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MUNICIPAL SOLID WASTE POTENTIAL AS MALAYSIAN BIOENERGY RESOURCE, REDUCE GHG EMISSION AND GENERATE ECONOMIC BENEFITS

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ABSTRACT

Objective: To estimate the potential of municipal solid waste (MSW) as a bioenergy resources that reduce greenhouse gas (GHG) emission and generate economic benefits. **Methods:** The viability of MSW-based bioenergy options, techno-economic and environmental impact assessments were conducted using life cycle assessment method (LCA). **Result:** The average volume of waste in Klang increased by 29.4% between 2011 (14,912.80 t/month ± 821.17) to 2017 (19,300.47 t/month ±829.44). In average, the area generates 199,593.48 ±16,094.14 t/yr of waste where 72% of the waste is a potential resource for bioenergy that has the potential to generate 1,977.97 kWh/yr of electricity. The amount also could reduce GHG emission of 784.91 t/yr CH_4 which is equivalent to 19,622.75 t/yr CO_2. This translates to approximately US$184.82/yr. of electricity selling and US$1,833.56/yr. of carbon credits. Environmental impact evaluation shows about 2.38 ha/yr. of land area and 41,914.63 m^3/yr leachate production can be avoided. The cost saving of US$142,300.26 for land area, US$351,483.69 for leachate treatment, and US$2,008,478.19 for tipping fee could be achieved. This strategy also removes the emission of other landfill gas constituents such as H_2S (56%) and NMOCs (44%) and avoids heavy metals contamination into the environment (35% Zn and Pb, 14% Cr, 11% Cu, and 5% Cd). **Conclusion:** MSW-based bioenergy option has a potential to be used as energy resource and creates considerable benefits to the environment and is economically feasible.

Keywords: Solid waste, climate change, green energy, LCA

1. Introduction

Municipal solid waste (MSW) comes from our homes, institutions, commercial sources and industrial sectors but excludes construction and demolition debris. Solid waste is defined *as "discarded or unwanted materials, whether or not intended for sale or for recycling, reprocessing, recovery or purification by a separate operation from that which produced the matter"* (Environment Protection Authority [EPA], 2009). Waste compositions includes food wastes, paper, plastic, textiles, leather, yard wastes, wood, glass, metal, ashes, special waste (bulky items, consumer electronics, white goods, batteries, oil, tires), household hazardous waste, and e-waste (Hoornweg & Perinaz, 2012).

Rapid urbanization, industrialization, and population growth are major factors of the fast generation of solid waste quantities in the worldwide (Hoornweg & Perinaz, 2012). At present, the global MSW generation is at 1.3 billion tonnes per year (t/yr.) and expected to increase up to 2.2 billion t/yr. in 2025 with generation per capita increase from 1.2 to 1.4 kg/capita/day (Hoornweg & Perinaz, 2012). In Malaysia, solid waste generation increased from 6.94 million t/yr. in 2005 to 13.94 million t/yr. in 2016 (Mohd Pauze, 2016). This is an increased of (please explain in %) This is expected to keep increasing up to 18.13 million t/yr. in 2020 with the estimation of a total population of 33.34 million (Ministry of Housing and Local Government (KPKT), 2015).

In terms of daily waste generation per capita, Singapore is the highest (1.33 kg/capita/day) followed by Malaysia (1.03 kg/capita/day) and other Asian countries such as Thailand (1.0 kg/capita/day), South Korea (0.99 kg/capita/day), Japan (0.98 kg/capita/day), Indonesia (0.70 kg/capita/day), China (0.63 kg/capita/day), and India (0.5 kg/capita/day) (Hoornweg & Perinaz, 2012). In Malaysia, 80-90% of the waste are disposed of in landfills (Uyen & Schnitzer, 2009). Malaysia is heavily dependent on landfill because this relates to the low recycling rate in the country which is only 17.5%; a figure that is much lower compared to other countries such as Austria (63%), Germany (62%), Taiwan (60%), Singapore (59%), South Korea (49%) and Japan (21%) (The Statistics Portal, 2018).

Pollutants from landfills, definitely will contaminate the soil, surface and groundwater, and release toxic gases into the air (Crowley et al., 2003). Heavy rainfalls causes 55 to 97% of leachate to percolates into the groundwater and 1 to 26% remains stored in the soil (Schueler & Mahler, 2007). Disposal of mixed wastes in landfills produces leachate containing heavy metals (i.e. arsenic, cadmium, chromium, copper, lead, zinc) (Vasanthi, Kaliappan, & Srinivasaraghavan, 2008) . A case study was done in Selangor (Malaysia) recently found a high concentration of heavy metals in the topsoil of non-sanitary landfills (Sharifah et al., 2015). Direct exposure of humans to heavy metals may be possible through consumption of vegetables and water from contaminated soil and water supplies that can cause adverse health effects not only to human but also to animals (Khaled & Muhammad, 2016).

Landfills generate methane (CH_4) from the anaerobic process of the organic waste which a complete reaction of one tonne MSW could generate 0.149 tonnes of methane biogas (Themelis & Ulloa, 2007). According to Tomonori et al., (2011), improper managed of landfills and dump sites were recognized as a major sources of greenhouse gases (GHG) emission that released 50% methane (CH_4), 45% carbon dioxide (CO_2), and 5% other gases such as hydrogen sulfide and volatile organic compounds. Poor solid waste management contributes 5% of GHG to the total global GHG emission (Hoornweg & Perinaz, 2012).

According to the Synthesis Report 2014 by the Intergovernmental Panel on Climate Change (IPCC), GHG is a major concern globally due to its potential to cause climate change and global warming (IPCC, 2014). The changes in climate are expected to increase the risk to people, assets, economies, and ecosystem due to heat stress, storms, extreme precipitation, inland and coastal flooding, landslides, air pollution, drought, water scarcity, sea level rise, food security, infrastructure, and agricultural incomes (IPCC, 2014). From the 1750s to 2011, there are 40% of anthropogenic GHG in the atmosphere, 30% CO_2 absorbed by the ocean, and 30% on land and plants. is the numbers are expected to keep increasing from year to year (IPCC, 2014).

