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Greenhouse gas emissions from biogenic waste treatment: options and uncertainty

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Abstract A simplified life cycle assessment was conducted to estimate greenhouse gas (GHG) emissions and energy production from each component of biogenic waste treated in an open dumping site, and by composting, anaerobic digestion, and incineration employed with additional options. The impact of uncertainties and sensitivities of the parameters in the treatment methods were investigated. We conducted a sensitivity analysis to identify the most sensitive parameters, and we discussed the relationship between uncertainty and sensitivity. Our results revealed that the moisture content of food waste and the biomass-derived carbon and methane concentration of the landfill gas of biogenic waste subjected to open dumping are the most sensitive parameters across all the treatment methods. The net GHG emissions from food waste treated in an open dumping site ranged over ten times $(0.30 - 3.67$ Gg CO_2 eq/Gg). In addition, by employing additional options for the open dumping site, including soil cover, a landfill gas collection system, shifting to a semi-aerobic condition, and energy conservation by using a gas engine, we found that the net GHG emissions could be reduced by 10, 27.9, 37.4 %, and up to 56.7 %, respectively. Shifting to a semi-aerobic system is the most effective method for reducing GHG emissions, followed by landfill gas collection.

Keywords Biogenic waste treatment · Food waste · Greenhouse gas emissions · Uncertainty and sensitivity analysis

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Introduction

In Southeast Asian countries, municipal solid waste (MSW) is made up of 50–90 % biogenic waste [1–3], the composition of which varies depending on time and location [4]. Organic components disposed of in open dumping sites decay naturally. Carbon compounds are converted to large amounts of methane (CH_4) and carbon dioxide (CO_2), and nitrogen compounds are converted to smaller amounts of nitrous oxide (N_2O). These are known as greenhouse gases (GHGs) [5]. In the developing countries of Southeast Asia, open dumping is a common practice involving huge amounts of MSW, and recycling is carried out mainly by waste collectors [6]. Therefore, a large amount of CH_4 is emitted from solid waste disposal sites. The National Greenhouse Gas Inventory in Thailand and Vietnam estimated (in 2000) that CH_4 emissions (CO_2 eq) from solid waste disposal sites in the waste sector were 53 and 72 %, respectively [7, 8]. In Japan, advanced incineration technology aims at energy recovery, and organic waste reduction technology is predominantly employed; 3R policy ('Reduce, Reuse, Recycle') is an integral part of the entire waste management system [9]. In the European Union (EU), the direct disposal of biodegradable organic waste in landfills has been reduced, as laid out in Article 5 (1) of the Council Directive of 1999/31/EC, by means of promoting recycling, composting, biogas production, and material/energy recovery [10, 11]. As a result, in the 27 countries of the EU, the amount of waste disposed of in landfills has decreased from 288 kg/capita (in 2000) to 186 kg/capita (in 2010). In contrast, waste treated by incineration, recycling, composting, and anaerobic digestion has increased from 79, 78, and 55 kg/capita (in 2000) to 108, 121, and 72 kg/capita (in 2010), respectively [12].

We use a life cycle assessment (LCA) tool to evaluate the environmental impact of biogenic waste treatment and to quantify GHG emissions. However, the use of LCA is always problematic [13] because of the combined effects of different sources of uncertainties, including data variability, failures in measurements, incorrect estimations, and unrepresentative data and modeling assumptions [14]. Clavreul et al. [14] classified uncertainties based on the framework developed by Huijbregts [15] into the following categories: (1) model uncertainties refer to mathematical models chosen to quantify GHG emissions; (2) scenario uncertainties deal with the specific technology employed; and (3) parameter uncertainties include the variability of data collected. Sensitivity analysis is useful for estimating the effects of uncertainties in a LCA of a MSW management study [13]. However, only a few studies (25 % from 20 published peer-reviewed journals between 2002 and 2008) mentioned sensitivity analysis explicitly in their studies [16].

The purpose of this study was to clarify the impact of uncertainties and sensitivities when investigating an effective treatment method for biogenic waste with regard to GHG reduction and energy savings. When a life cycle approach is applied to biogenic waste treatment, we have to consider each treatment method and the various options it provides. It is meaningful to analyze the uncertainties and the sensitivities for each parameter. The effects of these parameters depend on the type of biogenic waste and the treatment method employed. Therefore, we also conducted a sensitivity analysis to identify the most sensitive parameters, and we discussed the relationship between uncertainty and sensitivity. The results are shown within a range to assess the variations in the uncertainties. Finally, we applied our model to a case study of biogenic waste treatment in Surabaya, Indonesia.

Materials and methods

Functional unit

"Treatment of 1 Gg-wet of each component of biogenic waste" is considered as a functional unit. The component of biogenic waste in this study consists of food, wood, paper, and natural textile fibers.

Biogenic waste composition

Table 1 lists the elemental composition [5, 17, 18] and lower heating value (LHV) of each biogenic waste type. Dry-base elemental compositions were converted into wet-base values. The moisture content of food waste, taken from the Guidelines for National Greenhouse Gas Inventories (IPCC) [5], is rather low, as it was measured before the waste enters the collection and treatment system.

