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Energy recovery potential and life cycle impact assessment of municipal solid waste management technologies in Asian countries using ELP model

Andante Hadi Pandyaswargo*, Hiroshi Onoda and Katsuya Nagata

Abstract

Natural resource scarcity and the effects of environmental destruction have pushed societies to use and reuse resources more efficiently. Waste should no longer be seen as a burden but rather as another source of material such as energy fuel. This study analyzes the potential of three waste management scenarios that include the combination of four waste management technologies - incineration with energy recovery, composting, anaerobic digestion, and sanitary landfill gas collection - as ways to recover energy and material from municipal solid waste. The study applies the environmental load point (ELP) method and utilizes municipal waste characteristics and composition from India, Indonesia, and China as case studies. The ELP methodology employs integrated weighting in the quantification process to get a one-unit result. This study particularly uses analytic hierarchical process questionnaires to get the weighting value of the nine impact categories: energy depletion, global warming, ozone depletion, resource consumption, ecosystem influence, water pollution, waste disposal, air pollution, and acid rain. The results show that the scenario which includes composting organic waste and sanitary landfill with gas collection for energy recovery has medium environmental impact and the highest practicability. The optimum material and energy potential is from the Chinese case study in which 254 tonnes of compost fertilizer and 60 MWh of electricity is the estimated output for every 1,000 tonnes of waste treated.

Keywords: Life cycle assessment, Environmental load point, Waste management, Analytic hierarchical process, Energy recovery, Asian developing countries

Background

Developing countries in Asia have a number of similarities in terms of their waste composition and characteristics. High moisture content due to the high percentage of organic waste composition results in low calorific value. This makes it is less suitable for thermal treatments and more suitable for biological treatments, such as composting and anaerobic digestion. The organic fraction of municipal waste equates to 62% in Indonesia, 63.4% in China, and 41.8% in India [1]. Waste volume in this region increases with the growth of population, urbanization, industrialization, and economic development. Indonesia, with a population of 232.7 million, generates 38.5 million tonnes of municipal waste annually. China, with a population of 1.3 billion, generates 1.8 billion tonnes. India, with a population of 1.2 billion, generates 66.69 million tonnes [1]. Another important waste characteristic is the generation rate per capita per day, which is 0.75 kg in Indonesia, 1.54 kg in China, and 0.2 to 0.5 kg in India, depending on the size of the city. Figures 1 and 2 summarize the waste characteristics in the three countries.

The current common practice of municipal waste treatment in these countries is the use of landfill. Almost 68.86% of waste generated in Indonesia is landfilled, and only 10% of the available landfills meet the requirements for a sanitary landfill. China deposits 56.6% of its municipal waste in landfills. India has a very limited number of sanitary landfills, and thus, open dumping is common and widespread. Incineration is not applied on a large scale in Indonesia, whereas 1.9% of China's municipal waste is incinerated. India initiated several projects to incinerate its waste, such as the 300 t/day capacity incineration plant in Timarpur. However, such projects proved to be unsuccessful [2]. Two pilot projects on incineration plants are ongoing in Delhi, with 1,950 and 1,300 t/day capacities [1]. In Indonesia, composting of

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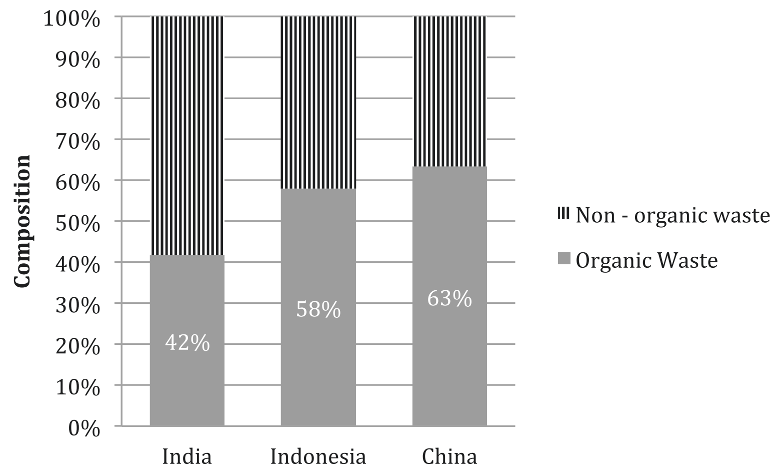

Figure 1 Municipal organic waste percentage in India, Indonesia, and China.

municipal waste is done both on the community level and on the final disposal site and utilizes 7.19% of the waste generated in Indonesia. A respectable 12.9% of waste is composted in China [1]. In India, vermi-composting and windrow composting are practiced in clusters. The municipal waste compost fertilizers often have difficulties in competing with the chemical fertilizers due to lower nutrient content and the presence of heavy metals.

Anaerobic digestion (AD) has proven to be quite successful when applied on a small scale but rather unsuccessful when applied on a large scale. For example, the 20 t/day and 30 t/day AD plants in Nagpur, Lucknow, Vijaywada, and Koyambedu flower market in India failed due to low-quality input [1,3]. Table 1 shows the waste treatment trend in each of the countries in this study.

