Journal of Environmental Management 301 (2022) 113882

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Harnessing landfill gas (LFG) for electricity: A strategy to mitigate greenhouse gas (GHG) emissions in Jakarta (Indonesia)

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ARTICLE INFO

Keywords:
Biogas
Circular economy
Climate change
Landfill
Renewable energy
Resource recovery

ABSTRACT

Due to its increasing demands for fossil fuels, Indonesia needs an alternative energy to diversify its energy supply. Landfill gas (LFG), which key component is methane (CH_4), has become one of the most attractive options to sustain its continued economic development. This exploratory study seeks to demonstrate the added value of landfilled municipal solid waste (MSW) in generating sustainable energy, resulting from CH_4 emissions in the Bantargebang landfill (Jakarta). The power generation capacity of a waste-to-energy (WTE) plant based on a mathematical modeling was investigated. This article critically evaluated the production of electricity and potential income from its sale in the market. The project's environmental impact assessment and its socio-economic and environmental benefits in terms of quantitative and qualitative aspects were discussed. It was found that the emitted CH_4 from the landfill could be reduced by 25,000 Mt annually, while its electricity generation could reach one million kW ·h annually, savings on equivalent electricity charge worth US$ 112 million/year (based on US' 8/kW · h). An equivalent CO_2 mitigation of 3.4×10^6 Mt/year was obtained. The income from its power sale were US$ 1.2×10^6 in the 1st year and 7.7×10^7 US$ in the 15th year, respectively, based on the projected CH_4 and power generation. The modeling study on the Bantargebang landfill using the LFG extraction data indicated that the LFG production ranged from 0.05 to 0.40 m^3 per kg of the landfilled MSW. The LFG could generate electricity as low as US' 8 per kW · h. With respect to the implications of this study, the revenue not only defrays the cost of landfill's operations and maintenance (O&M), but also provides an incentive and means to further improve its design and operations. Overall, this work not only leads to a diversification of primary energy, but also improves environmental protection and the living standard of the people surrounding the plant.

1. Introduction

Over the past decades, cities worldwide have consumed about 80% of their resources (Verma, 2010). As a result, changes in the consumption patterns of their urban dwellers have led to a quantum leap in the generation of municipal solid waste (MSW) worldwide. For this purpose, different countries have their own solid waste management policies, depending on their respective legislation (Table 1).

Currently, 70% of the global MSW is disposed of in landfills, while

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https://doi.org/10.1016/j.jenvman.2021.113882
Received 11 August 2021; Received in revised form 14 September 2021; Accepted 28 September 2021
Available online 9 October 2021

List of abbreviations

ADB	Asian Development Bank
CDM	clean development mechanisms
CE	circular economy
EIA	environmental impact assessment
EPA	Environmental Protection Agency
EPR	extended producer responsibility
GDP	gross domestic products
GHG	greenhouse gas
GW	gigawatt
GWP	global warming potential
ICE	internal combustion engines
IEE	initial environmental examination
IPCC	Intergovernmental Panel on Climate Change
LFG	landfill gas
kWh	kiloWatt hour
MSW	municipal solid waste
Mt	metric tonne
Mtoe	million tons of oil equivalent
O&M	operations and maintenance
SDG	sustainable development goals
SWM	solid waste management
Tg	teragram
UN	United Nations
US$:	United States Dollar
VOC	volatile organic compounds
WTE	waste to energy

only 14% of the waste is recycled and recovered (Kurniawan et al., 2021a; Fu et al., 2021a). Landfill is widely used for the disposal of MSW in developing world. After landfilling, the MSW undergoes its physico-chemical decomposition due to microbial processes and then, generates landfill leachate and landfill gas (LFG) (Lim et al., 2014).

Precipitation range, time, landfill cover (slope and integrity) along with design and operational parameters affect the LFG formations (Slezak et al., 2015). Both CH_4 and CO_2 are the key components in LFG, in spite of the temporal variation in its volumes and characteristics (Fig. S1). As the solid-moisture ratio of the waste in landfills varies with the quantity and type of organic content, the LFG production rate ranges from 0.05 to 0.40 m^3 per kg of the landfilled waste (Verma et al., 2017).

There are four stages of LFG production viz aerobic decomposition, anoxic, non-methanogenic, unsteady methanogenic, and steady methanogenic (Fig. 1) (Benato et al., 2017). The first two stages are transient in nature for 50–100 days, where the volume of nitrogen and hydrogen gas peaks and then declines to insignificance in the 3rd stage. During the steady methanogenic phase after 300 days with over 90% of LFG formation, the CH_4 and CO_2 production finally attains stability (Table S1) (Kurniawan et al., 2020).

Over the past six decades spanning 1960–2020, the global warming has witnessed over a three-fold increase from 9.34 to 33.1 billion metric tonnes (Mt) of $CO_{2\text{-eq}}$ emissions (Kurniawan et al., 2010). It is projected that about 1.6 billion Mg of $CO_{2\text{-eq}}$ were emitted from the MSW disposal in open dumps, contributing to 5% of global GHG emissions in 2020 (Fu et al., 2021b).

It is also estimated that emissions from landfills worldwide contribute to almost one-fifth of the total anthropogenic CH_4 annually, ranging from 8 to 50 Tg (teragram) (Lombardi et al., 2006). Although CH_4 comprises 18% of global greenhouse gases (GHG) emissions, it has twenty-one fold higher global warming potential (GWP) than CO_2. Therefore, the emissions of CH_4 from landfills represents a clear indicator of the GHG implications (Kurniawan et al., 2011; Ng et al., 2014).

In the same period, the world's population and its gross domestic product (GDP) have seen a multifold increase. The urbanization of people globally have spiked from less than a quarter in 1960 to over a half in 2020, and this would reach two-third by 2050 (Coskuner et al., 2020). As the expansion of urban population often outpaces the generation of MSW, the growth of the MSW has risen and further reached beyond the capacity of municipal authorities in developing countries to manage its volume (Premakumara et al., 2014). Due to budgetary limits and a lack of institutional coordination, the authorities often dump the MSW untreated around the outskirts of their cities (Themelis and Ulloa, 2007). As a result, this has long-term consequences on the quality of life and public health over the marginalized people living in close proximity to such open dumps (Meunier, 2007; Chen et al., 2007).