Each biogenic waste type has a different amount of biomass-derived and fossil-derived carbon that leads to GHG emissions. Biomass-derived carbon is a source of CH_4 and CO_2 emissions when biodegraded under anaerobic conditions, while fossil-derived carbon forms CO_2 when incinerated. Only CO_2 emission derived from fossil-derived carbon is considered important, since biomass-derived carbon is thought to be carbon neutral. Nitrogen is also considered as a sensitive parameter, since it changes into N_2O during the biodegradation or wastewater treatment phase, in particular in anaerobic digestion plants. We estimated the LHV using proximate analysis by Bento's model [19] with the following equation:

$$LHV = (44.75 \times C_{comb} - 5.85 \times C_{moi} + 21.2) \times 4.19 \tag{1}$$

where LHV is the lower heating value (GJ/Gg), C_{comb} the combustible content (%-wet) and C_{moi} is the moisture content (%-wet).

System boundary and environmental impacts

The system boundary of waste treatment in this study comprised the process from when waste was delivered to the treatment facilities, through to final disposal. Waste collection is also an important process since it is connected to waste treatment. The impact of collection depends on the net distance, as determined by the amount of collected waste and the capacity of the truck. However, as it is a complicated process and its optimal structure is different

Table 1 Elemental composition of each biogenic waste type

	Unit	Food	Paper	Wood	Textile	Reference
Moisture	%-wet	60.0	10.0	15.0	20.0	[5]
Ash	%-wet	7.3	6.2	5.3	1.7	[17, 18][a]
Combustible	%-wet	32.7	83.8	79.7	78.3	[17, 18][a]
Biomass-derived carbon	%-wet	15.2	41.0	42.5	32.0	[5][a]
Fossil-derived carbon	%-wet	0.0	0.4	0.0	8.0	[5][a]
Nitrogen	%-wet	1.2	0.2	0.7	2.3	[17][a]
Lower heating value	GJ/Gg	4,742	15,551	14,652	14,267	Eq. 1

[a] Calculation

among different countries, it has not been included here. The system boundary of fossil-derived fuel consumed in waste treatment is considered to start from the extraction of the raw materials.

Global warming was considered as the environmental impact with CO_2, CH_4, and N_2O, as these are held to be the most important gases causing global warming. The global warming potential (GWP) 100-year value was used for characterization [20] and the amount of Net GHG emissions was estimated by Eq. 2. Net energy consumption was also considered as an indicator and estimated from Eq. 3.

$$GHG_{Net} = GHG_{Waste} + GHG_{Fuel} - GHG_{Avoid} \qquad (2)$$

where GHG_{net} is the net GHG emissions (Gg-CO_2 eq), GHG_{net} the net GHG emissions (Gg-CO_2 eq), GHG_{waste} the GHG emissions derived from waste decomposition (Gg-CO_2 eq), GHG_{Fuel} the GHG emissions derived from fossil fuel consumption (Gg-CO_2 eq), GHG_{Avoid} is the avoided GHG emissions attributed to the production of substitution (Gg-CO_2 eq).

$$E_{Net} = E_{Waste} + E_{Fuel} - E_{Avoid} \qquad (3)$$

where E_{Net} is the net energy consumption (GJ), E_{Waste} the LHV of the biogenic waste (GJ), E_{Fuel} the energy derived from fossil fuel consumption (GJ), E_{Avoid} is the avoided energy consumption derived from the production of substitution (GJ).

Compared treatment methods and applicable options

Open dumping, composting, incineration, and anaerobic digestion were considered as viable treatment methods for biogenic waste. Table 2 lists the employed treatment methods for each biogenic waste type. Open dumping can be regarded as the base scenario, since most Southeast Asian countries currently employ this as a MSW treatment method. Composting is a good recycling method for treating food waste; however, CH_4 and N_2O are emitted in this treatment process. Biogenic waste is not suitable for incineration because of its high moisture content, although this method does result in scarcely any CH_4 and N_2O

Table 2 Treatment methods employed for each biogenic waste type

Treatment method	Food	Paper	Wood	Textile
Open dumping	√	√	√	√
Composting	√	−	√	−
Incineration	√	√	√	√
Anaerobic digestion	√	√	√	−

√, employed; −, not employed

emissions. Incineration can be employed if biogenic waste is treated together with waste containing a high caloric value, such as plastic waste. Anaerobic digestion produces biogas and can be used for energy recovery by power generation with a gas engine. Many previous studies using life cycle analysis have reported the effects of anaerobic digestion on biogenic waste [21–23].

Each treatment method was considered as a separate entity, although there were some options that could be adapted to incorporate multi-treatment methods. For instance, an open dumping site might be able to provide a landfill gas collection cell. Table 3 shows the parameter lists of each treatment method and additional options used in this analysis. "Default" values are representative values used before uncertainty analysis while "Min" and "Max" values are the range caused by its uncertainties.