The main objective of this study is to identify the most appropriate technology to be adopted in the region by using the environmental load point (ELP) methodological approach. Furthermore, this study attempts to measure the environmental impact and energy recovery potential by applying life cycle assessment (LCA) to different scenarios of waste treatment in the three countries. The scenarios proposed are adjusted to the waste characteristics, which can be described as mixed waste with high organic composition. Composting and anaerobic digestion are proposed to favor the high organic composition, incineration is proposed to respond to the mixed state of the waste collected, and landfill gas collection for energy recovery is chosen to make use of the sanitary landfill that already exists in the region.

Methods

Methodological approach

Study areas

Three developing countries in Asia - Indonesia, China, and India - are selected as the study areas to represent Asia because of their similarities in high organic waste

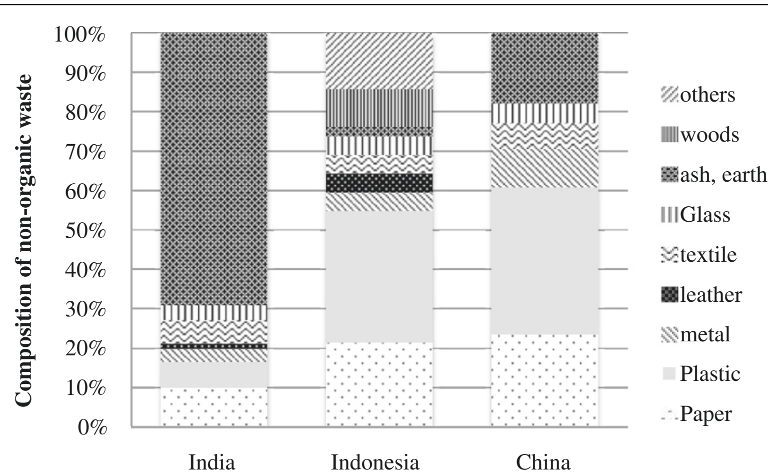

Figure 2 Municipal non-organic waste compositions in India, Indonesia, and China.

Table 1 Current trends of municipal waste treatment technologies applied in the countries

Country	Landfill	Anaerobic digestion	Composting facility	RDF	Incineration facility	Other
Indonesia	68.86% is landfilled; only 10% of the landfills are sanitary landfill	NA	7.19% of the municipal waste is composted	NA	4.49% are burned in the open space, 6.59% are burned in small scale incineration plant	2.99% of the waste are dumped into the river, 9.58% are buried
China	56.6% of waste dumped is into the landfill, and 28.6% are open-dumped	NA	12.9% of waste is composted	NA	1.9% of waste is incinerated	
India	Non-existence of sanitary landfill; open dumping is common	Unsuccessful large-scale AD plants in Nagpur, Lucknow, Vijaywada (20 t/day), and Koyambedu flower market (30 t/day) due to low-quality input	Vermi-composting and aerobic windrow composting are practiced in clusters; product quality is not optimal	Unsuccessful RDF plants in Deonar, Mumbai(80 t/day), Bangalore (5 t/day), Hyderabad (700 t/day), and Vijaywada (600 t/day) due to low calorific value	Unsuccessful incineration plant in Timarpur (300 t/day). Two on-trial incineration plants in Delhi (1,950 t/day) and (1,300 t/day)	

Source: [1]. RDF, refuse-derived fuel.

composition and the current low levels of energy and resource potential utilization.

Data used

Both primary and secondary data were used in this study. Primary data was inventory data collected from the EcoInvent database 2010 and Japan Environmental Management Association for Industry (JEMAI). Secondary data was collected from existing literature on emissions and energy recovery potentials of treatment processes. In addition, a questionnaire survey was conducted at national universities in the selected countries. The data collected was used to weigh the results in order to get a better representation of geographic, social, and political interests in the country [4].

Methodology used

In the year 2002, a thorough guideline of LCA application in municipal solid waste (MSW) was prepared by Nordtest Finland [5]. This guideline, along with ISO14040 [6], ISO 14044 [7], and an LCA methodology study by Finnveden [8], has significant contributions in applying ELP methodology in this study. The ELP methodology is an Excel-based LCA tool that allows for a high degree of adjustability and transparency as well as social factor integration to refine and personalize results. This methodology has been used to assess municipal incinerators and water supply plants as well as product manufacturing factories in Japan [9-12]. The study done by Onoda analyzed six options for municipal waste management in Kitakyushu City. The business of usual incineration + ash landfilling was compared to five other scenarios elaborated in Table 2. The result showed that the scenario where the non-organic waste is incinerated and organic waste is digested anaerobically has the lowest Environmental Load Point, highest energy recovery, and lowest CO_2 emission.

