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Manuscript ID: IJROWA-2111-1379

Manuscript Title: **Performance of Takakura Composting Method in the Decentralised Composting Centre and its Comparative Study on Environmental and Economic Impacts in Bandung City, Indonesia**

Date: 2021-11-28

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MANUSCRIPT DETAILS

TITLE: **Performance of Takakura Composting Method in the Decentralised Composting Centre and its Comparative Study on Environmental and Economic Impacts in Bandung City, Indonesia**

ABSTRACT:

Purpose Takakura Composting Method (TCM) is a simple and cost-effective aerobic composting method using locally available materials and has been widely introduced in Indonesia and other countries. This study tracked the progress of scaling the TCM up to 1 tonne/day at the decentralised composting centre in Bandung City, Indonesia.

Methods A comparative study using a combination of the Life Cycle Assessment (LCA) and Cost-Benefit Analysis (CBA) was performed to compare the net greenhouse gas (GHG) emissions and Net Present Value (NPV) of six different municipal solid waste treatment scenarios to treat 1 tonne of food waste. The impacts were also assessed between different system boundaries with or without compost use, and by applying different emission factors for composting to the static windrow and TCM.

Results Home composting showed the least GHG emissions and highest NPV, and is thus suggested to be the most favourable option. The least favourable options were either landfilling that showed the highest GHG emissions, or incineration that showed the lowest NPV. The expanded system boundary that included compost use revealed higher emissions and was more costly compared to the core system boundary that did not include compost use. The difference in net GHG emissions between the static windrow and TCM at the decentralised composting centre was limited due to a large amount of avoided emissions from landfilling and transportation.

Conclusion This study proved that TCM can potentially contribute to the reduction of GHG emissions and would be a cost-effective tool for municipal solid waste management.

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Manuscript ID: IJROWA-2111-1379

Manuscript Title: **Performance of Takakura Composting Method in the Decentralised Composting Centre and its Comparative Study on Environmental and Economic Impacts in Bandung City, Indonesia**

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Reviewer’s comments:

Abstract: give some numerical results

Introduction: very good justification

Method: Good description. All assumptions and system boundary are clearly detailed

Results: comprehensive discussion

Conclusion: if possible, shorten the paragraph

Reference list: Relevant but write all author names do not use et al style.

HASIL REVIEW

Responses to reviewers

The responses to reviewers are described in blue text below each relevant comment that suggested changes.

Reviewer 1:

the manuscript is discussing cost-effective aerobic composting method for solid waster treatment. The manuscript is complete, however, some point here that could improve to manuscript:

1. The mass-balance of the waste should be added to let us know more detail about the process balance. Not all system, but one or two examples are enough

>The mass-balance for 1 tonne of solid waste under the condition of source separation and introduction of TCM at the studied site was described both in text and figure (newly added Figure 1).

2. Characteristic of the feed should be described or evaluated more detail. This will be important to know the possible product that could be produced.

>Waste composition of the feed for composting as well as other waste that are carried to the landfill was described together with the above description on the mass-balance.

Other than that, In my opinion, this is an excellent contribution.

Reviewer 2: (Sugeng Triyono)

Abstract: give some numerical results

>The abstract was revised by incorporating the numerical results and adjusted to be less than 250 words (as indicated in the guide for authors).

Introduction: very good background and justification

Method: Good description.   All assumptions and system boundary are clearly detailed

Results: comprehensive discussion

Conclusion: if possible, shorten the paragraph

>The conclusion section was revised and shortened

Reference list: references are relevant but write all author names do not use et al style.

>The citation setting of *et al.* in the bibliography was changed in Mendeley (Harvard reference format). Now all authors' names are shown in the bibliography.

Performance of Takakura Composting Method in the Decentralised Composting Centre and its Comparative Study on Environmental and Economic Impacts in Bandung City, Indonesia

Abstract

Purpose Takakura Composting Method (TCM) is a simple and cost-effective aerobic composting method using locally available materials and has been widely introduced in Indonesia and other countries. This study tracked the progress of scaling the TCM up to 1 tonne/day of organic waste input at the decentralised composting centre in Bandung City, Indonesia. A comparative study to assess the environmental and economic impacts was conducted by using its performance data.

Methods A combination of Life Cycle Assessment (LCA) and Cost-Benefit Analysis (CBA) were performed to compare the net greenhouse gas (GHG) emissions and Net Present Value (NPV) of six different municipal solid waste treatment scenarios to treat 1 tonne of food waste. The impacts were also assessed between different system boundaries with or without compost use, and by applying different emission factors for composting to the static windrow and TCM.

Results Home composting showed the least GHG emissions (-601 kg CO_2-eq/t) and highest NPV (IDR 518,790/tonne) and is thus suggested to be the most favourable option. While the least favourable options were either landfilling that showed the highest GHG emissions (628 kg CO_2-eq/t), or incineration that showed the lowest NPV (IDR -818,373/tonne).

Conclusion As the home composting was not considered to be a realistic option for wide application, a combination of one large centralised composting centre and a small decentralised composting centre in each sub-district was suggested in the case of Bandung City.

Keywords:
Municipal solid waste management, Life cycle assessment, Cost-benefit analysis, Composting, Takakura composting method

Introduction

Southeast Asia is a rapidly growing economy, with a population that has been steadily increasing and is projected to continue increasing toward 2050. More than half the population in this region reside in urban areas. Indonesia is the largest country in the region by population and generates the largest amount of waste (64,000,000 tonnes per year as of 2016) (UNEP, 2017). The main method of final disposal in Indonesia has been landfilling. Due to environmental and sanitation issues as well as difficulty in acquiring sites for landfills, the government of Indonesia issued Act No. 18/2008 which mandated all local governments to stop open dumping and follow the technical and environmental requirements of the landfill by 2013. However, most landfills were still operating as open dumpsites as of 2019 (Emalya et al., 2020; Sutra et al., 2020). A high proportion of food waste (60%)(UNEP, 2017) at open dumpsites generate CH_4 emissions under anaerobic conditions, making landfills the largest greenhouse gas (GHG) emission source in the waste sector (Bogner et al., 2007).

As an alternative method for final disposal, the government issued Presidential Regulation No. 35/2018 (which replaced Presidential Regulation No. 18/2016) to accelerate the development of waste-to-energy projects, selecting 12 candidate cities in Indonesia as model cases to lead other cities. Bandung City, the capital city of West Java Province, is the fourth largest city in Indonesia by population and is one of the target cities of Presidential Regulation No. 35/2018. The current landfill site (Tempat Pembuangan Akhir, TPA) for Bandung City is the TPA Sarimukti which is the regional site for West Java Province, accepting municipal solid waste from cities and regencies within the province. It is located to the north-west of Bandung, approximately 50 km away from the city centre (approx. 100 km per round trip) and it is estimated to be full by 2023. West Java Province is thus currently constructing an alternative regional landfill in Legok Nangka to the south-east of Bandung, at a similar distance from the city centre. It plans to introduce an incineration facility with energy recovery to generate electricity aside from the landfill in response to Presidential Regulation No. 35/2018 (Agunan, 2019).

Incineration with energy recovery helps to reduce the volume of waste and thus prolongs the lifespan of landfills as well as provides a substitute to fossil fuel for generating power (Kamuk and Haukohl, 2013). However, in general, to maintain stable combustion of waste at high temperatures and ensure efficient energy recovery as well as to reduce the generation of toxic dioxins, the lower heating value (LHV) of waste must not fall below 6 MJ/kg, which is often difficult in many low-mid income countries where there is a proportion of organic waste (Chen and Christensen, 2010; Kamuk and Haukohl, 2013). A study that analysed the waste composition in Bandung City revealed that LHV of waste without any treatment was 3.15 MJ/kg and did not satisfy sufficient calories for incineration (Anggoro et al., 2017). Shifting from landfilling to incineration also increases waste management costs and becomes a financial burden to local governments. The typical waste management cost of open dumping is USD 3–10/tonne of waste in lower-middle-income countries while that of waste-to-energy incineration in high-income countries would be in the magnitude of USD 40–200/tonne of waste (The World Bank Group, 2018). The government of Indonesia is intending to cover the increased cost by a Power Purchase Agreement with the national electric company on feed-in tariffs and by waste tipping fees (gate fees) of up to Indonesian Rupiahs (IDR) 500,000/tonne of waste (approximately USD 36/tonne of waste from USD/IDR rate of 14,000) with a contribution from the central government (Government of Indonesia, 2018). According to the Department of Environment and Hygiene (DLHK) of Bandung City, the waste tipping fee at the landfill in Legok Nangka is expected to be IDR 386,000 upon application of government subsidy. However, this is about six-folds higher than the waste tipping fee at the current landfill, TPA Sarimukti (IDR 65,000/tonne of waste as of July 2020). These costs are therefore likely to become a huge problem for local governments in the West Java Province including Bandung City.

To tackle waste issues, the government of Indonesia has also set a target to achieve a 30% reduction of solid waste and ensure that 70% of waste is properly handled by 2025 in Presidential Regulation No. 97/2017 on National Strategy and Policy on Solid Waste Management (*Jakstranas*). To achieve these targets, all local governments including Bandung City were mandated to develop and implement a local strategy on solid waste management (*Jakstrada*) in line with the *Jakstranas*. In light of this, Bandung issued the Mayor's Regulation No.1426/2018 concerning Regional Policies and Strategies in the Management of Household Waste and Types of Household Waste as the city's *Jakstrada* in 2018 (Bandung City Government, 2018). The city also placed solid waste management as one of the top priority policies in its Regional Medium Term Development Plan (RPJMD) 2018-2023 (Bandung City Government, 2019a). Based on these policies and strategic directions, the city identified the promotion of source separation of waste and composting of organic waste, which makes up more than half of all municipal waste, as a core strategy in the Waste Management Action Plan 2019-2023 of Bandung City (Bandung City Government, 2019b).