Modeling of each treatment method

Open dumping

CH_4 is the main source of GHG emissions owing to decomposition of the organic fraction of MSW. The equation provided in Ref. [5] was used to estimate GHG emissions from open dumping sites and CH_4 emissions were estimated by the first-order decay model (Eq. 4). The fraction of degradable organic carbon that can decompose (DOC_f) was assumed to be different for each biogenic waste type [5]. In this study, we assumed that there were no biogas collection cells or soil cover at dumping sites to estimate maximum GHG emissions. Soil cover, landfill gas collection, energy recovery, and the change to semi-aerobic conditions were regarded as additional options. Electricity and diesel consumption by heavy machinery used at the dumping sites was also considered [24].

The methodology for estimating N_2O emissions is not provided [5], since N_2O emission from landfill sites is considered to be insignificant compared to CH_4 emission. Therefore, N_2O emission from open dumping was not considered in this study.

$$EM_{CH_4} = (1 - OX) \times DOC_f \times MCF \times \sum (W_i \times DOC_i) \times F \times 16/12 \times GWP_{CH_4} \qquad (4)$$

where EM_{CH_4} is the amount of CH_4 emission, OX the oxidation factor, DOC_f the fraction of degradable organic carbon decomposed, MCF the CH_4 correction factor for aerobic decomposition, W_i the amount of biogenic waste type i, DOC_i the fraction of degradable organic carbon in waste type i, F the fraction of CH_4 in generated landfill gas, and GWP_{CH_4} is the global warming potential of CH_4.

Table 3 Parameter list of each treatment method with additional options and uncertainty ranges

Treatment methods	Parameters	Value			Unit	Sensitivity analysis	Reference and remarks	
		Min	Default	Max			"Default"	"Min" and "Max"
Process-specific parameters								
Open dumping	Electricity consumption	–	6.38	–	MWh/Gg	–	[24]	–
	Diesel consumption	–	0.763	–	kL/Gg	–	[24]	–
	CH$_4$ correction factor for aerobic decomposition in anaerobic condition	–	0.8	–	–	–	[5]	–
	Oxidation factor by no soil cover	–	0	–	–	–	[5]	–
	CH$_4$ concentration of landfill gas	50	50	55	%	√	[5]	[5]
	Fraction of degradable organic carbon decomposed							
	Food	–	38	–	%-dry	–	[5]	–
	Paper	–	46	–	%-dry	–	[5]	–
	Wood	–	50	–	%-dry	–	[5]	–
	Textile	–	50	–	%-dry	–	[5]	–
Composting	Electricity	–	50	–	MWh/Gg	–	[32]	–
	Diesel	–	0.30	–	kL/Gg	–	[23]	–
	CH$_4$ conversion rate	0.02	0.61	1.20	%	√	[5]	[5]
	N$_2$O conversion rate	1.59	7.16	12.73	%	√	[5]	[5]
Incineration	Electricity consumption	100	150	250	MWh/Gg	√	[23]	[33]
	Complete combustion rate	–	98.90	–	%		[28]	–
	Moisture content of residue	–	18.08	–	%		[18]	–
	CH$_4$ emission factor	–	0.2	–	kg-CH$_4$/Gg		[5]	–
	N$_2$O emission factor	–	47	–	kg-N$_2$O/Gg		[5]	–
Anaerobic digestion	Electricity consumption for digestion	321.75	357.50	393.25	MWh/Gg-TS	√	[23]	±10 %
	Electricity consumption for waste water treatment	29.29	32.54	35.79	MWh/Gg-waste water	√	[23]	±10 %
	Biodegradation rate							
	Food	76	84	92	%	√	[23]	±10 %
	Paper	59	66	73	%	√	[23]	±10 %
	Wood	54	60	66	%	√	[23]	±10 %
	Moisture content of residue	–	60	–	%		[23]	–
	CH$_4$ concentration of biogas	54	60	66	%	√	[23]	±10 %
	The efficiency of gas engine	30	37	40	%	√	[23]	Assumption
	CH$_4$ emission factor from wastewater treatment	–	5.9	–	g-CH$_4$/m^3		[23]	–
	N$_2$O emission factor from wastewater treatment	–	4.5	–	g-N$_2$O/m^3		[23]	–

