

Estimation of Greenhouse Gas Emission from Organic Fraction of Municipal Solid Waste Treatment

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Abstract
This study aims to estimate greenhouse gas emissions from urban organic waste management. Three management system scenarios were considered as the basis for the analysis. Scenario 1, centralized composting part of the organic waste and the rest being stockpiled in a controlled landfill as a representation of current conditions. In scenario 2, apart from increasing the amount of waste being managed, it also involves home composting. In scenario 3, part of landfill gas in scenario 2 is burned openly. Operational data on municipal solid waste (MSW) management by Buleleng Regency Environmental Office (DLH) by Buleleng Regency was used in this study in addition to the databases available in the IPCC model and other literatures. In scenario 1, 2562 Gg CO_{2-e} comes from gas landfills emission. The centralized composting can only contribute to the avoidance of emissions by 0.158 Gg. In scenario 2, emissions were generated from landfills are 5896 Gg CO_{2-e} with avoided emissions obtained from the application of compost of 0.252 and 0.044 Gg CO_{2-e} respectively for compost produced from centralized composting and home composting. The contribution from landfills is greater in scenario 2 compared to scenario 1 in line with the amount of waste collected and managed. If 50% of landfill gas from scenario 2 is collected from gas collection facilities and then burned (scenario 3), then the avoided GHG emission from this system is 2929.5 Gg CO_{2-e}. This shows that the avoidance contribution of burning or utilizing landfill gas is much greater than that of composting.
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1. Introduction

The organic fraction of waste is the largest component in urban waste. Based on the report by The National Waste Management Information System (SIPSN), for 2021, 65.5% of the composition of waste generated in urban areas in Indonesia is biodegradable organic waste. Among them, 40.4% are food waste, 12.9% are wood/twigs, and 11.7% are paper/cardboard. Although it is biodegradable, organic waste can also harm the environment if it is not managed properly. Currently, apart from being dumped in a landfill, composting is the main alternative for organic waste management that is applied in cities in Indonesia. Through this effort, it is hoped that it can take advantage of its nutritional content and reduce the accumulation of waste in landfills.

Basically, in addition to reducing the amount of waste that is stockpiled, composting is one way to reduce greenhouse gas (GHG) emissions from waste management (Biala, 2011). This is made possible by the reduced organic fraction of waste that is stored in landfills, the less landfill gas is generated. Bearing in mind, OSFM in landfills will undergo anaerobic degradation which produces landfill gas. If landfill gas containing methane is not managed properly or collected, methane gas as a GHG will be emitted into the atmosphere. In addition, the compost produced also has a positive effect on GHG emissions because its application causes carbon to remain bound to the soil (Monni et al., 2006). The use of this compost is also considered to reduce the need for N, P, and K fertilizers (Biala, 2011). In this context, composting organic waste can contribute negatively to GHG emissions.

However, although composting is a natural biochemical decomposition process, GHGs are also released from the composting facility. GHGs are mainly generated from the degradation of organic matter during composting and the use of energy during the composting operation as well as the transport of compost or compost material. Methane (CH_4) and N_2O are gases defined as GHG emissions resulting from the degradation of organic matter, CO_2 generated from the use of energy or fuels (Biala, 2011; Monni et al., 2006). According to Hao et al. (2004), during composting, most of the organic carbon is converted into CO_2, while methane accounts for less than 6%. However, it should be noted that although CO_2 is a major part of emissions, it does not add to global warming because it comes from biogenic carbon. On the other hand, CH_4 and N_2O have a direct impact on global warming. The global warming potential (GWP) for CH_4 is 25 and 298 for N_2O, indicating that both are GHGs that are 25 and 298 times stronger than CO_2 over a 100-year period (Forster et al., 2007). However, GHG emissions from the composting process depend on the type and composition of the waste, the technological system used (static and dynamic processes, open and closed systems, presence or absence of a gas treatment unit) and the final use of compost (Biala, 2011).

