



The potentials of landfill gas production: a review on municipal solid waste management in Indonesia

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Abstract

Municipal solid waste (MSW) becomes a complex problem in Indonesia due to various reasons such as the increase of population, increasing quantity of waste, environmental health caused by unorganized waste, and also lack of public awareness. Various considerations have influenced the methods of waste management in different countries, such as amount and type of waste produced, type of waste collection, available area, and environmental regulations practiced. One of the methods suitable for MSW condition in Indonesia is landfill gas (LFG) production. This study reports about the MSW management in Indonesia, which main focus is the landfill gas production using the LandGEM equation and Intergovernmental Panel on Climate Change (IPCC) methodology. Both approaches are applied to several cities in Indonesia including Medan, Jakarta, Semarang, Yogyakarta, Denpasar, Pontianak, and Makassar which has a higher percentage of waste generated compared to other cities. The findings of this paper indicated that 20.23×10^6 tons/year MSW produced in Indonesia could generate as much as 875,130 tons/year of methane as the main component of landfill gas. As additional information, this amount of waste theoretically could generate 54,142 MW electricity/year.

Keywords Indonesia waste production · Landfill gas production · Municipal solid waste · LandGEM equation · IPCC methodology

Abbreviations

MSWT	Total municipal solid waste generated (tons)	CO ₂	Carbon dioxide
MSW _F	Fraction of municipal solid waste disposed of to landfills	CH ₄	Methane
MCF	Methane correction factor	MTOE	Million tons of oil equivalent
DOC	Fraction of degradable organic carbon	GDP	Gross domestic product
DOC _F	Fraction of total DOC that actually degrades	TPS	Intermediate disposal site
F	Fraction of methane in LFG	GHG	Greenhouse gas
P	Fraction of papers in municipal solid waste	GtCO ₂ e	Giga ton CO ₂ equivalents
K	Fraction of kitchen garbage in municipal solid waste	LFG	Landfill gas
W	Fraction of woods/leaves in municipal solid waste	MoE	Ministry of environment
MSW	Municipal solid waste	EPA	Environment protection agency
		Mt	Million tons
		IPCC	Intergovernmental panel on climate change
		CDM	Clean development mechanism
		NGO	Non-governmental organizations
		3R	Reduce, reuse, recycle

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Introduction

Energy crisis, environment pollution and climate change due to carbon dioxide (CO₂) produced from the use of fossil fuels are the serious challenges to people worldwide. This circumstance attracts more public attention in the development

and utilization of alternative, non-petroleum-based renewable sources of energy to slow down global warming and develop a society in an environmentally sustainable method. It is critical today to focus on the use of existing limited resources and to identify new technologies and renewable resources for future energy supply [1]. For a long time, various sources of renewable energy are being investigated to meet the increasing energy consumption rate. The developing countries, such as Indonesia, are going ahead to face the shortage of available energy. Currently, the final energy supply in Indonesia is dominated by oil, gas, and coal which totally achieved 95.8% of the final energy consumption of 97 MTOE [2].

Indonesia is a country with about 242 million total populations, comprised of 33 provinces, 17,508 islands, and around 1890,000 km² total area. Indonesia has a high population growth rate which is about 1.2% per year [3]. The Gross Domestic Product (GDP) growth rate in Indonesia averaged at 5.0% p.a. from 2013 to 2016. This growth average will be stable at 5.0% until 2021 based on the forecast of the Economist Intelligence Unit [4]. In line with the GDP growth rate, the energy and electricity demand in Indonesia has increased significantly. The electrification ratio and electricity consumption vary across the Indonesian archipelago. The national electrification ration in 2016 was 91.16% with uneven distribution. The more the industrialized areas, such as the western parts of the country, the higher the ratio, as high as 99.98% (DKI Jakarta). Meanwhile, the eastern parts of Indonesia have a lower ratio as low as 4.78% (Papua). The electrification ratio in Indonesia is set to increase to 97.4% by 2019 and to 99.7% by 2025 based on the 2017–2026 PLN Electricity Supply Business Plan [4]. In 2018, electricity consumption per capita in Indonesia is 199 billion kWh/year which is considered higher compared to some low–middle-income countries such as Vietnam (134 billion kWh/year), Philippine (74 billion kWh/year), Pakistan (86 billion kWh/year), Lao PDR (4 billion kWh/year), Cambodia (5 billion kWh/year), and Sri Lanka (12 billion kWh/year) [5].

Meanwhile, the rapid development in population and acceleration of economic activity give rise to higher volumes of organic wastes, plastic packaging, and industrial by-products. The increment of waste amount without strict waste management further has created the tendency of waste accumulation at the end point, landfill [6]. In Indonesia, Municipal Solid Waste (MSW) becomes a complex problem due to a variety of reasons such as the increasing quantity of MSW, lack of public awareness, and complicated municipal administration policies in different cities and surrounding regencies [7]. Other than the high waste generation over the past decade which is about 0.8 kg to 2.1 kg/capita/day, several problems regarding waste management in Indonesia exist such as low quality of waste management, limited final disposal sites, and financial problems [8,

9]. The amount of waste generated and low-quality waste management have created problems in almost all steps of waste management including storage, collection, transferring, and transporting [7]. Commonly, the collected waste is brought to intermediate disposal site (in Indonesia is called TPS). It is estimated that a total of 59,000 TPS are scattered throughout Indonesia. In most cases, these wastes are then transported to the landfills near the area using waste transportation trucks. However, approximately 31% of waste in Indonesia is not collected by the municipal services. This non-collected waste is managed by the communities themselves in terms of collection, transportation to dump sites, buried, composted, burnt in the open air, or thrown into the rivers [10, 11]. The percentage of MSW handling methods is shown in Fig. 1 [10, 11].

From the environmental point of view, the waste sector is the fourth biggest greenhouse gas (GHG) emission contributor among other sectors such as forestry, agriculture, and industry [12, 13]. According to the Indonesia GHG inventory, in 2000, the net emission of GHG in Indonesia was 1.38 Giga ton CO₂ equivalents (GtCO₂e) and will become 2.95 GtCO₂e in 2020. Improper waste management not only led to CO₂ emission but also methane (CH₄) emission. Methane has a 21% higher global warming than CO₂. It is, therefore, not surprising that eliminating methane emissions from MSW can substantially lower the world's overall GHG emissions [13]. On the other hand, MSW is considered as one of the most promising options for the production of Landfill Gas (LFG) which acts as an alternative source of energy [14].