From past studies, composting has proved to be a cost-effective method in reducing and recycling municipal solid waste and reducing environmental impacts in various regions (C. P. Bong et al., 2017; Jara-Samaniego et al., 2017; Mu et al., 2016; Seng et al., 2013). Reducing organic waste helps to lower GHG emissions and also leads to a reduction in the use of auxiliary fuel for incineration (Kamuk and Haukohl, 2013; Yang et al., 2012a). Composting itself is a biological degradation process and is a source of GHG emissions. These emissions can be offset or could turn into net reductions, depending on management and treatment across their entire lifecycle (Sánchez et al., 2015). Among various composting methods, Bandung City identified the Takakura Composting Method (TCM) as the most appropriate technology for their pilot project, based on experiences in other cities in Indonesia. TCM is a simple and cost-effective aerobic composting method using locally available materials such as fermentation foods. It was developed and introduced in Surabaya City in 2004 and contributed to a 30% reduction of waste disposed in landfills – from 1,500 tonnes/day in 2004 to 1,000 tonnes/day in 2009 – through various waste reduction and recycling efforts including composting centres and home composting baskets (this is generally called the Takakura Home Composting method). The method was gradually expanded to other cities in Indonesia and other countries (Kurniawan and Puppim de Oliveira, 2014; Maeda, 2009; Nuzir et al., 2019).

This study tracked the performance of TCM at a decentralised composting centre in Bandung City for one full year from launch to full-scale operation (capacity: 1 tonne/day) as one of the pilot projects toward achieving the city's waste reduction target. The term 'decentralised' was used to illustrate the intended functionality of such a small scale composting centre which treats organic waste collected from nearby communities in a dispersed manner throughout the city. It is differentiated from 'on-site' treatment which refers to independent home composting at individual households and/or communal composting by neighbourhoods, as well as being different from a 'centralised' composting centre which covers a wider collection area and has a larger processing capacity. Based on the actual case studies of TCM at different scales, a comparative study was undertaken using Life Cycle Assessment (LCA) and Cost-Benefit Analysis (CBA) in combination.

The objectives of this study were to provide a better understanding and insights on the environmental and economic impacts of introducing TCM at different scales for decision-making by policymakers and practitioners. Although TCM has been introduced and practised in many cities in Indonesia and other countries for more than 1.5 decades, to the best of our knowledge, there is a lack of performance data on small-scale composting centres (capacity of approximately 1-2 tonne/day) and up to now, LCA and/or CBA studies on TCM have never been published. Moreover, food waste makes up a high proportion of municipal solid waste in Bandung and the city is in the midst of a transition from the conventional landfill-based final disposal to the modern incineration-based final disposal. This kind of situation is typical in some large cities in growing economies, and therefore, the result of this study can serve as a useful reference widely in developing nations.

Method

Project background

The study site for the decentralised composting centre was the TPS-3R Babakansari in Kiaracondong sub-district, Bandung City. TPS (*Tempat Pembuangan Sementara*) is a temporary waste transfer station located in most Indonesian cities. Waste is collected from neighbouring areas by a waste collector with a pushcart and then is placed temporarily in the TPS, to be reloaded onto trucks before being transported to the landfill sites. TPS-3R is a new type of facility which applies the 3Rs (reduce, reuse, recycle) as well as waste transfer functions. In Bandung, there are in total of 160 TPS and 10 of these have TPS-3R functions (Bandung City Government, 2019a). The TPS-3R Babakansari is one such station and also served as the satellite office for the Bandung City Cleansing Agency (PD Kebersihan Kota Bandung: PDK), a semi-government enterprise providing cleansing services. The existing construction of the composting centre at the TPS-3R Babakansari is a simple shed with a roof and concrete floor measuring 151.2 m^2 (21.6 m × 7 m). The facility used to apply a static windrow composting method whereby market waste was chopped by a shredder and piled up without being turned. However, as the acceptance capacity of organic waste was too small, DLHK decided to introduce TCM as a more efficient composting method.

The process to introduce TCM in TPS-3R Babakansari was initiated in November 2018 by making seed compost (approximately 2 m^2) and the initial input amount of organic waste was about 15 kg per day. This amount was gradually increased following an increase in the volume of the compost bed to ensure operators get accustomed to and confident with the method. Mature compost was reused repeatedly as seed compost to prioritise the scaling of acceptance capacity and was not extracted for use until there was a sufficient amount of seed compost. The acceptance capacity of organic waste reached up to 1 tonne/day after one year (November 2019) of gradual scaling. Initially, 1-2 m^2 of compost piles were separated and a continuous input system (adding of organic waste and turning took place every day continuously on the same pile) was applied. However, at a later stage when available floor space became limited, a three-week rotation system was introduced to increase the treatment capacity. Detailed methods of the three-week rotation system by TCM is available (Hibino et al., 2020). The number of the operator was also increased from one staff to three staff following an increase in the daily amount of waste accepted at the facility. Daily operations were carried out manually and data were monitored and recorded on the daily amount of waste input, the temperature of compost bed, and moist content. The mature compost made by TCM met the technical standards of the Indonesia National Standard (SNI) on domestic organic compost (SNI: 19-7030-2004) in 2018 at Balikpapan City (Beetle Engineering Co., Ltd., personal communication, July 2020) and also met the technical standard of organic compost in Vietnam (Circular No. 41/2014/TT－BNNPTNT) in May 2016 at Hai Phong City (Nuzir et al., 2019).

The organic waste generated from approximately 1,000 households mainly from 18 RW (*rukun warga*: community associations) in Babakansari (administrative village) and some from outside Babakansari was used as the feed for composting. These communities applied source separation and collection by two categories – biodegradable (organic) waste and other waste. A bucket collection system was introduced where separated food waste from households was collected in covered plastic buckets and carried to the compost centre by motorised tricycles. Non-organic waste was collected separately and carried to the landfill site after taking out recyclable waste such as aluminium cans, pet bottles, cardboard, etc. Figure 1 describes the mass balance for 1 tonne of solid waste when source separation and TCM were both introduced at the TPS-3R Babakansari. The waste composition data sampled at the TPS-3R Babakansari (data provided by DLHK, Bandung City) indicated that the materials used as the feed for composting (food waste 45.2% and garden waste 3.3%) occupied about half of the solid waste generated from the nearby communities. The organic separation rate was generally high and foreign materials such as plastics were minimal. Therefore, this study assumed that all materials carried to the composting centre were organic waste and 50% was used to calculate the ratio of organic waste for ease of understanding and calculation.

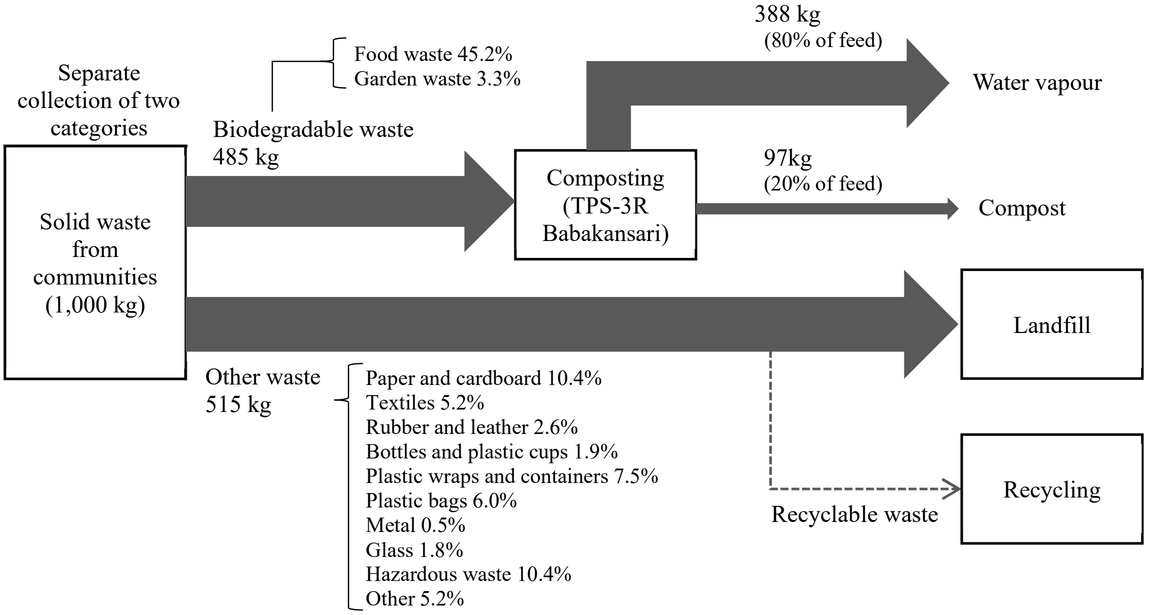

Figure 1. Conceptual diagram of mass balance for 1 tonne of solid waste when source separation and TCM were introduced at the TPS-3R Babakansari. The waste composition is based on 2016 data at TPS-3R Babakansari (data provided by DLHK, Bandung City).