Like other developing countries, Indonesia has also witnessed an accelerated economic development, as indicated by the rising income of its inhabitants recently (Zhu et al., 2020a). The urbanization and industrialization in Indonesia's urban centers such as Jakarta make the capital continuously confront with the overwhelming generation of MSW (Fig. 2). About 9.5 million of population currently inhabited the city in 2020 (Kurniawan et al., 2021a, 2021b, 2021b). With 3% of annual urban population growth and 95% of its total inhabitants of 10.60 million residing in an area of 660 km^2, Jakarta generates about 8, 000 Mt (metric tonnes) MSW daily with its per capita of 1.31 kg per day (Handayani and Filatova, 2021).

Based on past trends and future projections, it is anticipated that by 2030, about 16,721 Mt of MSW will be generated in Jakarta with 2.5 kg/day as the per capita generation rate (Abila, 2014). The continuous growth in MSW generation implies that Jakarta will run out of landfill spaces far earlier than expected because the recovery rate of the disposed MSW in local landfills was still less than 30% out of total MSW generation annually (Bogale and Viganò, 2014). In spite of government's efforts to encourage people to recycle and reuse the waste through circular economy (CE) approaches, the city's generation rate of MSW still increases annually by 3% (Kurniawan et al., 2021b).

With 481 million tons of oil equivalent (mtoe) of primary energy consumption and 618 Mt of $CO_{2\text{-eq}}$ emissions (in 2020), Indonesia stands out among the World's top ten carbon emitters (ADB, 2020). Based on the past trends, the average of annual growth of the energy supply in Indonesia is projected to increase by 4% in the next decade (Chen, 2016). According to the National Electricity Supply Business Plan (2019–2028), Indonesia's installed power capacity is expected to leap forward by 50% from 56.5 to 112 GW. It is estimated that domestic demand for energy would rise by 7% annually, with electricity demand being projected to triple between 2010 and 2030. Over a half of this energy demand will be routed through fossil-based fuels.

Due to its limited energy resources, in recent years, Indonesia has imported most of its energy from Middle East. As international oil price has surged recently over US$ 70 per barrel (Zhu et al., 2020b), the development of renewable energy resources has become a priority for the country. However, renewable energy sources accounted for only one-eighth of its energy mix in 2019, far short of the government's target of 23% by 2025 (Jayadi et al., 2019). The upsurge in fossil fuel demand not only possesses serious challenges to energy security, but also increases the amount of GHG emission from various sources that would pollute the environment (Tsai, 2005; Huang and Wu, 2007).

Therefore, the development of renewable energy in Indonesia from non-conventional sources such as landfill gas is required to augment energy security and boost economic development (Nishio and Nakashimada, 2007). Further inclination towards carbon intensive sources can stall the country's commitment to the Kyoto Protocol with respect to GHG emissions reduction to a half of the 1990 level by 2050 (Chen et al., 2007).

Preliminary studies on the reduction of GHG emission from landfills

Table 1
Status of waste management policies vis-à-vis SWM and landfills in different countries.

Country	Policies and legislative instruments	Status of solid waste management and landfills
South Korea	Framework Act on Resource Circulation (FARC)/2018	Only 8% and 27% of its waste are disposed of in landfills and incineration, respectively. Imposition of charges on polluters disposing in landfills through volume-based waste disposal fees, and extended producer responsibility (EPR).
Japan	Law for Environmental Pollution Control (1967) and Environmental Plan (1994)	As Japan faces a shortage of landfill sites, the Waste Management and Public Cleansing Law aim at preventing waste from dumping if other options are available, even if at a higher cost.
European Union-28	Waste Framework Directive (2008/98/EC)	Only 38% of waste in the EU is recycled and over 60% of household waste still goes to landfill.
United States of America (USA)	Resource Conservation and Recovery Act (RCRA)	Although special provisions are given due to the Land Disposal Program Flexibility Act (LDPFA), 65% of the waste is dumped in landfills, while only 35% is recycled
Australia	Protection of the Environment Operations Act 1997	Provision of fines and penalties for dumping offences.
Hong Kong (SAR)	Waste Disposal Ordinance (WDO) Chapter 354	In 2019, 5.67 million tonnes were generated, of which 29% was recycled and the rest went to landfills.
People's Republic of China (PRC)	Law on Prevention and Control of Environmental Pollution by Solid Waste	2013 Framework of MSW collection, recycling, and disposal
Russian Federation	Federal Law No. 89-FZ/1998 on Production & Consumption of Waste	The law defines the general requirements for waste management, including the responsibilities of the Russian Federation (RF), constituent entities of the RF and local government authorities on waste management.
Indonesia	Law No. 18/2008	Waste separation through recyle, reuse and recovery (3 R)
Palestine	Environmental Law No. 7/1999	1. Closure and/or rehabilitation of random dumpsites. 2.Promoting initiatives to reduce, separate, reuse, and recycle MSW, and collect LFG from sanitary landfills.
Jordan	Management of Solid Waste Regulation No. 27/2005	Ministry of Environment provided incentives to private sectors to invest in solid waste (SW) treatment and recycling.

undertaken by Manasaki et al. (2021) focused on the techno-economic assessment of LFG to electricity. In spite of their novelty, their studies did not directly address the circular economy (CE) aspects of MSW conversion to LFG as a part of sustainability solutions in mitigating climate change due to MSW overgeneration.

With respect to its novelty, this exploratory study seeks to demonstrate the added value of landfilled MSW in generating sustainable energy, resulting from CH_4 emissions in the Bantargebang landfill (Jakarta). The power generation of a waste-to-energy (WTE) plant based on a mathematical modeling was investigated by adjusting on-site parameters. This work also critically evaluated the production of electricity and income from power generation based on the CE paradigm. The project's environmental impact assessment, its socio-economic and environmental benefits in terms of quantitative and qualitative aspects are also elaborated.

2. Methodology

2.1. Study area

Geographically, the Bantargebang landfill in Bekasi is located at 06°15′ South latitude and 106°30′ East longitude. The 108 ha-landfill is situated about 40 km or around 1 h drive from the eastern Jakarta (Fig. 3). Having its commissioning operations since 1989, the landfill has been under the control of the Province's Sanitary Agency. Initially it was designed to accommodate 19 million Mt of solid waste annually. So far, 54% of its capacity has already been filled. Currently, the landfill receives 7000 Mt of MSW daily from the capital. Although over a half of the waste deposited in the landfill is organic refuse, the landfill also receives valuable non-organic materials such as paper, metals, glass, and electronic waste due to the lack of waste segregation mechanisms at sources.