Clean Development Mechanism (CDM) projects were established and implemented by the United Nations Framework Convention on Climate Change (UNFCCC) under the Kyoto-Protocol that aims to reduce the GHG emission and earns certified emission reduction credits (CER) or carbon credit selling to gain the revenue (Lim, Lam, & Shamsuddin, 2013). CDM is one of the flexible mechanism that allow carbon to be traded in emission trading schemes. In 2015, CDM worldwide projects totalling to 350 projects reduced GHG emission of 51,295,568 metric tons of CO2 equivalent per year (CO_2-eq/year) (Potdar et al., 2016), where most of the projects focus on the renewable energy such as wind (28%), hydro (26%), and biomass (10%) (Lim et al., 2013). In 2010, Malaysia has 108 CDM projects (i.e. the CDM project in the palm oil industries) that gained 18 million CER equivalent to the capital flow of US$ 0.3 to 1 billion (Pedersen, 2008).

According to Getahun, Gebrehiwot, Ambelu, Gerven, & Bruggen (2014), mixed waste has a potential to generate a high amount of biogas, which contains a high caloric value for renewable energy production, due to the optimum ratio of carbon and nitrogen content, and synergistic effect of mixed waste. Thus, the implementation of landfill gas (LFG) recovery technology in landfills to produce renewable energy from landfill biogas could be important for a country to achieve economic saving, environmental protection, and GHG emission reduction (Getahun et al., 2014). In 2016, Malaysia has 28 biogas energy projects with the capacity of 1.00 – 3.18 Megawatt (MW) (Suruhanjaya Tenaga, 2015) that can be used for various purposes such as cooking fuel, industrial heating, lighting, mechanical power, and electricity generation (Bhattacharjee, Miah, & Sazzad, 2013).

Moreover, materials recovery could reduce the quantity of waste in a landfill as well as to increase landfill lifespan (Fauziah & Agamuthu, 2010; Yiing & Latifah, 2017). In general, landfill can operates for more than 20 years depending on the amount of waste disposed in it. Malaysia targets at 40% waste diversion by 2020 through solid waste segregation and recycling that have a potential value on land saving around RM 129.6 million and RM 16 million of leachate treatment (KPKT, 2015). Avoiding from constructing a new landfill will save more than RM30 million (Zaipul & Ahmad, 2017).

From our literature search, very limited research was done to study the potential of MSW as bioenergy resources especially in Malaysia. The objective of this study was to estimate the global potential of municipal solid waste (MSW) as a resource for bioenergy. The assessment was conducted to assess the viability of MSW-based bioenergy options through techno-economic and environmental impact assessments. The GHG emission and environmental impact assessment on leachate production, heavy metals emission, and land use was conducted in order to evaluate the potential economy revenue through avoidance cost and energy production. The outputs of this study provide information on the feasibility of the bio-energy approach as the new MSW strategies to be implemented to control GHG emission and reduce the impact on the environment in the country.

2. Materials and Method

2.1. Study Location

This study included Klang, Selangor (Malaysia) as the study area since it is the major waste generator in the country which is 1.35 kg/capita/day or 9,702 metric tonne/day of solid waste (JPSPN, 2013) (Figure 1). The total population of this area was 861,189 based on 2010 census (changed +2.36% every year) with an area of 672km^2 and the density of 1,374/km^2. Waste collection in Klang is operated at three times per week for domestic or households waste, and 12 or 36 times collection in a month for garden and illegal dumping waste. The collected wastes are disposed of in Jeram sanitary landfill (Klang Municipal Council (KMC), 2018).

2.2. Data Collection

The available datasets of generated MSW disposed of in the landfill (tonnes) from 2011 to 2017 were collected from KMC. The data was provided in tonnes of solid waste by month and year. The category (i.e. household, commercial and institutional, and industrial) and compositions (i.e. food waste, paper, plastic, garden waste, diapers, etc...) of MSW in Klang were determined using literature data on the fractions of MSW from National Solid Waste Management Department [JPSPN] (2013) to complete the calculation analysis.

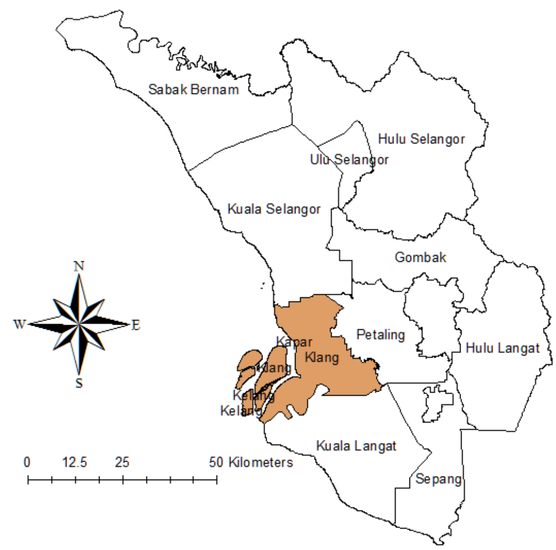

Figure 1: The location of study area, Klang was highlighted in the map.

2.3. Mathematical Equations

2.3.1. Methane emission

Methane (CH_4) emission in a landfill was calculated using Eq.1 and Eq.2 (IPCC, 2006);

DOC=$\sum[\mathbf{0.15}\boldsymbol{F} + \mathbf{0.20}\boldsymbol{G} + \mathbf{0.40}\boldsymbol{P} + \mathbf{0.43}\boldsymbol{W} + \mathbf{0.24}\boldsymbol{T} + \mathbf{0.24}\boldsymbol{D} + \mathbf{0.00}\boldsymbol{O}]$ **---Eq.1**

The range of degradable organic carbon (DOC) is from 0.08 to 0.21 and the recommended value by the IPCC of 0.15 can be used. In this study, the DOC was estimated by using Eq.1, where the DOC for food waste, garden waste, paper (including Tetra Pak), wood, textile, diapers, and other waste (i.e. glass, metal, plastic, rubber, leather, household hazardous waste (HHW), and other waste) is 0.15, 0.20, 0.40, 0.43, 0.24, 0.24, and 0.0 respectively (IPCC, 2006). F is the fraction of food waste in MSW, G is the fraction of garden waste in MSW, P is the fraction of paper in

MSW, W is the fraction of wood in MSW, T is the fraction textile in MSW, D is the fraction of diapers in MSW, and O is the fraction of other waste in MSW. Thus, the emission of CH_4 was estimated by Eq.2;