Various methods are available to estimate GHG emissions from composting including those carried out aerobically. Research conducted by (Suprihatin et al., 2008) using the principle of mass balance is used as the main method in the analysis of the potential for methane emission reduction. According to (Suprihatin et al., 2008), by producing one ton of compost, emissions of 0.21-0.29 tons of methane, equivalent to 5-7 tons of carbon dioxide, could be avoided. In Indonesia, studies on the contribution of composting to reduce greenhouse gas emissions have not been widely carried out. Composting raw organics in the lowest GHG emissions, at 41 kg $CO_{2\text{-}e}$ per ton of waste (Nordahl et al., 2020). In this study, GHG emissions from composting are estimated based on the database of the LCA tools it uses. It confirmed that the composting process is a source of greenhouse gases (GHG) that contribute to climate change (Zhu-Barker et al., 2017). Estimates were made by monitoring three windrows of field-scale green waste compost over a period of one year. Methods for estimating GHG emissions from composting are also provided in the 2006 IPCC Guidelines. The IPCC considers CH_4 and N_2O emissions from composting. Unlike the previous method, the IPCC method is provided in 4 Tiers whose selection can be adjusted to the conditions and data availability in each country. Indonesia has also adopted this method. Each approach has advantages and disadvantages. With the lack of studies conducted in Indonesia and the proliferation of composting, its contribution to GHG is important to analysis. Quantification of GHG emissions from composting facilities is important for the development of emission mitigation technologies and increasing the accuracy of the compost emission model parameters quantitatively.

This study aims to estimate GHG emissions and their mitigation potential from composting the organic fraction of urban waste. The assessment will be carried out on the waste managed by DLH Buleleng Regency, Bali Province. This research provides basic data to support decision-making and development of waste management strategy options at the local level and in the context of a global perspective.

2. Method

Three scenarios of organic waste management were created and compared their potential contribution to GHG emissions. Scenario 1 is collection and stockpiling by means of centrally composting part of organic waste and the rest is stockpiled in a controlled landfill as a representation of current conditions, scenario 2 is collection and stockpiling by means of centrally composting part of organic waste, home composting, and the rest is stockpiled in a sanitary landfill. and in scenario 3 the same as in scenario 2 but landfill gas is burned openly. As a case study in this study, the organic matter of urban waste managed by the Buleleng Regency Government was selected.

2.1 Scenario

Scenario 1, the service rate for 2021, is 28% used. The service level is assumed to increase by 2% in 2022 and then increase by 5% annually so that by 2030 it will be 70%. The composition of organic waste is assumed to be constant and the percentage of composted waste is 0.72% in 2021 and an increase of 0.1% annually to 1.6% in 2030. Landfills are managed semi-aerobic (Semi-aerobic managed solid waste disposal sites). Centralized composting is done with an open window. Scenario 2, transportation and service levels are the same as in scenario 1. The composition of organic waste is assumed to be constant and the percentage of waste that is centrally composted is the same at 0.72% in 2021 and increases by 0.2% annually. In addition, composting is also carried out at the household level starting in 2022 at 0.05% and increasing by 0.01% every year. The landfill technology and centralized composting are the same as those used in scenario 1. Home composting is carried out in a plastic tub. Scenario 3, the same as scenario 2, only 50% of landfill gas is collected and open burning.

2.2 Applications of HMS

GHG estimates are calculated using the IPCC tier-2 model with some adjustments made. The GHG emissions considered related to landfills and composting are CH_4 and N_2O while from CO, CO_2 and N_2O transportation. Taking into account the fertilizing properties of the compost, the system is credited for the nitrogen and phosphate content and it is assumed that the N and P provided by the compost can replace urea and mineral fertilizers such as ammonium nitrate and triple super phosphate. N_2O, NO_X and NO_3 emissions associated with mineral fertilizer application were calculated using models available in the literature. Operational data on waste management by the DLH of Buleleng Regency, was used in this study in addition to the databases available in the IPCC model and those collected from various literatures (Biala, 2011; Andersen et al., 2011; Solomon et al., 2007; Bjarnadóttir et al., 2002).

Table 1. Data on waste operations managed in 2021.

No.	Operations condition	Quantity	Unit
1	Total managed waste	52762.20	Ton/year
2	Organic fraction of managed waste (87.25%)	46035.02	Ton/year
3	Total composted organic waste (0.72%)	329.28	Ton/year
4	Total organic waste piled up in landfills (99.28%)	163.56	Ton/year
5	Total premium/pertalite/pertamax fuel required for waste transport vehicles	348416	L/year
6	Total diesel fuel required for vehicles transporting waste to the landfill site	348416	L/year
7	Total fuel required for operation at the landfill site	55339	L/year
8	Electrical energy required for the operation of the composting facility	1200	Kwh
9	Total compost produced from composting facilities used by the agency	91.65	Ton/year
10	Total diesel fuel required for vehicles transporting organic waste to the composting facility	1808	L/year
11	Total fuel required for equipment operation at the composting facility	2635	L/year
12	Electrical energy needed for TPA and TPS operations	2200	Kwh

3. Results and Discussion

3.1 Scenario 1

There are two main ways composting can remove GHGs: i) GHG emissions from using fossil energy (eg electricity and diesel) for composting operations; and ii) GHG emissions from organic waste degradation (IPCC, 2006; Biala, 2011). GHG emissions from operational activities due to burning fossil fuels are calculated by the equation:

$$Emission_{operation} = \frac{Fuel(L)}{Waste(ton)} \, x \, energy(\frac{MJ}{L}) \, x \, EF\left(\frac{kgCO_2}{MJ}\right) \quad (1)$$

Where, EF represents the emission factor of fuel usage.

