for different waste management methods. For the incinerated waste, the transportation of the ash to landfills was included in the calculations. The amount of ash was 20% of the initial waste mass [14]. In addition, for the material not recovered by the WTU and the sludge from the anaerobic digester, transportation to landfill was included, assuming a mass of 50% of the initial waste amount in both cases [6]. For open burning in Scenario 1, the waste was assumed to be burned at source; hence, gaseous emissions are not produced by transport.

2.4. Emissions caused by open burning

Open burning is defined as burning materials without controlling the temperature or burning time, and smoke and air pollutants are released into the environment without passing through any air pollution control devices. Open burning is a significant local source of GHG emissions in developing countries; however, due to the manner in which it is carried out, no accurate statistics are available. GHGs such as CO_2, CH_4, and N_2O are emitted through open burning. The amount of CO_2 emitted by open burning depends on the waste composition and the oxidation factor, which is only 58%. As a considerable amount of carbon in the waste is not oxidized, CH_4 is more relevant in open burning [18].

2.5. Emissions caused by incineration

Emissions caused by incineration were calculated by considering the electricity generated and the related reduction in emissions. Currently, the power plant in Depok uses coal, and EFs for electricity generation from coal are 0.32232 kg CO_2/kWh for CO_2, 0.00006 kg CO_2-eq/kWh for CH_4, and 0.00280 kg CO_2-eq/kWh for N_2O [17]. The calorific value of Depok's waste is 2000 kcal/kg or 2.32 kWh/kg [21]. As the electricity generated from waste can reduce coal usage, the reduction in emissions was assumed to be equal to the emissions produced by the electricity generation from coal.

In this study, GHGs emitted by the incinerator were calculated using Eq. (2), and the EF for CO_2 was calculated on the basis of the IPCC Guidelines for GHG inventories [18]. Incineration conducted via a semi-continuous process with a stoker and all of the produced ashes are then sent to landfill. The amount of ash is 20% of the total amount of waste incinerated [14].

Table 2
Waste management strategies for Depok.

Scenario	Composting (tons/day)	Open burning (tons/day)	Waste Treatment Unit (tons/day)	Anaerobic digestion (tons/day)	Incineration (tons/day)	Controlled landfill (tons/day)	Total (tons/day)
1	40	70	60	340	–	600	1110
2	150	–	80	500	–	390	1120
3	200	–	100	500	100	220	1120
4	250	–	120	500	150	100	1120

2.6. Emissions caused by Waste Treatment Units (WTUs)

WTUs apply similar processes to Material Recovery Facilities (MRFs). However, in Depok, most of the material recovery is currently conducted by informal sectors using conventional tools. Instead, of using well-known MRF technologies such as those utilized in developed countries, manual labor for separating, sorting, and storing materials is applied in WTU. Typically, recovered materials are sold to second-hand goods vendors [12]. Several studies conducted in developed countries have reported WTU EFs ranging from 0.047 to 4.448 [14,19]. Here, the EF is assumed to be