Different LFG prediction models are available based on zero-order equation such as EPER Germany, and SWANA zero order; first-order decay equation such as LandGEM,

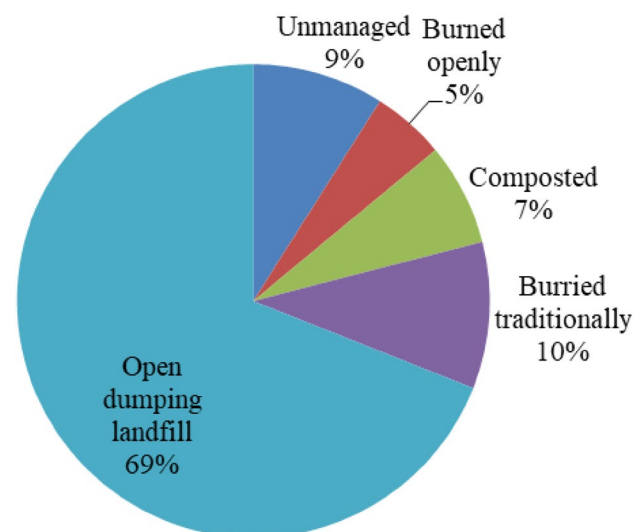


Fig. 1 Indonesia's MSW handling methods [10] [11]

Intergovernmental Panel on Climate Change (IPCC), SWANA TNO, GasSim, Afvalzorg, EPER France, Mexico, and LFGGEN. Complex mathematical model such as Halvadakis method is also available which is considered hard to be calculated since it follows the carbon in methane production chain from solid carbon up to carbon in CH_4 [15]. IPCC and LandGEM are commonly used in several previous studies to predict the potential LFG (methane) production.

Several measurements have been done in Indonesia which indicates the high potential of LFG production in several cities. The measurement also becomes important to discover whether the LFG produced is feasible to be mined and recovered. In 2007, the Indonesian agency for the assessment and application of technology (BPPT) had carried out the direct LFG measurement using equation LandGEM published by the environment protection agency (EPA) under the United States [16, 17]. Asiyanthi et al. has conducted a field survey to measure CH_4 concentration on three Indonesian landfill sites: Bantar Gebang landfill in Bekasi, Cipayung landfill in Depok City, and Tamangapa landfill in Makassar City [18]. They were using Laser Methane Detector (LMD) and pole measurement to measure ambient CH_4 concentration, LMD and chamber to measure CH_4 flux, and Geotechnical Analysis (GA) 2000 for analyzing underground CH_4 concentration [19, 20]. The highest ambient CH_4 concentration in Bantar Gebang, Cipayung, and Tamangapa landfill sites are 1,718.2 ppm, 4445.2 ppm, and 3043.2 ppm. The highest CH_4 flux in Bantar Gebang, Cipayung, and Tamangapa landfill sites are 74.23 $\text{g/m}^2/\text{h}$, 53.55 $\text{g/m}^2/\text{h}$, and 53.70 $\text{g/m}^2/\text{h}$, while underground CH_4 concentration measurement are 52.93%, 54.40%, and 53.83% for Bantar Gebang, Cipayung, and Tamangapa, respectively [18]. Alan et al. has observed the potential of landfill gas production in Basirih final disposal site in Borneo Island to be developed into a waste power plant using LandGEM equation [17]. The result shows that the Basirih final disposal site has a potency to produce landfill gas as much as 8,176,975 m^3/year which can be converted into 12,848,929 kWh electrical power [17].

This paper is expected to provide comprehensive information regarding waste in Indonesia, including policies, the technology to convert waste into energy, landfilling and LFG potential production, and also challenges in waste management in Indonesia. Moreover, this study also describes the significance of contribution of waste as a renewable energy resource as well as for renewable energy generation.

Waste policies in Indonesia

Compared to other developing countries, the level of MSW management quality in Indonesia provided by the municipalities is rather low. Inadequate waste regulations,

low implementation, low budgets and low private participation are some of the causes for the low level of service in MSW Management. Regarding the waste policies, the first regulation on MSW in Indonesia is a National Regulation no. 21/PRT/M/2006 on the National Policy and Strategies for the Development of Waste Management System issued by The Minister of Public Works [21]. This regulation addressed that communities should be involved in waste management. However, in this law, the methods and techniques of sustainable waste management were not yet provided, therefore, resulting in negative impacts on environmental health [21, 22]. To overcome this problem, the President of the Republic of Indonesia enacted Act no. 18 the year 2008 on waste management that covers public service principles, waste minimization, handling of domestic solid waste and specific waste, incentives and disincentives mechanism, local government responsibility, financial system, and also private and public sector participation [8, 22, 23]. It is stated in the Act that the management of wastes should be done in a comprehensive and integrated manner to give economic and health benefits, and environmentally safe [8], [22]. However, this law was considered weak in terms of accommodating regional waste regulations [10].

Another regulation regarding waste management in Indonesia is Regulation of The Minister of the Interior no. 33 of 2010 on The Guidelines for Waste Management [24]. According to this regulation, waste management is systematic, comprehensive, and continuous activities including planning, reducing, and handling the wastes. The management of waste by local authorities is conducted through sorting, collection, transportation, treatment, and final disposal of waste [17, 25, 26]. The latest regulation about waste in Indonesia is the Act no. 81 the year 2012 as an implementation of Act no. 18 year 2008 [27]. One aspect that is emphasized in this legislation is to provide the implementation of the 3R (reduce, reuse, and recycle) by requiring the citizens to segregate their waste as well as establishing a formal procedure for waste handling.

Indonesia's Ministry of Environment (MoE) in February 2014 straightens up a new regulatory framework regarding the distribution of industrial waste into three types of hazardous and toxic materials [28]. These materials include physically hazardous waste that comprised of explosive and flammable materials, dangerous to human health waste that comprised of materials capable of harming the human body, and environmentally damaging waste that comprised of materials that negatively affect marine life and the ozone [28]. In the near future, the Indonesian government (GoI) indicates the upcoming legislation to tackle the present shortcomings in waste management infrastructure and facilities.