Based on Table 1, for 2021, the total consumption of fossil fuels (diesel) is 4443 Liters/year. The total amount of composted organic waste is 329.28 tons/year, the energy content of diesel fuel is 36.42 MJ/L, and the CO_2 emission factor for diesel is 0.074 kg CO_2/MJ). Therefore, the emission resulting from the use of diesel fuel during the composting operation for 2021 is 11974.24 kg CO_2. In addition, 1200 KWh is required in operation so that with an average emission factor of 0.794 kg CO_2/kWh (IPCC, 2006), the emissions released from the use of electrical energy for 2021 are 952.8 kg CO_2. The total emission contributed from the use of electric and solar energy for 2021 is 12927.04 kg CO_2.GHG emissions from waste degradation during composting are calculated by the following equation:

$$Emission_{degradation} = E_{CH_4} \, x \, GWP_{CH_4} + E_{N_2O} \, x \, GWP_{N_2O} \quad (2)$$

Where, *GWP* represents the global warming potential.

Basically, the degradation process of organic waste during composting is aerobic where most of the degraded organic carbon in the waste is converted into CO_2. CO_2 emissions are not taken into account in GHG calculations because they have a biogenic origin. However, in addition to CO_2, CH_4 and N_2O also have the potential to be produced from the degradation of organic matter by microbes. CH_4 can be formed due to the anaerobic degradation of waste in the deep layers of the compost heap. However, CH_4 is mostly oxidized in the aerobic part of the compost heap. Composting can also produce N_2O emissions in small concentrations. In this case, the IPCC tier 1 method provides an average default emission factor of 4 kg CH_4/ton of wet-based organic waste and 0.3 kg of N_2O/ton of wet-based organic waste to calculate GHG emissions from composting (IPCC, 2006). The global warming potential (GWP_{CH4}) CH_4 is 21 kg CO_2/kg CH_4 (Solomon et al., 2007) and the global warming potential of N_2O (GWP_{N2O}) is 310 kg CO_2/kg N2O (Solomon et al., 2007). Thus, the emission from the degradation of organic waste for 2021 is 58282.56 kg $CO_{2\text{-}e}$ and is increasing every year in line with the increase in the amount of organic waste that is composted. Total GHG emissions from composting are calculated by adding GHG emissions from operations and waste degradation. Therefore, the emission from composting is 72003.60 kg $CO_{2\text{-}e}$ per ton of composted organic waste for 2021.

The use of compost as a soil conditioning agent can also be considered as carbon sequestration because it is stable for a period of 100 to 1000 years (Biala, 2011). According to (Biala, 2011), it is estimated that between 9 and 14% of compost carbon is still bound and absorbed in the soil. Therefore, it can be credited as the avoidance of CO_2 emissions from composting. If the carbon content in compost (Cinput) and the fraction of carbon absorbed in the soil are expressed as C_{seq} (percentage to C_{input}), then CO_2 sequestration can be calculated by the following equation 3 (Biala, 2011):

$$CO_{2seq} = C_{input}\ x\ C_{seq}\ x\ {}^{44}\!/_{12} \tag{3}$$

Where, CO_{2seq} represents the CO_2 sequestration.

If the carbon content in the compost meets the minimum SNI 9.8% (BSN, 2004) and 8% (average value adopted from (Biala, 2011) of this carbon is absorbed in the soil, then the CO_2 sequestration can be calculated up to 7.84 kg CO_2 per tonne of compost. For 2021, the amount of compost produced is 92 tons. If all this compost produced is applied to the soil, then for this year the carbon avoidance from composting can reach 721.28 kg CO_2.

The use of compost can also supply at least some of the mineral nitrogen that would otherwise have to be provided through mineral fertilizers. Replacing the use of mineral fertilizers through the use of compost offers an opportunity to reduce GHG emissions caused by the manufacture and transport of fertilizers. To estimate the potential for GHG emission reductions, the typical nutrient content of the compost must be determined, as well as the GHG emission levels associated with the manufacture and transport of various fertilizers (Biala, 2011).