Goal and scope definition

Municipal solid waste management is a basic public service directly linked to the daily lives of the citizens and utilising public funds. It requires balanced decision-making for investment, particularly considering both the environmental and costs aspects for long-term sustainability. There are various sustainability assessment tools (International Organisation for Standardisation, 2006), and each tool has specific boundaries and limitations. The combined use of these tools, for example, focusing on environmental impact and costs, ensures that the methods can cover wider gaps and broaden the scope of the assessment (Hoogmartens et al., 2014; Jeswani et al., 2010). LCA is a well-known sustainability assessment tool that examines the environmental impacts of entire stages of the product, process or services – from the extraction of raw materials, production and use, to final disposal. CBA and Life Cycle Costing (LCC) are similar sustainability assessment tools that evaluate the monetary value of the entire lifecycle of the products or projects (Finnveden and Moberg, 2005). LCC is viewed as an economic counterpart of LCA but typically does not include benefits (Finnveden and Moberg, 2005) which is an important parameter for policy decisions. On the other hand, CBA is a more recognised and widely used policy decision-making tool for projects (Thomas and Chindarkar, 2019). Therefore, as a matter of practical convenience, the authors have chosen to use CBA for the economic evaluation carried out in this study, while keeping the same timeframe, system boundaries, and functional units used by the LCA for consistency. Similar combined use of LCA and CBA has been applied in several waste management studies for the selection of appropriate systems and/or optimising existing systems (C. P. C. Bong et al., 2017; Lam et al., 2018; Lim et al., 2019; Sparrevik et al., 2014; Zhong et al., 2013).

This study followed the basic procedural steps for LCA, to i) define the goal and scope of the study, ii) develop an inventory of relevant inputs and outputs of the system, iii) assess their potential impacts, and iv) interpret the results. Likewise, the study also followed the basic procedural steps for CBA, to i) identify costs/benefits, ii) place values on the costs/benefits (avoid double counting), iii) compute net social benefits, and iv) select the best alternative based on the net social benefit (Thomas and Chindarkar, 2019). The net social benefits were expressed in net present value (NPV).

Goal settings

The objective of the combined LCA and CBA studies was to evaluate the environmental and economic impacts of the decentralised composting centre using TCM in comparison with other scales of TCM, static windrow method composting, and case scenarios without introducing TCM (landfill and incineration).

Impact categories

Among many impact categories of LCA, the Global Warming Potential (GWP) as defined by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2014) was selected. Different gaseous emissions were normalised to kg CO_2-eq/tonne of wet waste to allow a comparison of the impacts of carbon footprints. It was selected as the most basic and widely studied impact category in LCA studies on municipal solid waste management in Asian countries (Yadav and Samadder, 2018).

Functional unit

In LCA, the functional unit provides a reference in which the number of inputs and outputs can be compared between different scenarios allowing comparative analysis of environment effects (International Organisation for Standardisation, 2006). The functional unit for this study was set as management of one tonne of food waste (wet waste) produced by households in Bandung City per day. This is consistent with the actual operating capacity of the decentralised TCM system performed at the TPA-3R Babakansari. This functional unit is also most commonly applied in LCA studies on municipal solid waste management in Asian countries (Yadav and Samadder, 2018).

Scenario creation

Six scenarios were set to analyse the life cycle inventory (LCI) and NPV of one tonne per day of organic waste treated, and compared emissions of various greenhouse gases based on GWP in carbon dioxide equivalent (abbreviated as CO2-eq) as well as the net social costs. All scenarios are based on actually available cases in Bandung City except S6 which assumes construction of a large-scale composting centre on the outskirts of the city. S1 is the current ongoing practice in Bandung and is considered as the 'business as usual' (BAU) scenario.

- S1: Controlled landfill – TPA Sarimukti (BAU scenario)
- S2: Incineration – TPA Legok Nangka
- S3: On-site composting (TCM) – Kampung Takakura
- S4: Decentralised composting centre (Static windrow) – TPS-3R Babakansari
- S5: Decentralised composting centre (TCM) – TPS-3R Babakansari
- S6: Centralised composting centre (TCM) – Pasir Impun

TPA Sarimukti (S1) is a controlled sanitary landfill equipped with a leachate treatment pond, gas ventilation pipes (no gas recovery), and regular soil coverage. It accepted municipal solid waste from cities and regencies in West Java Province including Bandung City. The specifications of the planned incineration facility at TPA Legok Nangka (S2) are yet to be clarified, therefore this study assumes a conventional stoker-type incinerator with a steam turbine electric generator.

Kampung Takakura (S3) is a community located in Sukamiskin administrative village, Arcamanik sub-district in Bandung City. It is a mid-high income community composed of 342 households (data provided by PDK). The name of the community 'Takakura' derived from TCM inspired by its success and the spirit of recycling. The majority of households have a Takakura composting basket, a home composting tool specifically designed for TCM which materials can be purchased and easily constructed with about USD 10 per unit (Calleja-amador and Romero-esquivel, 2018; Maeda, 2009) for composting food waste. The members of the voluntary women's association (PKK) of the community are acting as the environment cadre and assisting communities in setting up the compost baskets, providing seed compost, and providing technical support for home composting. The percentage of households that practice home composting is approximately 75% (data provided by PDK). The mature compost is then used on the community farm and/or for respective home gardening. In effect, the majority of food waste is treated on-site and the amount of residual waste that is collected and brought to the landfill is extremely small compared to other communities. This study, therefore, assumes that 75% of organic waste in S3 is treated on-site and the remaining 25% is going to the landfill.

S4 and S5 are composting options in the decentralised composting centre at the TPS-3R Babakansari. S4 is a static windrow with no turning of the compost piles, and S5 is active turning by TCM.

Pasir Inpun (S6) is the candidate site for a large-scale centralised composting centre owned by PDK. This study assumed that a large-scale composting centre with an input capacity of 200 tonnes/day (mixed waste) will be developed at Pasir

Inpun. All the input data were based on estimates from a successful demonstration facility in Wonorejo, Surabaya City, with a capacity of 20 tonnes/day that applied TCM. That facility was developed in 2014 and operated by the Nishihara Shoji Co., Ltd. with financial assistance from JICA (JICA and Nishihara Shoji, 2016). With an input of 200 tonnes/day, the waste composition was assumed to be 50% (100 tonnes/day) organic waste for compost production, 20% (40 tonnes/day) is recyclables and 30% (60 tonnes/day) of residue which will be transported to the landfill.

System boundaries

The extent of data availability and differences in scope lead to different results in GHG emissions and NPV accounting. For transparency and consistency in GHG accounting for waste management, one study proposed an upstream-operation-downstream (UOD) framework that distinguished between indirect upstream emissions, direct operation emissions, and indirect downstream emissions (Gentil et al., 2009). Some LCA studies on composting have focused only on direct emissions of waste management (operation) aspects (Abduli et al., 2011; Cadena et al., 2009; Colón et al., 2010). However, how compost is used after production provides a holistic picture of its life cycle (Boldrin et al., 2009; Martínez-blanco et al., 2013; Saer et al., 2013). In Bandung City, the city government is responsible for both waste management and landscaping, meaning that the compost could be used by the city itself as part of public works for gardening in parks and streets. However, the responsible departments are different. Therefore, this study examined the differences in GHG emissions and NPV by applying two different system boundaries: A) core system boundaries which only focused on operation, and B) extended system boundaries that included the upstream/downstream application of compost as a fertiliser. The indirect upstream emissions including the production of waste, fuel and electricity, and the construction of facilities and equipment, as well as the indirect downstream emissions from the demolition of facilities and equipment, were not included following the 'cut-off' principle (Martínez-Blanco et al., 2009; Oldfield et al., 2018) as these burdens are not directly relevant and can be considered independent from the system. Meanwhile, the production of mineral fertiliser, as part of indirect upstream emissions, was accounted for as a substitute for organic fertiliser (compost). Based on this understanding, the system boundaries of the different scenarios are illustrated in Figure 2.