Table 3 continued

Treatment methods	Parameters	Value			Unit	Sensitivity analysis	Reference and remarks	
		Min	Default	Max			"Default"	"Min" and "Max"
Parameters of applicable options								
Open dumping	Oxidation factor by soil cover	–	0.1	–	–		[5]	–
	Landfill gas collection rate	10	20	80	%	√	[5]	[27]
	The efficiency of gas engine	30	37	40	%	√	[23]	Assumption
	CH$_4$ correction factor for aerobic decomposition in semi-aerobic condition	–	0.8	–	–		[5]	–
Incineration	The efficiency of steam turbine	5	10	15	%	√	[28]	±10 %
Commonly used parameters								
Elemental composition	*Moisture content*							
	Food	50	60	90	%	√	[5]	[5]
	Paper	5	10	15	%	√	[5]	[5]
	Wood	7.5	15	22.5	%	√	[5]	[5]
	Natural textile fibers	10	20	30	%	√	[5]	[5]
	Biomass-derived carbon							
	Food	20	38	50	%-dry	√	[5]	[5]
	Paper	42	46	50	%-dry	√	[5]	[5]
	Wood	46	50	54	%-dry	√	[5]	[5]
	Natural textile fibers	25	50	50	%-dry	√	[5]	[5]
Energy conversion factor	Conversion factor for primary energy	–	9.36	–	GJ/MWh		[34]	–
	Conversion factor for secondary energy	–	3.6	–	GJ/MWh		[34]	–
Global warming potential	GWP$_{CH_4}$	–	25	–			[20]	–
	GWP$_{N_2O}$	–	298	–			[20]	–

√, parameter used in sensitivity analysis

Composting

Electricity and diesel consumption in the composting facility and production of CH_4 and N_2O by biodegradation were considered. Some amounts of CH_4 and N_2O are thought to be emitted in the composting process under aerobic conditions. To reflect the differences of biodegradable carbon and nitrogen content in each biogenic waste type, conversion rates were calculated based on the emission factors of CH_4 and N_2O per dry weight of waste as reported [5].

GHG emissions from chemical fertilizer production were counted as avoided GHG emissions since produced organic fertilizer was assumed to substitute for it. Both organic and chemical fertilizers emit N_2O during their land use process. However, GHG emissions from land use was not considered since Japan Ministry of the Environment [25] reported that there is no statistical evidence that emission factors are different between organic and chemical fertilizers.

Incineration

A situation in which biogenic waste is collected and incinerated separately is not thought to be realistic. It is more natural to assume that biogenic waste is incinerated together with other MSW fractions. Therefore, it should be noted that GHGs derived from other MSW contents such as plastics may be emitted.

Electricity use was included in the energy consumption considerations. An electricity production facility was regarded as viable option in this case. CH_4 and N_2O emissions from waste combustion were also considered and the residue after incineration was assumed to be treated in a dumping site.

Anaerobic digestion

For this treatment method we assumed that the produced biogas was used for energy recovery. It was also assumed that biodegradation rates were different among biogenic waste types. The biodegradation rates of food, paper and wood waste were assumed to be 84, 66 and 60 %, respectively [26].

Electricity consumption in anaerobic digestion was divided into consumption in the digestion process and that in the wastewater treatment process. Electricity consumption in the digestion process was assumed to be proportional to the amount of total solid fraction, while electricity consumption in the wastewater treatment process was assumed to be proportional to the amount of wastewater generated. One of the problems with anaerobic digestion is that the wastewater treatment step needs to be tightly controlled. NH_3 concentration during digestion is a key parameter, because it counteracts the digestion of organic

content. Therefore, the amounts of digestive fluid and wastewater were determined to keep the NH_3 concentration under 2,500 ppm. The amount of NH_3 was estimated using the nitrogen content in each biogenic waste type and CH_4 and N_2O emissions from wastewater were also considered.

The CH_4 concentration in produced biogas was assumed to be 60 % as a default value and this biogas was used for electricity production with a gas engine at 37 % efficiency [23].

Applicable options

Soil cover

The oxidation factor (OX) in Eq. 4 reflects the amount of CH_4 from a landfill site that is oxidized by methanotrophic microorganisms in the soil cover. A value of 0.1 for OX is justified for covered, well-managed disposal sites, while the default value is zero [5].

Landfill gas collection

Adopting a biogas collection cell reduces CH_4 emissions. Collected landfill gases were assumed to be combustible. The landfill gas collection rate depends on the capacity of the utilization facility. It is estimated that a 20 % recovery efficiency is achieved [5].

Energy recovery facility

In open dumping sites with a landfill gas collection cell, energy recovery is possible. In this study landfill gases were combusted in a gas engine and the produced electricity was used as recovered energy. Landfill gases can only be used in a gas engine after moisture and H_2S are removed.

The model incineration plant was assumed to include a steam turbine to produce electricity from waste energy.

Shift to semi-aerobic condition

Semi-aerobic sites are managed passively to introduce air to the waste layer to create a semi-aerobic environment within landfill sites [5]. The CH_4 correction factor for aerobic decomposition (MCF) in Eq. 4 is reduced to 0.5 from 0.8 in unmanaged open dumping sites.

Sensitivity analysis

Parameters that have a significant effect on the estimated result, such as moisture content in waste, should be

determined carefully. It is meaningful to know the degree of sensitivity that each parameter has. Therefore, increase–decrease rate (I–D Rate$_i$) was defined by the following equation (Eq. 5):

$$I{-}D \text{ Rate}_i = (\text{GHG}_{\text{Net},10\%} - \text{GHG}_{\text{Net,Def}})/(P_{i,10\%} - P_{i,\text{Def}}) \qquad (5)$$

where I–D Rate$_i$ is the increase–decrease rate of parameter i (%), $\text{GHG}_{\text{Net},10\%}$ the net GHG emissions by using increased parameter i (Gg-CO_2 eq), $\text{GHG}_{\text{Net,Def}}$ the net GHG emissions by using default parameter i (Gg-CO_2 eq), $P_{i,10\%}$ the increased parameter i by 10 %, and $P_{i,\text{Def}}$ is the default parameter i.