TCH_4 = $\sum[(MSWT \times MSWF \times MCF \times DOC \times DOCF \times F) \times \frac{16}{12}]$ **---Eq.2**

Where, total methane (TCH_4) is defined as total CH_4 emission in tonne (t), total municipal solid waste (MSWT) is total MSW disposed of in landfills by the study area (tonne), municipal solid waste fraction (MSWF) is 0.8 as Malaysia disposed 80% of waste in landfills (Dong et al., 2010). Methane correction factors (MCF) is range from 0.4-1.0, value 0.6 can be used for Malaysia landfill (Anwar, Saeed, Haslenda, Habib, & Mat, 2012). Degradable organic carbon (DOC) of 0.16 was estimated by using Eq.1, and the default value of degradable organic carbon fraction (DOCF) of 0.77 was used (Anwar et al., 2012). Fraction (F) refers to methane fraction which is 0.05 value was used as the global estimation of CH_4 emission from landfills is 5% (Hoornweg & Perinaz, 2012), and 16/12 is the conversion of carbon (C) to CH_4 (IPCC, 2006).

2.3.2. Carbon dioxide equivalent emission

Carbon dioxide equivalent (CO_2-eq) emission was calculated using Eq.3;

TCO_2-eq = $\sum[TCH4 \times 25]$ **---Eq.3**

Where, the total carbon dioxide equivalent (TCO_2-eq) is defined as 100-year global warming potential (GWP) factors by multiplying the estimated total CH_4 emission (TCH4) (Eq.1) by 25 as CH_4 has 25 times GWP than CO_2 (IPCC, 2006). Potential profits of carbon credits through LFG recovery was calculated through using Eq.5 (Poh, Haslenda, Wai, & Sie, 2017;Anwar et al., 2012);

2.3.3. Landfill gas constituents

The landfill gas constituents or NMOCs was calculated using Eq.4 that recommended by the U.S EPA (2005).

LGCs = $\sum_P [1.82 \times TCH4 \times (CP/(10^6))]$ **---Eq.4**

The emission of landfill gas constituents of hydrogen sulfide (H_2S) and non-methane organic compounds (NMOCs) (m^3-year) was estimated based on the total volume of CH_4-biogas (TCH_4) produced from Eq. 1 and Eq.2 (converted to m^3, which 1 tonne = $0.42m^3$). The *P* refers to the type of LGCs as shown in Table 1, the multiplication factor of 1.82 was used as 55% CH_4 and 45% CO_2 produced in a landfill, the default value of concentration of compound *P* (C*P*) in Table 1 was used, and the 1 x 10^6 is the conversion of ppmv to m^3.

Table 1: The default concentration of landfill gas constituents' concentration (NMOCs and H_2S)

Compound (P)	Concentration (ppmv)
Acrylonitrile	6.33
Carbon disulfide	0.58
Carbon tetrachloride	0.004
Carbonyl sulfide	0.49
Chlorobenzene	0.25
Chloroethane	1.25
Chloroform	0.03
Dichlorobenzene	0.21
Dichloromethane	14.3
Ethylbenzene	4.61
Hydrogen sulfide (H_2S)	35.5

Source: U.S EPA (1997)

2.3.4. Carbon credits

Potential profits of carbon credits through LFG recovery was calculated through using Eq.5 (Poh, Haslenda, Wai, & Sie, 2017;Anwar et al., 2012);

Carbon credit = $\sum[TCO2eq \times PP]$ **---Eq.5**

The total carbon dioxide equivalent (TCO2eq) was estimated from Eq.3. The product price (PP) of carbon credits selling recommended by two case study in Malaysia are RM55.21 (US$13.2) / t of CO_2 (Anwar et al., 2012) and RM64.34 (US$15.38) / t of CO_2 (Sie et al., 2015). In this study, the latest PP of carbon credits selling of RM64.34 (US$15.38) / t of CO_2 was used (Sie et al., 2015).

2.3.5. Electricity production

A potential electricity production was calculated using Eq.6;

EP = $\sum[(EC \times Mb) \times 0.4 \times 0.39]$ **---Eq.6**

Electricity production (EP) is total electricity generated through biogas recovery in the landfill in kWh. The energy content of $6kWh/m^3$ of biogas (CH_4) was used in this study (Poh et al., 2017). The mass of

CH_4-biogas (Mb) produced in the landfill was estimated from Eq.1 and Eq.2 (converted to m^3, 1 tonne = $0.42m^3$). In this study, the mass of CH_4-biogas produced was estimated based on the degradable organic carbon (DOC), gas production rate for each organic waste, and the fraction of food waste, garden waste, paper (including Tetra Pak), wood, textile, diapers, and other waste as shown in Eq.1. The efficiency of biogas conversion to electricity of 40% (0.4) (Poh et al., 2017) and the price of electricity selling in Malaysia of RM0.39 (US$0.093) per kilowatt-hour (kWh) (Sie et al., 2014) were used in this study.

2.3.6. CO_2 emission avoidance

A potential CO_2 emission avoidance was calculated using Eq.7 (Sie et al., 2014);

CO_2 avoidance emission = $\sum[\boldsymbol{EP} \times \boldsymbol{EFC}]$ **---Eq.7**

The CO_2 emission avoidance emission is a total of GHG emission reduction through electricity production (EP) by multiplying by the emission factor of CO_2 (EFC). The EP is estimated from Eq.6 and the value of 0.000619 t CO_2/kWh was used as the EFC (Sie et al., 2015).

2.3.7. Leachate production

Leachate production in a landfill was calculated using Eq.8 (KPKT, 2015);

VL = $\sum[\boldsymbol{MSWT} \times \boldsymbol{0.21}]$ **---Eq.8**

Where, the volume of leachate (VL) is defined as a total volume of leachate produced (m^3) based on the total MSW disposed of in a landfill. Total municipal solid waste (MSWT) is the total of MSW disposed of in the landfill (tonne), and 0.21 refers to one tonne of waste will generate $0.21m^3$ of leachate (KPKT, 2015).

2.3.8. Leachate treatment cost

The cost for leachate treatment was calculated using Eq.9;

LTC = $\sum[\boldsymbol{VL} \times \boldsymbol{TP}]$ **---Eq.9**

Where, leachate treatment cost (LTC) is a total of leachate volume (VL) produced (m^3) multiply by the treatment price (TP). The VL is estimated from Eq.8 and the TP is RM35 (US$8.39) per m^3 of leachate volume produced (KPKT, 2015).