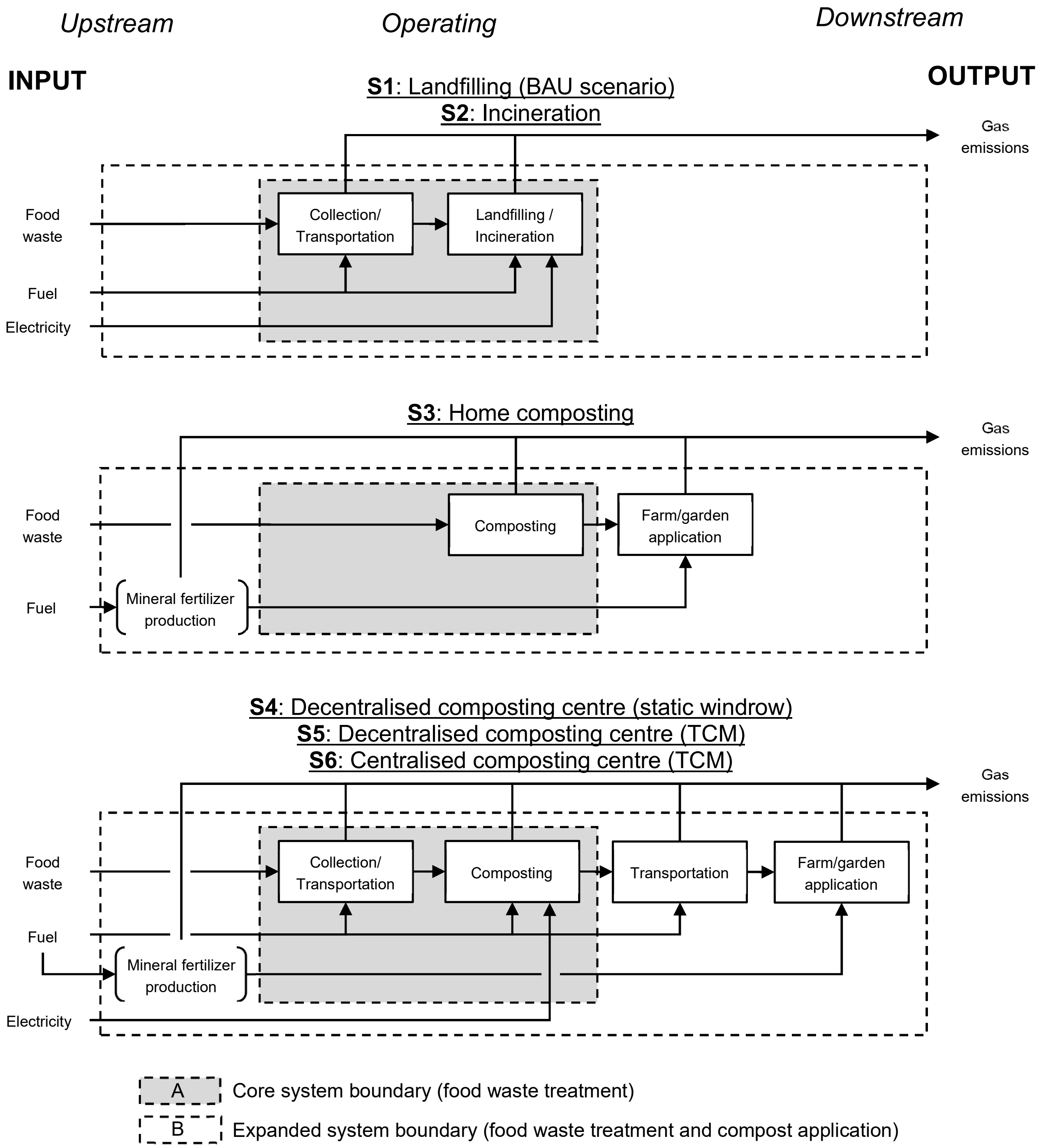

Figure 2. Two different system boundaries of the six comparative scenarios. Core system boundaries for food waste treatment are enclosed by dotted lines with grey shades (A) and expanded system boundaries including food waste application are enclosed with plain dotted lines (B). The items in the bracket indicate that they are avoided emissions substitutes for compost use.

Life cycle inventory

The life cycle inventory analysis for all scenarios was conducted through the estimation of net GHG emissions by normalising the emissions into kg CO_2-eq per tonne of food waste treatment. CH_4 and N_2O emissions were converted to CO_2 equivalent by multiplying the 100-year time horizon Global Warming Potential (GWP) from the IPCC Fourth Assessment Report (AR4) (ie, $CH_4 = 25$; $N_2O = 298$) (Forster et al., 2007).

Non-biogenic emissions

Non-biogenic emissions associated with fuel consumption were calculated for CO_2, CH_4, and N_2O, respectively, using the IPCC Tier 1 method for mobile combustion and stationary combustion (IPCC, 2006) as shown in equation (1), and fuel consumption was calculated using equation (2). The IPCC default emission factors were also applied as presented in Table 1. Activity data were obtained from PDK and literature.

$$Emission_f = \sum_a \left[Fuel_a \times EF_{fa} \right] \tag{1}$$

$$Fuel_a = V_a \times \frac{D_a}{1{,}000{,}000} \times NCV_a \tag{2}$$

Where:

$Emission_f$ = emissions in kg (CO_2, CH_4, N_2O)
$Fuel$ = fuel consumed, TJ (as represented by fuel sold)
EF_f = emission factor for fuel consumption, kg/TJ
V = volume of fuel consumed, l
D = density of fuel, kg/l
NCV = net calorific values, TJ/Gg
a = fuel type a (diesel, gasoline)

Table 1. Summary of input parameters and default values applied for calculating the GHG emissions of non-biogenic emissions.

Symbol	Parameter	Value	Unit	Source
Non-biogenic emissions associated to fuel consumption: equations (1), (2)				
EF_f	CO_2 emission factor for fuel consumption (gasoline)	69,300	kg/TJ	IPCC default value (IPCC, 2006)
	CO_2 emission factor for fuel consumption (diesel)	74,100	kg/TJ	IPCC default value (IPCC, 2006)
	CH_4 emission factor for fuel consumption (gasoline)	33	kg/TJ	IPCC default value (IPCC, 2006)
	CH_4 emission factor for fuel consumption (diesel)	3.9	kg/TJ	IPCC default value (IPCC, 2006)
	N_2O emission factor for fuel consumption (gasoline)	3.2	kg/TJ	IPCC default value (IPCC, 2006)
	N_2O emission factor for fuel consumption (diesel)	3.9	kg/TJ	IPCC default value (IPCC, 2006)
NCV	Net calorific value (gasoline)	44.3	TJ/Gg	IPCC default value (IPCC, 2006)
	Net calorific value (diesel)	43.0	TJ/Gg	IPCC default value (IPCC, 2006)
D	Density (gasoline)	0.745	kg/l	(Crawley, 2013)
	Density (diesel)	0.832	kg/l	(Crawley, 2013)
Non-biogenic emissions associated with grid electricity consumption: equation (3)				
EF_e	Grid electricity emission factors	0.862	tCO_2/MWh	Java–Madura–Bali electrical system (Institute for Global Environmental Strategies, 2020)
Biogenic emissions from landfills: equations (4), (5), (6)				
R	Recovered CH_4	0	Gg	CH_4 is not recovered at TPA Sarimukti
OX	Oxidation factor	0.1		IPCC default value (IPCC, 2006)
F	A fraction of CH_4 in landfill gas	0.5		IPCC default value (IPCC, 2006)
DOC	Degradable organic carbon	0.15	Gg C/Gg waste	IPCC default value for food waste (IPCC, 2006)
DOC_f	Fraction of DOC	0.5		IPCC recommended value (IPCC, 2006)
MCF	CH_4 correction factor	0.5		IPCC default value for managed semi-aerobic type (IPCC, 2006)
Biogenic emissions from composting: equations (7), (8)				
N	Amount of N input	13.75	kg N / tonne food waste	Mean value of typical N content of food waste (6.0 – 21.5 kg N /tonne food waste) (Boldrin et al., 2009)
EF_c	Emission factor for N_2O from N inputs	0.01	kg N_2O–N / kg N input	IPCC default value (IPCC, 2006)

Non-biogenic emissions associated with grid electricity consumption can be calculated using equation (3). The emission factor for grid electricity consumption in Bandung City will apply the emission factor for Java–Madura–Bali electrical system to which Bandung City belongs (Institute for Global Environmental Strategies, 2020). Applied default values are presented in Table 1.

$$Emission_e = E_c \times EF_e \tag{3}$$

Where,

$Emission_e$	= emissions from electricity consumption, tCO_2
E_c	= grid electricity consumption, MWh
EF_e	= grid electricity emission factors, tCO_2/MWh

Biogenic emissions from landfills

CO_2 and CH_4 are the major biogenic emissions from landfills (IPCC, 2006). CH_4 emissions from landfills by the food waste were estimated using the First Order Decay (FOD) Tier 1 method provided by IPCC (IPCC, 2006) as shown in equations (4), (5), and (6). Applied default values are presented in Table 1. Activity data were obtained from PDK.

$$CH_{4\,Emissions} = (CH_{4\,Generated} - R) \times (1 - OX) \tag{4}$$

$$CH_{4\,Generated} = DDOC \times F \times \frac{16}{12} \tag{5}$$

$$DDOC = W \times DOC \times DOC_f \times MCF \tag{6}$$

Where:

$CH_{4\,Emissions}$	= CH_4 emitted, Gg
R	= recovered CH_4, Gg
OX	= oxidation factor, (fraction)
$CH_{4\,Generated}$	= CH_4 generation potential, Gg CH_4
$DDOC$	= mass of decomposable DOC deposited, Gg
F	= fraction of CH_4 in generated landfill gas (volume fraction)
$16/12$	= molecular weight ratio CH_4/C (ratio)
W	= mass of food waste deposited, Gg
DOC	= degradable organic carbon in the year of deposition, fraction, Gg C/Gg waste
DOC_f	= fraction of DOC that can decompose (fraction)
MCF	= CH_4 correction factor for aerobic decomposition in the year of deposition (fraction)

Emissions from incineration

The current landfill site for Bandung City (TPA Sarimukti) is expected to be full by 2023 (according to DLHK, Bandung City), so the West Java Province is currently constructing a new regional landfill at Legok Nangka and an incineration facility with electricity generation is also being considered. As the specifications of the incineration facility including technologies and capacity are yet to be clarified, and there are no reliable performance data of a similar scale municipal solid waste incinerator in Indonesia that could be used for reference, CO_2 emissions from incineration were calculated using the Tier 1 method provided by IPCC based on waste composition (IPCC, 2006) as shown in equation (7). For waste composition, country-specific data for Indonesia provided by IPCC (IPCC, 2006) were used. The result using equation (7) was 229.36 kg CO_2-eq/tonne of wet waste. This equation does not consider emissions recovered by the electric generator, so it should be seen as a conservative estimation. This is backed by the emission factors identified from six incinerators equipped with electricity generators in China where the waste composition is similar to Indonesia (LHV ranged between 3.7 and 6.5) that ranged 25 – 207 kg CO_2-eq/tonne of wet waste (Yang et al., 2012b).

$$CO_{2\,Emissions} = MSW \times \sum_j \left(WF_j \times dm_j \times CF_j \times FCF_j \times OF_j\right) \times \frac{44}{12} \tag{7}$$

Where:

$CO_{2\,Emissions}$	= CO_2 emitted, Gg
MSW	= total amount of municipal solid waste as wet weight incinerated, Gg
WF	= fraction of waste type/material of component j in the MSW as wet waste incinerated

dm = dry matter content in the component j of the MSW incinerated
CF = fraction of carbon in the dry matter of component j
FCF = fraction of fossil carbon in the total carbon of component j
OF = oxidation factor, (fraction)
$44/12$ = conversion factor from C to CO_2
j = component of the MSW incinerated