Based on the limited information available, it is assumed that the compost content complies with (BSN 2004) for 0.4% nitrogen, 0.1% phosphorus, and 0.2% potassium, respectively. Thus, in the 92 tons of compost produced for 2021, it contains 0.368 tons of nitrogen, 0.184 tons of phosphorus, and 0.092 tons of potassium. Furthermore, GHG emission factors equivalent to 3,500 kg CO_{2-e} per ton nitrogen, 350 kg CO_{2-e} per ton phosphorus, and 300 kg CO_{2-e} per ton potassium from their manufacture and transportation are used to estimate the potential GHG savings by replacing mineral fertilizers with nutrients supplied in the compost (Biala, 2011). As a result, if all the compost produced is applied, the avoided GHG emission for a period of 10 years is approximately 157800 kg CO_{2-e}. The GHG savings will be higher if the compost produced has a higher nutrient level.

To estimate CH_4 formation from landfill, many default values are required and the amount of methane production is highly dependent on the accuracy of these factors. A detailed explanation of the required default values is presented in Table 2 and the results of the estimated emissions are presented in Table 2.

Table 2**.** Required factors and default values for IPPC dump model applications.

Factor	Unit	Value Used
Degradable Organic Carbon (DOC)	DOC	0.2
DOC fraction that decomposes under Anaerobic conditions (DOC_f)	DOC_f	0.70
Methane generation rate constant	k	0.1
Half-life ($t_{1/2}$, years)	h=ln(2)/k	6.9
exp^1	exp(-k)	0.90
Process starts in year of decomposition, month (M)	M	13
exp^2	exp(-k*((13-M)/12))	1
Fraction to CH_4	F	0.50
Methane Oxidation in landfill cover	OX	The IPCC recommendation value for a sanitary landfill with a landfill cover is 0.1. for open dumps, the OX value will be zero
MCF for landfill/open dump	MCF	0.71

Source: (IPCC 2006)

The calculation results show that the remaining organic waste that is stockpiled in the TPA produces methane gas emissions of 122 Gg (2562 Gg CO_{2-e}) until 2064. This is obtained on the basis of calculations from landfills that have been carried out since 2021 and consider the age of the TPA to be 10 years. The increase in the number of emissions every year is in line with the projected increase in the amount of landfilled waste and the scope of waste management services and the phase after landfilling is no longer carried out.

In addition to GHG emissions from landfilled waste, GHG emissions are also contributed from the activities of transporting, organizing, and compacting waste to and at landfill sites as well. Based on Table 1, for 2021 the total consumption of fossil fuels (diesel) is 403,755 L/year. The total amount of landfilled waste is 52432.92 tons/year, the energy content of diesel fuel is 36.42 MJ/L, and the CO_2 emission factor for diesel is 0.074 kg CO_2/MJ. Therefore, the emission resulting from the use of diesel fuel during the composting operation is 1,088,152.03 kg CO_2. In addition, the operation also requires 2200 KWh so that with an average emission factor of 0.794 kg CO_2/kWh (IPCC 2006) (IPCC, 2006), the emission released from the use of electrical energy is 1746.8 kg CO_2. The total emission contributed from the use of electricity and solar energy for 2021 is

1,089,898.83 kgCO_2/ton of composted waste. Thus, the contribution and avoided emissions from activities in scenario 1 can be summarized as in Table 3.

Table 3. Emission Contribution from Scenario 1

No.	Activity	Subactivity	Emission (Gg CO_{2-e})
1	Centralized Composting	Emissions from Energy Usage	0.132
		Emissions from waste degradation during composting	6.687
2	Landfilling	Emissions from Energy Usage	11.148
		Emissions from waste degradation in landfills	2562.000
3	Avoiding Emissions from applying compost		0.158

3.2 Scenario 2

It is different from scenario 1. In this scenario, the amount of organic waste that is composted centrally is increased by 0.2% annually. Thus, the total GHG emissions from composting concentrated on waste degradation during composting is 9987890.00 kg CO_{2-e} for a period of 10 years (from 2021-2030). The total emission from energy use is 132218.11 CO_{2-e}. If all the compost produced is applied, the avoided GHG emission for a period of 10 years is around 252027 kg CO_{2-e}. The GHG savings will be higher if the compost produced has a higher nutrient level.

GHG emissions from the use of fossil energy (e.g. electricity and diesel) for the operation of centralized composting in this scenario are considered to be the same as those from scenario 1. However, the emissions from degradation during centralized composting are higher than in scenario 1. Centrally composted organic matter is slightly higher than in scenario 1.