2.2. Research design

As CH_4 is the bedrock of the power generation from the LFG (Sasaki and Araki, 2014), there are statistical and kinetic models, which can gauge its production. Major models include the biodegradable component, IPCC (Intergovernmental Panel on Climate Change), and stoichiometric ones. The 'Biodegradable Component' model calculates the amount of biodegradable organic matter to determine the yield of the LFG produced. However, it cannot be directly used as the basis for calculating CH_4 utilization in a landfill (Tsai and Chou, 2006).

Unlike the previous models, the IPCC model prerequisites a waste segregation of biodegradable organic carbon (Siregar et al., 2018). Due to the varying waste classifications in different countries, the IPCC model cannot be universally applied. The Stoichiometric model empirically uses chemical equations, assuming that all organic matter can be completely degraded and converted into LFG. However, landfills are dynamic and do not strictly observe anaerobic conditions. This results in an overestimation of LFG production values (Rehl and Müller, 2011).

2.3. Study approach

For an effective LFG measurement, it is necessary to assess the potential of LFG production and predict the pattern and rate of gas extraction. Kinetic models help us understand the dynamics of waste vis-à-vis its composition, flowrate, and decomposition rates (Table 2). This provides a basis for predicting the stabilization of the landfill. Based on the time-dependent relationship of LFG production, the kinetic models can be divided into zero-order and first-order models. While assuming that the rate of CH_4 production is independent of the amount of waste, the zero-order model does not support the long-term trend of LFG production.

The models given by Gardner and Marticorena are the two most popular ones for the first-order (Safril et al., 2017). The Gardner's model includes the explanatory rate of waste and the proportion of explanatory organic carbon in each component of the organic carbon (Tan et al., 2014). However, the Gardner's model theoretically assumes a complete conversion of biodegradable organic carbon to CO_2 and CH_4.

By assuming that waste is landfilled in layers according to the duration (years), the Marticorena model is more pragmatic than the Gardner's in giving year-wise cumulative CO_2 and CH_4 generation breakdown. This model neglects the intermediate process of converting organic matter to CH_4. This involves the first-order dynamic equation that describes the formation of CH_4 during MSW decomposition (Talyan et al., 2008). Eventually, this helps landfill operators assess revenue income by power generation from the CH_4 (Marticorena et al., 1993). The incorporation of production cycle factors, and the anticipated results and the addition of cycle parameters of waste gas generation that

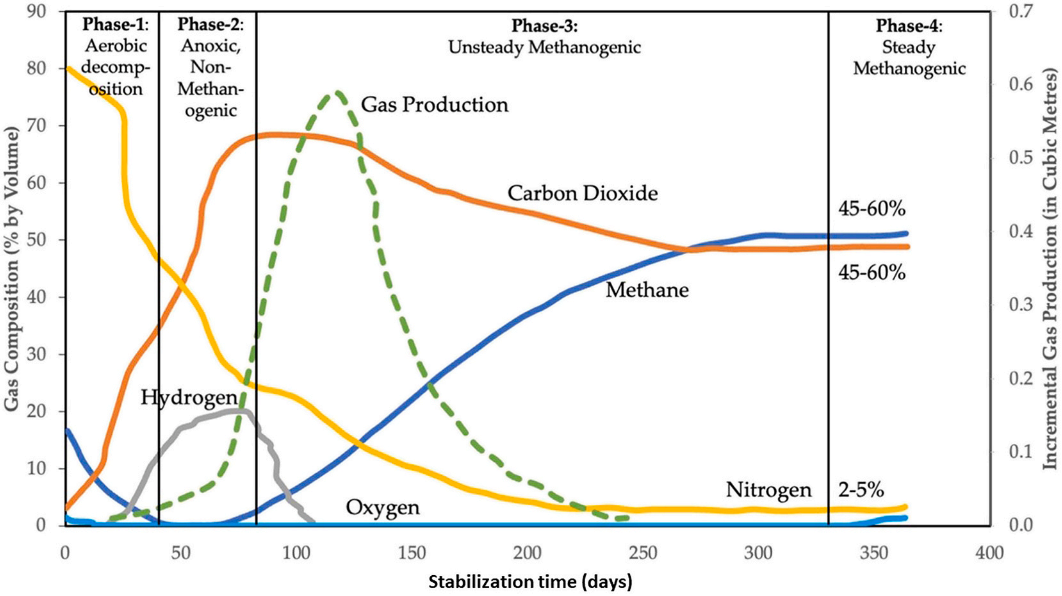

Fig. 1. Stages of waste decomposition after landfilling (Kurniawan et al., 2021a).