Biogenic emissions from composting

Composting is an aerobic digestion process where a large fraction of degradable organic carbon in the waste materials are converted to CO_2 (IPCC, 2006). CH_4 and N_2O are also emitted as a consequence of the management of the composting process and will be subject to calculation as GHG emissions. The CH_4 and N_2O emissions of biological treatment can be estimated using the IPCC Tier 1 method (IPCC, 2006), as shown in equations (8) and (9).

$$CH_{4\,Emissions} = \frac{W \times EF_{CH4}}{1{,}000} - R \tag{8}$$

$$N_2O_{Emissions} = \frac{W \times EF_{N2O}}{1{,}000} \tag{9}$$

Where,
CH_4 *Emissions* = total CH_4 emissions of type a in inventory year, Gg
N_2O *Emissions* = total N_2O emissions of type a in inventory year, Gg
W = mass of food waste treated for composting, Gg
EF_{CH4} = CH_4 emission factor, g/kg waste treated
EF_{N2O} = N_2O emission factor for emission type a, g/kg waste treated
R = total amount of CH_4 recovered in inventory year, Gg CH_4

IPCC (2006) provides default emission factors for CH_4 and N_2O for the biological treatment of solid waste. However, past studies showed that both CH_4 and N_2O emissions vary depending on the conditions of composting including feedstock types, C/N ratio, ventilation, temperature, moist contents, etc. (Amlinger and Peyr, 2008; Boldrin et al., 2009; Ermolaev et al., 2015; Jiang et al., 2011; Sánchez et al., 2015; Thomas et al., 2020). To apply appropriate emission factors for TCM and static windrow, emission factors of CH_4 and N_2O identified from similar conditions in past studies were applied. One study measured the CH_4 and N_2O emissions from food waste composting under different temperatures and aeration conditions in a controlled laboratory experiment (Ermolaev et al., 2015). The results of high temperature and aerated conditions (0.006g CH_4/kg waste and 0.016g N_2O/kg waste) were applied to TCM, and low temperature and limited aeration conditions (1.26g CH_4/kg waste and 0.003g N_2O/kg waste) were applied to static windrow. The R-value for estimating CH_4 emissions in equation (8) applied 0 (zero), as neither TCM nor static windrow had CH_4 recovery systems.

Avoided emissions from the use of mineral fertilizers

Compost can supply mineral nutrients needed for plant growth that would otherwise have to be provided by mineral (chemical) fertilisers. Thus, substituting the use of mineral fertiliser through compost can reduce GHG emissions caused by the manufacturing and transportation of fertilisers. To estimate these values, data on typical nutrient contents of compost as well as the GHG emission factors on the manufacturing and transportation of fertilisers are needed (Biala, 2011). In this regard, analysis was carried out on potential GHG emissions from the production of mineral fertilisers from six works of literature and the amount of mineral fertilisers that could be replaced by the use of compost from eight works of literature (Boldrin et al., 2009). This study applied a mean value after adding the three main mineral fertiliser types (i.e. N, P, K) which resulted in 42.7 kg CO_2-eq / tonne of food waste.

Biogenic emissions from the use of compost

Compost contains readily degradable, slowly degradable and stable organic matters. The application of compost to the land for farming or gardening as a soil amendment will facilitate oxidisation of the degradable organic matter and result in emissions of CO_2. The remaining fraction of stable organic matter will stay in the soil for a longer period (Boldrin et al., 2009). Because the amount of carbon sequestration to the soil after 100 years is estimated to be 2-10% of the input of compost (Boldrin et al., 2009) and as food waste generally consists of readily degradable organic matter, this study did not account for the amount of carbon sequestration. Meanwhile, when compost is applied to the soil, N_2O is also released through the process of nitrification (aerobic microbial oxidation of ammonium to nitrate) and denitrification (anaerobic microbial reduction of nitrate to nitrogen gas). IPCC provides a methodology to estimate N_2O emissions by human-induced N additions or change of land-use and/or management practices that mineralise soil organic N (IPCC, 2006). By restricting the factors to the input of compost to soils only, the equation for direct N_2O emissions from managed soils (Tier 1) can be simplified as shown in equation (9).

$$N_2O_{Direct} = N \times EF_c \times \frac{44}{28} \tag{9}$$

Where,

N_2O_{Direct} = direct N_2O emissions produced from managed soils, kg N_2O / tonne food waste

N = amount of N applied to soils by compost, kg N / tonne food waste

EF_c = emission factor for N_2O emissions from N inputs, kg N_2O–N / kg N input

$44/28$ = conversion factor of N_2O–N emissions to N_2O emissions

Cost-Benefit Analysis

All the direct costs and benefits incurred in each scenario were valued in monetised terms using the Net Present Value (NPV) in IDR. The USD/IDR = 14,000 conversion rate (as an approximate average for five years: 2016-2021) was applied when the currency is shown in USD. Benefits also comprise avoided future capital and operational costs that may be incurred in the BAU scenario. Indirect costs (non-monetary values) such as environmental values and social values were not calculated in this study to avoid double counting. NPV was calculated using equation (10) (Thomas and Chindarkar, 2019).

$$NPV = \sum \frac{B_t - C_t}{(1+s)^t} \tag{10}$$

Where,

NPV = net present value

B = total benefit of year t

C = total cost of year t

S = social discount rate

t = year

Calculation of costs included capital costs, operational costs and feedstock costs. Calculation of benefits included the sales revenue of compost which is assumed to substitute purchasing of mineral fertilisers. The land procurement costs were not considered in this study as the properties were mostly government-owned lands. Given the lack of reliable cost data including government subsidies and to avoid double-counting, the waste tipping fees were considered to cover the capital costs, operational costs, and closure costs of the landfill (S1) and incineration (S2). The amortization period of facilities and equipment in all scenarios was set at 15 years for simplicity, so all the capital costs of facilities and equipment were normalised for 15 years. A social discount rate (interest rate applied to costs and benefits that is expected to occur in the future) of 10% was applied as a representative rate for public infrastructure projects in Indonesia following other CBA studies (Prihandrijanti et al., 2008; You et al., 2017).

In general, in Bandung City, waste generated from households is collected by a waste collector using a pushcart and gathered at TPS before being transported to TPA by truck. However, the organic waste carried to TPS-3R Babakansari for composting was collected separately by small trucks and/or motorised tricycles under a special arrangement. For simplicity and fair comparison, waste collection methods for all scenarios were considered to be by a waste collector using a pushcart and not using small trucks and/or motorised vehicles. Waste management fees that each household pays to the city government (called retribution) were originally meant to cover the transportation cost between TPS and TPA according to Regional Regulation No. 11/2012. However, the fees are almost equivalent to the personnel expenditure of the waste collectors who collect waste and bring it to TPS. Thus, it was considered that retribution will cover the cost of waste collection from each household to TPS.

For the CBA analysis, NPK 15-15-15 fertiliser, a typical mineral fertiliser used in Indonesia, was assumed to substitute the use of compost. From the past comparative studies on municipal solid waste compost and NPK 15-15-15 fertiliser, two tonnes/ha of organic compost was comparable to 200 kg/ha of NPK 15-15-15 due to different concentrations of nutrients (Adekayode and Ogunkoya, 2011). Thus, it was considered that the necessary amount of NPK 15-15-15 was 1/10 of the amount of organic compost.

Assumptions and limitations

Within the scope of system boundaries (Figure 2), the following assumptions and limitations were applied to the LCA and CBA calculations unless stated elsewhere:

- Biogenic CO_2 emissions are considered to be carbon neutral and were not calculated
- Emissions in the form of leachate were not considered
- GHG emissions from water use were not calculated given the limited use in the processes and uncertainty of activity data as well as the emission factors
- Home composting (S3) is carried out manually so it was assumed that electricity and/or fuel was not consumed and cost for labour was not incurred
- GHG emissions concerning the construction and demolition of infrastructure and equipment are not considered
- Activities of landscaping and gardening (use of compost) were not accounted for as they are part of existing public works services of the Bandung City and no additional costs would occur by composting.
- Methane is not considered to occur from the landfilling of ash after the incineration process (S2).

Result and Discussion

Performance of TCM in decentralized composting centre

The results of daily monitoring on the amount of organic waste input and the average temperature of compost beds in the decentralised composting centre using TCM (S5) are shown in Figure 3. The monitoring was carried out for one full year from 19 November 2018 until 28 November 2019. The discontinued portion of the line charts indicates that monitoring and/or waste input had to be stopped due to holidays (when waste was not collected) and/or during changes in the composting system. The amount of organic waste input gradually increased and reached 1,000 kg/day (Max: 1,097 kg/day). Fluctuations in the daily input amount indicate that some adjustments were needed when the rotation system was changed for scaling up or when the input amount had to be reduced temporarily for operational purposes. The average temperature throughout the monitoring period was 68.6 ºC (Min: 54.0 ºC; Max: 79.8 ºC). Space efficiency is another indicator for effectivity in composting. The available floor space for composting at the TPAS-3R Babakansari was 151.2 m^2 (21.6 m × 7 m).