Waste to energy

In Indonesia, although the 3R activities have the highest priority in the waste hierarchy, the most preferred method for waste handling is disposal into landfills as shown in Fig. 2a. Regulation regarding waste management hierarchy was already amended in year 2012; however, it is low implemented due to low citizen’s awareness. Lack of socialization and monitoring of the implementation of regulation also become the cause. Intensive socialization to citizen and strictly continuous monitoring by government officials are highly needed to follow the waste management hierarchy. As a comparison, waste hierarchy based on The European Union’s Sixth Environment Action Programme (2002–2012) is shown in Fig. 2b [7, 22, 29]. Meanwhile on EPA hierarchy, the strategies for handling the solid waste have been ranked into source reduction and reuse as the most preferred method, followed by recycling and composting, waste to energy, and, lastly, treatment and disposal [30]. Energy recovery, also known as waste to energy, converts the wastes into heat, electricity, or fuels through various processes such as chemical conversion,

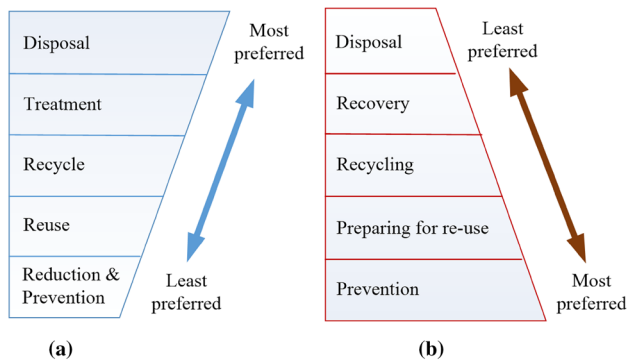
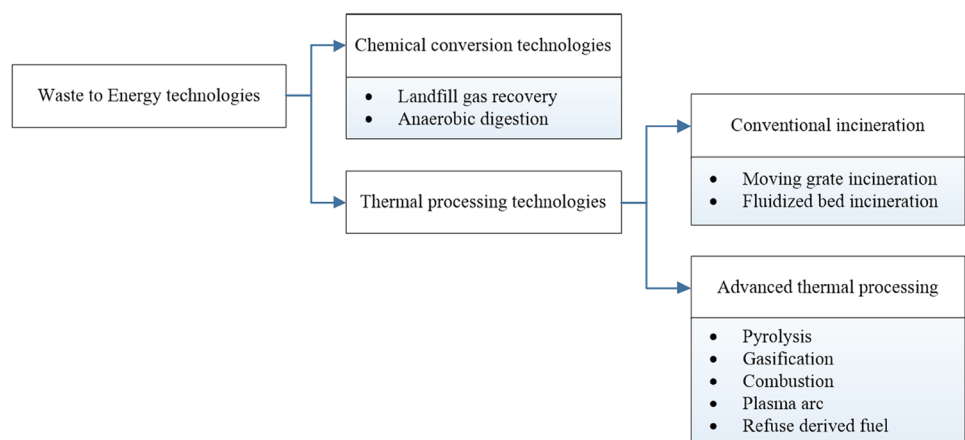


Fig. 2 Waste management hierarchy. **a** New paradigm in Indonesia **b** based on The EU’s Sixth Environment Action Programme [7, 22, 29]

Fig. 3 Schematic summary of waste to energy technologies [31]

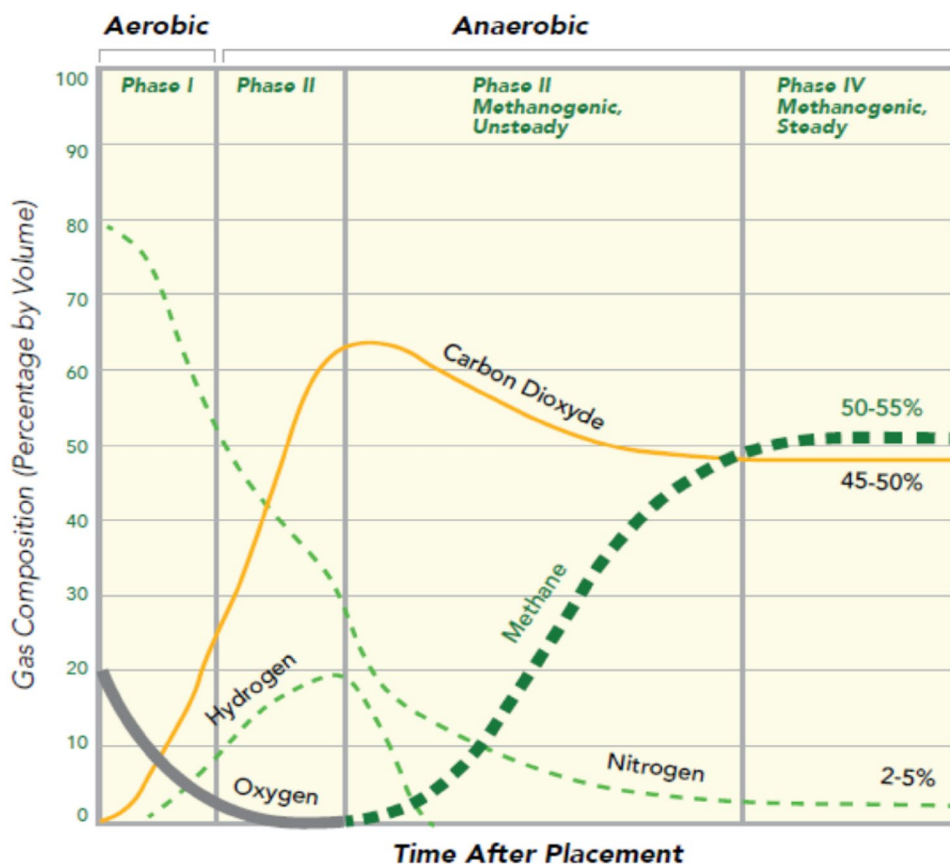


conventional incineration, and advanced thermal processing as shown in Fig. 3 [31].

Landfill gas recovery has been recognized as an advanced chemical conversion technology. It technically relies on the same biological decomposition process as other anaerobic digestion technologies. Landfill gas itself takes the form of a water-saturated gas mixture produced during anaerobic decomposition of biodegradable fractions in solid wastes, by which the produced gas contains about 40–60% methane [25]. Practically, LFG production begins shortly after waste is buried in a landfill and will continue to occur as long as organic waste is present. In general, organic wastes go through four main decomposition phases to produce LFG (Fig. 4) [32, 33], which occur after waste placement in the landfills. First, an oxygen decomposition occurs, taking 7–30 days from the whole decomposition process. Second, an acidic fermentation takes 1–6 months to produce intermediate products. Third, an unsteady methanogenic process occurs, in which specific chemical reactions take place in 3–30 months to process the intermediate products from previous phases, resulting in methane as the main product. Meanwhile, a steady methanogenic process takes 5–50 years depending on waste availability. In fact, the long gas production timeframe is acknowledged as an advantage of LFG production [32, 33]. In practices, critical factors affecting the amount of LFG being produced in a landfill include the mass of waste, its period of existence, and annual precipitation within the landfill [33]. Besides, the velocity of waste degradation, moisture as well as temperature affect LFG production, all of which may vary in different parts of a landfill area [34].