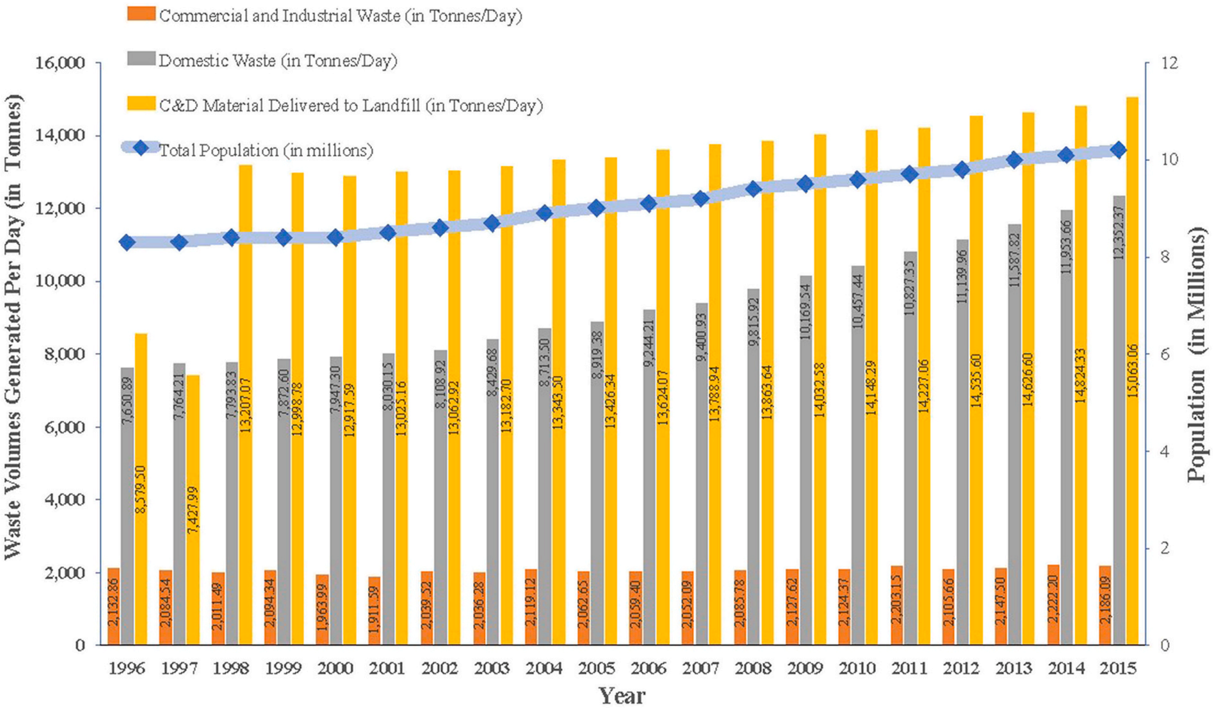

Fig. 2. Trends of MSW generation (1996–2015).

can be measured by field sampling are close to the actual scenario in the Marticorena's model. For this reason, the Marticorena's model was applied as a reference.

The Bantargebang landfill (Jakarta) was chosen for setting and anchoring the model template because of its waste types, volumes, and physico-environmental conditions. This enables us to develop a standard template for the amount of CH_4 produced and electricity linked with the income generation. Based on this approach, the CH_4 and electricity production volumes from the landfill were estimated.

The Marticorena's model can be used to calculate the Bantargebang's LFG potential (Ham and Barlaz, 1989). The model's variables and their explanations are listed in Table S2. The Marticorena model equation is presented as follows:

$$MP = MP_0 \exp\left(-\frac{t}{d}\right) \tag{1}$$

$$D(t) = -\frac{dMP}{dt} \tag{2}$$

Once the specific methanogenic potential (MP) of garbage was determined, the rate of CH_4 production can be calculated by substituting equation (1) into equation (2):

$$D(t) = \frac{MP_0}{d} \exp\left(-\frac{t}{d}\right) \tag{3}$$

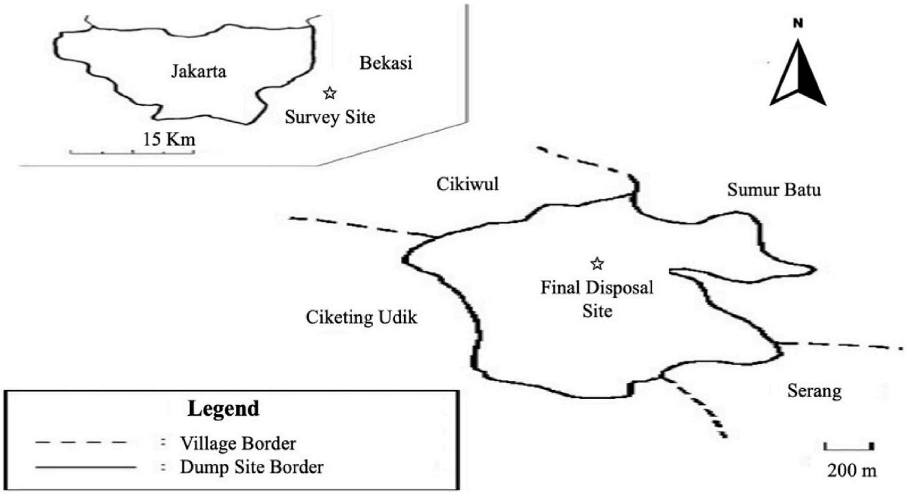

Fig. 3. Location of Bantargebang landfill in Bekasi (Indonesia).

Table 2
Comparison of mathematical models of CH_4 production from landfill.

Category	Model	Assumption	Limitation
Statistical models	Biodegradable component	The amount of biodegradable organic matter	CH_4 production from landfills cannot be calculated directly.
	IPCC	Classification of wastes containing biodegradable organic carbon	Classification scenarios vary from country to country.
	Stoichiometric	Empirical chemical equations	The calculated result is higher than the actual output.
Kinetic models	Zero-order	A relatively constant rate of gas production	No suitable conditions for CH_4 production.
	Gardner model	With the addition of parameters of degradation rate and the content of degradable organic carbon	The calculated result is higher than the actual output.

Equation (4) is used to determine the total CH_4 yield of the landfill.

$$F(t) = \sum_{i=1}^{t} T_i D(t-i) \tag{4}$$

Substituting equation (3) into equation (4) enables the total CH4 yield of the landfill to be achieved according to the rate and cycle of waste gas production:

$$F(t) = \sum_{i=1}^{t} T_i \left[\frac{MP_0}{d} \exp\left(-\frac{t-i}{d} \right) \right] \tag{5}$$

After obtaining the production of CH_4 using the Marticorena model, the heat generated by CH_4 combustion was calculated based on the calorific value and production of CH_4. Equation (6) was used to determine the heat:

$$Q_C = \frac{F(t) \times q_C}{1000} \tag{6}$$

Equation (7) assumes that CH_4 has been completely burned. The heat produced by CH_4 is the main source of heat for power generation of internal combustion engines (ICE). The heat consumption of the ICE was estimated in equation (7):

$$g = \frac{\frac{G_t}{t \times P_R} H_u}{365 \times 24} \tag{7}$$

where the G_t in equation (7) was calculated as equation (8):

$$G_t = g_t \times 24 \times 365 \times t \tag{8}$$

Equation (7) and equation (8) are based on the fact that there are 365 days in a year and 24 h in one day and one night. Substituting equation (8) into equation (7) gives a thermoelectric conversion relation as follows:

$$g = \frac{\frac{G_t}{t \times P_R} H_u}{365 \times 24} = \frac{g_t \times 24 \times 365 \times t}{t \times 365 \times 24 \times P_R} H_u = \frac{g_t}{P_R} H_u \tag{9}$$