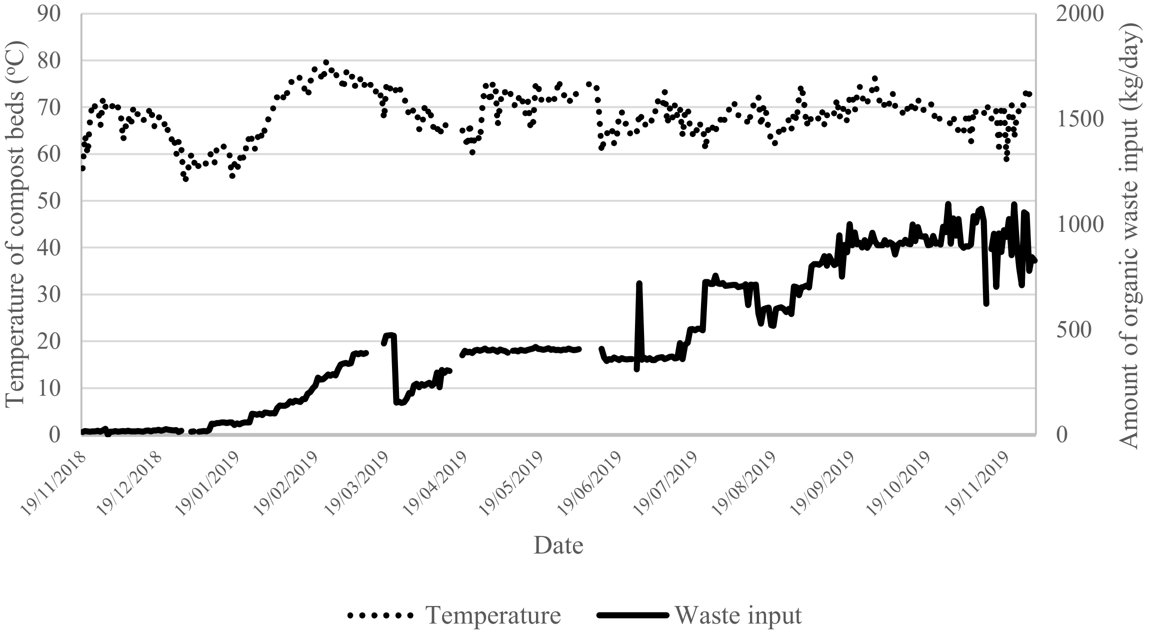

Figure 3. The total amount of organic waste input (solid line) and average temperature (dotted line) of compost beds in a decentralized composting centre at TPAS-3R Babakansari (S5).

Life cycle impact assessment

The results of the life cycle impact assessment on GHG emissions in the expanded functional unit are summarised in Table 2. There was a clear contrast in GHG emissions between the BAU scenario (S1) which exhibited positive net GHG emissions (628 kg CO_2-eq/t) and other scenarios that exhibited net negative GHG emissions ranging between -281 kg CO_2-eq/t and -601 kg CO_2-eq/t (S2, S3, S4, S5, S6) (Figure 4). The percentage difference of net GHG emissions between the four composting scenarios was limited and ranged between 0.7% and 4.9%. A major factor for this sharp contrast was a large amount of avoided emissions from transportation and landfilling in the composting scenarios.

Table 2. Summary of life cycle inventory on the input and output energy reference flows and resulting GHG emissions of six waste management scenarios to treat 1 tonne of food waste in the expanded functional unit.

Element	Flow	Scenario						Unit
		S1	S2	S3	S4	S5	S6	
Input								
Food waste		1	1	1	1	1	1	tonne/day
Transportation (waste)	Diesel	21.79	21.79	0	0	0	5.84	l/tonne
Transportation (compost)	Diesel	0	0	0	0.46	0.46	0.46	l/tonne
Landfilling	Diesel	2.00	N/A	0	0	0	0	l/tonne
	Electricity	0.50	N/A	0	0	0	0	kWh/tonne
Incineration	Diesel	0	N/A	0	0	0	0	l/tonne
	Electricity	0	N/A	0	0	0	0	kWh/tonne
Composting	Diesel	0	0	0	0	0	4.81	l/tonne
	Gasoline	0	0	0	0.30	1.30	N/A	l/tonne
	Electricity	0	0	0	0	0	0.85	kWh/tonne
Output								
Transportation	CO_2	57.78	57.78	0	1.06	1.06	15.79	kg CO_2/tonne
	N_2O	< 0.01	< 0.01	0	< 0.01	< 0.01	< 0.01	kg N_2O/tonne
	CH_4	< 0.01	< 0.01	0	< 0.01	< 0.01	< 0.01	kg CH_4/tonne
Landfilling	CO_2	6.16	N/A	0	0	0	0	kg CO_2/tonne
	N_2O	0.00	N/A	0	0	0	0	kg N_2O/tonne
	CH_4 (non-biogenic)	0.00	N/A	0	0	0	0	kg CH_4/tonne
	CH_4 (biogenic)	22.50	N/A	0	0	0	0	kg CH_4/tonne
Incineration	CO_2-eq	0	229.36	0	0	0	0	kg CO_2/tonne
Composting	CH_4	0	0	0.01	1.26	0.01	0.01	kg CH_4/tonne
	N_2O	0	0	0.02	0.00	0.02	0.02	kg N_2O/tonne
	CO_2	0	0	0	0.69	2.97	13.47	kg CO_2/tonne
Compost use	N_2O	< 0.01	< 0.01	0.22	0.22	0.22	0.22	kg N_2O/tonne
Mineral fertiliser (avoided)	CO_2-eq	< 0.01	< 0.01	-42.70	-42.70	-42.70	-42.70	kg CO_2/tonne
Gross emissions	CO_2-eq	628	288	27	56	31	56	kg CO_2/tonne
Avoided emissions	CO_2-eq	0	-569	-628	-628	-628	-628	kg CO_2/tonne
Net emissions	CO_2-eq	628	-281	-601	-572	-597	-571	kg CO_2/tonne

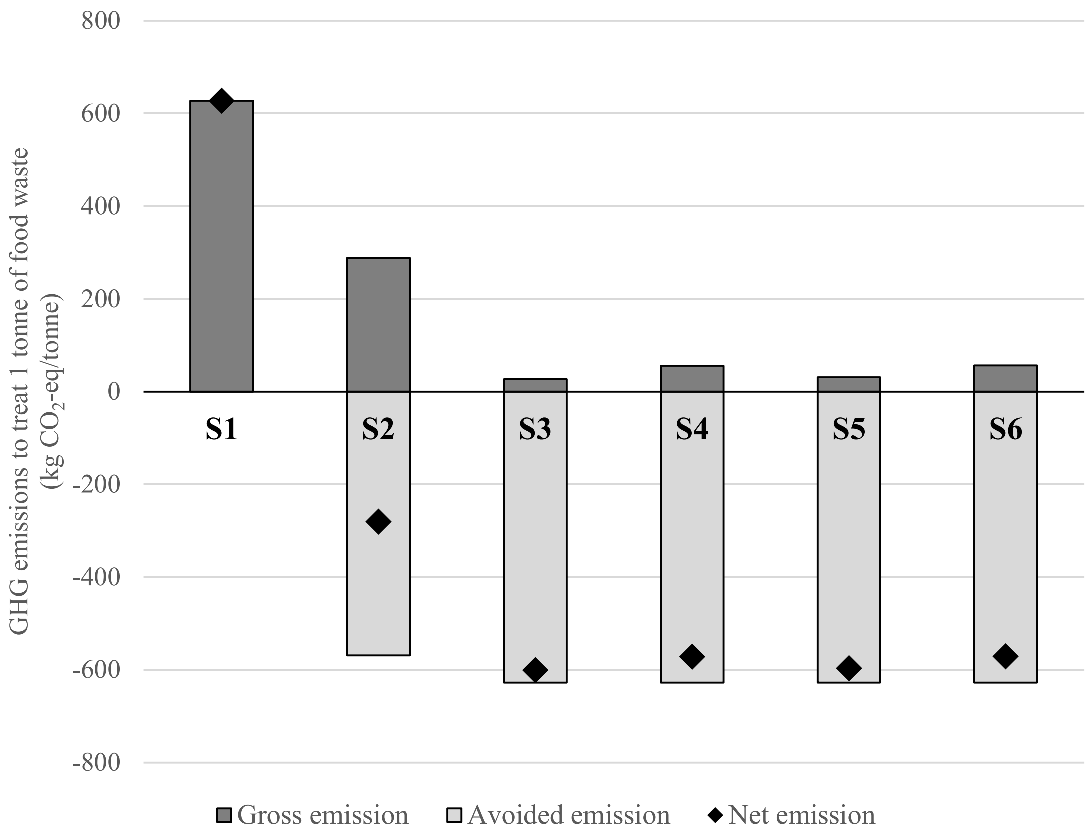

Figure 4. Comparison of six waste management scenarios on GHG emissions to treat 1 tonne of food waste in the expanded functional unit. Avoided emissions are expressed in negative values.

Cost-benefit analysis

The result of the cost-benefit analysis in the expanded functional unit is summarised in Table 3. Four composting scenarios (S3, S4, S5, S6) exhibited positive NPV while other scenarios (S1, S2) turned out to be negative NPV. Home composting (S3) showed the highest positive NPV (IDR 518,790/tonne) and incineration (S2) showed the highest negative NPV (IDR -818,373/tonne) (Figure 5).

Table 3. Summary of economic costs and benefits to treat 1 tonne of food waste of six waste management scenarios in the expanded functional unit. Costs are expressed in negative value. All values are in IDR.

