Environmental Sustainability Framework for Plastic Waste Management - A Case Study in Bubble Tea Streets of Ss15, Subang Jaya

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Research Article

Keywords: Bubble tea industry, plastic waste, sanitary landfill, waste to energy incineration, life cycle assessment, sustainability framework

Posted Date: March 17th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-157966/v1>

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Abstract

Economic growth and rapid industrialisation have led to enormous increase in municipal solid waste (MSW) in the urban areas. Lack of waste management alternatives and ineffective waste policy implementation are the major challenges for government to materialise a sustainable solid waste management framework, especially for plastic waste. Booming bubble tea industry has aggravated the situation by generating more plastic waste which are either non-recyclable or rejected by recycling facilities as they have low or no economic values. Hence, this study aims to evaluate the overall environmental performance of existing and alternative waste management technologies that are available in Malaysia based on net greenhouse gas (GHG) emission in terms of carbon dioxide equivalent per tonne of plastic waste that are analysed through life cycle assessment (LCA) methodology. Waste management technology with better environmental performance is taken into account in environmental sustainability framework development for plastic waste management based on the case study in Bubble Tea Streets of Subang Jaya. Two scenarios of waste management technologies are considered: (A) sanitary landfill; (B) waste to energy (WTE) incineration. Results showed that Scenario B (WTE incineration) is more environmentally preferable as it has a negative net GHG emission of -573.80 kg CO₂-eq as compared to GHG emission of existing sanitary landfill (566.15 kg CO₂-eq.). Negative net GHG emission in WTE incineration is mainly due to higher GHG saving achieved through cleaner electricity generation as compared to conventional power production. This proposed alternative technology has the potential to reduce the dependence on landfills and is served as the basis of framework development. The environmental sustainability framework for plastic waste management can be baseline for the local authorities or policy makers for other plastic waste generation hotspots other than bubble tea industry to improve plastic waste management via WTE incineration.

Keywords: Bubble tea industry, plastic waste, sanitary landfill, waste to energy incineration, life cycle assessment, sustainability framework

List of symbols

Φ_P : Total electricity consumption for production of bubble milk tea (kWh)

W_i : Power rating of each electrical appliance (kW)

$HR_{Average}$: Average operating hours (h)

N_{Shops} : Number of bubble tea shops

$E_{CO_2,P}$: CO₂ emission from electricity consumption (kg CO₂-eq)

- 57 EF_{mix} : Emission factor of CO₂ based on electricity generation mix in Malaysia
 58 (kg CO₂-eq/kWh)
 59 $E_{CO_2,T}$: CO₂ emission from transportation (kg CO₂-eq)
 60 NCV_{diesel} : Net calorific value of diesel (MJ/kg)
 61 EF_{diesel} : Emission factor of CO₂ from diesel combustion (kg CO₂-eq /TJ)
 62 $E_{CO_2,L}$: CO₂ emission from landfill (kg CO₂-eq)
 63 PW: Plastic waste (t)
 64 $EF_{CO_2,L}$: Emission factor of CO₂ from landfill (kg CO₂-eq/t)
 65 Φ_L : Electricity consumption for compacting the waste in landfill (kWh)
 66 ρ_{CO_2} : Density of CO₂ (kg/m³)
 67 ρ_{CH_4} : Density of CH₄ (kg/m³)
 68 NCV_{CH_4} : Net calorific value of CH₄ (kWh/m³)
 69 Q_{CH_4} : Volume of CH₄ in landfill gas (m³)
 70 σ : Capturing efficiency of LGRS
 71 η_L : Electrical energy production efficiency of LGRS
 72 $E_{CO_2,SL}$: GHG saving from electricity generation from LGRS (kg CO₂-eq)
 73 EF_{CH_4} : Emission factor of CO₂ from CH₄ combustion (kg CO₂-eq /TJ)
 74 $E_{CO_2,I}$: Emission of CO₂ from incineration (kg CO₂-eq)
 75 Dm: Dry matter content of plastic waste
 76 CF: Fraction of carbon in dry matter
 77 FCF: Fraction of fossil carbon
 78 OF: Oxidation factor (fraction)
 79 44/12: Conversion factor from C to CO₂
 80 Φ_I : Electricity consumption for start-up of incinerator
 81 $Fuel_I$: Natural gas consumption for start-up of incinerator (MJ)
 82 EF_{gas} : Emission factor of CO₂ from natural gas combustion (kg CO₂-eq /TJ)
 83 $E_{N_2O,I}$: Emission of N₂O from incineration (kg N₂O)
 84 $EF_{N_2O,I}$: Emission factor of N₂O from incineration (kg N₂O/t)
 85 NCV_{PP} : Net calorific value of PP plastic (kWh/kg)
 86 η_I : Electrical energy production efficiency of incineration
 87 $E_{CO_2,SI}$: GHG saving from electricity generation from WTE incinerator (kg CO₂-eq)