The considered parameters are listed in Table 3.

Uncertainty analysis

Some parameters include uncertainties that come from waste compositions and/or treated conditions. The effects caused by these uncertainties should be considered since it is difficult to exclude them completely and choose a representative value. Therefore, the uncertainties in some parameters are given as "Min" and "Max" ranges, as shown in Table 3 along with their estimated results.

Uncertainty parameters

Moisture content and biomass-based carbon content of biogenic waste

The range of 50 % against default values was set for moisture content. However, only food waste was between 50 and 90 % since food waste is a wet biomass. The moisture content of food waste fluctuates because of both moisture transfer between coexisting wastes and weather conditions [5]. Higher moisture content means a lower LHV of waste and a small amount of dry organic fraction. The former effects energy recovery during incineration, and the latter effects CH_4 emission in open dumping sites.

The range of biomass-based carbon contents as reported in Ref. [5] was used. This parameter affects the amount of CH_4 generated from open dumping, composting and anaerobic digestion.

CH_4 concentration of landfill gas and biogas

The range of landfill gas was set at 50–55 % [5]. Compared with biogas produced by anaerobic digestion, the mechanism is complicated and the amount of generated CH_4 is a significant parameter. Therefore, the range of 10 % against default values was set for CH_4 concentrations in biogas.

Landfill gas collection rate

Landfill gas collection rate depends on the capacity of collection equipment and 10–80 % was used, as suggested by Oonk and Boom [27].

CH_4 conversion rate and N_2O conversion rate in composting process

Conversion rates from carbon to CH_4, and from nitrogen to N_2O were set at 0.02–1.20 and 1.59–12.7 %, respectively. CH_4 and N_2O emission units have uncertainty ranges depending on waste composition: 0.08–20 g-CH_4/kg-waste and 0.2–1.6 g-N_2O/kg-waste (both dry weight) [5].

Energy consumption in incineration plant

Energy consumption in an incineration facility differs according to its treatment capacity, treated waste composition, and incineration method. The energy consumption unit was set in the range of 100–250 kWh/t-waste [23].

The efficiency of electricity production

The efficiencies of steam turbines and gas engines were set to 5–15 % [28] and 30–40 % [23], respectively.

Biodegradation rate of each biogenic waste fraction

The biodegradation rate depends on the biogenic waste type and the range of 10 % against default values was set. The biodegradation rate is a significant parameter, since the amount of biogas produced was estimated by this parameter.

Relationship between sensitivity and uncertainty

Equation 5 is applied when the estimation formula is assumed to be a linear model. The relationship between sensitivity and uncertainty is illustrated in Fig. 1. Here, I–D Rate$_i$ is the slope of a straight line and parameter i is sensitive when the slope is steep. The range of parameter i on the x-axis is the uncertainty range. Therefore, even if the sensitivity is low, the range of net GHG emissions is large when the range of parameter i uncertainties are wide, and the reverse is equally true. Both sensitivity and uncertainty are equally important.

Results and discussion

Sensitivity analysis

The I–D Rate$_i$ results shown in Table 4 indicate the sensitivity of parameter i for each treatment method. A positive
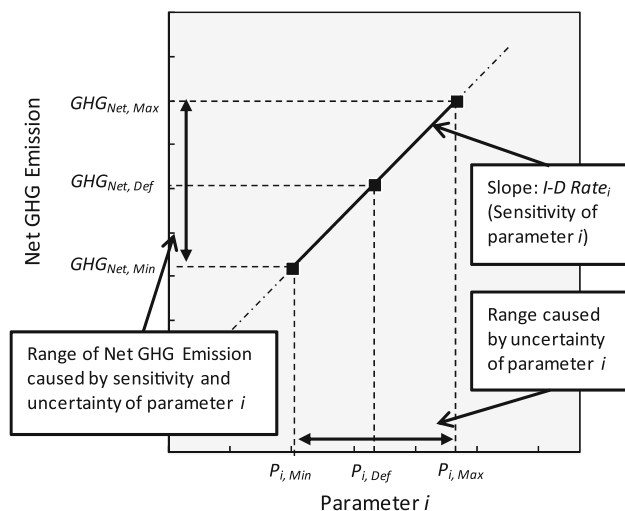
Fig. 1 Net GHG emissions of each biogenic waste type (composting of paper and textile, anaerobic digestion of textile were excluded)

value means an increase of net GHG, while a negative one means a decrease when parameter i is increased. The sensitivities of food waste across all treatment methods appear lower than that of the other biogenic wastes, apart from moisture content. This result implied that moisture content indirectly affects the other parameters. Another sensitive parameter is the biomass-based carbon content in open dumping. These parameters should be carefully considered

when estimating GHG amounts. CH_4 concentration of landfill gas, landfill gas collection rate, CH_4 concentration of biogas and gas engine efficiency were also comparatively sensitive. N_2O conversion rate and steam turbine efficiencies were found to be less sensitive.