2.3.9. Heavy metals

Estimation of heavy metals quantity released was calculated using Eq.10;

HQ = $\sum_{h}[\boldsymbol{VL} \times \boldsymbol{Ch}]$ **---Eq.10**

Where, HQ is a total of heavy metals quantity released in kg per year (kg-year), *h* refers to the type of heavy metals (i.e. Cadmium, Cd; Chromium, Cr; Copper, Cu; Lead, Pb; Zinc, Zn) considered in this study, total volume of leachate (VL) produced (m^3) is estimated from Eq.2, and the concentration (C) is the average of heavy metals concentration (kg-m^3) in landfill leachate which the average value from a case study of Malaysia landfill leachate characteristic was used to estimate the emission per year (Cd = 2.00E-06; Cr = 6.00E-06; Cu = 5.00E-06; Pb = 1.50E-05; Zn = 1.50E-05) (Agamuthu & Fauziah, 2010).

2.3.10. Land use

Required land area for waste disposal in a landfill was calculated using Eq.11 and Eq.12 (Khajuria, Yamamoto, & Morioka, 2010; KPKT, 2015);

LFS =$\sum[(\boldsymbol{MSWT}/\boldsymbol{Density\ of\ waste})]$ **---Eq.11**

Thus,

RLA = $\sum[(\boldsymbol{LFS}/\boldsymbol{Landfill\ height})/\boldsymbol{1000})]$

Where, Required land area (RLA) is total area required in hectare (ha) when MSW disposed of in a landfill. RLA is equivalent to landfill space (LFS) - total landfill space required annually in cubic meter per year (m^3/year) divide by the total municipal solid waste (MSWT) disposed of in a landfill with the density of waste. The density of waste value of 0.7 tonne per cubic meter (t-m^3) and 12 meter (m) standard height of landfill were used (Khajuria, Yamamoto, & Morioka, 2010; KPKT, 2015) and 10 000 is the conversion of m^2 to hectare (ha).

2.3.11. Land use cost

The cost for land use was calculated using Eq.13 (KPKT, 2015);

LUC = $\sum[\boldsymbol{RLA} \times \boldsymbol{LP}]$ **---Eq.13**

The cost for land use (LUC) is the total cost for required landfill area (RLA) for waste disposal by multiplying by the land price (LP). The RLA is estimated from Eq.11, and the LP is RM250, 000 (US$59,903.05) per hectare (ha) of land use (KPKT, 2015).

2.3.12. Tipping fee (waste disposal)

The tipping fee of waste disposal in a landfill was calculated using Eq.14 (KPKT, 2015);

TF = $\sum[\boldsymbol{MSWT} \times \boldsymbol{TFP}]$ **---Eq.14**

The tipping fee (TF) of waste disposal is equal to a total of municipal solid waste (MSWT) times by the price of tipping fee (TFP). The TFP in Malaysia is RM42 (US$10.06) per tonne of waste (KPKT, 2015). The value was used to calculate the tipping fee of waste disposal in Klang.

3. Results

3.1. MSW generation in Klang

Table 2 shows the monthly MSW generated (tonnes) in Klang from 2011 to 2017. The volume of waste has increased by 29.4% from 14,912.80 t/month ±821.17 in 2011 to 19,300.47 t/month ±829.44 in 2017. This is proportionate to the population growth of 881,771 in 2011 and 1,005,263 in 2017. In average, this area generates about 199,593.48 ±16,094.14 tonnes of waste per year (t/yr). High volume of waste was generated in January and December.

3.2. MSW compositions

Table 3 shows the estimation of waste generated in the study area according to its compositions. The highest waste generated was food waste with the mean ±SD of 79,408.26 t/yr ±6,403.06, followed by plastic (33,272.23 t/yr ±2,682.89), paper (26,515.99 t/yr ±2,138.10) and diapers (15,737.95 t/yr ±1,269.02). The waste also consists of garden waste (9,610.42 t/yr ±774.94), glass (6,776.20 t/yr ±546.40), textile (6,596.56 t/yr ±531.91) metal (6,277.22 t/yr ±506.16), tetra Pak (3,912.03 t/yr ±315.44), rubber 3,842.18 t/yr ±309.81), wood (2,864.17 t/yr ±230.95), household hazardous waste (HHW) (2,714.47 t/yr ±218.88), others waste (1,327.30 t/yr ±107.03), and leather (738.50 t/yr ±59.55). Increased in waste composition from 2011 to 2017 is proportionate to the increased in waste quantity generated in the area.

3.3. Greenhouse gases (GHG) emission

The estimation of GHG emission reduction (i.e. methane (CH_4) and carbon dioxide equivalent (CO_2-eq) and the revenue through gas captured is shown in Table 4. The mean ± SD of CH_4 emission was 784.91 ±63.29 t/yr and equivalent to 19,622.75 ±1,582.28 t/yr of CO_2-eq. These values produce an average of 329.66 ±26.58 m^3/yr of biogas that could generate the electricity of 1,977.97 ±159.50 kWh/yr through biogas captured. The revenue of US$184.82 ±14.90 per year from electricity selling and US$1,833.56 ±147.85 per year for carbon credits could be achieved. The production of electricity from the biogas could replace the use of fuel to avoid the emission of 1.23 ±0.10 t/yr of CO_2. Based on the total of seven years of waste volume from 2011 to 2017, the mean ± SD of the total potential profits (electricity selling and carbon credits) was US$2,018.39 ±162.75 per year.

3.4. Leachate production (m^3)

The estimation of the avoidance of leachate production in volume (m^3) and the treatment cost saving is shown in Table 4. In general, the MSW could potentially avoid leachate production of 41,914.63 ±3,379.77 m^3/yr with the saving cost of US$351,483.69 per year for landfill leachate treatment. From the total of seven years, 293,402.42 m^3 potential leachate with the treatment cost of US$2,460,385.86 can be avoided.