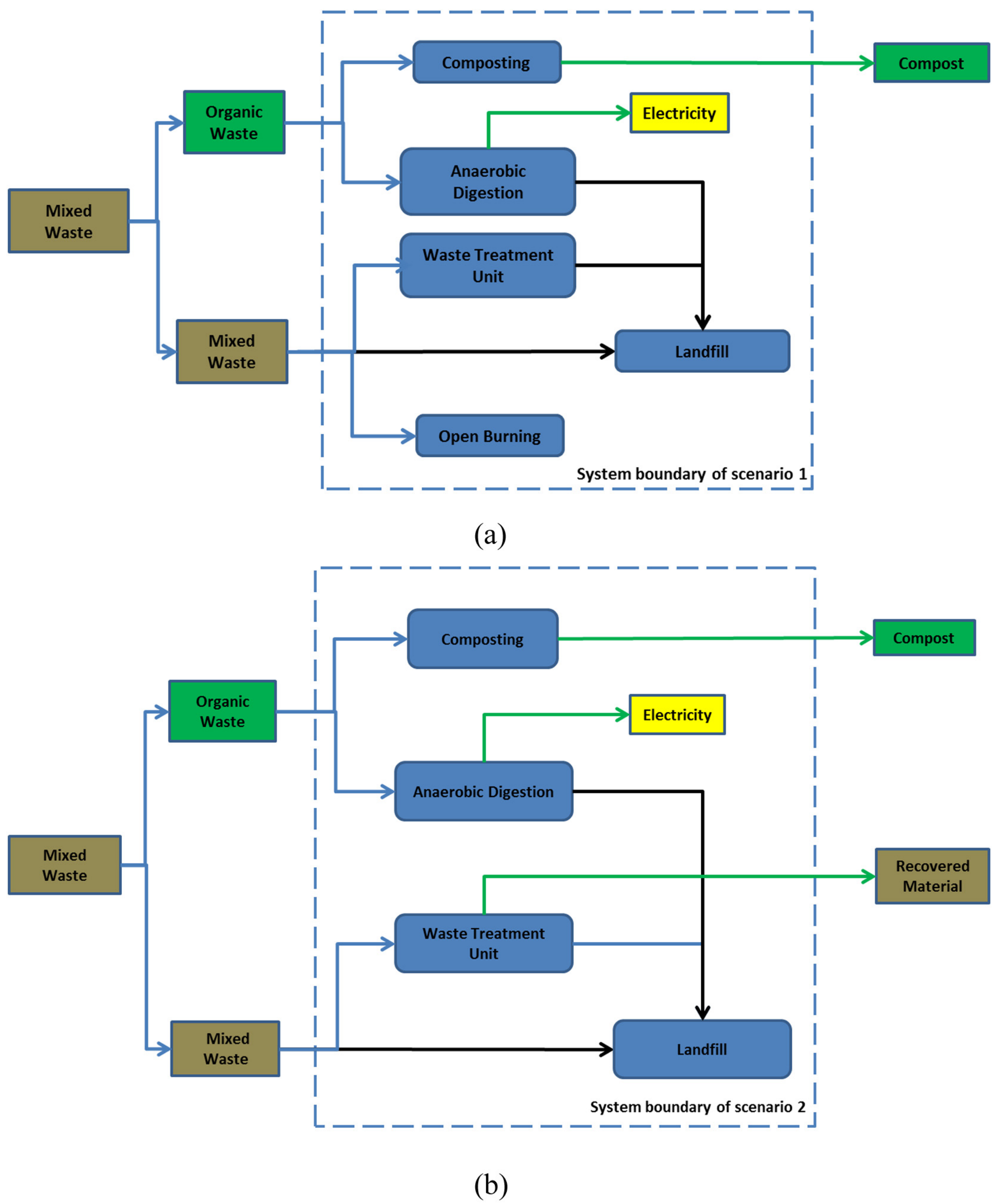

Fig. 3. The system for (a) scenario 1, (b) scenario 2, and (c) scenario 3 and scenario 4.