Here we use the heat from the burned CH_4 to estimate electricity generation. For this process, we need to consider the heat consumption of the generator and the efficiency of power generation. Then the power generation was obtained according to equation (10):

$$G = \frac{Q_C \rho_H \rho_P}{g} \tag{10}$$

Substituting equations (5) and (6) and equation (9) into equation (10) gives the amount of electricity generated as follows:

$$\begin{aligned} G &= \frac{Q_C \rho_H \rho_P}{g} \\ &= \frac{\frac{F(t) \times q_C}{1000}}{\frac{g_t}{P_R} H_u} \rho_H \rho_P \\ &= \frac{\frac{\sum_{i=1}^{t} T_i \left[\frac{MP_0}{d} \exp\left(-\frac{t-i}{d} \right) \right] \times q_C}{1000}}{\frac{g_t}{P_R} H_u} \rho_H \rho_P \\ &= \frac{\sum_{i=1}^{t} T_i \left[\frac{MP_0}{d} \exp\left(-\frac{t-i}{d} \right) \right]}{1000 g_t H_u} q_C P_R \rho_H \rho_P \end{aligned} \tag{11}$$

By assuming that the electricity price remains constant, if the above-mentioned power generation is linked to the grid and commercialized, the landfill's electrical revenue can be calculated as follows:

$$I = G \times P \tag{12}$$

3. Results and discussion

3.1. LFG power generation

Numerous countries have built and been profited from waste-to-energy plants (WTE) with respects to socio-economic and environmental aspects. Using the Bantargebang landfill (Indonesia) as a model, Fig. 4 depicts the LFG power generation status between January 2020 to May 2021. The CH_4 and energy generation were projected using the landfill's power generation model.

The figure also illustrates the actual power generation of a three-generator power plant. The plant was equipped with two 1000 kW and one 1500 kW generating sets after several periods of expansion. In the WTE plant, CH_4 and CO_2 content were 80% and 19%, respectively. Switch No. 1 or No. 2 generator handled the production of LFG after anaerobic fermentation, and No. 3 generator continued to generate electricity. The Switch No. 2 did not generate electricity for 6 months from February 2020, while the Switch No. 1 did not generate electricity for 4 months from February 2021. The estimated LFG production in Fig. 4 was obtained after complete anaerobic fermentation in the landfill's cells.

As depicted in Fig. 4, the power station's average monthly gas output exceeded 500,000 m^3 and its average monthly electricity generation exceeded 1 million $kW{\cdot}h$. Three biogas' internal combustion generators were included in the biogas power generation. The plant was extended to meet an increasing demand for garbage disposal. In the first and second phases, a total of 4,200 Mt of MSW was disposed of. The third phase of the plant has been commissioned and designed to process the landfilled MSW daily.

3.2. CH_4 production

Landfill operators can increase revenue by generating power during CH_4 combustion (Banaget et al., 2020). As the manufacturing of CH_4 is a continuous process, numerous machines exist to convert biogas to electricity, their capacities range from 100 kW to 1 MW and their electrical efficiency is between 34% and 40% (Benato et al., 2017). ICE has higher electric energy yields than turbines, microturbines, and gradual oxidations (GOs) (Manasaki et al., 2021). Therefore, ICE is selected to convert biogas to electricity.

According to the US Environmental Protection Agency (EPA), the power generation of the Bantargebang landfill has the capacity to use 60–90% of the CH_4. A landfill equipped with a daily processing capacity of 1000 *Mt* and a power of 1000 *kW* was set and the life span of the MSW was set to six years. Table S3 lists the parameters of the chosen generator and other model variables.

The power generation modeling was conducted using CH_4 in the LFG according to the landfill's power generation model. By assuming that a total of 7.5 $\times 10^6$ *tonne* of MSW was landfilled during the period, the simulation examined CH_4 production and power generation for 15-year.

The accumulation of waste in landfills continued to produce LFG, which in turn led to a high CH_4 production. Fig. 5 displays that CH_4 production was 5.42×10^6 m^3/year in the 1st year and 3.51×10^8 m^3/year in the 15th year, respectively. The CH_4 production was lower in the first year, as less MSW was buried in the landfill in the beginning of its operation. The CH_4 production in the 15th year was much higher than that in the 1st year. It is higher if the Bantargebang landfill continues to be used with the increasing disposal of MSW.

Based on the projected CH_4 production, the power generation forecast is presented in Fig. 6. The Figure shows that the power generation was 1.2 $\times 10^7 kW{\cdot}h$ in the 1st year and as much as 7.7 $\times 10^8$ $kW{\cdot}h$ in the 15th year. Furthermore, this can be extrapolated from year 1 or year 15 by assuming that 1 m^3 of CH_4 can produce over 2 $kW{\cdot}h$ of electricity.

By assuming that all the electricity generated is sold and that the price of electricity continued to be 0.1 US\$/($kW{\cdot}h$), the sales income could be estimated. Fig. 6 also shows that the income from power generation was US\$ 1.194 $\times 10^6$ in the 1st year and US\$ 7.73 $\times 10^7$ in the 15th year based on the projections of CH_4 and power generation. Giving the power generated to WTE plants for their own use could minimize the cost of buying power from the grid and reduce the electricity's sales revenue annually. This would significantly benefit landfill operators (Kurniawan et al., 2021c).

It is important to note that the difference in the efficiency of generators, number and type of generators, and power rate of the generators affects power generation (Chakraborty et al., 2013). In addition, the power plants depend on the capacity of landfills and their waste disposal capacity. Larger landfills emit more LFG due to more waste being broken down, leading to a higher electricity output.

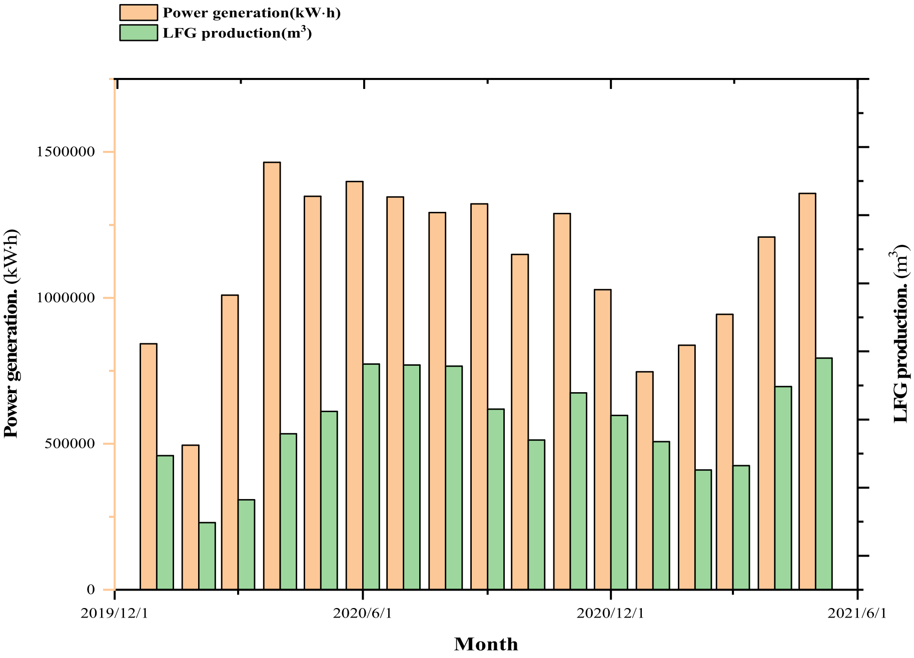

Fig. 4. Power generation of a WTE plant.