The ELP has nine impact categories. These categories are energy depletion, ozone depletion, acid rain, resource scarcity, air pollution, ocean and water pollution, problem of waste disposal, and ecosystem effect. Each of the impact categories has indicators, such as oil, natural gas, and coal for energy depletion; CH_4 and CO_2 for global warming; chlorofluorocarbon and hydrofluorocarbon for ozone depletion; NO_x and SO_x for acid rain; Fe, Ni, Sn, Au, and Ag for resource scarcity; PM_{10} and $PM_{2.5}$ for air pollution; biological oxygen demand (BOD), chemical oxygen demand (COD), and suspended solids for ocean and water pollution; solid waste for problem of waste disposal; and

Table 2 Previous ELP study result on Kitakyushu municipal waste management scenarios

Case	Scenario	ELP	Energy recovery	CO_2 emission
1	Incineration (electric) + ash landfilling	100	100	100
2	Incineration (electric) + ash melting + ash landfilling	93	100	102
3	Incineration + ash melting + metal recycling	92	100	102
4	Direct melting (gas) + ash landfilling	98	95	103
5	Direct melting (gas) + metal recycling	96	95	104
6	Incineration (electric) + organic waste anaerobic digestion	91	125	99

Since the processes are similar, the figures were adjusted relative to business as usual (case 1) as baseline unit (100). Source: [11].

petrol, benzene, and dioxin for ecosystem effect. The complete list of indicators is comprised of 186 items. Table 3 shows the impact categories and the indicators relevant to this study that were incorporated for analysis.

The mathematical equation for the LCA model consists of a three-step calculation. The first step is determining the annual load (*A*). *A* is the result of multiplying the weight coefficient of each item in the impact category fixed by the laboratory literature (*C*) listed in Table 3 with the national annual consumption and emission (TQ).

Equation 1. Annual load formula

$$A_j = \sum_k \left(C_{j,k} \times TQ_k\right) \quad (1)$$

Aj, annual load in j impact category
$C_{j,k}$, weight coefficient for *k* indicator in *j* impact category
TQ_k, annual consumption or emission for *k* item
Suffix *j*, impact category
Suffix *k*, indicator in impact category

The second step is to calculate the environmental load factor (ELF), which is the result of multiplying the coefficient (*C*) listed in Table 3 and the weighting value (*W*), divided by the annual load (*A*) from the Equation 1 results. The weighting value (*W*) is derived from surveys and questionnaires of the related stakeholders or communities. In this study, the methodology of analytic hierarchical process (AHP) questionnaire was adopted.

Equation 2. Environmental load factor formula

$$ELF_k = \sum_j \left(C_{j,k} \times {W_j}/{A_j}\right) \quad (2)$$

ELF_k, integrated coefficient for *k* item

Table 3 ELP impact categories

Impact category (*j*)	Indicators (*k*)	Weight coefficient (*C*)[a]
Energy depletion	Oil, natural gas, coal	0.089
Global warming	CO_2, CH_4	0.082
Ozone depletion	(not used in this study)	0.098
Acid rain	NOx, SOx	0.086
Air pollution	SO_2, NO_2, CO, $PM_{2.5}$, PM_{10}	0.072
Resource consumption	Iron (Fe), nickel (Ni), tin (Sn), aluminum (Al), gold (Au), silver (Ag)	0.134
Ocean and water pollution	BOD, COD	0.135
Problem of waste disposal	Slag, residues	0.107
Ecosystem influence	(Not used in this study)	0.197

[a]Fixed by laboratory and literature result [13].

W_j, weight coefficient (category importance) from questionnaire in *j* impact category
$C_{j,k}$, weight coefficient for *k* indicator in *j* impact category
A_j, annual load in *j* impact category
Suffix *k*, indicator in impact category
Suffix *j*, impact category

The final step is multiplying the ELF with the total indicator's consumption or emission of the process or production of the related MSW technologies from the EcoInvent database to get the environmental load point as the final output. Equation 3 shows the formula used for this calculation.

Equation 3. Environmental load point formula

$$ELP_i = \sum_k \left(ELF_k \times Q_{i,k}\right) \quad (3)$$

ELP_i, integrated indicator
ELF_k, integrated coefficient for *k* indicator
$Q_{i,k}$, total consumption or emission for *k* indicator in process *i*
Suffix *i*, process or product
Suffix *k*, indicator in impact category

Life cycle and impact assessment

Goal and scope definition

To find the most appropriate municipal solid waste management (MSWM) technology by using the ELP methodology, this study selected the most relevant six categories out of the nine available ELP impact categories. The six categories covered in this study are energy depletion, global warming, acid rain, resource consumption, air pollution, and waste disposal. The functional unit of the LCA study has been set as thousand metric tonnes. The incorporated inventory data are the resources taken from nature and the emissions released into the air and soil. The indicators taken into account in this study are oil, natural gas, coal, CO_2, CH_4, NO_x, SO_2, Fe, Ni, Sn, Al, Au, Ag, SO_2, CO, $PM_{2.5}$, PM_{10}, slag, and residue from the waste management processes. The emission factors of conventional electricity production are taken from the electricity grid fuel mix of the country. The study estimated the emission from both the mining process and the power plants of fossil fuel-based electricity substituted by the energy recovered from the waste treatment processes. The study also estimated the net energy recovery potential of waste treated in each country as well as the emission from mineral fertilizer production substituted by the compost fertilizer.

System boundary

The transport distance of waste from the sources to all process systems is assumed to be equal, and therefore, it is excluded from the system boundary. It is also assumed that the heat recovery, although identified in kWh-heat, is not usable due to the lack of a district heating system in the region. Due to the absence of a district heating system in the majority of the area in the region, the calculated heat recovery is not considered in the environmental impact avoided. However, further study on a cooling system by a heat exchanger that utilizes the heat waste would be recommendable. The other assumption is that the inventory data for each process are similar to those of the European and the Japanese databases available, which is why the use of local input data, such as waste composition, national emission and resource consumption, and the survey and questionnaire, provides significant contributions in personalizing the results of this study.