The correlation between moisture content, food waste volatile solids (VS) and net GHG emissions is shown in Fig. 2a, b. In this figure, only the default options were considered. Higher moisture content seems to have a negative effect on net GHG emissions in open dumping and anaerobic digestion, however, as shown in Fig. 2b, GHG emissions do not depend on moisture content but rather on VS.

Uncertainty analysis

Figures 3 and 4 show the results of net GHG emissions and net energy consumption with uncertainty ranges. Although the values were different for each biogenic waste type, the overall trends were similar. The range of net GHG emissions for open dumping, for example with food waste (0.30–3.67 Gg-CO_2 eq/Gg), was over ten times greater compared to others. This is because every parameter showed comparatively high sensitivities compared to those in other treatment methods. The emission factor of N_2O in composting had a higher sensitivity than that of CH_4 although the former had a narrower range than the latter. As a result, the N_2O emission factor had a greater effect on

Table 4 Sensitivity analysis, $I\text{-}D$ Rate$_i$ results

| Treatment methods	Parameters	Food	Paper	Wood	Textile
Open dumping	Moisture content of waste	−3.04	−0.61	−1.00	−1.07
	Biomass-based carbon content of waste	2.03	5.46	5.67	4.27
	CH_4 concentration of landfill gas	2.03	5.46	5.67	4.27
	Landfill gas collection rate	−0.43	−1.15	−1.20	−0.90
	The efficiency of gas engine	−0.06	−0.17	−0.18	−0.13
Composting	Moisture content of waste	−0.05	–	−0.02	–
	Biomass-based carbon content of waste	0.03	–	0.09	–
	CH_4 conversion rate	0.03	–	0.09	–
	N_2O conversion rate	0.41	–	0.24	–
Incineration	Moisture content of waste	−0.03	−0.01	−0.01	−0.08
	Biomass-based carbon content of waste	0.02	0.08	0.06	0.34
	Electricity consumption	0.13	0.13	0.13	0.13
	The efficiency of steam turbine	−0.17	−0.54	−0.51	−0.50
Anaerobic digestion	Moisture content of waste	0.49	0.08	0.11	–
	Biomass-based carbon content of waste	−0.44	−0.94	−0.89	–
	Biodegradation rate	−0.43	−0.92	−0.87	–
	CH_4 concentration of biogas	−0.44	−0.94	−0.89	–
	Electricity consumption for digestion	0.12	0.27	0.26	–
	Electricity consumption for wastewater treatment	0.09	0.00	0.04	–
	The efficiency of gas engine	−0.44	−0.94	−0.89	–
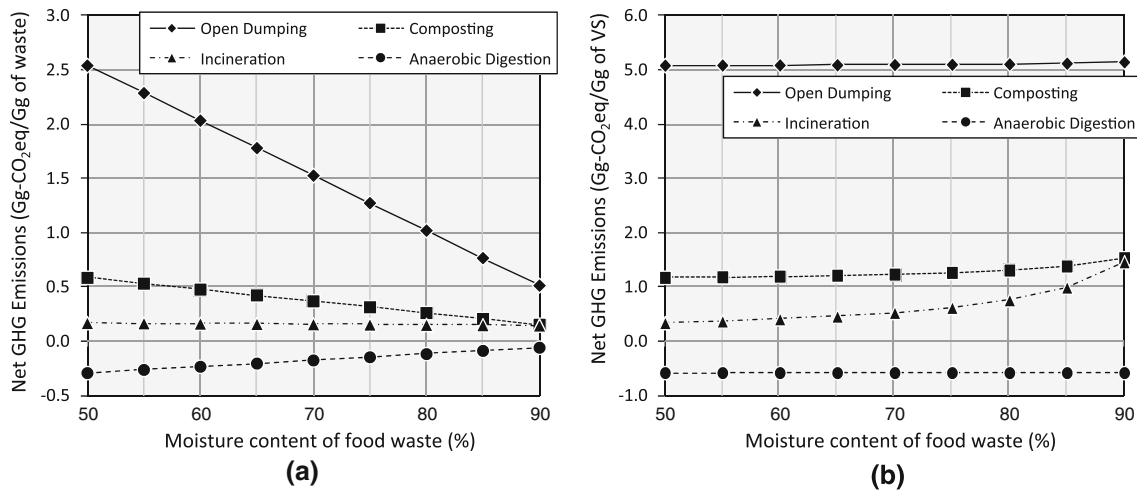
Fig. 2 Net energy consumption of each biogenic waste type (composting of paper and textile, anaerobic digestion of textile were excluded)
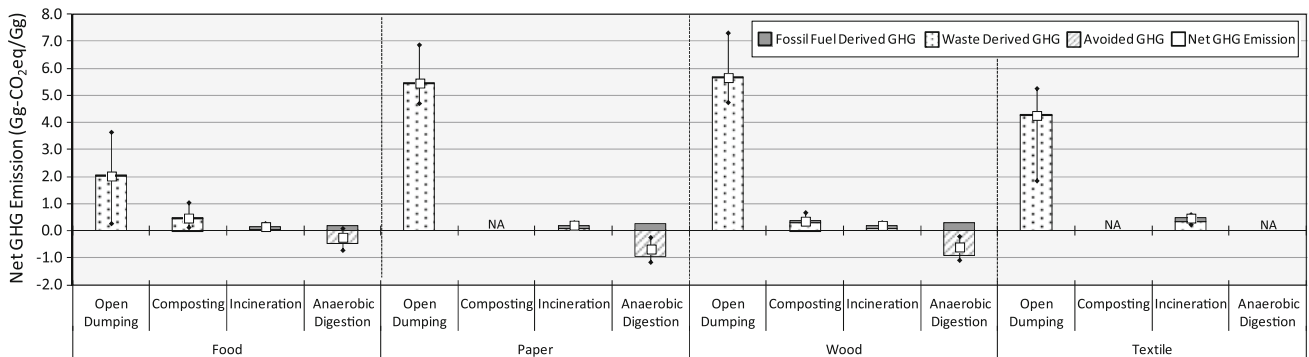