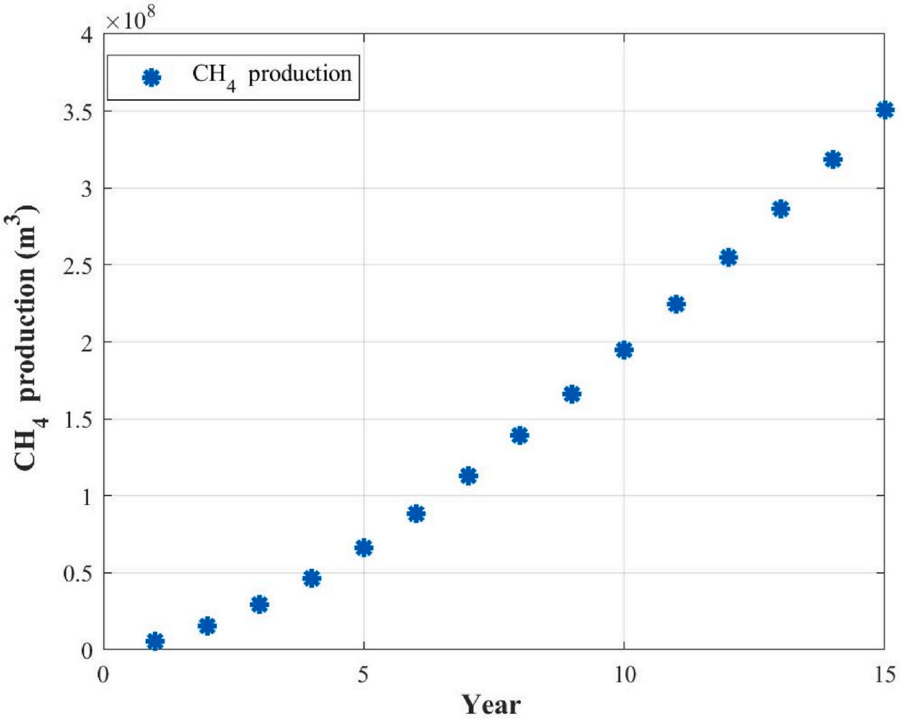

Fig. 5. Production of CH_4.

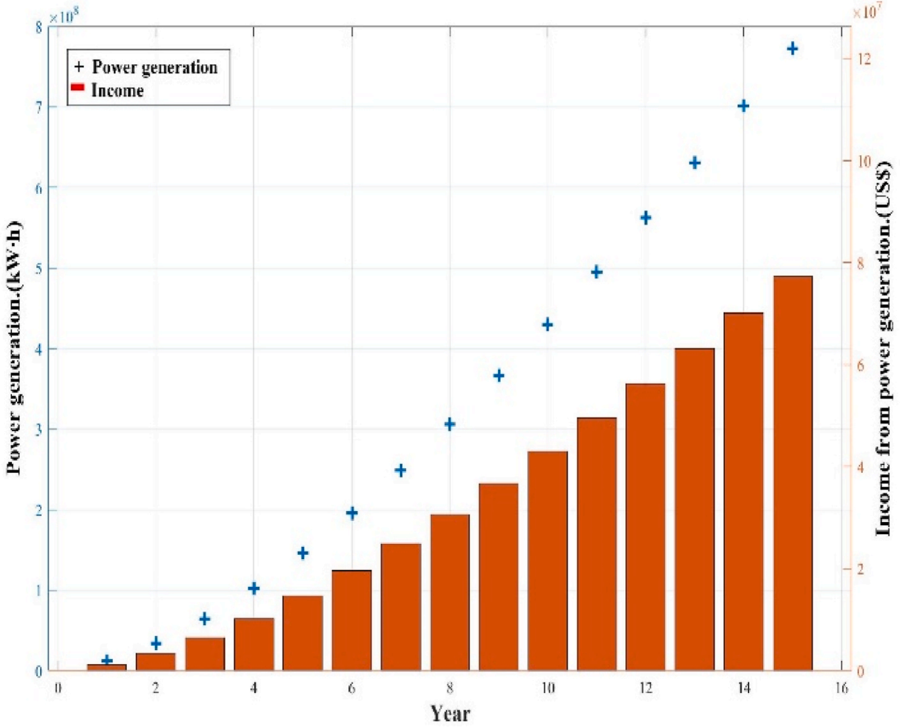

Fig. 6. Production of electricity and income from power generation.

Additionally, the discharge of LFG varies with the age and environmental conditions of the landfills (Manasaki et al., 2021). Therefore, the CH_4 production, power generation, and income from power generation are presented to illustrate the power generation capacity of CH_4 and the economic aspects of the WTE plant.

3.3. *Cost-benefit analysis of WTE conversion*

Both economic and environmental benefits in terms of quantitative and qualitative aspects are elaborated. Quantitatively, the CH_4 could be reduced by 25,000 Mt annually and electricity generation could reach 1.0×10^6 kW ·h/year, consequently savings on equivalent electricity charges worth US\$ 1.2×10^7/year (based on US' 8/kW · h). An equivalent CO_2 mitigation of 3.4×10^6 Mt/year (based on its GWP with 100-year time horizon) was also obtained.

On the other hand, qualitative benefits such as diversification of Indonesia's primary energy and improvement in terms of environmental protection and living quality by reducing odor problems, mitigating hazards due to volatile organic compounds (VOCs), and preventing landfills from unexpected fires. This can potentially accelerate their remediation and increase public activity space.

Therefore, harnessing LFG for electricity is one of the most promising options to reduce CH_4 emissions and the atmospheric pollution in Jakarta. The modeling study on the Bantargebang landfill using the LFG extraction data indicates that the LFG production ranged from 0.05 to 0.40 m^3 per kg of the landfilled MSW. This suggests that the energy supply from domestic waste materials saves on fuel cost in industries. In contrast to fossil fuels, utilizing LFG does not emit CO_2 into the environment. Due to the low contents of sulfur in MSW, its direct utilization as electricity in the combustion risks public health much less than that of fossil fuels (Nishio and Nakashimada, 2007).