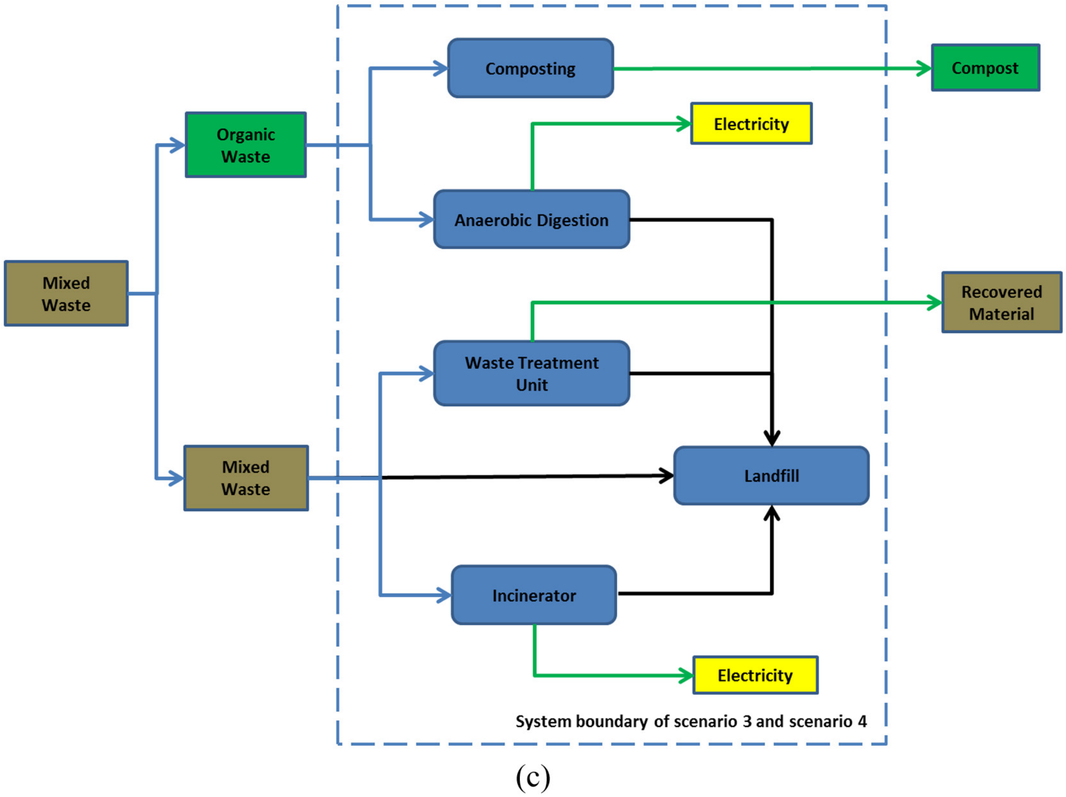

Fig. 3 (*continued*).

0.047 kg CO_2-eq/ton MSW due to the simplicity of the process. In addition, the emission reduction and energy savings achieved by using recycled, rather than virgin, materials are not included.

In Depok, the current WTUs cannot recover 100% of the materials they receive as all types of wastes are comingled and difficult to separate, not to mention that waste separation is not conducted at source. Hence, in this study, 50% of the waste received by this sector is assumed to not be recovered and is sent to landfills instead [6].

2.7. Emissions caused by anaerobic digestion

As for incineration, calculations for anaerobic digestion also take account for the reduction in emissions due to electricity generation. Here, 100 kWh of electricity is assumed to be generated by the anaerobic digestion per ton of waste [22], reducing emissions by the amount produced by the electricity generation from coal. The energy required to run anaerobic digesters is not considered.

Table 3
GHG emission factors according to the waste management method.

Sector	Type	Emission factor	Unit	Source
Transportation	CO_2	0.0191	kg CO_2/km/ton MSW	[17]
	N_2O	0.0497	kg CO_2-eq/km/ton MSW	[17]
Incineration	CO_2	1381.4	kg CO_2/ton MSW	[18]
	N_2O	14.9	kg CO_2-eq/ton MSW	[18]
	CH_4	0.15	kg CO_2-eq/ton MSW	[18]
Anaerobic digestion	CH_4	125	kg CO_2-eq/ton MSW	[15]
Composting	CH_4	100	kg CO_2-eq/ton MSW	[15]
	N_2O	71.52	kg CO_2-eq/ton MSW	[15]
WTUs	CO_2	0.05	kg CO_2/ton MSW	[14,19]
Open burning	CO_2	801.2	kg CO_2/ton MSW	[18]
	CH_4	162.5	kg CO_2-eq/ton MSW	[18]
	N_2O	44.7	kg CO_2-eq/ton MSW	[18]
Controlled landfill	CH_4	300	kg CO_2-eq/ton MSW	[20]

Although anaerobic digestion is anaerobic, sometimes, some aerobic conditions occur; hence, CO_2 emissions are still produced, such as during start-up, shutdown, material transfer, and storage, as well as by malfunctions [6,23]. Here, CO_2 emissions are not considered as they are of biogenic origin or are derived from the natural carbon cycle [15]. The produced biosolids or sludge are sent to landfills and are assumed to be equivalent to 50% of the initial waste received [6].

2.8. Emissions caused by composting

Composting essentially treats waste aerobically and affords CH_4 emissions due to anaerobic processes. Other gases such as N_2O, NH_3, CO, and CO_2 are also emitted. As the CO_2 produced by composting is of biogenic origin and not derived from fuel, it is not considered to be a GHG; thus, it is not considered herein [15,16]. The composting facility in Depok is mostly managed by untrained workers; therefore, poor composting management affords higher emissions, especially of CH_4 and N_2O [13].

2.9. Emissions caused by controlled landfill sites

Landfill is the main contributor to CH_4 emissions in the waste sector. Poorly managed landfill sites in which gas extraction systems are not utilized or where waste is simply dumped into an excavated hole are ubiquitous in developing countries [6,12,24]. In this study, the landfill EF is applied as a controlled landfill with commingled waste [20]. The emitted CO_2 is considered to be of biogenic origin; thus, it is not a GHG.