Items	Scenario					
	S1	S2	S3	S4	S5	S6
Capital cost						
Infrastructure	N/A	N/A	0	-265,670	-66,418	N/A
Truck (waste)	-29,069	-29,069	0	0	0	-37,790
Truck (compost)	0	0	0	-9,963	-9,963	-9,963
Shredder	0	0	0	-1,411	-1,411	N/A
Home composting basket	0	0	-15,814	0	0	0
Seed compost materials	0	0	-3,163	0	-415	N/A
Capital costs for S6 (all inclusive)	N/A	N/A	N/A	N/A	N/A	-51,073
Sub-total	-29,069	-29,069	-18,976	-277,044	-78,207	-98,825
Operational and maintenance cost						
Transportation (waste)	-102,038	-102,038	0	0	0	-27,322
Transportation (compost)	0	0	0	-2,140	-2,140	-2,140
On-site machinery and electricity	N/A	N/A	0	-1,786	-7,741	-23,569
Maintenance (equipment)	-581	-581	0	-227	-227	-955
Personnel cost (waste collection)	-60,606	-60,606	-15,152	-60,606	-60,606	-60,606
Personnel cost (transport waste)	-42,441	-42,441	0	0	0	-55,174
Personnel cost (transport compost)	0	0	0	-24,242	-24,242	-24,242
Personnel cost (composting)	0	0	0	-90,909	-272,727	-90,909
Waste tipping fee	-118,182	-701,818	0	0	0	-35,455
Sub-total	-323,849	-907,485	-15,152	-179,912	-367,684	-320,372
Direct benefits						
Compost replacement (with mineral fertiliser)	0	0	200,000	200,000	200,000	200,000
Sub-total	0	0	200,000	200,000	200,000	200,000
Avoided future capital and O&M costs						
Avoided capital costs	0	0	29,069	29,069	29,069	29,069
Avoided O&M costs	0	118,182	323,849	263,243	263,243	263,243
Sub-total	0	118,182	352,918	292,312	292,312	292,312
Net present value (IDR/tonne)	-352,918	-818,373	518,790	35,356	46,421	73,115

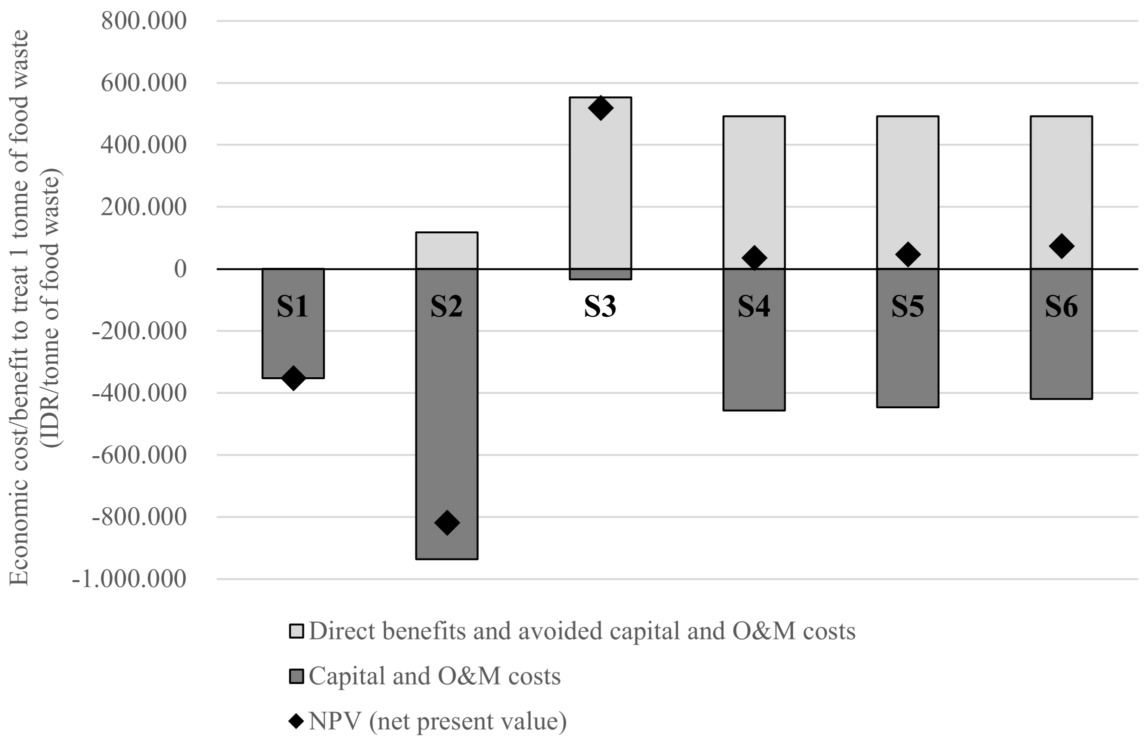

Figure 5. Comparison of six waste management scenarios on economic cost/benefit to treating 1 tonne of food waste in the expanded functional unit. Capital and operation and maintenance costs are expressed in negative values.

All the composting scenarios (S3, S4, S5 and S6) exhibited higher GHG emissions in the expanded system boundaries compared to the core system boundaries due to emissions occurring in the transportation of compost and compost use (Table 4). Meanwhile, decentralised and centralised composting centre scenarios (S4, S5 and S6) exhibited higher NPV in core system boundaries compared to the expanded system boundaries due to more costs incurred for capital (trucks), transportation and personnel costs. Compared to the BAU scenario, the differences in net GHG emissions (22.8 kg CO_2-eq/tonne) and NPV (IDR -36,345/tonne) were 3.6% and 10.3%, respectively.

Table 4. Comparison of net GHG emissions and net cost/benefit (NPV) among six waste management scenarios between core and expanded system boundaries.

Items	System boundaries	Scenario					
		S1	S2	S3	S4	S5	S6
Net GHG emission (kg CO_2-eq/tonne)	A. Core (food waste treatment)	628	-281	-623	-595	-620	-594
	B. Expanded (food waste treatment and compost application)	628	-281	-601	-572	-597	-571
	Difference (B-A)	0	0	21.7	22.8	22.8	22.8
NPV (IDR/tonne)	A. Core (food waste treatment)	-352,918	-818,373	518,790	71,701	82,766	109,460
	B. Expanded (food waste treatment and compost application)	-352,918	-818,373	518,790	35,356	46,421	73,115
	Difference (B-A)	0	0	0	-36,345	-36,345	-36,345

A dot diagram that combined both the results of the net GHG emissions and NPV is shown in Figure 6. It visualises the comparative position of the scenarios combining both parameters at a glance. In general, scenarios plotted on the lower-right-hand side of the diagram can be considered as the favourable options that satisfy both low emission and low cost, and the scenarios plotted on the upper-left-hand side can be considered non-favourable options from high emission and high cost. In the case of this study, home composting (S3) was the most favourable option and landfilling (S1) was the least favourable option. If the cost dimension was more weighed, then the incineration (S2) option could also become a non-favourable option due to having the highest cost. There were limited differences between the decentralised and centralised composting scenarios (S4, S5 and S6).

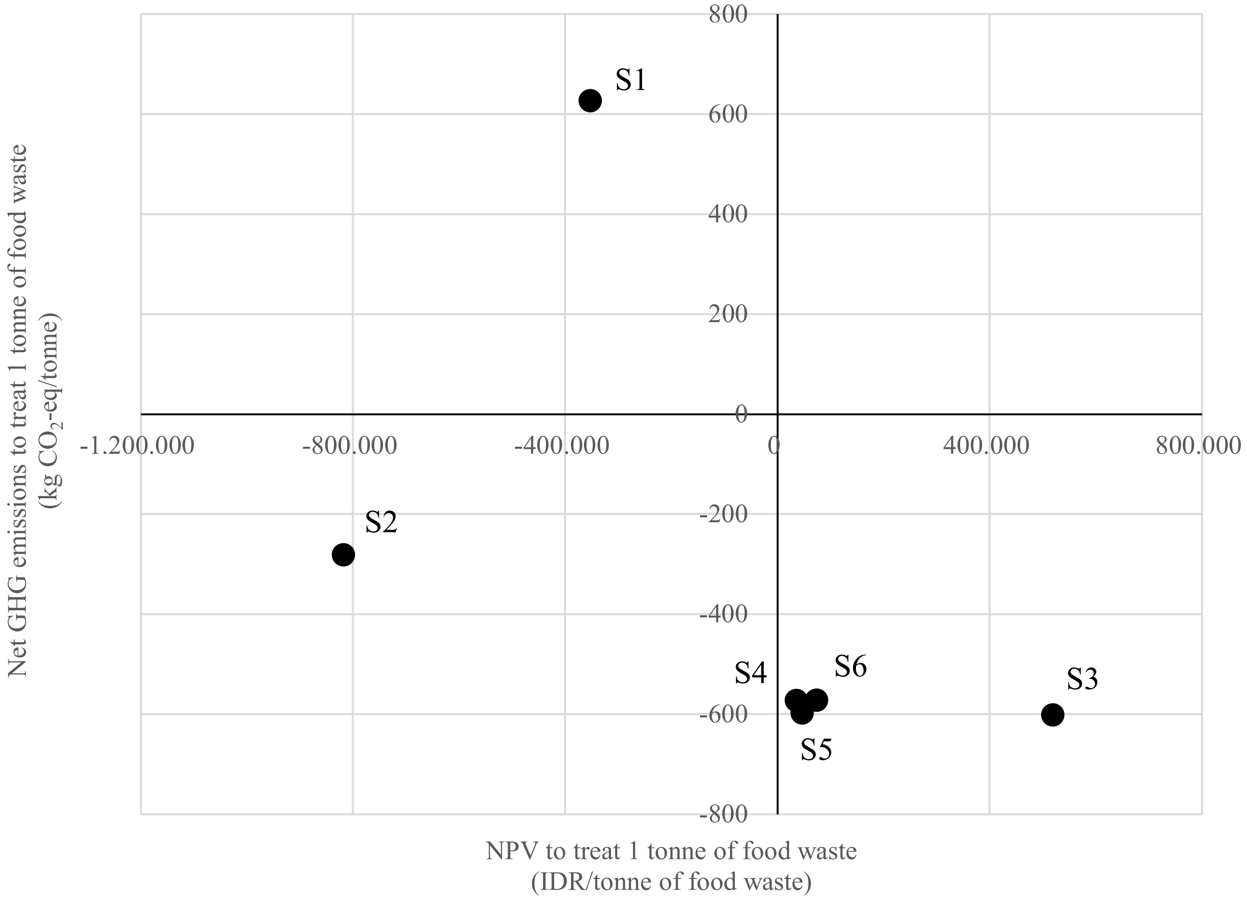

Figure 6. Combined plot diagram on the net GHG emission (Y-axis) and NPV (X-axis) of six waste management scenarios to treat 1 tonne of food waste in the expanded functional unit.