Inventory data analysis

Inventory data for the processes involved in the study were taken from the EcoInvent database 2010 [14], the JEMAI, and from literature that examined the existing local processes. The three scenarios constructed for the MSW treatment are a mix of incineration, sanitary landfilling, composting, and anaerobic digestion. In scenario 1, the entire amount of the mixed municipal waste is incinerated. In scenario 2, the organic waste is composted whereas the rest of the waste is landfilled in the sanitary landfill. The CO_2 and CH_4 (biogas) from the sanitary landfill are collected for energy recovery with a cogeneration unit. In scenario 3, the organic waste is digested anaerobically, and the rest of the waste is to be landfilled in the sanitary landfill, with the biogas emitted being collected for energy recovery. The desired output of the first scenario is electricity and heat. The desired output of the second scenario is electricity and compost fertilizer. The desired output of the third scenario is digested matter, which can be used as soil conditioner, and biogas to generate electricity. To estimate the emission avoided from fossil fuel-based electricity, the mining and electricity production from coal, natural gas, hydropower, and crude oil are accounted. Table 4 summarizes the scenarios and the desired output. The system boundary of each scenario is elaborated in Figures 3, 4, and 5.

MSW treatment technologies

MSW may be treated thermally or biologically. Thermal treatment includes incineration, pyrolysis, and gasification, while biological treatment includes anaerobic digestion and composting. Thermal treatment requires high calorific value. Therefore, dry combustible waste such as plastic, rubber, and paper are desirable for this treatment. Biological treatment requires high organic content. Therefore, food waste and garden waste are desirable for this treatment methodology [15]. In this study, the technologies adopted in the scenario constructed are (1) sanitary landfill, (2) incineration, (3) composting, and (4) anaerobic digestion.

Table 4 Scenario and output

Case	Scenario	Desirable output
1	Incineration + energy recovery	Electricity, heat
2	Composting + sanitary landfilling + landfill gas collection for energy recovery	Fertilizer, electricity, heat
3	Biogas + sanitary landfilling + landfill gas collection for energy recovery	Digested matter, electricity, heat

Sanitary landfill Landfill is still the common practice of MSWM in the developing world. Sanitary landfills, although quite limited in number, exist especially in larger cities. A sanitary landfill has a proper leachate capture system and liners to prevent contamination of the groundwater. Although landfill is a less preferable solution, especially for non-inert waste, due to the limited lifetime (30 to 50 years) and slow biodegradation process for organic waste [16], sanitary landfill is selected in this study as an option because of the possibility of landfill gas collection for energy recovery. Sanitary landfill inventory data used in this study include landfill gas incineration and landfill leachate treatment in the wastewater treatment plant (WWTP) as well as the WWTP sludge disposal in the municipal incinerator.

Incineration Incineration is perceived as a costly solution for MSWM due to its operational energy requirements and the flue gas treatment. It is also technically feasible only for a relatively high calorific value of 1,433 kcal [17], which is often quite high for developing Asian countries' waste to meet. For example, the calorific value of Indian waste is only 700 to 1,000 kcal [18]. However, modern incinerators have improved with efficient combustors and flue gas treatments [16]. Moreover, some plants add auxiliary fuels like crop waste and/or tires to improve the calorific value. Significant amounts of methane gas released into the atmosphere are not achieved with this technique, especially when compared to the landfilling option. The inventory data used in this study for incineration include the landfilling of the residual materials, such as the fly ash and the scrubber sludge. The energy recovery potential per kilogram of waste incinerated is elaborated in Table 5.

Composting Composting organic biodegradable waste takes a significant amount out of the waste stream going to incineration and landfill. This implies less

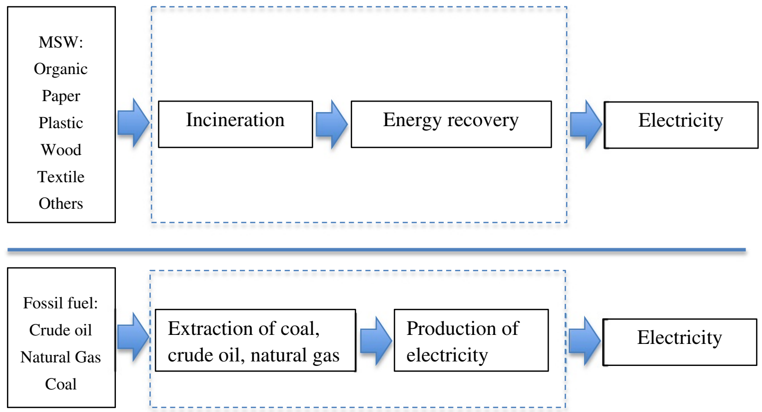

Figure 3 Scenario 1. Incineration + energy recovery (above the line) and the replaced process to produce the same amount of energy with the business as usual practice (below the line).

landfill gas and leachate production. The bigger-scale composting plants in developing Asian countries often use open windrow composting. This aerobic composting approach typically takes about 4 to 6 weeks to reach the stabilized end-product stage. The composting process in this study incorporates emissions both from the energy demand for plant operation and infrastructure. The assumed water content is 50% by weight [15]. The assumed replaced mineral fertilizer is potassium nitrate (KNO_3), as N. This mineral fertilizer has N content of 14%, while that of the municipal waste compost fertilizer ranges from 10% to 22% [19,20]. The release of N from mineral fertilizer is, however, quite significant in the first year (up to 80%) and low in the following years, while municipal waste compost fertilizer releases N gradually throughout the years (about 10% per year) [5]. Therefore, the amount of replaced mineral fertilizer is assumed to be equal.