In addition to regular waste, landfill also receives incineration ash, biosolids from anaerobic digesters, and unrecovered materials from WTUs. However, only the unrecovered materials are considered during the calculation of the total landfill GHG emissions as CH_4 gas is produced in landfill sites by the activity of microorganisms [6], while ash is not considered to be biodegradable, and the CH_4 produced by biosolids is weaned off by anaerobic digestion. In this study, the electricity needed to run office buildings at landfill sites or fuel needed for heavy equipment, such as bulldozers and excavators, is not considered as it is negligible compared to the released CH_4 [20].

3. Results and discussion

3.1. Total GHG emissions

Table 4 summarizes the calculation results of the GHG emissions. Gross GHG emission, which is the emission without being subtracted by the reduction through electricity generation, was the lowest for Scenario 2 (219,200 kg CO_2-eq/day) and the highest for Scenario 4 (364,900 kg CO_2-eq/day). While the net GHG emission, which is the value of emission after being subtracted by the emission reduction through electricity generation, was the lowest for Scenario 2 (202,900 kg CO_2-eq/day) and the highest for Scenario 1 (299,600 kg CO_2-eq/day). Figs. 4 and 5 show breakdowns of the gross and net GHG emissions for all scenarios in terms of the waste treatments used.

The highest GHG emissions were different between the gross and net GHG results due to the GHG reduction being the highest for Scenario 4 (129,000 kg CO_2-eq/day) and the lowest for Scenario 1 (11,100 kg CO_2-eq/day). Around 60% of the waste treatment in Scenario 1 (controlled landfill and open burning) afforded no GHG reduction, while in Scenario 4, 58% of the MSW generated electricity, which was included in the net GHG calculations. Moreover, in this scenario, 33% of the MSW was treated by methods that potentially eliminated GHG emissions, but were not included in the calculations. For example, WTUs could help to reduce the use of virgin materials and shorten the long material production process from excavation to the final product. Similar goes to composting also, the end product of composting enabled carbon sequestration.

Furthermore, Scenario 2, 35% of the MSW was sent to controlled landfills, which did not reduce GHG emissions, while in Scenario 4, only 9% of the MSW was treated by methods that did not reduce GHG emissions.

3.2. Analysis of emissions caused by transportation

Typically, MSW is transported from one point to another as part of waste management. In Scenarios 1–4, the transportation of wastes generated 1700, 1940, 1980, and 2000 kg CO_2-eq/day of GHGs, respectively. This increasing trend of GHGs emissions from Scenario 1 to 4 is related to the increase in the amount of waste transferred to WTUs. Incinerators, WTUs, and anaerobic digesters are not the final step in the waste management flow, and further transport to the landfill is required. The amounts that are transported to landfill are 20%, 50%, and 50% of the original waste that are sent into the facility for incinerator, MRF, and anaerobic digester respectively. Therefore, to this reason, the more integrated a waste treatment process in one area, the better. In general, GHG emissions caused by transportation were still less than those caused by waste treatment.

3.3. Analysis of emission caused by open burning and incineration

Thermal waste treatment exhibited the highest EF. Open burning and incineration exhibited gross EFs of greater than 1000 kg CO_2-eq/ton MSW, while other waste treatments had gross emission factor less than 500 kg CO_2-eq/ton MSW. Open burning was only considered in the first scenario as it was not a waste treatment, but rather an unavoidable condition of current limited waste processing. In Scenario 1, open burning generated 70,590 kg CO_2-eq/day of GHGs from 70 tons of MSW. Meanwhile, Scenarios 3 and 4 utilized incinerations even though its gross EF was greater than that observed for open burning; however, unlike open burning, incineration can generate electricity, thereby reducing GHG generation. Gross GHG emissions by incineration for scenarios 3 (100 tons of MSW) and 4 (150 tons of MSW) were 139,600 and 209,400 kg CO_2-eq/day, respectively, while the corresponding values for net GHG emissions were 64,200 and 96,300 kg CO_2-eq/day. Unlike Indonesia, Taiwan has utilized incinerators for more than two decades. More than 6.5 million tons of MSW of Taiwan is sent to waste to energy plants, generating more than 3 million kWh of electricity annually. The net GHG emissions by the treatment of 20,000 tons of MSW in Taiwan were calculated to be 4.39×10^6 kg CO_2-eq/day, which was calculated on the basis of a net GHG EF of 219.5 kg CO_2-eq/ton MSW by incineration [14]. The net GHG EF of incinerator in Taiwan could be one third of this study, must be due to the technology (incinerator or air pollution control device) advance and their expertise in applying the technology.