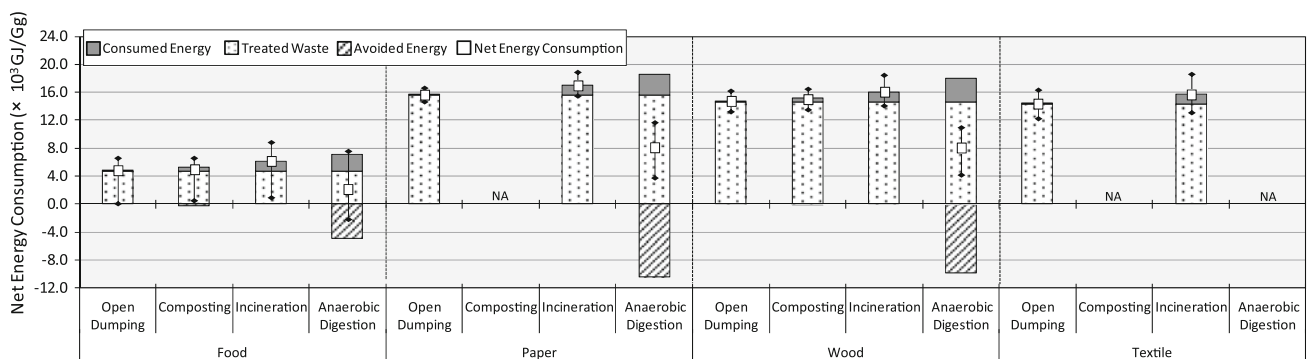Fig. 3 Net GHG emissions for each biogenic waste type (Gg-CO$_2$ eq/Gg)

Fig. 4 Net energy consumption for each biogenic waste type ($\times 10^3$ GJ/Gg)

net GHG emissions than CH$_4$ emissions. Therefore, it was implied that the behavior of nitrogen might be more important than that of other elements in estimating the amount of GHG emissions in composting. The range of net GHG emissions for incineration is narrow. This is because GHG emissions derived from fossil fuel consumption were

dominant and depended on the amount of treated waste. The range of net GHG emissions for anaerobic digestion was determined by the range of avoided GHG emissions. The sensitivity of biomass-based carbon content, biodegradation rate, CH$_4$ concentration rate and the efficiency of the gas engine are shown in Table 4.
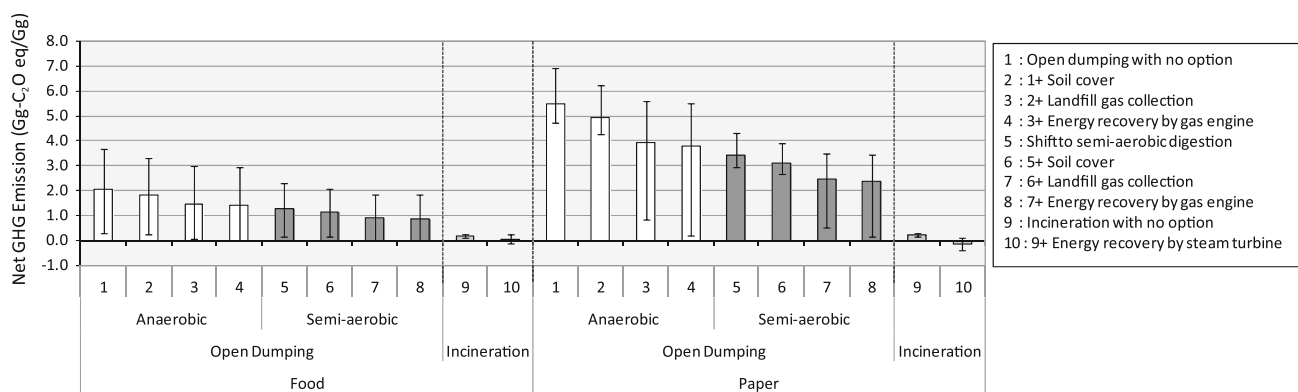
Fig. 5 Correlation between moisture content of food waste and net GHG emissions