Anaerobic digestion Anaerobic digestion is by far more efficient when compared to collecting landfill gas as the waste is processed in a closed container with conditioned temperature and the absence of oxygen creates the optimal environment for biogas generation. A study shows that a ton of waste in a controlled anaerobic digestion produces two to four times more methane in 3 weeks than a ton of waste in a landfill would produce in 6 to 7 years [21]. The input of

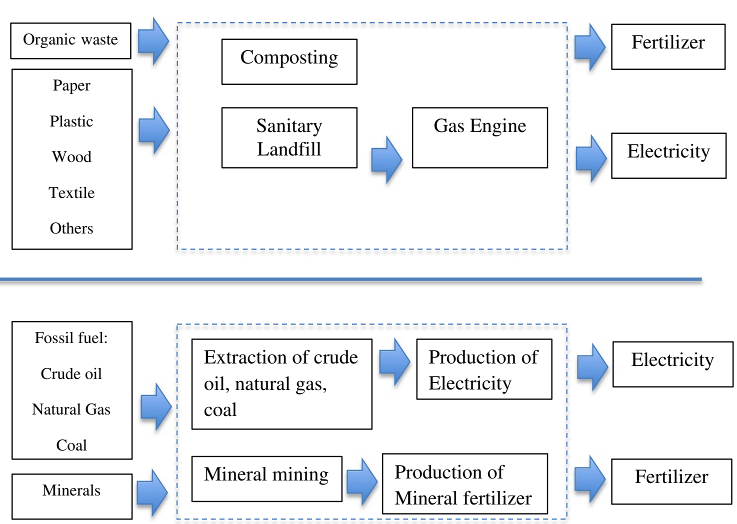

Figure 4 Scenario 2. Composting + sanitary landfill + energy recovery (above the line) and the replaced processes to produce the same amount of output with business as usual (below the line).

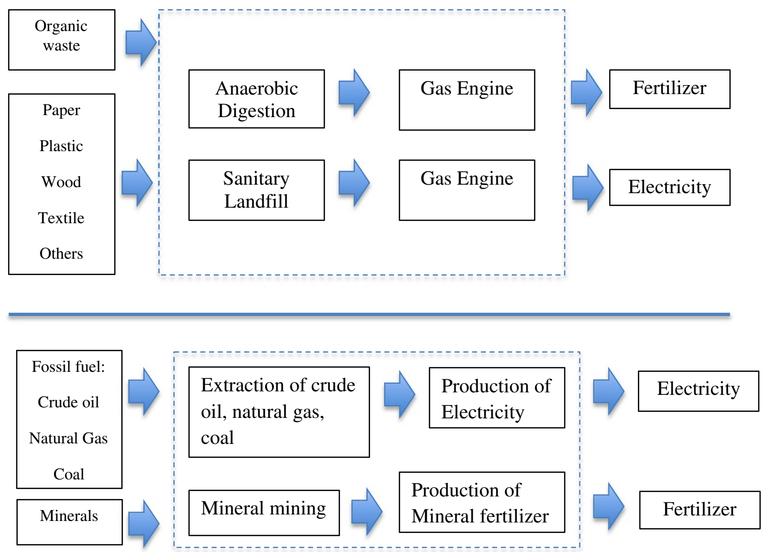

Figure 5 Scenario 3. Anaerobic digestion + sanitary landfill + energy recovery (above the line) and the replaced processes to produce the same amount of output with business as usual (below the line).

anaerobic digestion should contain relatively pure organic material, the output being biogas with 55% to 60% CH_4 and 40% to 45% CO_2 that can be burned in a gas engine to generate electricity, and the residue being in the form of digested matters which can be used as soil conditioner. While biogas contains both CH_4 and CO_2, only CH_4 is considered to be convertible to electricity. Additionally, the heat value assumed in this study is 6 kWh/m^3 CH_4 [5]. The assumed digested matter usable as soil conditioner (fertilizer) in this study is 40% of the organic matter input. Spreading the product fertilizer from this process might take more energy when compared to mineral fertilizer because the nutrient content is less; thus, a larger amount is required. For this reason, the emission from the spreading activity is included.

Table 5 Electricity generated from waste incineration energy recovery

Type of waste	Net electricity produced per kilogram of waste treated (kWh/kg)
Biowaste	0.04
Paper	0.36
Plastic	0.96
Glass	0
Wood	0.36
Textiles	0.37
Others (20% water content)	0.28

Source: EcoInvent database, 2010.

Replaced fossil-based electricity

The substituted electricity uses the national electricity grid thermal fuel mix. For example, in Indonesia, the fuel mix for JAMALI (Java, Madura, Bali) is used. This grid that provides 78% of the national electricity consumption [22] utilizes 53.7% natural gas, 18.74% coal, and 27.69% oil [23]. For China, the consumption of coal, oil, and gas of a thermal power plant is 96.62%, 1.87%, and 1.51%, respectively [24]. For India, the coal-based thermal power plant air emission [25] and the fuel mix of the thermal power plant, which is 82% coal, 17% gas, and 1% diesel [26], were used.