1. Introduction

Kaza et al. (2018) stated that 242 million tonne of global plastic waste has been generated, which was 12 % of global municipal solid waste in accordance to the statistics from The World Bank in year 2016. 91 % of the plastic waste is not recyclable. This plastic waste will lead to global warming and climate change as they are either burned in open environment or being disposed into landfills, and only 12 % of the plastic waste has undergone proper treatment such as incineration. Packaging industry is the primary source of plastic waste generation and approximately 141 million tonne of global plastic waste has been generated by this industry in year 2015. This is because packaging plastics products from this industry have a very short life cycle of not more than six months. Therefore, this industry is responsible for two-thirds of the global plastic waste generation (Geyer et al., 2017).

Recently, bubble tea industry has created a hype to the whole world with their signature brown sugar milk bubble tea and since then, bubble tea has become an iconic drink in which every youngster is craving for it. Besides, bubble tea shops can be found almost everywhere around the commercial areas due to the hype, especially at the famous Bubble Tea Streets in Subang Jaya, Malaysia. It is reported approximately 74 brands of bubble tea vendors in Malaysia (Tan, 2019). High demand of bubble tea has led to significant increase in production of plastic waste. However, landfill is the only existing waste disposal method for plastic waste in Malaysia and plastic waste takes longer time to degrade in landfill as compared to other types of municipal solid waste (MSW) in which the high rate of plastic waste generation from bubble tea industry will speed up the filling up rate of landfill in the long run. As a result, the authorities have been struggling to materialise a sustainable waste management framework to deal with increase in plastic waste issue.

According to current Solid Waste Management Lab Report produced by Ministry of Housing and Local Government Malaysia (KPKT) (2015), the government had set a target to divert 40 % waste from landfills by year 2020. However, the booming of bubble tea industry in year 2019 has aggravated the situation making the target harder to achieve. This is because bubble tea vendors tend to utilise petroleum based single-use plastics with added additives as packaging materials in which are either non-recyclable or rejected by recycling facilities as they have low or no economic values. On top of that, ineffective waste policy implementation and lack of recycling awareness among Malaysian have led to low rate of plastic recycling (Alias et al., 2018). Furthermore, first waste to energy (WTE) incinerator in Malaysia is expected to begin

its operation in 2021 (Aziz, 2020). As a result, plastic waste from bubble tea industry will still ended up in the landfills. Therefore, all these factors have hastened the government's plan to begin operation of WTE incinerator as soon as possible to tackle the increasing plastic waste issue.

It is also well noting that only 10 out of the 166 landfills in Malaysia are sanitary landfills with landfill gas recovery system (LGRS) which lead to serious global warming issue (KPKT, 2015). As Malaysia has yet to begin operation of any WTE incinerator and therefore, the environmental performance of this alternative technology is not known. As a result, GHG emission from sanitary landfill and WTE incineration cannot be compared which hinder the sustainable plastic waste management framework development for government to tackle increasing rate of plastic waste generation.

Therefore, this study aims to evaluate the overall environmental performance of existing sanitary landfill and alternative WTE incineration via life cycle assessment (LCA) with Bubble Tea Streets of Subang Jaya in Malaysia as case study. An environmental sustainability framework for plastic waste management based on case study is developed which highlights the engagement between government, waste contractors, bubble tea vendors and public to ensure a long term application of the proposed framework in managing the municipal plastic waste efficiently.