According to Permadi & Oanh [25], in Indonesia's cities, open burning mostly occurs at transfer stations when the MSW has been piled up too long without being sent to a landfill site and in city outskirts where no waste collection service is available. On the other hand, in rural areas, the waste is either directly discharged into the environment or composted. Their studies stated that the open burning of MSW can generate as much as 256 Gg CO_2-eq/year, with considerable amounts originating from cities on the Java Island [25].

Table 4
GHG emission factors by the waste management method.

Scenario	Gross GHG (kg CO_2-eq/day)	GHG reduction (kg CO_2-eq/day)	Net GHG[a] (kg CO_2-eq/day)
1	310,700	11,100	299,600
2	219,200	16,300	202,900
3	319,400	91,700	227,700
4	364,900	129,000	235,400

[a] Net GHG = Gross GHG − GHG Reduction.

3.4. Analysis of emissions caused by WTU

WTUs generated the lowest GHG emissions in all scenarios: For Scenarios 1–4, the emissions were 3, 4, 5, and 6 kg CO_2-eq/day, respectively. In this study, the emissions and energy reduction due to the use of recycled, rather than virgin, materials were not considered. Another study, conducted in Canada, did consider this point and concluded that WTUs can reduce more than two times the emissions compared with those eliminated by anaerobic digestion although their energy consumption is 10 times greater than that observed for anaerobic digestion, composting, or incineration [19]. However, the reduced energy requirements for processing virgin materials compensated for the additional emissions due to the higher energy consumption.

The energy requirements of WTUs in Depok were assumed to be low as WTUs depended on manual labor. That said, the percentage of recovered material also was extremely low. Previous studies have reported that only 26% of the input waste is recovered even though theoretically 83% of the MSW can be separated [12]. In addition, the waste received was commingled waste that had not been separated at source, indicating that a considerable amount of this material is of low quality or even damaged. For example, paper products were often found to be wet or dirty; thus, these products are sold at a low price. In addition, due to the lack of community awareness on waste separation, the government also was responsible, with inadequate waste collection trucks mixing up the waste that some communities had separated, no waste separation regulations, and poor internal–external coordination, indicative of the lack of commitment by the government in this area.

WTUs demonstrate immense potential for reducing GHG emissions, as shown by a study of WTUs in Taiwan [14]. WTUs can mitigate up to $\sim 3.8 \times 10^6$ kg CO_2-eq/year or 3×10^4 kg CO_2-eq/day, with the greatest potential benefits coming from metal (1.83×10^6 kg CO_2-eq/year) and paper (7.38×10^5 kg CO_2-eq/year), followed by plastic and food waste [14]. A previous study has reported that glass bottles and plastics are the most widely recovered waste products in Depok WTUs [12]. By contrast, in this study, the second- and third-largest components of the waste corresponded to paper (79.3 tons/day) and plastic (40 tons/day), respectively. The largest component was food waste, which was sent for composting or anaerobic digestion in this study. Given the value of the metal, it was assumed to be sold by either waste generators or original

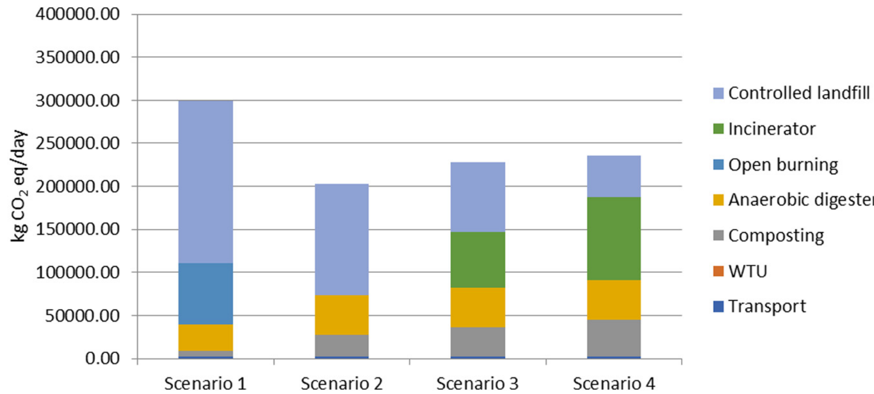

Fig. 4. Detail division of gross GHG emissions for all scenarios with the inclusion of electricity generation.

sources. In conclusion, WTUs in Depok still exhibit an extremely low efficiency although they demonstrate immense potential for GHG mitigation.