Results and discussion

The result of the first equation (*A*) is summarized in Table 6. The TQ value required for this calculation was collected from the government and institutions that provide the national annual consumption and emission of the related country, such as the US Energy Administration for the energy consumption [27], the Indonesian Ministry of Environment for the greenhouse gas (GHG) emission of Indonesia [28], and the United Nations Statistics [29], a study of air pollution in Asia [30], mining product consumption information from the National Statistics Office [31], China Mining Association [32], and index mundi [33].

To get the *W* value for the second step of the calculation using Equation 2, AHP questionnaires were distributed. Respondents are randomly selected from faculties in top universities in the related countries, such as the Institute of Technology Bandung, Indonesia, University of Delhi, India, and Beijing University, China. University students were selected as group of respondents for the

Table 6 Annual load results derived by equation 1

Impact category	India	Indonesia	China
Energy depletion	6.46E+10	1.49E+12	2.58E+12
Global warming	1.86E+13	1.00E+11	1.21E+14
Acid rain	9.00E+09	1.80E+09	4.56E+10
Resource consumption	2.46E+11	1.80E+09	1.62E+11
Air pollution	2.10E+10	2.10E+10	1.00E+11
Waste disposal	4.20E+10	4.20E+10	1.80E+09

ease of regular updating and comparability across countries. Figure 6 shows the questionnaire results. In the questionnaire, respondents were asked to compare and rate which of the nine ELP impact categories deserve the priority of concern in their countries and which deserve less. According to the total 300 university students surveyed in the three countries, energy depletion comes in the first rank of the most important impact category in Indonesia and China, while global warming is the most important issue in India. On the second rank is global warming in Indonesia, resource consumption in China, and ozone depletion in India.

Table 7 summarizes the ELF result. ELF is the value of ELP per kilogram emission or resources emitted or consumed in a process. Figure 7 summarizes the total of ELP quantification results of the three scenarios constructed in each country. The description of the results is described country-wise for each impact category, followed with a logical discussion in order to support the results.

The major findings extracted through our analysis are following:

India

The environmental load of the 'energy depletion' impact category in the Indian case study is lowest in scenario 1, second lowest in scenario 3, and highest in scenario 2. This is because electricity replaced by energy recovered in the incineration plant significantly reduced the consumption of coal and natural gas in the fossil-based fuel thermal power plant. The 'global warming potential' impact category is lowest in scenarios 2 and 3. This is mainly due to the biological processes in these scenarios which take out CH_4 from the global warming potential, as well as the subsequent conversion of this gas into electricity. The 'acid rain' impact category, which consists of

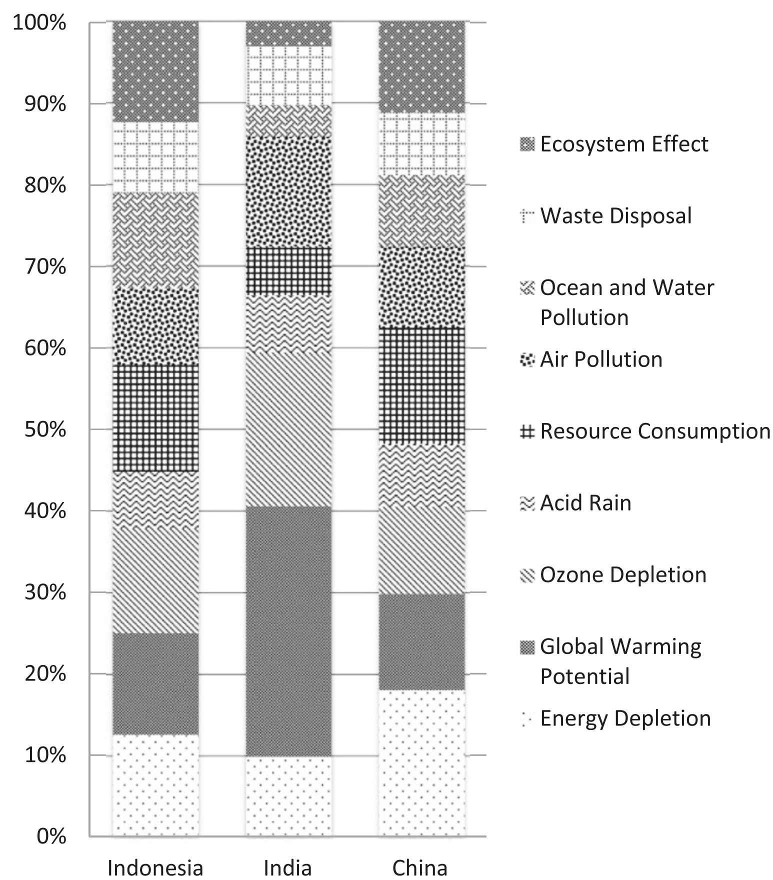

Figure 6 Weighting values from the AHP questionnaire.