In the literature, waste as LFG raw material has been posited as a major source of GHG, which is responsible for ozone depletion and, therefore, global warming [35–37]. Due to a general consensus in which CO₂ from landfills is of a biogenic origin, only CH₄ is accounted for as contributing to global warming in the estimation of GHG emissions from landfills [36, 38–40]. Experimental researches and process

Fig. 4 LFG generation and changes overtime [33]



modelling have generally assumed one million tons (Mt) of unsorted MSW to contain an approximately 0.3 Mt of carbon in various forms. Of the amount, about 0.2 Mt would be converted to LFG, consisting of 0.09 Mt CO₂, 0.09 Mt CH₄, and other trace constituents [41, 42].

LFG in many ways has the potential to act as a natural fuel source in producing high-quality natural gas that can be directly injected into pipelines with the introduction of gas recovery systems [43]. In typical applications, LFG recovery systems apply a collection field consisting of wells, trenches and networked pipes. Besides, LFG is productively utilized as a substitute for natural gas at gas burning equipment and for electricity power generation. Electrical power can practically be generated from LFG through different applications, including internal combustion engines, gas turbines and microturbines [44]. Despite being beneficial, recovering CH₄ from landfills has proven to only be partially successful since up to 60% of generated CH₄ escapes through various leakages. Both advantages and disadvantages of LFG-powered electricity generation are summarized in Table 1 [44]. In an LFG-powered electricity generation process, technically, a large volume of CO₂ and other contaminants reduce its heating value and limiting its economic feasibility. Depending on its end use(s), therefore, different treatment steps on landfill gas are necessary. Thus, it is important to have an optimized

upgrading process that consumes low energy and has a high efficiency in producing high methane content [45].

Landfilling in Indonesia

In general, wastes produced in Indonesia mainly consist of organic matters (65%) with the major sources being residential zones [7, 22]. Almost all waste streams are disposed into various landfills, making most of the landfills to approach their maximum capacity [31, 32]. Figure 5 summarizes the country's MSW composition and sources based on data from 2008 [31, 32].

According to the data, there are approximately 550 landfills available throughout Indonesia [46] which were originally designed as controlled landfills. Some of them were even built as sanitary landfills. In fact, all of them are operated with an open dumping system. The system appears to get unintentionally applied as there are irregular soil cover applications, a lot of waste pickers on landfills, an inadequate leachate treatment, no technical treatment carried out on any incoming waste, and an open release of non-treated landfill gas emissions to the atmosphere. Table 2 provides general characteristics of open dumping, controlled landfills, and sanitary landfills [17, 33].

Table 1 Summary of advantages and disadvantages of electric power generation methods [44]

Methods	Advantages	Disadvantages
Internal combustion engines	<ul style="list-style-type: none"> High efficiency compared with gas turbines and microturbines Adequate engine size that complements the gas output of many landfills Relatively low cost of installation Efficient at converting landfill gas into electricity (up to 30-40%) Generally used at landfills where gas quantity is capable of producing 800 kW–3 MW 	<ul style="list-style-type: none"> Relatively high maintenance costs Relatively high air emissions
Gas turbines	<ul style="list-style-type: none"> The size is relatively compact Low operational and maintenance cost compared to other methods The generating cost per kW decrease as the size of the gas turbine increases More resistance to corrosion Low nitrogen oxide emissions 	<ul style="list-style-type: none"> Requires treatment to remove siloxanes Efficiencies drop when the unit is running at partial load High gas compression is required, 165 psig or greater High parasitic load loss
Microturbines	<ul style="list-style-type: none"> Low gas flow requirement Able to use landfill gas with lower percent methane content (35%) Low nitrogen oxides emissions Interconnection is comparatively easy due to lower generation capacity 	<ul style="list-style-type: none"> Some treatments for landfill gas are required to remove moisture, siloxanes, and other contaminants

Fig. 5 Summary of Indonesia’s MSW **a** sources and **b** composition [31] [33]

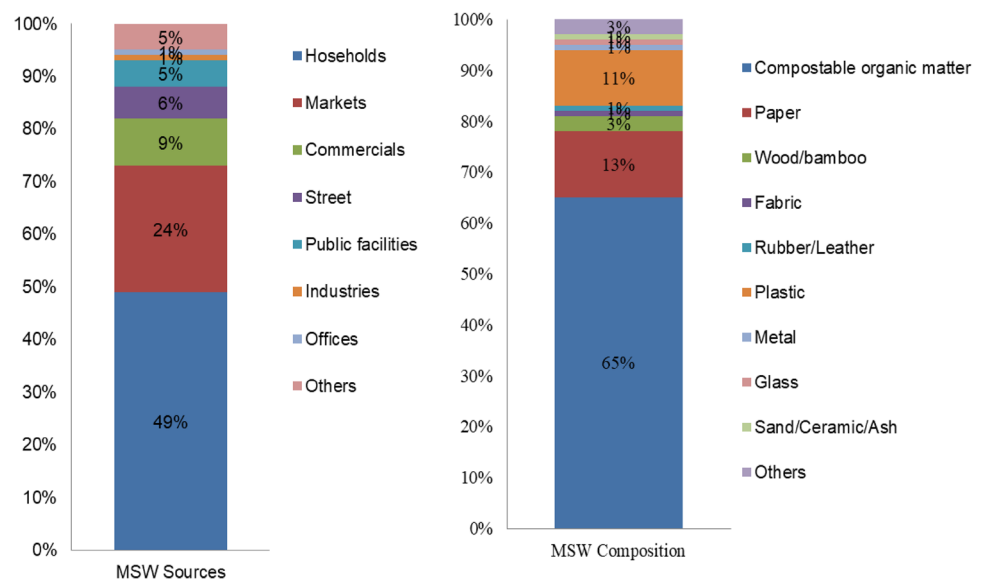


Table 2 A summary of the general characteristics of land disposal facilities [17, 33]

Criteria	Open dumping	Controlled landfills	Sanitary landfills
Site preparation	Very less or no site preparation	Soil gradation from the bottom of the disposal site Drainage and surface water control along the periphery of the disposal site	Extensive site preparation
Leachate management	No leachate management	Partial leachate management	Full leachate management
Gas management	No gas management	Partial or no gas management	Full gas management
Application of soil cover	Occasional or no soil cover for the waste	Regular application of soil cover for the waste	Daily, intermediate and final soil cover application for the waste

According to the Waste Management Act (18/2008) in Indonesia, a sanitary system requires landfills to provide a properly functioning ventilation sub-system for the gas, an operational waste cell, a leachate control, and active treatments of LFG being produced [47, 48]. Recently, LFG treatments by utilizing advanced developments of flaring system have been applied to several cities through the Clean Development Mechanism (CDM) projects [48]. In practices, utilization of LFG produced from landfills for flaring or power generation creates a chance for Indonesia to earn carbon credits from landfill management in CDM projects [20]. One of the country's landfills applying the system is Bantar Gebang landfill in Bekasi, West Java [48].