3.5. Analysis of emissions caused by anaerobic digestion and composting

Anaerobic digestion enables the reduction in the GHG emissions produced by electricity generation. In Scenario 1, the gross and net GHG emissions were 42,500 and 31,400 kg CO_2-eq/day, respectively. In Scenarios 2, 3, and 4, similar amounts of waste (500 tons) were sent for anaerobic digestion, yielding gross and net GHG emissions of 62,500 and 46,200 kg CO_2-eq/day, respectively. The coal power plant emitted 0.325 kg CO_2-eq/kWh; hence, the GHG reduction per ton of waste is 32.5 kg CO_2-eq/day.

Compared to the anaerobic digester in Daejeon, Korea, which handled 58,400 tons/year of food waste and predicted to generate 25,880 GJ/year [22], if all food wastes generated by Depok (298,205 tons/year) were treated in the same manner by an anaerobic digester, they potentially would produce electricity amounting to 69,780 GJ/year. In this study, 500 tons of food waste per day was treated by anaerobic digestion, and the produced electricity could supply 12,250 people, assuming that Indonesia's electricity consumption is 3.42 GJ/year/capita [26].

Besides anaerobic digestion, composting is another biological waste treatment option that emits less GHGs than those emitted by anaerobic digestion [27]. The GHG emissions for Scenarios 1–4 were 6800; 25,700; 34,300; and 42,900 kg CO_2-eq/day, respectively. Another study that compared the compost produced under meticulously controlled conditions (i.e., strict waste composition, humidity, temperature, pH, and aeration requirements) with that produced under normal conditions, revealed that normal compost, which is typically created by communities, emits 4.6 and 5.8 times more CH_4 and N_2O, respectively, than meticulously controlled compost created by experts [16]. They suggested that high CH_4 emissions correspond to the lack of aeration, while high N_2O emissions correspond to a high moisture level. That said, although their GHG emissions are different, both composts can satisfy the government requirements [16].

3.6. Analysis of emissions caused by controlled landfills

Landfill CH_4 is the waste sector's largest GHG source. For Scenarios 1–4, the GHG emissions were 189,000, 129,000, 81,000, and 48,000 kg CO_2-eq/day, respectively. The GHG EFs for four types of landfill were examined, and the GHG EFs for open dumping landfill, conventional landfill with commingled waste (50% organic, 50% inert waste), engineered landfill with gas utilization, and low-organic-waste landfill were 688–963, 58–327, 58–327, and 19–74 kg CO_2-eq/ton waste, respectively. In this study, 300 kg CO_2-eq/ton was adopted due to the waste's high organic content and the inefficient application of conventional landfills in Depok [12].

In developing these scenarios, Depok's waste management strategy was expected to change in the future and would adopt one of the new scenarios, namely Scenarios 2–4. These scenarios can treat 76–89% of the organic waste via anaerobic digestion and composting, sending the remaining waste, with less than 36% organic content, to incinerators, WTUs, and controlled landfill sites, thereby reducing landfill emissions. In addition, previous studies have reported that sinking biogenic carbon and recovering CH_4 for energy in landfills can mitigate GHG emissions by up to 180 and 140 kg CO_2-eq/ton waste, respectively [20]. The carbon sunk by landfills depends on the concerned materials, with inert materials sinking up to two-thirds as much carbon compared to organic ones. Thus, it is crucial to reduce the amount of organic materials sent to landfills.

In addition, methane emissions varied depending on the waste composition and landfill practices and continued for several decades, indicating that incineration, composting, and other technologies are preferred for GHG mitigation in the short to medium term. On the other hand, the