Table 7 ELF results derived by equation 2

Impact category	India	Indonesia	China
Energy depletion	3.65E+09	8.25E+06	2.55E+07
Global warming	1.52E+05	1.02E+06	1.02E+06
Acid rain	2.94E+05	9.36E+05	9.36E+05
Resource consumption	3.25E+02	4.59E+09	4.59E+09
Air pollution	1.31E+06	3.24E+07	3.24E+07
Waste disposal	1.70E+04	2.37E+04	2.37E+04

NO_x and SO_2 as indicators, has the lowest impact in scenario 2, second lowest in scenario 3, and highest in scenario 1. The biggest contribution is from the avoided NO_x emission from the production of mineral fertilizer. The 'resource consumption' impact category, which has Fe, Ni, Sn, Al_2O_3, Au, and Ag as indicators, has the lowest environmental load in scenario 3, followed by scenarios 2 and 1, as the amount of fertilizer produced by anaerobic digestion replaces the production of mineral fertilizer. The 'air pollution' impact category has the lowest environmental load in scenario 1, followed by scenarios 2 and 3, especially because of the NO_x emission from the biogas and landfill gas cogeneration units. The 'waste disposal' impact category is highest in scenario 1 because the amount of inert material contained in Indian municipal waste produces significant amounts of slag and residues.

From the three scenarios proposed in the Indian study, the lowest environmental load is from scenario 1, in which the whole volume of municipal waste is incinerated. This result is mainly contributed by the significant amount of coal (82%) used in the Indian electricity grid fuel mix. Moreover, the weighting from community survey by the AHP questionnaire in this study ranked global warming potential and air pollution in the top three most concerning environmental issues in India. The estimated net electricity generated from combusting 1,000 tonnes of Indian waste in the incineration plant is 208 MWh.

In reality, incineration is not feasible for Indian waste due to its low calorific value. The refuse-derived fuel (RDF) method, which increases the calorific value of waste by taking out the moisture content by gasification and pelletization before feeding it to the incineration plant, is practiced. The product of RDF is often mixed into the coal power plant [1].

Indonesia

The environmental load of the 'energy depletion' impact category in the Indonesian case study is lowest in scenario 3, mainly due to the avoided energy to produce the mineral fertilizer replaced by the digested matter from anaerobic digestion. The 'global warming potential' impact category, whose indicators are CH_4 and CO_2, is lowest in scenario 3, mainly because of the closed tank of anaerobic digestion preventing gas release into the atmosphere and enabling its conversion into electricity. The 'acid rain' impact category is lowest in scenarios 2 and 3, mainly because of the emission avoided from the

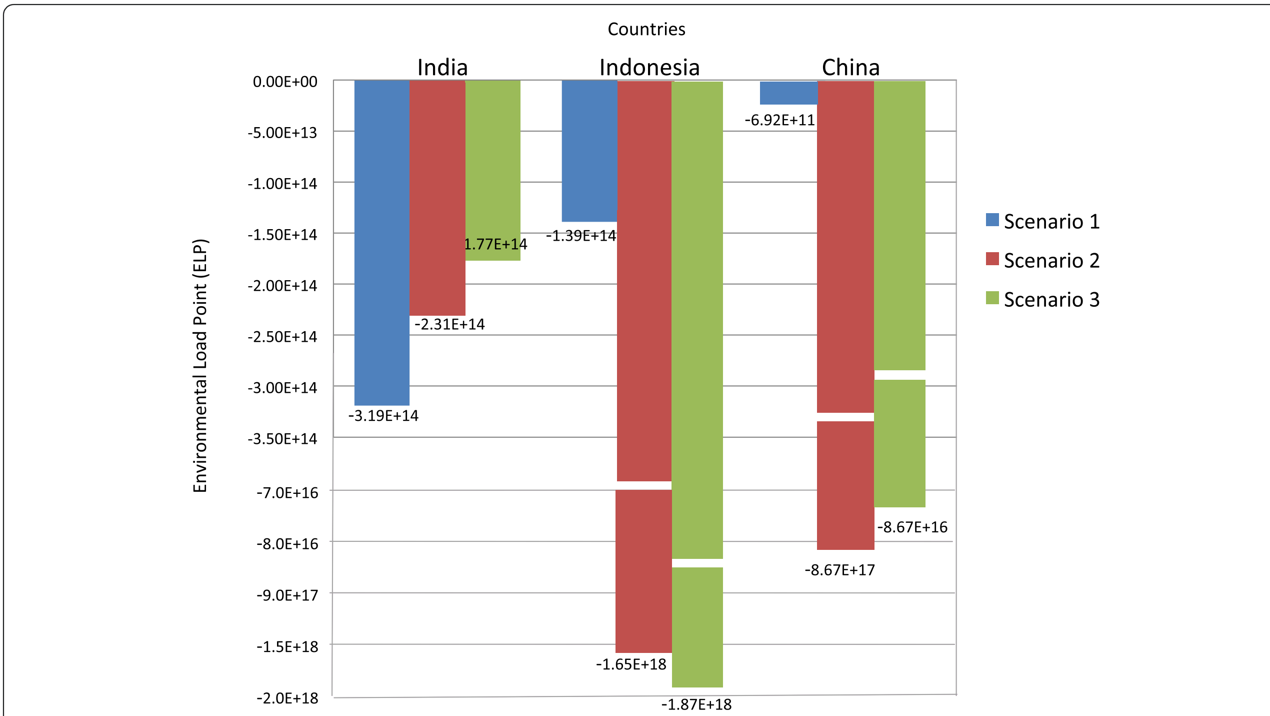

Figure 7 Total ELP of scenarios 1, 2, and 3 in India, Indonesia, and China.

production of replaced mineral fertilizer. Similarly, the lowest environmental load for the 'resource consumption' impact category also lies in scenarios 2 and 3 because of the resources saved from the replaced mineral fertilizer production. The 'air pollution' impact category is highest in scenario 1 and lowest in scenario 3, mainly because of the CO and NO_x emitted by the incineration plant. The 'waste disposal' impact category is highest in scenario 2 due to the amount of waste going to the landfill plus the residual waste from the composting activity.