The Bantar Gebang Landfill (*Tempat Pengolahan Sampah Terpadu—TPST*) has been in operation since 1989, covering an area of 108 hectares divided into five waste deposition zones. It was first designed to handle $19 \times 10^6 \text{ m}^3$ of waste and still expandable. Since its opening, an approximately $8.3 \times 10^6 \text{ m}^3$ of waste had been deposited, by which more than 25,000 tons of CH_4 had been produced yearly. Technically, it is equivalent to more than half a million tons of CO_2 . In the Bantar Gebang landfill, a business plan has been proposed to capture methane gas and convert the gas into electricity, which is expected to generate about 10 MW

electricity during early operation and to increase to 25 MW power generation by 2023 [12, 46]. In the landfill, LFG is extracted by applying vertical and horizontal extraction wells. Then the LFG is cleaned and fed into a gas engine for electricity generation. The generated electricity has been providing an approximately 80,000 MWh of electricity per year to the national grid, which is expected to increase up to 100,000 MWh within the first few years, hence displacing the majority of coal-fired grid power generation [49]. Existing processes developed in a gas power plant within Bantar Gebang landfill area include weighing, dumping-related activities (unloading, relaying, leveling and staging the wastes), soil/plastic covering, pipeline installation, and gas collection [50]. Figure 6 depicts parts of pipeline installation and gas collection sub-system in the Bantar Gebang landfill.

In Indonesia, LFG power plant has been considered as a solution for addressing waste management problem due to the very large amount of existing wastes and landfills. As aforementioned, landfills in Indonesia are generally operated as open dumping sites, producing a large accumulation of waste without any separation of organic–inorganic and hazardous wastes. Therefore, an LFG power plant is posited as a short-to-middle-term solution in the country's waste



Fig. 6 Pipeline installation and gas collection at Bantar Gebang Landfill—Bekasi (authors' collections)

management problem. Existing open dumping landfills should hence be transformed into sanitary landfills, which were their first designated function, through a good handling of leachate and a thorough as well as proper functioning management of any produced gas. According to information gathered from site operators in several landfills, installing pipes for gas collection is considered as a more effective action compared to building bioreactor for gasification. In fact, it is particularly caused due to the type of landfill wastes in Indonesia. Looking at the field facts, this work primarily focuses on the potentials of LFG recovery for waste management in Indonesia.

Potential of landfill gas generation

To calculate the potentials of landfill gas production from MSW in several cities in Indonesia, data were gathered from wastes generated by some of the country's major cities in 2017 [51]. Looking at the literature [7, 22], primary municipal waste generators in Indonesia include provincial-level capital cities such as Medan, Jakarta, Surabaya and Bandung (Table 3). In this work, methane, which is the main LFG component, was calculated according to the LandGEM model, which was first published by the United States Environmental Protection Agency (US-EPA), and the IPCC methodology. Practically, the LandGEM model was applied to calculate methane production in three final disposals, while IPCC methodology was used to predict the methane production in several Indonesian cities based on waste being generated.

Conceptually, LandGEM is a quantification model for quantifying emissions of total landfill gas, methane, carbon dioxide from the decomposition of landfilled waste in MSW landfills. It has been recognized as a preferred model since it is technically an automated tool based on a first-order decomposition rate equation for the quantification. LandGEM is possible to apply for estimating emissions by utilizing either site-specific data or default parameters if no site-specific data are available [52]. In general, the first-order decomposition rate produces an estimated amount of methane that will be generated in a specific period of time (year). In the US-EPA's Excel-based LandGEM software, LFG generation is estimated based on the methane content of LFG, in which its default value is 50% [53]. Besides, LandGEM basically assumes that a methane generation process is at its peak shortly after anaerobic conditions achieved a stable state in a landfill (steady methanogenic phase) and decreased exponentially as organic materials are consumed by bacteria [53]. Inputs for calculation in LandGEM model include (1) landfill area and capacity, (2) annual amount of received waste, (3) methane generation rate constant (k)

and methane generation potential (Lo), and (4) total years of landfill operation [15].

Figure 7 provides calculated potentials of landfill gas production in Bantar Gebang landfill (Bekasi), Sarimukti landfill (Bandung), and Benowo landfill (Surabaya) produced by utilizing the software. These results are practically based on waste recipient rates in landfills and other model parameters, including nutrients, acidity (pH), moisture content, and temperature of waste mass. In terms of LFG production timeframe, Sarimukti and Benowo landfills would reach their steady methanogenic process within 10–14 years, while Bantar Gebang landfill would achieve the state within 65–70 years. The difference might occur due to the amount of waste received per day by each landfill. Sarimukti and Benowo landfills have been receiving waste at about 1350 ton/day and 1500 ton/day streams, respectively. Due to the extensiveness of landfill area, Bantar Gebang landfill has been receiving waste at about 6800–7000 ton daily stream.

Furthermore, methane gas being generated is also estimated by applying IPCC methodology [38, 41]. The method has also been preferably used since it is a considerably simple approach to perform the first-order decomposition model that has a linear correlation with maximum potentials of methane production per weight unit of waste, providing an estimated annual methane emission [15]. According to IPCC methodology, methane emission from a landfill is estimated by applying the following equation:

$$\text{CH}_4\text{emissions [ton]} = \text{MSWT} \times \text{MSW}_F \times \text{MCF} \\ \times \text{DOC} \times \text{DOC}_F \times F \times 16/12, \quad (1)$$

where MSWT is the total MSW generated (tons), MSW_F is the fraction of MSW disposed of to landfills, MCF is the methane correction factor, DOC is the fraction of degradable organic carbon, DOC_F is the fraction of total DOC that actually degrades, and F represents fraction of methane in LFG.

In a typical situation, MCF has default values of 0.4–1.0, depending on different practices of MSW landfill operation. If most of the observed landfills are considerably unmanaged, the MCF value is set at 0.6 [41]. Technically, an MCF value represents the possibility of aerobic decomposition of top-layer waste fraction that leads to less-than-theoretically possible methane production in landfills [54]. According to IPCC, DOC ranges from 0.08 to 0.21, while its estimation is expressed as

$$\text{DOC} = 0.4P + 0.15K + 0.3W, \quad (2)$$

where P is the fraction of papers in MSW, K is the fraction of kitchen garbage in MSW, and W is the fraction of woods/leaves in MSW.