Composting at the household level is managed by the owner of the garden or private house but in most cases, the control over the composting unit is very limited. No water is added to the unit during composting, as the input waste is already relatively wet. No electricity or fuel or materials are used during composting. Therefore, in general, the only contribution to the environmental burden of the house composting process is from gas emissions and through leachate production (Andersen et al., 2011). According to Andersen et al. (2011), GHG emission factors from composting range from 0.4 to 4.2 kg/Mg of wet waste for CH_4 and from 0.3 to 0.55 kg/Mg of wet waste for N_2O. Given the limitations of the data, in this study, the average values of these ranges were determined 2.3 kg/Mg for CH_4 and 0.425 for N_2O, respectively. The compost products produced from home composting range from 0.27 to 0.45 kg/kg of wet waste (Andersen et al., 2011). The average conversion of 36% was used for this process. Table 4 showed the results of the emission estimation.

Table 4. Emission Contribution from Scenario 2.

No.	Activity	Sub-activity	Emission (Gg CO_{2-e})
1	Centralized Composting	Emissions from Energy Usage	0.132
		Emissions from waste degradation during composting	9.988
2	Home composting	Emissions from Energy Usage	0
		Emissions from waste degradation during composting	0.529
3	Landfilling	Emissions from Energy Usage	11.139
		Emissions from waste degradation in landfills	5859
4	Avoidance of Emissions from the application of compost resulting from centralized composting		0.252
5	Avoiding Emissions from the application of compost produced from home composting		0.044

Thus, in the landfill age of 10 years, the contributed and avoided emissions from scenario 1 are as shown in the following table. As in scenario 1 the largest contribution (5859 Gg) comes from landfills. The emission avoidance obtained from the application of composting is around 0.252Gg from centralized composting and 0.044 Gg from home composting. Thus, the contribution of avoiding GHG emissions from composting is also very low. This is due to the fact that the amount of organic waste that is composted is still much lower than that which is stored in landfills. Therefore, in scenario 3, some of the GHG emissions from landfills will be burned openly.

3.3 Scenario 3

This scenario is in principle the same as scenario 2. However, landfill gas that is returned from landfills is collected through gas collectors. In this case the gas collector becomes part of the sanitary landfill facility that is installed and operated. Gas produced from landfilling can be directed to three treatment options: released directly into the atmosphere (without collecting energy), burned before being released (without collecting energy), and used to drive electricity generating machines (collection of electrical energy). In this scenario, landfill gas is burned without collecting the energy used. The calculations required are related to the volume of landfill gas produced, collection efficiency, and combustion efficiency. Uncollected landfill gas (methane) undergoes partial oxidation when it migrates to the top layer of the landfill. The oxidation factor is determined as the percentage removed from the component in the gas. The volume of gas generated, the efficiency of collection, the concentration of the material in the gas and the oxidation factor determine the remaining amount of pollutants emitted into the air.

$$EGL_p = \sum \left(LFgas_t \, x \, c_p \, x \, (100\% - coll.eff_t) \, x \, (100\% - ox.fact_p) \right) \quad (4)$$

Where, EGL_p represents the total pollutant emission p released directly into the atmosphere (g), c_p is the pollutant concentration p in landfill gas (g/Nm^3), LFgast is the landfill gas produced in period t (Nm^3), $coll.eff_t$ is the collection efficiency landfill gas in period t (%), $ox.fact_p$ is the pollutant oxidation factor p (%) and t is the landfill operating period.

In this study, the collection efficiency was determined to be 50%. As for the oxidation factor is set at 10% (IPCC 2006). As for the combustion efficiency, 100% is used, while the emission factors from burning landfill gas for CO, NOx, and SO_2 are 39.7, respectively; 162,931 per kg of landfill gas (Bjarnadóttir et al., 2002).

Based on data in scenario 2, emissions from waste degradation in landfills are 5859 Gg. If 50% that can be collected from the gas collection facility and then burned, then the avoided GHG emission from this system is 2929.5 Gg. Greater emission avoidance will be achieved if the collection efficiency is also greater. However, for operational cost savings, collection can be done between 2029 and 2041, when landfill gas is at its peak. The more profitable thing, of course, is to use landfill gas as fuel. However, the initial processing for its purification is quite expensive.

4. Conclusion

Three scenarios were developed to assess the potential for reducing GHG emissions from the management of the organic waste fraction in Singaraja City, Bali, Indonesia. The results show that composting does not contribute significantly to reducing GHG emissions. However, composting can reduce GHG if done massively while reducing the need for land for landfills. In all scenarios, the involvement of landfill gas burning in scenario 3 produces the least amount of GHG. Greater abatement contributions can be made if you can use them to replace fossil fuels.

Suggested future works include other waste conversion, exploring the use of waste to energy options, social acceptance, and attaching a costing framework to determine the specific cost of each options or to help achieving the sustainable municipal solid waste management.

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