3.5. Land use

Transforming the MSW into bio-energy may reduce the required land area for waste disposal. In average, 2.38 ±0.19 ha/year of land potential to be avoided from the use as landfill with the saving cost of US$142,300.26 per year ±11,567.47 (Table 4). This land area can be used for other purpose such as agriculture that can generate more profit to the country. The total of land area that can be saved for seven years (2011 to 2017) was 16.63 ha with the estimated total cost of US$996,101.85.

3.6. Tipping fee (waste disposal)

The estimation of tipping fee is shown in Table 4. In average, the avoided tipping fee cost was US$2,008,478.19 per year through transformation of MSW into bio-energy. The total cost saving for seven years that could be achieved including leachate treatment, and land use was US$ 17,515,835.07 or US$ 2,502,262.15 per year.

3.7. Landfill gas constituents and heavy metals

Table 5 shows the avoidance of non-methane organic compounds (NMVOCs) ($m^{3)}$ and heavy metals (kg/year) released to the environment. The highest amount of NMOCs avoided was hydrogen sulfide followed by dichloromethane, acrylonitrile and ethylbenzene. The estimation of heavy metals removed from this alternative was Pb > Zn > Cr > Cu and Cd.

Figure 2 shows the percentage of avoided NMOCs released in to the environment. The highest percentage of emission avoid was hydrogen sulfide (56%) followed by dichloromethane (23%), acrylonitrile (10%) and ethylbenzene (7%). Other NMOCs such as Chloroethane (2%), carbon disulfide (1%) and carbonyl sulfide (1%) also could be avoided. Small percentage of chlorobenzene (0.4%), dichlorobenzene (0.3%), carbon tetrachloride (0.01%) and chloroform (0.01%). Figure 3 shows both 35% of Pb and Zn can be avoided from released to the environment followed by 14% Cr, 11% Cu and 5% Cd.

4. Discussion

Data obtained from this study shows that the generation of MSW in Klang has increased by 29.4% from 2011 to 2017. Increase in waste generation in the study area is proportionate to the population growth. Besides, Klang status as a municipality and the urban area of Klang Valley also influenced the waste generation in the area (JPSPN, 2013). Residents in Klang was reported to produce more waste, which is 1.35 kg/capita/day than other regions in Malaysia. Based on the national survey on waste generation, the recycling rate in Klang was 9.4% which is very low compared to other cities in the country such as Kuantan (18.4%), Kota Bahru (15.7%), and Sibu (15.6%) (JPSPN, 2013). Since Selangor does not implement Act 672 that make compulsory for household to segregate their waste, this possibly cause low recycling rate reported. This is also one of the possible factors that cause the increase of waste being dumped in the landfill in this area.

The trend of waste generation from 2011 to 2017 also shows that most of the generated waste was mainly high in January and December. This possibly due to festival season and public holiday (i.e. School Holiday, New Year Celebration) celebrated during those months. Food waste is the major type of waste in the waste fraction (39.78%) and degradation of organic waste is potential for LFG recovery technology in the landfill to produce biogas energy. Other generated organic wastes that have a potential value to produce biogas energy in this study includes garden waste, paper, wood, textile, diapers, and Tetra Pak.

Approximately 72.46% of Klang's MSW has the potential to be converted into biogas (39.78% food waste, 32.68% other organic wastes). The present work reported that production of biogas energy significantly reduces the emission of CH_4 and CO_2. The finding from the previous Malaysian case study in 2015 also reported that LFG recovery reduced the GHG emission at 17% (Sie et al., 2015). Another study also stated that about 13% of GHG emission could be avoided through the implementation of LFG recovery technology in a landfill (Menikpura, Sang-Arun, & Bengtsson, 2016). In another study, the percentage of emission reduction was slightly higher. For instance, Dong et al., (2014) in China reported that 42% of CH_4 emission avoidance could be achieved when 70% of the efficiency of biogas capture technology is applied.

In this study, the transformation of 329.66 m^3/yr of biogas from MSW has a potential to generate 1,977.97 kWh/yr of electricity that can be sold to support the demand of electricity use in the country. A case study in Malaysia has been also described the potential of waste as a source of renewable energy, which conversion of food waste (7,594.67 t/d) into biogas energy (60 million m^3/yr) to produce 143,073,689 kWh/yr of electricity significantly reduce the GHG emission in a landfill (Poh et al., 2017). In another study by Sie et al., (2015) reported that production of biogas (131,175.00 m^3) from landfill gas capture generates 275,470 kWh/day of electricity. The present study has stated the use of electricity from biogas could avoid 1.23 t/yr of CO_2 emission to the environment. This supported by Pour, Webley, & Cook (2018) as they stated that the production of electricity from LFG capture significantly avoid 1.35 t of CO_2-MWh of electricity produced or 2.4 x 10^{-4} t CO_2-t of waste in Australia. An amount of electricity produced from biogas, however, depends on organic waste quantity, calorific value, energy content, and technology efficiency (Poh et al., 2017).

The application of LFG recovery technology in the landfill could reduce the emission of leachate. Leachate can be collected and used as leachate recirculation on methane production to improve the quality of biogas being produced. This has been reported by Plocoste, Jacoby-Koaly, Mollinie, & Roussas (2016), a case study in France, where raw leachate has been used to increase CH_4 production and reduce the cost and quantity of leachate to be treated.

The conversion of MSW in Klang into bioenergy increased the reduction of land usage. In the United States of America, the LFG project is recognized as an effective method to reduce the land usage which is 15% to 30% of landfill capacity savings had been achieved in 2008 after the implementation of the project in 2001 (U.S EPA, 2012). The implementation of this technology in a landfill will enhance solid waste decomposition as well as increase landfill capacity, and mitigate the costs of constructing a new landfill or expanding existing ones (U.S EPA, 2012).

Moreover, this study estimates that the LFG project avoids the tipping cost of waste disposal when all generated waste is transformed into biogas energy. This also reported in a Malaysia case study by Sie et al., (2015) where the tipping cost of US$150,000.00/day for 2,500 t/day of waste could be saved through landfill gas recovery system. In total (leachate treatment, land use, and tipping fee) around US$2,502,262.15 per year could be saved by the government through advanced waste management technology of LFG recovery in a landfill.

Table 2: Total MSW generated (disposed of in a landfill) in Klang, Selangor (tonne).