In this study, the default DOC value was set at 0.16. The value was applied by considering organic carbon fraction

Table 3 Waste generated and collected in Indonesia (data in the year 2017) [51]

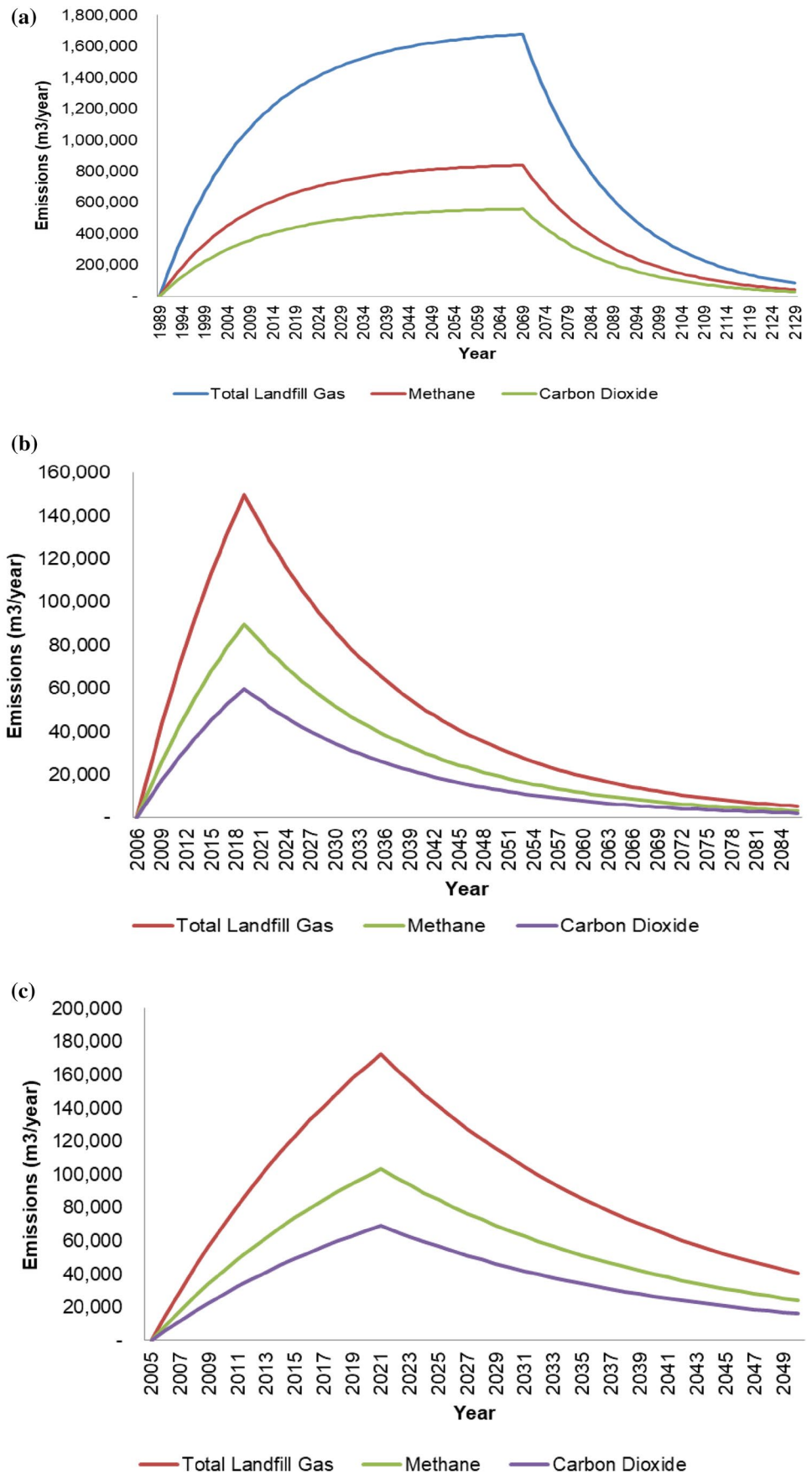
City	Waste generated (ton/day)	Percentage of waste generated (%)	Organic waste (ton/day)	Percentage of organic waste (%)	Waste collected (ton/day)
Banda Aceh	275.00	0.49	132.50	48.18	250
Medan	1892.00	3.42	1230.00	65.01	1675.00
Padang	624.24	1.13	349.20	55.94	495.50
Pekanbaru	764.19	1.37	202.88	26.55	362.28
Jambi	1534.35	2.77	451.98	29.46	1059.01
Palembang	682.82	1.23	–	–	682.82
Bengkulu	774.86	1.40	310.10	40.02	452.57
Bandar Lampung	800.00	1.44	400.00	50.00	700.00
Pangkal Pinang	623.00	1.12	337.00	54.09	486.00
Tanjung Pinang	470.62	0.84	51.33	10.91	308.25
DKI Jakarta	7099.08	12.93	3693.80	51.56	6872.18
Bandung	1469.00	2.89	543.10	33.94	1120.00
Semarang	5080.51	9.32	2817.28	54.56	4544.00
Yogyakarta	904.80	1.90	582.40	55.57	1040.00
Surabaya	9710.61	17.86	2947.65	29.78	5427.45
Serang	1638.00	2.96	–	–	710.00
Denpasar	3657.20	6.60	2283.75	62.45	3276.55
Mataram	350.00	0.63	168.00	48.00	280.00
Kupang	684.00	1.23	309.20	45.20	552.00
Pontianak	1802.50	3.25	1000.00	55.48	1547.00
Palangkaraya	892.50	1.61	–	–	435.50
Banjarmasin	568.00	1.02	344.00	60.56	545.30
Samarinda	686.56	1.24	–	–	217.24
Tanjung Selor	751.70	1.36	751.70	100	751.70
Manado	2064.00	3.72	–	–	1680.00
Palu	1058.42	1.91	–	–	456.00
Makassar	6485.65	11.70	4560.93	70.32	6163.42
Kendari	221.69	0.001	84.53	38.13	165.75
Gorontalo	490.14	0.88	255.80,	52.19	367.39
Mamuju	192.00	0.35	–	–	97.77
Ambon	200.00	0.36	98.00	49.00	151.60
Ternate	60.64	0.11	31.61	52.13	43.23
Manokwari	113.32	0.21	11.10	9.8	25.23
Jayapura	416.55	0.75	–	–	44.76
TOTAL	55,425.98	100	22,840.81	41.21	42,985.50

in waste that was accessible to anaerobic decomposition. On the other hand, the default DOC_F value was set at 0.77 by considering that the biodegradation of DOC is not completely occurred over a long period of time. In fact, only a fraction of DOC was practically converted into CH_4 and CO_2 , while the rest were stored in a landfill as stable organic matters or degrade through other biological or chemical processes. Table 4 provides calculation results of methane generation in various areas in Indonesia based on the IPCC methodology.