2. Literature Review

Sanitary landfill is a well-designed system that has geomembrane which is made of high density polyethylene (HDPE) as foundation, drainage system to channel leachate accumulated at the bottom of landfill to leachate treatment plant and LGRS to capture methane (CH₄). The dominant types of GHG emission from landfilling are CH₄ and CO₂. Landfilling is the major source of CH₄ emission which account for 53 % of CH₄ emission in Malaysia and CH₄ emission from non-sanitary landfills are much greater than the emission from sanitary landfills. It is predicted that 370,000 tonne of CH₄ is to be produced in year 2020, which is equivalent to 9.25 million tonne CO₂-eq (Yong et al., 2019). This amount of greenhouse CH₄ is 25 times more potent than CO₂ in warming the earth. Although sanitary landfills can reduce these negative environmental impacts as compared to non-sanitary landfills, establishing a new sanitary landfill to trap CH₄ can be a challenging task for authorities due to land scarcity, high land cost

around urban area and negative perception from residents/communities who are living near the landfills.

Incineration is a thermal waste treatment technology that burn waste under high temperature into ash, heat and flue gas. The dominant types of GHG emission from incineration process are CO₂ and nitrous oxide (N₂O). There are two types of incineration i.e. incineration with and without energy recovery, with the latter one does not harness useful energy from flue gas to generate electricity. Incineration is the most common thermal treatment of plastic waste as compared to pyrolysis and gasification. There are several major challenges for Malaysia to establish WTE incinerators. Firstly, the moisture content in the municipal solid waste in Malaysia is approximately 45 % will lead to ineffective incineration process. However, non-organic waste such as plastic waste with very low moisture content and high calorific value making it suitable for thermal treatment (Yong et al., 2019). Secondly, high capital and maintenance costs hinder developing countries like Malaysia to invest money on establishing more WTE incinerators. Nevertheless, incineration saves cost in the long run as it reduces volume of waste by converting them into energy.

Malaysia has installed her first large scale WTE incinerator in Negeri Sembilan. This incinerator is scheduled to operate in 2021 which can help to divert MSW including plastic waste from landfills (Aziz, 2020). Besides, the most common type of WTE incineration is moving grate incinerator which has numerous benefits such as it does not require waste sorting or pre-treatment of waste, accommodate large waste volume and having the ability to handle all types of MSW as well as able to achieve complete combustion to maximise the extraction of heat energy from waste for electricity generation or district heating (Lew, 2020).

Recycling plastic waste has its challenges as majority of plastic products fall under the category of plastic grade four to seven which are rarely to be recycled or non-recyclable (Kaza et al., 2018). Plastic of all grades usually contain additives, adding difficulties in recycling. Moreover, plastic products such as packaging plastics often consist of more than a single type of plastic grade, which are usually termed as mixed plastics, adding more difficulties in sorting and recycling these plastics. Besides this, production of biodegradable plastics is very low, which is only one percent of global plastic production. Plastic products from grade one and two which are widely recycled can only be recycled once or twice and recycling processes often produce plastic products of lower quality and these products will eventually ended up either in the

landfills or incinerators (Ritchie and Roser, 2018). Thus, it is more economical to incinerate plastic waste if these plastics are too difficult to be sorted and recycled. Furthermore, recycling plastic is difficult as compared to recycling metals and glasses. Therefore, many developed nations get rid of their plastic waste in a cheap way by exporting them to developing nations such as China and Malaysia for recycling purposes (Wang et al., 2019). However, many of these discarded plastics are not recyclable and this plastic waste will eventually ended up in landfills or incinerators in which both waste management technologies can create electricity from the plastic waste. Although recycling plastic waste is a better option in accordance to waste hierarchy, but WTE technology is compatible or even does better than recycling in circular economy from overall sustainability point of view as it recovers both energy and materials from non-recyclable waste which keeps the environmental and humans free from toxic substances (Van Caneghem et al., 2019).

New Zealand (NZ), a country having a very similar waste composition is keen to explore sustainable waste treatment alternative such as WTE technologies to divert MSW from landfills. Three WTE thermal treatment technologies were studied and compared based on contexts of NZ, which are incineration, pyrolysis and gasification. The result of the literature suggested that incineration is still the most suitable WTE technology to replace landfill due to its ability to largely reduce volume of waste, matured technology, ability to handle variant of MSW and suitable for large scale application to deal with increasing MSW in the long run. Besides, pyrolysis and gasification create more side products that require further downstream treatment processes which will lead to greater emission whereas bottom ash from incineration can be used as construction material. Moreover, modern WTE incinerators have an electrical energy production efficiency of 30 % which is higher than the efficiency of gasification and pyrolysis of 27 % and 25 % respectively (Perrot and Subiantoro, 2018).