Month/Year	**2011[a]**	**2012[a]**	**2013[a]**	**2014[a]**	**2015[a]**	**2016[a]**	**2017[a]**
January	14,857.88	18,141.89	17,752.05	**17,509.88**	**16,599.55**	15,592.51	**21,225.6**
February	**13,643.14**	16,073.45	15,898.69	**14,435.70**	**14,987.17**	**14,661.38**	**17,968.04**
March	14,946.38	16,816.00	16,327.37	15,255.97	16,434.41	15,058.41	19,976.91
April	14,635.24	16,395.24	16,368.96	15,898.36	15,827.07	15,032.03	18,552.34
May	14,293.91	16,908.78	16,570.20	16,425.29	15,857.25	16,013.09	19,320.88
June	14,152.00	15,620.39	**15,234.33**	16,566.55	16,168.70	15,260.63	18,991.99
July	15,212.24	16,466.87	**17,595.90**	17,116.36	16,235.22	16,917.88	18,995.75
August	15,985.03	15,383.99	16,757.09	16,024.48	16,044.96	19,371.41	19,264.74
September	14,467.28	**15,378.63**	16,344.14	15,686.28	15,301.52	17,548.19	18,528.30
October	14,843.00	16,001.95	16,962.07	16,689.30	15,931.96	19,087.59	19,683.97
November	15,206.47	17,000.18	16,245.01	15,728.03	16,262.52	18,844.31	19,468.67
December	**16,710.99**	**18,183.34**	17,079.04	16,842.80	16,184.52	**19,688.31**	19,628.44
Total	**178,953.56**	**198,370.71**	**199,134.85**	**194,179.00**	**191,834.85**	**203,075.74**	**231,605.63**
Min	13,643.14	15,378.63	15,234.33	14,435.70	14,987.17	14,661.38	17,968.04
Max	16,710.99	18,183.34	17,752.05	17,509.88	16,599.55	19,688.31	21,225.60
Mean	14,912.80	16,530.89	16,594.57	16,181.58	15,986.24	16,922.98	19,300.47
±SD	821.17	941.65	699.41	852.89	457.59	1905.46	829.44
Total Population	**881,771[b]**	**902,53[b]**	**922,935[b]**	**943,517[b]**	**964,099[b]**	**984,681[b]**	**1,005,263[b]**

[a]Data from local authority (*Klang Municipal Council*)
[b]Estimation based on census 2010 (Change:+2.36%/year)

Table 3: Waste compositions in Klang (tonne)

Result	Year								Statistic				
	2011[a]	**2012[a]**	**2013[a]**	**2014[a]**	**2015[a]**	**2016[a]**	**2017[a]**	**Total**	**Fraction (%)**	**Min**	**Max**	**Mean**	**SD**
Composition													
Food waste	71,196.67	78,921.79	79,225.80	77,254.11	76,321.49	80,793.68	92,144.30	555,857.84	39.78	71,196.67	92,144.30	79,408.26	6,403.06
Plastic	29,831.56	33,068.40	33,195.78	32,369.64	31,978.87	33,852.73	38,608.66	232,905.64	16.67	29,831.56	38,608.66	33,272.23	2,682.89
Paper	23,773.98	26,353.55	26,455.07	25,796.68	25,485.26	26,978.61	30,768.80	185,611.95	13.28	23,773.98	30,768.80	26,515.99	2,138.10
Diapers	14,110.49	15,641.53	15,701.79	15,311.01	15,126.18	16,012.52	18,262.11	110,165.63	7.89	14,110.49	18,262.11	15,737.95	1,269.02
Garden	8,616.61	9,551.55	9,588.34	9,349.71	9,236.85	9,778.09	11,151.82	67,272.97	4.81	8,616.61	11,151.82	9,610.42	774.94
Glass	6,075.47	6,734.68	6,760.63	6,592.37	6,512.79	6,894.42	7,863.01	47,433.37	3.40	6,075.47	7,863.01	6,776.20	546.40
Metal	5,628.09	6,238.76	6,262.79	6,106.93	6,033.21	6,386.73	7,284.00	43,940.51	3.15	5,628.09	7,284.00	6,277.22	506.16
Textile	5,914.41	6,556.15	6,581.41	6,417.62	6,340.14	6,711.65	7,654.56	46,175.94	3.30	5,914.41	7,654.56	6,596.56	531.91
Tetra Pak	3,507.49	3,888.06	3,903.05	3,805.91	3,759.97	3,980.29	4,539.47	27,384.24	1.96	3,507.49	4,539.47	3,912.03	315.44
Rubber	3,444.86	3,818.64	3,833.35	3,737.94	3,692.83	3,909.20	4,458.41	26,895.23	1.93	3,444.86	4,458.41	3,842.18	309.81
Leather	662.13	733.97	736.80	718.46	709.79	751.38	856.94	5,169.47	0.37	662.13	856.94	738.50	59.55
Wood	2,567.99	2,846.62	2,857.59	2,786.47	2,752.83	2,914.14	3,323.54	20,049.18	1.44	2,567.99	3,323.54	2,864.17	230.95
HHW[b]	2,433.77	2,697.84	2,708.23	2,640.84	2,608.95	2,761.83	3,149.83	19,001.29	1.36	2,433.77	3,149.83	2,714.47	218.88
Others	1,190.04	1,319.17	1,324.24	1,291.29	1,275.70	1,350.45	1,540.18	9,291.07	0.67	1,190.04	1,540.18	1,327.30	107.03

[a] Estimated based on **Klang Valley Household Waste Compositions:** Food waste (44.3%), Plastic (11.7%), Paper (9.4%), Diapers (11.7), Garden waste (5.9%), Glass (3.5%), Metal (2.2%), Textile (3.9%), Tetra Pak (1.4), Rubber (2.1%), Leather (0.3%), Wood (1.4%), Households hazardous waste[b] (1.5%), Others (0.7%) (JPSPN, 2013) and **Malaysia Institutional, Commercial, and Industrial** Waste Compositions: Food waste (31.4%), Plastic (25.9%), Paper (20.5%), Diapers (0.8), Garden waste (2.8%), Glass (3.2%), Metal (4.9%), Textile (2.2%), Tetra Pak (3.0), Rubber (1.6%), Leather (0.5%), Wood (1.5%), Households hazardous waste[b] (1.1%), Others (0.6%) (JPSPN, 2013).

Table 4: Environmental avoidance, energy production, costs saving and profits through biogas capture in the landfill.