In the current study, the potentials of electricity production from waste processing were investigated according to

an existing approach proposed by Siddiqui et al. [55]. Taking data from Table 3, the quantity of MSW generated per year in Indonesia appeared to be at 20.23×10^6 tons/year. Looking at the calculation, 20.23×10^6 tons/year waste produced from several major cities in Indonesia could generate as much as 875,130 tons/year of methane as the main component of landfill gas. The amount of waste as such could theoretically generate 54,142 MW electricity/year. Input for calculation by Siddiqui et al.'s approach include (1) quantity of MSW generated per year in Indonesia, (2) collection efficiency of MSW, (3) quantity of MSW collected per year 2017, (4) percentage of MSW disposed in open dumping landfill, (5)

Fig. 7 Total landfill gas, methane, and carbon dioxide generation **a** in Bantar Gebang landfill, **b** Sarimukti landfill and **c** Benowo landfill



quantity of MSW disposed in landfill in year 2017, (6) percentage of organics/biodegradables in MSW, and (7) quantity of organics disposed in landfill in year 2017. Table 5 provides the technical steps of the calculation. Meanwhile, Table 6 provides a comparative calculation of methane being generated and its potentials for electric power generation for several provinces in Indonesia [46, 47].

Prospect and challenges in MSW management in Indonesia

Furthermore, Fig. 8 provides data on the flow of waste treatment from sources to final recovery and methane as well as electricity production potentials based on IPCC methodology and Siddiqui et al.'s approach [55]. Both theoretical calculations take the real situation of waste management in Indonesia into account, including less percentage of waste collection and less percentage of waste brought to a landfill. In fact, the real amount of LFG being produced within a

Table 4 Estimated methane generated from landfills in several cities in Indonesia

City	MSW ^a (tons/year)	MSW _F	MCF	DOC ^b	DOC _F	F	16/12	CH ₄ tons/year ^c
Medan	690,580	0.80	0.60	0.16	0.77	0.55	1.33	29,873.10
DKI Jakarta	2615,053	0.80	0.60	0.16	0.77	0.55	1.33	113,121.94
Semarang	1884,757.80	0.80	0.60	0.16	0.77	0.55	1.33	81,530.82
Yogyakarta	382,520	0.80	0.60	0.16	0.77	0.55	1.33	16,547.04
Denpasar	1334,878	0.80	0.60	0.16	0.77	0.55	1.33	57,744.13
Pontianak	657,912.5	0.80	0.60	0.16	0.77	0.55	1.33	28,459.97
Makassar	2,367,262.25	0.80	0.60	0.16	0.77	0.55	1.33	102,402.99

^aFrom Table 3

^bCalculated from Eq. (1)

^cCalculated from Eq. (2)

Table 5 The potency of electricity from MSW generated in Indonesia in year 2017 [55]

Steps	Descriptions	Value
1	The quantity of MSW generated per year in Indonesia	20,230,482.70 tons/year
2	Collection efficiency of MSW (based on Table 3)	77%
3	The quantity of MSW collected per year 2017	15,689,707.5 tons/year
4	The percentage of MSW disposed in open dumping landfill	69%
5	The quantity of MSW disposed in landfill in year 2017	10,825,898.2
6	The percentage of organics/biodegradables in MSW	41.21%
7	The quantity of organics disposed in landfill in year 2017	4,461,352.7 tons/year
8	100 tons of MSW with 50% organics can generate 1–1.5 MW electricity power	54,142.6 MW/year

Table 6 Location of open dumping landfills and their potential LFG production [46, 47]

Regions	Open dump- ing landfills	Average final treatment	LFG production (100 m ³ /ton solid waste)	LFG to energy
	(Location)	(Ton per year/location)	m ³ LFG/h	MWh electricity
Sumatra	152	60,789	694	101.07
Java	165	151,100	1725	272.72
Bali, NTB, NTT	39	61,183	698	26.10
Borneo Island	61	41,250	471	27.52
Sulawesi	79	40,131	458	34.68
Maluku	22	21,333	244	5.13
Papua	32	20,496	234	7.17
Total	550			474.40

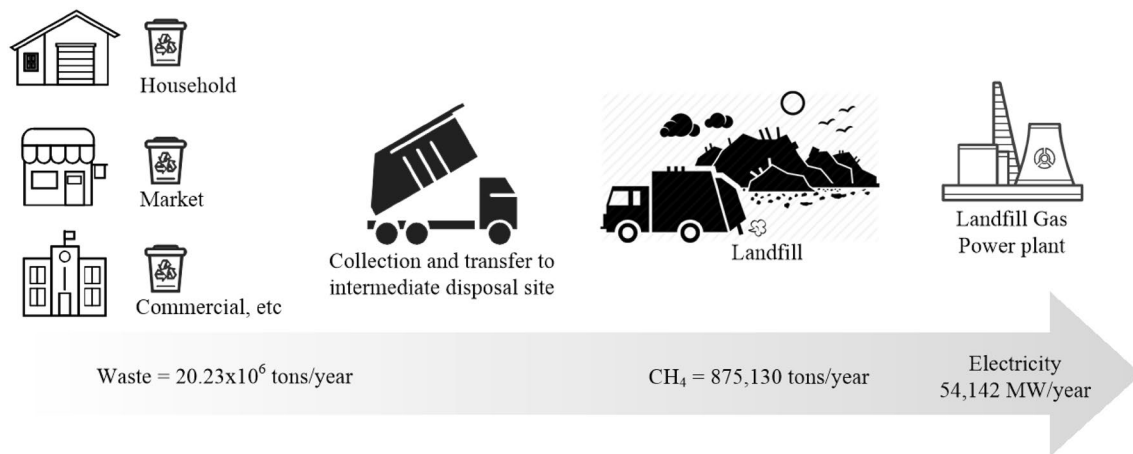


Fig. 8 Process of LFG production and its potential in Indonesia

specific year was smaller than the theoretical calculations, which might occur due to an inefficient LFG collection system applied in Indonesia. To improve the country's MSW management, the Government of Indonesia must progressively pursue a comprehensive MSWM concept involving various societal and governmental levels from household to city/country. Besides, it must also be integrated into every level of waste handling from sources of the waste to landfills. At household, community and city/country levels, the concept needs to recover MSW materials through a reuse–reduce–recycle–segregate MSW mindset. To support the purpose, the Government of Indonesia must improve MSW service access and quality for the public, including a continuous development of sanitary landfills and active technical and financial supports for implementing the MSW management concept. Figure 9 depicts the proposed solid waste management concept for Indonesia. In general, advantages being offered include a comprehensive treatment of waste as a recoverable and reusable resource to produce more beneficial materials. Besides, it can deliver simultaneous benefits across a multitude of fields, including less investments, opening job opportunities, supporting livelihoods, contributing to economic growth, protecting public health and improving quality of the environment [25].