According to United States Environmental Protection Agency, USEPA (2016), incineration of MSW generates lesser GHGs than coal, oil and natural gas as shown in Table 1. This is a good news for Malaysian as 86 % of current power generation in Malaysia are from non-renewable resources as shown in Fig.1 (Abdullah et al., 2019). Therefore, WTE incineration is an environmental friendly option to reduce dependence on fossil fuels, divert 40 % of MSW, especially plastic waste from landfills and reduce effect of global warming by reducing GHG emission from burning of fossil fuels and landfilling.

Table 1 Summary of CO₂ emission from combustion of different types of combustible fuel (USEPA, 2016).

Fuel	GHG emission (kg CO₂ per MWh)
MSW	461
Coal	1020
Oil	758
Natural Gas	515

Table 2 Power generation sources in Malaysia in 2016 (Abdullah et al., 2019).

Power Generation Sources	Contribution to Energy Production of Malaysia in Percentage (%)
Natural Gas	43.5
Coal	42.5
Hydropower	13.0
Oil	0.3
Diesel	0.3
Others	0.4

Global temperature has increased by more than 1 °C since pre-industrial times. This is mainly caused by human activities that generate huge amount of GHGs in to the atmosphere. Approximately 36 billion t of CO₂ emitted globally every year and this amount is too huge that it is needed to be reduced in order to reduce the impacts of climate change (Ritchie and Roser, 2017). Therefore, this study focuses on reducing GHG emission from the waste sector, especially for plastic waste by comparing overall environmental performance of existing sanitary landfill and alternative WTE incineration to determine which waste disposal/management technology is environmentally more suitable in handling plastic waste. The 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories is the guideline recognised by worldwide and widely used in literature studies which provide methodologies to determine for three major types of GHG emission, namely CO₂, CH₄ and N₂O from man-made activities such as waste management (Eggleston et al., 2006).

LCA is the methodology used in environmental sustainability evaluation to quantify the environmental impacts of different waste management technologies based on energy and resource inputs as well as the GHG emission and saving. LCA has four main components, which are goal and scope definition, inventory analysis, impact assessment and interpretation

of result (Arvanitoyannis, 2008). LCA enables ones to perform different analysis based on defined system boundary, inventory analysis and made assumptions (Tan et al., 2017).

3. Methodology

This study focuses on utilisation of plastic cups and downstream process which mainly on management of plastic waste from Bubble Tea Streets in Subang Jaya, Malaysia. It is important to collect information such as (i) plastic cup grades, (ii) number of bubble tea shops and (iii) type of electrical appliances used in these shops via site visit and walk-in interview with bubble tea vendors as these primary data are the important inputs for this LCA study.

Goal and Scope Definition

The goal of this LCA study is to evaluate environmental impacts of the existing and alternative waste management scenarios (*Scenario A: Sanitary Landfill* and *Scenario B: WTE Incineration*) by quantifying GHG emission of the plastic waste from bubble milk tea industry. These two waste management technologies are to be compared for identification of better scenario with lowest net GHG emission. The functional unit is served to be the basis of comparison in the LCA system and the functional unit for this study is one tonne of plastic waste from Bubble Tea Streets of Subang Jaya. This LCA is a gate to grave system. The system boundary of LCA includes four phases, which are: production of bubble milk tea, consumption of bubble milk tea contained in plastic cups, plastic waste collection and transportation and disposal of plastic waste. Fig.1 and Fig.2 show the system boundaries of Scenario A and B respectively.

Please take note that plastic cup waste is termed as plastic waste in this study. There is no consumption of energy and emission during milk tea consumption by customer and material (plastic cup) is similar as input and output. Therefore, no inventory data analysis and impact assessment are conducted for this particular phase.

Fig.1 System boundary of existing plastic waste management for Scenario A

Fig.2 System boundary of plastic waste management for Scenario B

Assumptions that are made within system boundary of LCA are as following:

1. Only CO₂, CH₄ and N₂O are considered in this study as these gases are the dominant anthropogenic GHG emission by IPCC (Eggleston et al., 2006)
2. Only CO₂ is considered for combustion of fossil fuel for transportation and electricity generation as emission factors of CH₄ and N₂O are much smaller than CO₂, typically both GHGs contribute to only one percent of overall GHG emission from combustion process (Eggleston et al., 2006)
3. The WTE incinerator besides Jeram Sanitary Landfill is estimated to be ready by year 2023 based but the actual commencement date is unknown (Zainul, 2018).
4. Volume of landfill gas is roughly 50 % CO₂ and 50 % CH₄ (USEPA, 2020)
5. CH₄ is excluded from LCA study as it typically contributes to less than 0.01 % of total GHG emission from incineration (Eggleston et al., 2006)

Life Cycle Inventory

Life cycle inventory (LCI) is the collection of input and output data related to each phase of plastic waste from bubble tea industry within the system boundary to achieve the goal of LCA study. The main primary data collected in this study are the plastic grade and types of electrical appliances used in the bubble tea shops. The secondary data such as resource and energy inputs as well as emission and energy outputs that are obtained from journal articles and online websites.