Among the three scenarios in the Indonesian case study, scenario 3, which is anaerobic digestion for the organic waste content and landfill gas collection for energy recovery, has the least environmental load. This is mainly contributed by the digested matter replacing mineral fertilizer. The fertilizer produced is a co-benefit of anaerobic digestion. This means that no additional input of energy or resources is required to produce fertilizer, and all of the potential energy is captured within the closed container of the biogas plant. Moreover, the Indonesian survey results for weighting rank resource consumption as the most important impact category. The estimated electricity recovered from anaerobic digestion in the Indonesian waste case study is 32.7 MWh for every 580 tonnes of organic waste treated, and the estimated electricity recovered from landfill gas collection is 57.7 MWh for every 370 tonnes of non-inert, non-biowaste dumped in the sanitary landfill. The estimated amount of digested matter for soil conditioner is 232 tonnes for every 580 tonnes of organic waste treated in the anaerobic digestion plant.

In practice, the technology of large-scale municipal waste aerobic digestion is not popular in Indonesia [34]. This technology is commonly applied to animal slurry or agricultural waste because of the pure organic waste content. However, countries like the Netherlands, Sweden, and Switzerland have fully developed anaerobic digestion plants for handling municipal waste [15].

China

The environmental load of the 'energy depletion' impact category in the Chinese case study is lowest in scenario 2, mainly due to the avoided coal and oil for mineral fertilizer production. The 'global warming' impact category is also lowest in scenario 2, mainly because of the avoided CO_2 emission from the production of the replaced mineral fertilizer. The lowest environmental load in the 'acid rain' impact category is in scenario 3 because of the avoided NO_x and SO_x emission from the replaced mineral fertilizer production. In the 'resource consumption' impact category, scenario 3 has the lowest environmental load. The biggest contribution to the load reduction is from the avoided iron and nickel consumed in the production of replaced mineral fertilizer. The impact category of 'air pollution' has the lowest environmental load in scenario 2. The $PM_{2.5}$ and NO_x emission avoided from the replaced mineral fertilizer have the biggest contribution to this result. Finally, the highest environmental load in the 'waste disposal' impact category is scenario 2 because of the higher amount of waste composted, resulting in a higher amount of residual waste from the composting activity.

Among these three scenarios in the Chinese case study, scenario 2, which is composting for organic waste and sanitary landfill with energy recovery, has the lowest environmental load point for the Chinese case study. This is mainly due to the large percentage of organic waste (63%) within the Chinese waste composition and the weighting of resource consumption as being the second most important impact category. Moreover, the impact category of waste disposal is scored as the lowest weight by the Chinese survey respondents. This makes the volume of waste dumped in the sanitary landfill less significant.

In practice, large-scale composting is practiced in large Chinese cities such as Beijing, Shanghai, and Urumqi. These plants are often registered as Clean Development Mechanism projects, receiving carbon credits [1]. The estimated compost fertilizer produced in the Chinese second scenario case study is 254 tonnes of waste for every 630 tonnes of waste treated. The recovered energy from landfill gas collection is 60 MWh for every 246 tonnes of non-inert, non-biowaste dumped in the sanitary landfill.

Considering the salient results, this study suggests scenario 2 (composting) as the preferable option because of its appearance as the second best option in two of the countries (India and Indonesia) and as the best option for China. This means that the environmental impact and risk of failure are considered as medium compared to the other options. This scenario also offers a significant amount of energy recovery potential from the sanitary landfill.

Conclusions

This study tried to analyze the LCA impact assessment using an ELP model for the very first time in the three selected Asian countries. Each goal that was set at the start of the study was achieved, and it was concluded that each country in this study gave different resulting scenarios of the lowest environmental load. The best result for the Indian case is the scenario with incineration; for the Indonesian case, the best result is the scenario with anaerobic digestion, and the best Chinese result is the scenario with composting. These are a reflection of what is most valued in the country based on the university students' questionnaire results, the waste characteristics, the country's annual emission and consumption, as well as the emission and energy recovered by each of the technology options. The unique and different results for each country show that the ELP methodology has the potential to provide personalized results that incorporate technical and social considerations.

This study was a preliminary effort to apply this methodology, and the results are only theoretical estimations. Future research in this field could enhance the results of this study by including economic and social evaluations of each scenario or by increasing the scope of countries to obtain a larger data field for validation.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
AHP carried out the country-specific research, collected the questionnaires, and wrote the manuscript, tables, and figures. HO conducted the previous applied studies in Japan and collected the other previous studies using similar methodology for the references. NK developed the methodology. All authors read and approved the final manuscript.

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