This study showed the scaling and performance data of food waste composting using TCM at a decentralised small-scale composting centre (1 tonne/day waste input capacity) for the first time. It was also the first of its kind to demonstrate the environmental and economic impacts of TCM in municipal solid waste management by using the combined LCA and CBA studies based on real case scenarios. The combined study of LCA and CBA on municipal solid waste composting enabled to provide better understandings and insights on GHG emissions and the cost/benefit of TCM in comparison with other composting methods and municipal solid waste management options at different scales.

The compost beds at TPS-3R Babakansari were kept at a high temperature (average: 68.6 ºC) which indicated that the beds were constantly in a thermophilic phase (usually >40 ºC) where the microbial breakdown of organic materials was actively occurring due to continuous input of food waste in three-weeks intervals, and that they did not enter the mesophilic phase (usually 10 – 40 ºC) which is the maturation stage. The long-term exposure to a high temperature above 60 ºC even under waste input and mixing conditions suggests that the majority of weed seeds and pathogens that cause deterioration of the quality of compost could have been effectively killed off (Dahlquist et al., 2007; Noble and Roberts, 2004).

The constant high temperature of the compost beds also suggested fast decomposition of organic materials which allowed a quick turnover of compost within a limited time and space. The available floor space of 151.2 m^2 (21.6 m × 7 m) was in a similar range compared to TCM composting centres in Surabaya City (Maeda, 2009). However, our experience suggested that more space would be needed to treat 1 tonne/day organic waste input in a more relaxed manner. Any increase in space would need to consider the ease of rotation of compost beds and account for extra space for stocking of mature compost and input materials, as well as allowing some flexibility to accept a sudden increase of input amount. The suggested space for 1 tonne/day capacity of TCM would thus be approximately 200 m^2. Compared to other large scale composting processes, this required space was considered to be smaller or at least equivalent. One study has reported that the required space for composting is 529.25 m^2 per tonne of feedstock per day (1.45 m^2 per tonne of feedstock per year) (McDougall et al., 2001). On the other hand, it has also been reported that the required space would be 202 m^2 per tonne of feedstock per day (if a feedstock density of 300 kg/m^3 was applied) (Tchobanoglous and Kreith, 2002). The scaling period of one year by applying a step-by-step approach was considered to be a reasonable timeframe and strategy in terms of avoiding failure, allowing a method of trial and error including adjustments of the separate collection system, and raising the capacity of the operators.

The most notable results of this combined LCA and CBA studies were that the home composting scenario (S3) was the most favourable option to take in terms of both net GHG emissions and NPV among the six scenarios, and the least favourable options were either landfilling (S1) in terms of net GHG emissions, or incineration (S2) in terms of NPV (Figure 6). These results were partly anticipated from similar studies in the past that showed home composting to be one of the best options in terms of least environmental impacts and cost compared to other waste treatment methods (Andersen et al., 2012; Lundie and Peters, 2005; Ray et al., 2020). From a practical point of view, however, expecting the majority of citizens to perform home/communal composting like Kampung Takakura (S3) is not realistic. The TCM's home composting basket gained popularity in Surabaya City where the city government disseminated more than 19,000 units to households free of charge. This was considered to be one of the success factors that contributed to achieving the 30% reduction of waste over five years in Surabaya City (Maeda, 2009). However, Takakura pointed out that the result could not have been so successful without social mechanisms that supported the home composting practices, including training and appointment of environment cadres in each community; effective utilisation of existing social networks (e.g., women's associations); promotion of waste banks (communal junk shops); and city-wide competition on green & clean communities (Takakura, 2016). Kampung Takakura created a way to operate this kind of self-supporting system but a social supporting mechanism is generally lacking in Bandung City and is expected to require a long time to institutionalise. Thus, taking a decentralised or centralised approach was considered to be a more realistic composting option in the case of Bandung City.

The capital costs of infrastructure and equipment for the 200 tonnes/day centralised composting centre (S6) was estimated to be IDR 30 billion (approx. USD 2.1 million) (JICA and Nishihara Shoji, 2016) which is a large amount. However, due to scale merit, NPV of centralised composting centre and 1 tonne/day small scale decentralised composting centres (S4, S5) became comparable at a similar range (Figure 5). Looking at the literature, it has been shown that composting at the centralised plant was the most economically feasible option (Rahim et al., 2012), while another study showed that medium-scale and lower large-scale composting is more financially feasible compared to a smaller and larger capacity (Pandyaswargo and Premakumara, 2014). These results suggested that the cost-effective scale options for composting can vary depending on how comparable conditions are set. In addition, there was minimal difference in NPV between the two decentralised composting options of the static windrow (S4) and TCM (S5). This was considered to be due to exclusion of land prices in the calculation as well as land availability. Considering the time required for the entire composting process, the static windrow requires a larger space than TCM (in this study, it was estimated that the space needs to be four times as large). This is not realistic in Bandung City which is densely populated and where land availability is limited. Therefore, from a practical point of view, a combination of one or a few large centralised composting centres and several small decentralised composting centres distributed throughout the city at strategic locations using TCM would be the most realistic and cost-effective option for Bandung.

A comparison of two different system boundaries enabled a better understanding of the dynamics of GHG emissions and NPV with or without compost application as a fertiliser. The expanded system boundary revealed higher emissions and more costly compared to the core system boundary but the differences were limited (3.6% on net GHG emissions and 10.3% on NPV compared to the BAU scenario). The increase of net GHG emissions under the expanded system boundary was partly expected as the emissions from transportation and use of compost are positive GHG emissions. However, while the benefits gained from replacing mineral fertiliser with compost did not contribute much to the increase of NPV, they were offset by the additional costs incurred by the transportation of compost and labour for gardening works. This suggested that collaboration between the responsible departments on waste management and landscaping in terms of production and use of compost can potentially further reduce net GHG emissions and minimise, if not increase, the reduction of the NPV.

This study applied different emission factors for composting on CH_4 and N_2O to the static windrow (S4) and TCM (S3, S5, S6). Several past studies have demonstrated that aeration of compost beds either by frequent turning, forced aeration, or keeping the compost piles small as well as keeping the appropriate moist content, reduces CH_4 emissions which are usually yielded under anaerobic conditions (Fukumoto et al., 2003; He et al., 2000; Shen et al., 2011; Szanto et al., 2007). On the other hand, N_2O emissions are more complicated. Some studies revealed enhanced ventilation or reducing the pile size reduced N_2O emissions (Fukumoto et al., 2003; Hellebrand, 1998; Shen et al., 2011; Szanto et al., 2007) while other studies showed an increase in N_2O emissions possibly by ammonia oxidization (Ahn et al., 2011; Jiang et al., 2011; Zhu-Barker et al., 2017). To avoid complications, this study used the emission factors of CH_4 and N_2O identified from a controlled laboratory experiment of food waste composting under different temperatures and aeration conditions (Ermolaev et al., 2015). Results from high temperature and aerated conditions (67ºC, O_2 concentration 16%) were used for TCM, and low temperature and limited aeration conditions (55ºC, O_2 concentration 1%) were used for static windrow. As a result, there was a major difference in gross emissions between S4 and S5 (44.9%) but this was reduced to 4.2% by net emissions due to a large amount of avoided emissions from the landfilling and transportation compared to the BAU scenario (Figure 4). This suggested that the advantage of active aeration in terms of reducing GHG emissions may be minimised if the other avoided emissions are large.

Bandung City is composed of 30 sub-districts (*kecamatan*) and 151 administrative villages (*kelurahan*). Assuming that one large centralised composting centre (200 tonnes/day capacity by TCM) will be developed on the outskirts of the city and that each sub-district will be equipped with one small decentralised composting centre (1 tonne/day capacity by TCM), then a total of 230 tonnes/day of food waste can be processed. This corresponds to 20.9% of the baseline amount of waste dumped in landfills from Bandung City in 2017 (1,101.19 tonne/day) (Bandung City Government, 2019a). By applying the results of this study, the potential impact of GHG reduction would be 132 tCO_2-eq/day and NPV would be IDR 16,015,635/day (USD 1,144 /day) of benefits. Based on this assumption, centralised and decentralised composting centres using TCM can make a massive contribution to the achievement of the 30% waste reduction target by 2025 in the *Jakstranas*/*Jakstada*.

Conclusion

A comparative study of combined LCA and CBA between six municipal solid waste treatment scenarios to treat 1 tonne of food waste revealed that home composting was suggested to be the most favourable option while the least favourable options were either landfilling that showed the highest GHG emissions or incineration that showed the lowest NPV. As the home composting was not considered to be a realistic option for wide application, a combination of one large centralised composting centre and a small decentralised composting centre in each sub-district was suggested in the case of Bandung City. This study proved that TCM can potentially contribute to the reduction of GHG emissions and would be a cost-effective tool for municipal solid waste management.

Compliance with Ethical Standards

Conflict of interest: The authors declare that they have no conflict of interest.

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