Result	Year							Statistic		
	2011	2012	2013	2014	2015	2016	2017	Total	Mean	±SD
Environmental avoidance										
CH_4 emission (t)	703.74	780.10	783.11	763.62	754.40	798.60	910.80	5,494.37	784.91	63.29
CO_2-eq emission (t)	17,593.50	19,502.50	19,577.75	19,090.50	18,860.00	19,965.00	22,770.00	137,359.25	19,622.75	1,582.28
CO_2 emission (electricity) (t)	1.10	1.22	1.22	1.19	1.18	1.25	1.42	8.58	1.23	0.10
Leachate (m^3)	37,580.25	41,657.85	41,818.32	40,777.59	40,285.32	42,645.91	48,637.18	293,402.42	41,914.63	3,379.77
Land use (ha)	2.13	2.36	2.37	2.31	2.28	2.42	2.76	16.63	2.38	0.19
Production										
CH_4 biogas (m^3)	295.5708	327.642	328.9062	320.7204	316.848	335.412	382.536	2,307.64	329.66	26.58
Electricity (kWh)	1,773.42	1,965.85	1,973.44	1,924.32	1,901.09	2,012.47	2,295.22	13,845.81	1,977.97	159.50
Cost saving (US$)										
Leachate treatment	315,136.85	349,330.40	350,676.06	341,948.80	337,820.77	357,615.98	407,857.00	2,460,385.86	351,483.69	28,341.74
Land use	127,582.50	141,359.01	141,957.99	138,364.12	136,567.18	144,952.88	165,318.17	996,101.85	142,300.26	11,567.47
Tipping fee	1,800,781.91	1,996,173.68	2,003,863.10	1,953,993.15	1,930,404.33	2,043,519.67	2,330,611.52	14,059,347.36	2,008,478.19	161,952.86
Total	2,243,501.26	2,486,863.09	2,496,497.15	2,434,306.07	2,404,792.28	2,546,088.53	2,903,786.69	17,515,835.07	2,502,262.15	201,861.62
Profit (US$)										
Electricity selling	165.71	183.69	184.40	179.81	177.64	188.05	214.47	1293.77	184.82	14.90
Carbon credit	1,643.95	1,822.33	1,829.36	1,783.83	1,762.29	1,865.54	2,127.64	12,834.94	1,833.56	147.85
Total	1,809.66	2,006.02	2,013.76	1,963.64	1,939.93	2,053.59	2,342.11	14,128.71	2,018.39	162.75

Table 5: The avoidance of heavy metals and non-methane organic compounds (NMVOC) released to the environment

Result	Year								Statistic			
	2011	2012	2013	2014	2015	2016	2017	Total	Min	Max	Mean	±SD
NMVOC (m^3)												
Acrylonitrile	3.41E-03	3.77E-03	3.79E-03	3.69E-03	3.65E-03	3.86E-03	4.41E-03	2.66E-02	3.41E-03	4.41E-03	3.80E-03	3.06E-04
Carbon disulfide	3.12E-04	3.46E-04	3.47E-04	3.39E-04	3.34E-04	3.54E-04	4.04E-04	2.44E-03	3.12E-04	4.04E-04	3.48E-04	2.81E-05
Carbon tetrachloride	2.15E-06	2.39E-06	2.39E-06	2.33E-06	2.31E-06	2.44E-06	2.78E-06	1.68E-05	2.15E-06	2.78E-06	2.40E-06	1.92E-07
Carbonyl sulfide	2.64E-04	2.92E-04	2.93E-04	2.86E-04	2.83E-04	2.99E-04	3.41E-04	2.06E-03	2.64E-04	3.41E-04	2.94E-04	2.35E-05
Chlorobenzene	1.34E-04	1.49E-04	1.50E-04	1.46E-04	1.44E-04	1.53E-04	1.74E-04	1.05E-03	1.34E-04	1.74E-04	1.50E-04	1.22E-05
Chloroethane	6.72E-04	7.45E-04	7.48E-04	7.30E-04	7.21E-04	7.63E-04	8.70E-04	5.25E-03	6.72E-04	8.70E-04	7.50E-04	6.04E-05
Chloroform	1.61E-05	1.79E-05	1.80E-05	1.75E-05	1.73E-05	1.83E-05	2.09E-05	1.26E-04	1.61E-05	2.09E-05	1.80E-05	1.46E-06
Dichlorobenzene	1.13E-04	1.25E-04	1.26E-04	1.23E-04	1.21E-04	1.28E-04	1.46E-04	8.82E-04	1.13E-04	1.46E-04	1.26E-04	1.01E-05
Dichloromethane	7.69E-03	8.53E-03	8.56E-03	8.35E-03	8.25E-03	8.73E-03	9.96E-03	6.01E-02	7.69E-03	9.96E-03	8.58E-03	6.93E-04
Ethylbenzene	2.48E-03	2.75E-03	2.76E-03	2.69E-03	2.66E-03	2.81E-03	3.21E-03	1.94E-02	2.48E-03	3.21E-03	2.77E-03	2.23E-04
Hydrogen Sulfide	1.91E-02	2.12E-02	2.13E-02	2.07E-02	2.05E-02	2.17E-02	2.47E-02	1.49E-01	1.91E-02	2.47E-02	2.13E-02	1.71E-03
Heavy metals (kg)												
Cadmium, Cd	7.52E-02	8.33E-02	8.36E-02	8.16E-02	8.06E-02	8.53E-02	8.38E-02	5.73E-01	7.52E-02	8.53E-02	8.19E-02	3.33E-03
Chromium, Cr	2.25E-01	2.50E-01	2.51E-01	2.45E-01	2.42E-01	2.56E-01	2.51E-01	1.72E+00	2.25E-01	2.56E-01	2.46E-01	1.02E-02
Copper, Cu	1.88E-01	2.08E-01	2.09E-01	2.04E-01	2.01E-01	2.13E-01	2.10E-01	1.43E+00	1.88E-01	2.13E-01	2.05E-01	8.36E-03
Lead, Pb	5.64E-01	6.25E-01	6.27E-01	6.12E-01	6.04E-01	6.40E-01	6.29E-01	4.30E+00	5.64E-01	6.40E-01	6.14E-01	2.51E-02
Zinc, Zn	5.64E-01	6.25E-01	6.27E-01	6.12E-01	6.04E-01	6.40E-01	6.29E-01	4.30E+00	5.64E-01	6.40E-01	6.14E-01	2.51E-02