While the initial capital costs to install a LFG project are high, it is estimated that the benefits of LFG capture for direct use can outweigh the costs (Tsai, 2005). This makes LFG capture appealing from an emission standpoint and an economic point of view. As a WTE plant generates electricity over 95% of the time (24 h a day), this represents an attractive emissions reduction initiative, in which the energy in the recovered biogas may be sold to the market. This approach not only is cost-effective to supply community's needs, but also creates job opportunities in the local economy.

This provides additional revenues for landfill operators through the sale of green power and transfer of emissions reduction credits. A WTE plant can generate electricity at a cost as low as US' 8 per kW · h. This revenue not only defrays the cost of landfill's operations and maintenance (O&M), but also provides an incentive and means to improve their design, thus developing a better waste management system in the long-term (Abila, 2014).

3.4. *Environmental impact assessment of the Bantargebang landfill*

In anticipating the environmental impacts of the project, the Bantargebang landfill (Jakarta) was evaluated. An initial environmental examination (IEE) was undertaken to assess its present situation and potential environmental impacts in the long-term. The scope of the IEE was conducted based on the Asian Development Bank (ADB)'s standards. The project was classified as 'A' Category according to the Environmental Impact Assessment (EIA) for the landfill (Chen and Wu, 2015).

The landfilled solid waste can contribute to renewable energy production in the form of LFG (Consonni et al., 2005). In the framework of resource recovery, the LFG contains a high concentration of CH_4 that can be utilized to generate power and heat. This bioenergy not only improves the added value of the landfilled MSW as unused resources, but also diversifies national energy supply and improves environmental protection. Therefore, another option such as LFG, which is locally and abundantly available, is economically attractive for promoting CE applications in waste management.

The LFG, which results from organic waste decomposition in landfills, has the potential to generate enough energy in the form of electricity (Consonni and Viganò, 2011). Rather than burning the waste for no gain, landfill operators can increase their revenue by generating power during the methane combustion (Demaria and Schindler, 2016). Numerous WTE plants exist to convert the biogas to electricity with their capacities ranging from 0.1 to 1 MW and their electrical efficiency ranges between 34 and 40% (Friege and Fendel, 2011). Hence, they augment the generation capacity as well as reduce the GHG emissions from the local landfill (Brunner and Rechberger, 2015).

The electricity, recovered from downstream waste disposal in landfills, can be reused to address climate change problems. In addition, this would ease growing environmental concerns over a rapid economic development in Indonesia. A win-win goal of environmental protection and economic growth could be achieved without sacrificing either of them in the battle against climate change.

Using LFG as a fuel would also benefit society in the long-term. The CH_4 derived from the LFG is more competitive in terms of efficiency and costs than other options such as heat and ethanol (Chen et al., 2007). The biogas not only has the potential to replace fossil fuel-derived energy and provides an additional revenue stream, but also reduces environmental impacts in the long-term.

For example, the LFG project may capture 85% of the CH_4 emitted from the Bantargebang landfill. The captured CH_4 is destroyed when the gas is burned to produce electricity. The GHG reduction benefit of a typical 1 MW LFG project is equal to planting over 16,000 acres of forest per year or removing the annual emissions from over 12,000 cars. This suggests that the use of LFG may reduce air pollution by offsetting the use of non-renewable resources.

Producing electricity from LFG eliminates the need to use non-renewable resources such as coal, oil, or natural gas to generate the same amount of electricity. This option can help Indonesia avoid power plant emissions of CO_2 and other pollutants such as SO_2 (a major contributor to acid rain), particulate matter (a respiratory health concern), nitrogen oxides (NO_x), and other trace air pollutants. Depending on the fuel and technologies used by power plant, the NO_x emission reductions from the power plant may not completely offset the NO_x emitted from the landfill. However, the overall improvement from the LFG generation project is important due to the substantial reduction in CH_4 emission. This would avoid using limited non-renewable resources that are more polluting than the emitted LFG (Bogale and Viganò, 2014).

Last, but not least, the potential for replicating the technology in local landfills nationwide may be promising. For the first installation of a biogas plant, training, and familiarization associated with its establishment may lower the overall price to US' 6 per kWh for the initial power production from the biogas plant (ADB, 2020). However, it is estimated that future installation may be inexpensive, as far as both installation and labor costs are concerned. It is expected that future biogas plants may produce electricity at competitive rates, less than US' 8 per kW · h, the current electricity price in Indonesia.

3.5. *Applications of CE in solid waste management*

Methane production from landfills is a continuous process. The CH_4 determines the calorific value of LFG, and influences the power generation capacity of a LFG to energy plant (Gohlke and Martin, 2007). To produce LFG, organic trash is fermented in anaerobic tanks. As LFG generates power using CH_4, it has to be cleaned off from unwanted gases such as CO_2 and H_2S, which have corrosive effects on gas transmission and power generation equipment (Grosso et al., 2010). Similarly, the water vapor has effects on the LFG burning. Therefore, before LFG can be utilized for power production, it needs to be desulfurized and dehydrated (Hossain et al., 2014).

After the processed LFG is sent for energy production, the electricity produced can be fed back into a power system for usage in residential areas, creating a closed loop of CE (Fig. 7) (Kalyani and Pandey, 2014). A continuous monitoring of CH_4 levels is required, while the engine is running. If the calorific value of LFG with CH_4 content increases, the combustion and performance of LFG also improve. After meeting the generator's operational criteria, the biogas enters the dynamo for power generation, which is then fed to the grid (Kropáč et al., 2011). The exhausted gas from a generator, which burns CH_4, contains a significant amount of heat (Leckner, 2015). The waste heat device recycles and distributes the excess energy throughout the system such as heating the fermenter (Fig. 7). The calorific value of the combustion is used to conserve resource to the maximum extent.