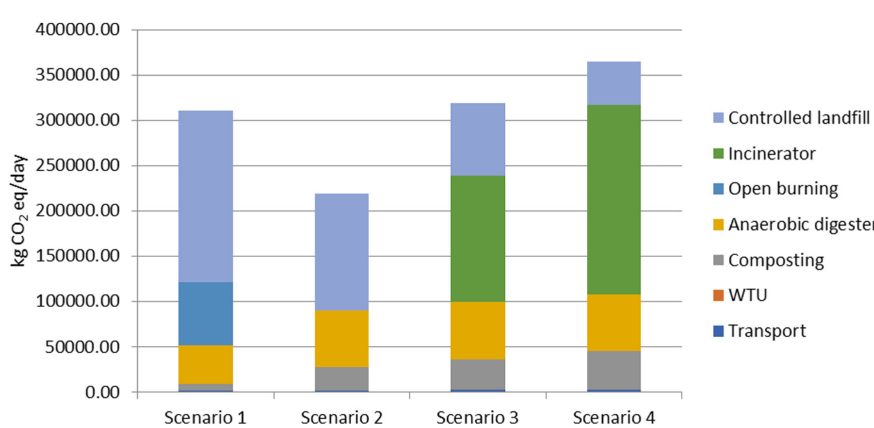

Fig. 5. Detail division of gross GHG emissions for all scenarios with the exclusion of electricity generation.

sunk carbon makes landfills a viable alternative for long-term GHG mitigation, especially when using energy recovery [6].

Full-scale landfill gas recovery for energy was started in 1975; hence, by 2030, GHG mitigation via landfill gas recovery is predicted to potentially reach greater than 1000 Mt CO_2-eq/year. With the improvement of waste treatment technologies and systems, landfills are becoming a less-utilized option, and their emissions are more stabilized in developed countries. On the other hand, as a high number of large cities are emerging, and controlled landfill practices are implemented in developing countries, emissions are increasing. The reported/predicted global GHG landfill emissions were/will be 550, 590, 700, 910, and 1500 Mt CO_2-eq, for 1990, 2000, 2010, 2020, and 2030, respectively. Specifically, developing countries in south and east Asia accounted for ~25 and 50 Mt CO_2-eq, respectively, while those of Europe and North America stabilized at ~100 Mt CO_2-eq between 1990 and 2000 [6]. The lack of awareness and funding among the governments of developing countries become significant factors in improving their waste management as other issues such as industry, trade, education, as well as other sectors, will clearly increase the GDP of these countries.

4. Conclusions

Four scenarios were developed for mitigating GHG emissions due to the waste management sector in Depok City, Indonesia. The results indicated that Scenario 2 emits the least GHGs by the treatment of 1120 tons/day of the waste generated from Depok City, including 150 tons/day by composting, 80 tons/day by recovery materials, 500 tons/day by anaerobic digestion, and 390 tons/day by controlled landfills. However, Scenario 4 also was considered due to its use of waste technologies that produce electricity that can help to mitigate GHG emissions. In all scenarios, the waste treatment of WTUs emitted the least GHGs. However, although incineration produced high GHG emissions, it also produced electricity, thereby mitigating GHG emissions. With regard to organic waste treatment, anaerobic digester emits less GHGs than composting and could be more suitable for food waste with high water content. But composting could be more suitable in Depok, due to availability of human resources and does not need advance technology to run. So, both biological treatments can be considered.

In future research, using WTUs to reduce the use of virgin materials, the carbon sequestration potential of composting, more accurate determination of the composition of MSW sent for incineration and the avoidance of fuel extraction from the earth due to MSW utilization as fuel, need to be considered as the potential for GHG mitigation could be as high or higher with the proper waste treatment strategy.

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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Author contributions

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References

[1] Goldenfum JA. Challenges and solutions for assessing the impact of freshwater reservoirs on natural GHG emissions. Ecohydrol Hydrobiol 2012;12(2):115–22.

[2] Hu B, Xu X, Zhang J, Wang T, Meng W, Wang D. Diurnal variations of greenhouse gasses emissions from reclamation mariculture ponds. Estuar Coast Shelf Sci 2020;237:106677.

[3] Kumar A, Yang T, Sharma MP. Greenhouse gas measurement from Chinese freshwater bodies: a review. J Clean Prod 2019;233:368–78.

[4] Malahayati M, Masui T. The impact of greenhouse mitigation policy for land use and forestry sector in Indonesia: applying the computable general equilibrium model. Forest Policy Econ 2019;109(2019):102003. https://doi.org/10.1016/j.forpol.2019.102003.

[5] Intergovernmental Panel on Climate Change (IPCC). Climate change 2013: The physical science basis. Working Group I contribution to the IPCC Fifth Assessment Report. Cambridge, United Kingdom: Cambridge University Press; 2013.

[6] Intergovernmental Panel on Climate Change (IPCC). In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA, editors. Climate change 2007: Mitigation. Contribution of Working Group III to the fourth assessment report of the Intergovernmental Panel in Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2007.