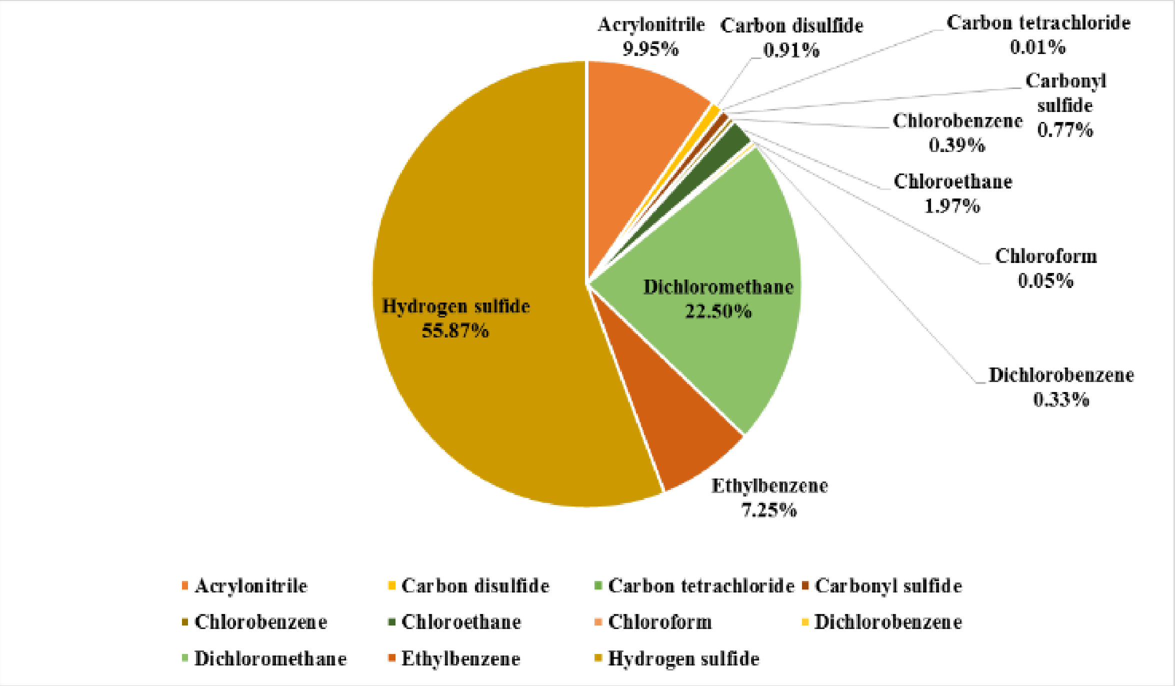

Figure 2: The percentage of avoided NMOCs release into the environment.

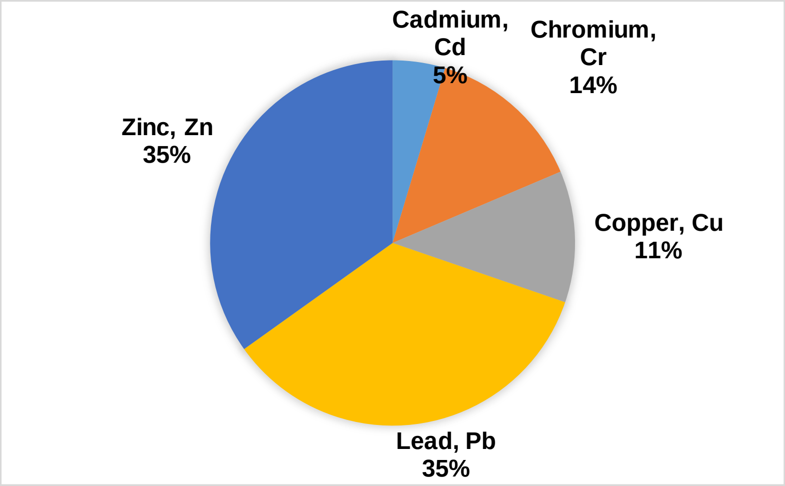

Figure 3: The percentage of avoided heavy metals release to the environment.

This study shows that the biogas capture able to avoid 56% of H_2S and 44% NMOCs emission in landfills. This is consistent with what has been modelled in China where the LFG recovery reduced H_2S emission from 70% to 30% and NMOCs from 71% to 29% emission for per tonne of waste produced (Dong et al., 2014). This shows that an LFG recovery project significantly will improve the quality of air and protect the surrounding community from hazardous pollutants emission. In addition, the avoidance of landfill leachate release into the environment significantly removes the emission of heavy metals from the landfill. This study addressed that 35% of Zn and Pb can be avoided release into the environment followed by 14% Cr, 11% Cu, and 5% Cd in kg per year.

Although this study managed to explore the potential of solid waste as bioenergy resources that reduce GHG emission and bring benefits to the economy but there are some limitations need to be adhere. The results of the study cannot be generalized to the whole Malaysia as its only consider the amount of waste generated in the specific study area of Klang, Selangor. It also abides to the waste fraction of this area where it might be different compared to other regions or country.

However, the study models and findings able to highlight the reduction in GHG emission, environmental impacts, and economic evaluation. This study also provides insight and baseline data that can be used to support stakeholders' decision-making in developing and planning policy or project related to MSW management in Malaysia. In a future study, other approaches such as integrated MSW management (i.e. a combination of waste reduction program, recycling, landfill, landfill gas recovery, composting, and/or waste to energy) should be considered and analyzed to identify the best strategy for a specific region or country.

4. Conclusion

In conclusion, waste generation and disposal increased every year, proportionate to the number of population. Increase of waste quantity disposed of in landfills will definitely increase the GHG emission that contributes to the global warming potential. The evaluation of LFG recovery to produce biogas energy from MSW generated in Klang has the potential to reduce GHG emission and CO_2. The biogas capture also could generate electricity that can generate income through electricity selling and carbon credits. On the other environmental point of view, biogas capture for energy production reduce the use of land area and release of leachate into the environment. Implementation of this strategy also could avoid the emission of hazardous pollutants into the air via H_2S and NMOCs and heavy metals emission into the soil and water.

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