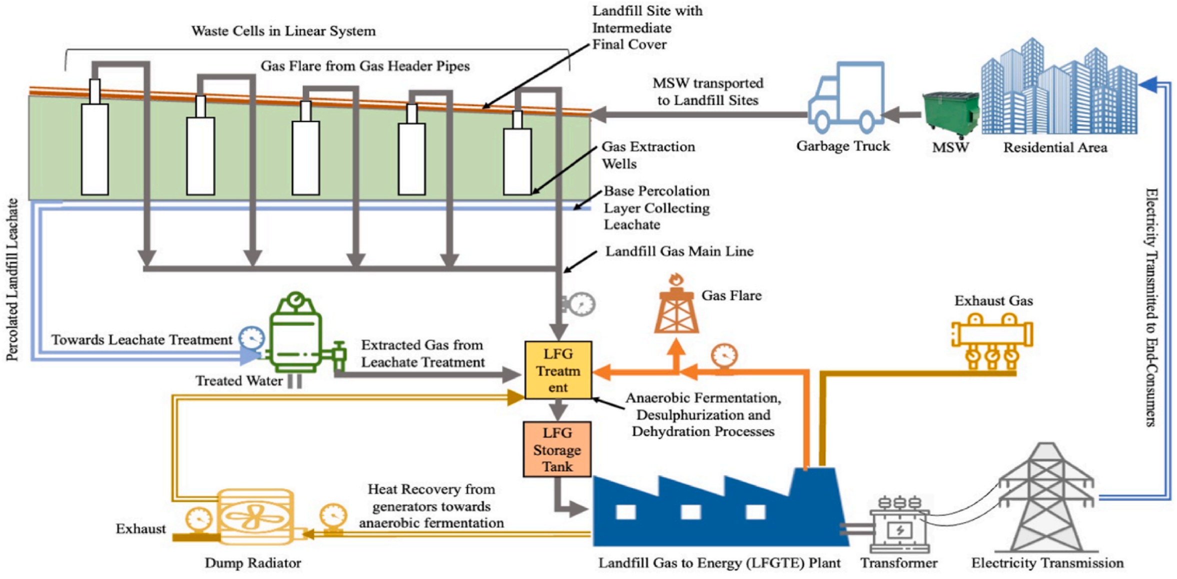

Fig. 7. Framework of MSW conversion into electricity.

Once constructed, the integrated biogas plant and landfill operations may be economically viable to generate profits by producing electricity that has a market value. Income from the sale of the product may be used to cover all operational costs of the plant and promote further biogas plants, as well as for the dissemination of biogas technology in Indonesia. The estimated annual profit of about US$ 150,000 generated from the WTE plant can be used to build other equally profitable biogas plants over the expected lifetime of the pilot biogas plant of 20 years (Chen, 2016). By thinking globally and acting locally, promoting resource recovery in this work has facilitated the recovered CH_4 from power plants to be re-used in such a way to meet the energy demands using engineering approaches, thus protecting the local environment and saving energy resources (Leme et al., 2014).

3.6. *Policy implication of WTE conversion in Indonesia*

Waste-to-energy conversion represents a closed loop of CE that eventually benefits solid waste management. Shifting to CE is essential to manage limited resources efficiently. The CE increases resource efficiency, while minimizing environmental impacts through GHG emission reduction, and saving on households energy bills (Giugliano et al., 2008a, 2008b, 2008b). For the sake of sustainability, the waste needs to be reduced, recovered, recycled, and reused (4Rs) in such a way that it could be turned into valuable resources with added technological values to promote resource recovery in the CE framework (Banaget et al., 2020). The conversion of the MSW into LFG for domestic consumption and reducing demand for fossil fuels contributes to affordable and clean energy, the 7th of the UN Sustainable Development Goals (SDG). If the growth of the MSW could be reversed by tackling it from upstream to downstream, this facilitates a sustainable resource recovery from unused waste.

With respect to CE applications in waste management, waste-to-energy conversion has become one of the most promising options to sustain a continued economic development in Indonesia in the future. To improve the performance of local landfills, the central government invites private sectors to be involved in waste management business, some of which are WTE programs financed by the clean development mechanism (CDM) scheme (Maier and Oliveira, 2014; Kurniawan et al., 2021c).

It is anticipated that producing electricity from LFG could eliminate the need of local residents to use natural resources such as fossil-based fuels to produce the same amount of electricity. This can help Jakarta avoid and minimize GHG emissions into the atmosphere. Large quantities of organic waste can be completely converted into CH_4 in a WTE plant. Further, the value of the renewable energy derived from the biogas can offset the cost of collecting and processing LFG to generate electricity without emitting any GHG into the atmosphere, thus improving environmental protection (Kurniawan et al., 2013; 2021d).

4. Conclusions

This exploratory study has demonstrated the added value of the landfilled MSW in generating sustainable energy, resulting from CH_4 emissions in the Bantargebang landfill (Jakarta). With the improving state-of-the-art of the WTE technology, the emitted CH_4 from the landfill can be reduced by 25,000 Mt annually, while electricity generation can reach 1.0×10^6 kW ·h/year. Consequently, this saves on equivalent electricity charges worth US$ 1.2×10^7/year (based on US’ 8/kW · h). An equivalent CO_2 mitigation of 3.4×10^6 Mt/year was also obtained. The income from power generation was US$ 1.2×10^6 in the 1st year and US$ 7.7×10^7 in the 15th year based on the projected CH_4 and power generation. The modeling study on the Bantargebang landfill using the LFG extraction tests indicate that the LFG production ranged from 0.05 to 0.40 m^3 per kg of the landfilled MSW. The LFG could generate electricity at a cost as low as US’ 8 per kW · h. As the implicationsof this study, this revenue not only defrays the cost of landfill’s operations and maintenance (O&M), but also provides an incentive to improve their design. Overall, this work not only leads to a diversification of primary energy, but also improves environmental protection and the living standard of people close to the plant.

Credit author statements

Tonni Agustiono Kurniawan was responsible for project supervision, re-writing original draft; Writing-review and editing; funding acquisition. Deepak Singh and Xue Liang were responsible for overall investigation and data collection. Tutuk Djoko Kusworo and Hui Hwang Goh were responsible for data analysis. Petros Gikas and Jawad Shoqeir were responsible for resources. Axel Olaf Kern was responsible for project administration. Mohd. Hafiz Dzarfan Othman and Ram Avtar were responsible for conceptualization and validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Dr Kurniawan gratefully acknowledge the Research Grant No. Q. J130000.21A6.00P14 from the Universiti Teknologi Malaysia (UTM) and the Award for Young Leaders in International Scientific Cooperation from the Victor Rabinowitch Memorial Symposium provided by the Richard Lounsbery Foundation for this work. He is also thankful for the grant support from the German Federal Ministry of Education and Research (BMBF) as a Green Talent awardee during his research stay.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.113882.

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