Applicable options

Figure 5 shows the result of net GHG emission treatment methods with additional options. The results of wood and textile are similar to that of paper waste. Soil cover reduces net GHG emissions by 10 %, and landfill gas collection reduces GHG emissions by a further 17.9 %. Semi-aerobic (passive) landfill condition controls, such as the Fukuoka method [29], significantly reduce GHG (37.4 %). Well-managed open dumping sites with all additional options reduce net GHG emissions by 56.7 %. The ranges of every applicable option were wide since open dumping with no options already includes the uncertainties and sensitivities as shown in Fig. 3 and Table 4. Net GHG emissions of incineration with energy recovery were estimated to be −0.41 to 0.13 $Gg-CO_2$ eq/Gg for paper.

It could be said that the uncertainties for each biogenic waste type were not large enough to change the ranking among treatment methods with regard to net GHG emissions. Since most South Asian countries currently employ open dumping, the GHG reduction effect by alternative treatments compared to open dumping is important. It should be noted that we have to take care not to underestimate or overestimate the net GHG emissions in open dumping since this includes significant uncertainties.

With regard to net energy consumption, every treatment method had a wide range. This implies that sensitivity for not only net GHG emissions but also the net energy consumption has to be considered.

Case study in Surabaya, Indonesia

As a case study, net GHG emissions in Surabaya, Indonesia [area 330 km^2, population 2.8 million (2010)] for different treatment methods were compared. The estimated amount of MSW generated is 438 Gg/year [30], and the amount of biogenic waste is 318 Gg/year (72.7 %) [31]. The treatment of the amount of biogenic waste in MSW in Surabaya

Table 5 Biogenic waste treated in Surabaya, Indonesia

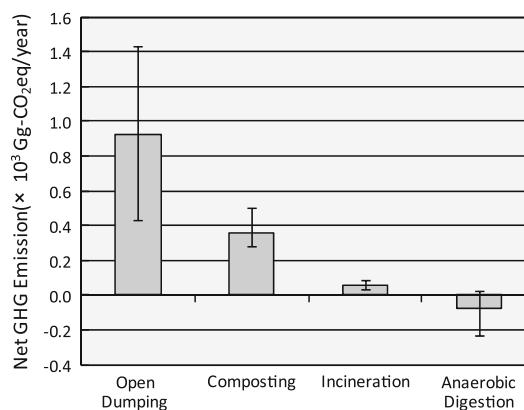|	Waste generation	
	Gg/year	%
Biogenic total	318.3	100.0
Food	238.5	74.9
Paper	38.0	11.9
Wood	36.6	11.5
Natural textile fibers	5.3	1.7

Fig. 6 Result of net GHG emissions and net energy consumption for case study in Surabaya, Indonesia

was considered as the functional unit. Food waste accounted for 74.9 % of the biogenic waste (Table 5).

Figure 6 shows the results with ranges for the case study. Net GHG emissions from open dumping, which is currently the dominant method employed in Surabaya, were estimated to be approximately 472–1,435 $Gg-CO_2$ eq/year (1.35–4.51 $Gg-CO_2$ eq/Gg of biogenic waste), a threefold difference between the minimum and maximum values. A maximum 828 $Gg-CO_2$ eq/year (57 %) reduction of the net GHG emissions is achieved by implementing the options, even if immediate avoidance of open dumping was

impossible to achieve. When the biogenic waste was treated by composting, 35.1–64.7 % of the net GHG emissions were reduced. In the case of incineration, the amount of net GHG emissions was estimated to be between 37 and 88 Gg-CO_2 eq/year. Anaerobic digestion could potentially reduce the GHG by 231 Gg-CO_2 eq/year.

Conclusion

We clarified the impacts caused by uncertainties and sensitivities when investigating effective treatment methods of biogenic waste with regard to GHG reduction and energy savings. The conclusions from this study are as follows:

- The most sensitive parameters were the moisture content of only food waste and biomass-based carbon content in waste for open dumping. These parameters should be considered carefully when estimating the amount of GHG.
- The uncertainties for each biogenic waste type were not large enough to alter the ranking among treatment methods with regard to net GHG emissions. However, underestimation or overestimation of the net GHG emissions in open dumping should be avoided as the range of net GHG emissions for open dumping is larger. For instance, the range for food waste is 0.30–3.67 Gg-CO_2 eq/Gg.
- By employing additional options, GHG emissions of open dumping are reduced by a maximum of 57 %. Shifting to semi-aerobic (passive) landfill sites was the most effective method, followed by landfill gas collection. Some options could also have a beneficial effect on reducing large amounts of GHG from open dumping sites, even though immediate avoidance might be difficult.

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