Then other strategic actions to improve waste management in Indonesia include a continuous improvement of the efficiency of waste collection and transportation, which would reduce waste quantity disposed through improper ways, and a progressive enhancement of utilizing the waste into energy generation [7]. Besides, intermediate treatments include a national-level composting management. In practice, the critically required action includes establishing an active collaboration involving a wide range of different stakeholders and sectoral interests. Those stakeholders must

include national, regional and local governments; the private sectors, which usually play a major role and make a major contribution of waste generation; workers, including those in the informal sectors; communities and their leaders; and others related parties such as non-governmental organizations (NGOs) and academics. Furthermore, the government should show its willingness and commitment to strengthen MSW management through the promulgation of new policies and regulation detailing MSW management steps; an increased financial support; and updated technologies for converting waste to energy. Table 7 provides key points, including prospects and challenges, for a good MSW management in Indonesia.

Conclusion

This study shows that waste management in Indonesia should be improved through various considerations including the technology, community, and policy aspects. From theoretical calculation, the findings of this paper indicated that 20.23×10^6 tons/year MSW produced in Indonesia could generate as much as 875,130 tons/year of methane as the main component of landfill gas. The amount of waste as such could theoretically generate 54,142 MW electricity/year. The real LFG and electrical power produced from MSW are possible to increase or decrease depending on the total amount of waste generated and the implementation of LFG recovery system in landfills. Seeing this great opportunity, the handling of MSW in landfills must be more comprehensive and efficient by considering various aspects such as method of waste handling, waste separation, type of engine and engine efficiency for electricity production.

Fig. 9 Municipal solid waste management concept in Indonesia [25]

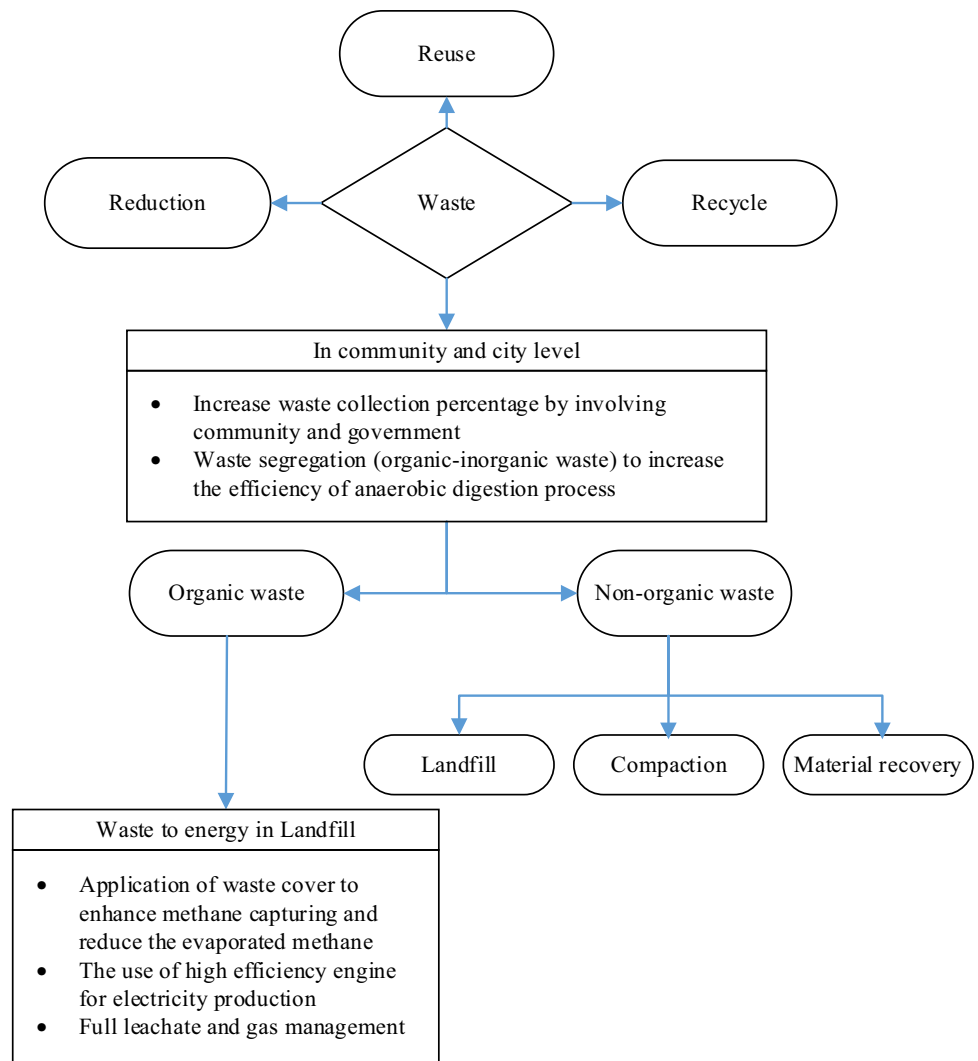


Table 7 Key points of prospects and challenges in MSW management in Indonesia [7]

Aspects	Key points
Institutional aspects	A comprehensive strategy on MSW management at local, regional, and national levels Institutional capacity and human resource development at local, regional, and national levels Integrated plan and coordination among interconnected ministries and other stakeholders
Policy and regulation aspects	A comprehensive regulation that synergize the local and national regulation regarding MSW management Comprehensive technical regulation and guideline that regulate standards and mechanisms in MSW management
Financial aspects	Reasonable budget allocation for MSW management at both national and local levels Financial efficiency through public–private cooperation, and international bilateral and multi-lateral cooperation
Technology aspects	Technology development for waste disposal and recycle Establish integrated MSW management system with that focus on waste to energy Improve the waste management using information system and accurate waste-related statistical data
Community aspects	Promotion of 3R program at local, regional, and national levels Improve educational system and intensive campaign programs to the youths with well-defined methods Establish compensation and penalty system in the community for infringement at local, regional, and national levels

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