[7] Tchobanoglous G, Theisen H, Vigil SA. Integrated solid waste management: engineering principle and management issue. New York: McGraw-Hill; 1993.

[8] Damanhuri E, Wahyu IM, Ramang R, Padmi T. Evaluation of municipal solid waste flow in the Bandung metropolitan area, Indonesia. J Mater Cycles Waste Manag 2009;11:270–6. https://doi.org/10.1007/s10163-009-0241-9.

[9] West Java Bureau of Statistics. West Java Province in figures 2016; 2016 [Indonesia].

[10] BPS-Statistic of DKI Jakarta Province. Jakarta in figures 2016. Indonesia: Jakarta; 2016.

[11] Depok Environmental Department. White book of Depok sanitation 2016. Depok: Depok Environmental Department; 2016.

[12] Kristanto GA, Gusniani I, Ratna A. The performance of municipal solid waste recycling program in Depok, Indonesia. Int J Technol 2015;6:263. https://doi.org/10.14716/ijtech.v6i2.905.

[13] Zhu-Barker X, Bailey SK, Paw U, Burger M, Horwath WR. Greenhouse gas emissions from green waste composting windrow. Waste Manag 2017;59:70–9. https://doi.org/10.1016/j.wasman.2016.10.004.

[14] Chen Y-C, Lo S-L. Evaluation of greenhouse gas emissions for several municipal solid waste management strategies. J Clean Prod 2016;113:606–12. https://doi.org/10.1016/j.jclepro.2015.11.058.

[15] Intergovernmental Panel on Climate Change (IPCC). Chapter 4 biological treatment of solid waste. 2006 IPCC guidelines for national greenhouse gas inventories volume 5 waste; 2006.

[16] Quirós R, Villalba G, Muñoz P, Colón J, Font X, Gabarrell X. Environmental assessment of two home composts with high and low gaseous emissions of the composting process. Resour Conserv Recycl 2014;90:9–20. https://doi.org/10.1016/j.resconrec.2014.05.008.

[17] Department for Environment, Food and Rural Affairs (DEFRA). Guidelines to Defra/DECC's conservation factors for company reporting, 2011; 2011.

[18] Intergovernmental Panel on Climate Change (IPCC). Chapter 5 incineration and open burning of waste. 2006 IPCC guidelines for national greenhouse gas inventories volume 5 waste; 2006.

[19] Mohareb AK, Warith MA, Diaz R. Modelling greenhouse gas emissions for municipal solid waste management strategies in Ottawa, Ontario, Canada. Resour Conserv Recycl 2008;52:1241–51. https://doi.org/10.1016/j.resconrec.2008.06.006.

[20] Manfredi S, Tonini D, Christensen TH, Scharff H. Landfilling of waste: accounting of greenhouse gases and global warming contributions. Waste Manag Res 2009;27:825–36. https://doi.org/10.1177/0734242X09348529.

[21] Sagala GAA. The effect of domestic solid waste composition on calorific value optimization of refuse derived fuel through biodrying. Department of Civil and Environmental Engineering, Universitas Indonesia; 2017 [Unpublished Thesis, in Bahasa].

[22] Yi S, Jang Y-C, An AK. Potential for energy recovery and greenhouse gas reduction through waste-to-energy technologies. J Clean Prod 2018;176:503–11. https://doi.org/10.1016/j.jclepro.2017.12.103.

[23] Phong NT. Greenhouse gas emissions from composting and anaerobic digestion plants; 2012.

[24] Tan ST, Hashim H, Lim JS, Ho WS, Lee CT, Yan J. Energy and emissions benefits of renewable energy derived from municipal solid waste: analysis of a low carbon scenario in Malaysia. Appl Energy 2014;136:797–804. https://doi.org/10.1016/j.apenergy.2014.06.003.

[25] Permadi DA, Oanh NTK. Assessment of biomass open burning emissions in Indonesia and potential climate forcing impact. Atmos Environ 2013;78:250–8. https://doi.org/10.1016/j.atmosenv.2012.10.016.

[26] Directorate General of Electricity. The Book of electricity statistics number 29 – 2016. Ministry of Energy and Mineral Resources; 2016.

[27] Maria FD, Sisani F. Greenhouse gas emissions and environmental impact from recycling the organic fraction of solid waste: comparison of different treatment schemes from a life cycle perspective. Recycling 2017;2:13. https://doi.org/10.3390/recycling2030013.