Data related to Production of Bubble Milk Tea

Eq. 1 calculates total electricity consumption of 26 bubble tea shops in Subang Jaya:

$$\Phi_P = (\sum W_i \times HR_{Average} \times N_{Shops}) \quad (\text{Eq. 1})$$

Eq. 2 calculates CO₂ emission from the total electricity consumption of these bubble tea shops:

$$E_{CO_2,P} = \Phi_P \times EF_{mix} \quad (\text{Eq. 2})$$

Inventory data as equation inputs related to production of bubble milk tea is tabulated in Table 3.

Table 3 Inventory data related to production of bubble milk tea

Input Parameters	Unit	Data	Sources
Survey Result			
N_{Shops}	-	26	
$HR_{Average}$	-	12	
Energy consumption of electrical appliances			
Sealer Machine		400.00	
Shaker Machine		75.00	(Mike, 2020)
Fructose Dispenser	W	300.00	&
Fridge		100.00	(Draftlogic, 2019)
Tube lights (x6)		22.00 (x6)	
Production emission			
EF_{mix}	kg CO ₂ -eq/kWh	0.87	(Fan et al., 2019)

290 Data related to Waste Collection and Transportation

291 Jeram Sanitary Landfill is responsible for MSW disposal from municipality of Subang Jaya
 292 (Yong et al., 2019). Besides this, there is an ongoing project of constructing a WTE incinerator
 293 at the Jeram Sanitary Landfill site. Thus, the distance of transportation of 1 tonne of plastic
 294 waste for both scenarios are the same. Considering to and fro by the transporter from Subang
 295 Jaya to the landfill site as shown in Fig.3, the total two ways distance is 72.40 km and the diesel
 296 consumption is estimated as 10.14 litres for distance of 72.40 km (Transport, 2020).

297
 298 Fig.3 Map showing travel distance from Subang Jaya to Jeram Sanitary Landfill (Maps,
 299 2020)

Eq. 3 calculates the CO₂ emission from road transport (Eggleston et al., 2006).

$$E_{CO_2,T} = \text{Diesel Consumption} \times NCV_{diesel} \times EF_{diesel} \quad (\text{Eq. 3})$$

Inventory data as equation inputs related to waste transportation is tabulated in Table 4.

Table 4 Inventory data related to plastic waste transportation

Scenario	Unit	Data	Sources
Diesel consumption	kg	8.62	(Transport, 2020)
NCV_{diesel}	MJ/kg	43.00	
EF_{diesel}	kg CO ₂ -eq /TJ	74 100.00	(Eggleston et al., 2006)

Data related to Sanitary Landfill

Plastic waste in Scenario A is sent to sanitary landfill in Jeram. Emission factor is used to determine the GHG emission from landfill. The emission factor used in this study is an estimated value for a period of 100 years which has taken both CH₄ and CO₂ into consideration (Eriksson and Finnveden, 2009). Eq. 4 is obtained from the combination of two sources to calculate the CO₂ emission from landfill (Eggleston et al., 2006; Fan et al., 2019).

$$E_{CO_2,L} = (PW \times EF_{CO_2,L}) + (\Phi_L \times EF_{mix}) \quad (\text{Eq. 4})$$

Volume of landfill gas emitted, $Q_{landfill}$ has to be determined in order to determine the volume of CH₄ in landfill gas. Eq. 5 is derived using density values of CH₄ and CO₂ and $EF_{CO_2,L}$.

$$EF_{CO_2,L} \times PW = (0.5 \times Q_{landfill} \times \rho_{CO_2} \times 1) + (0.5 \times Q_{landfill} \times \rho_{CH_4} \times 28) \quad (\text{Eq.5})$$

Eq. 6 calculates the amount of electricity generated from combustion of biogas captured by landfill gas recovery system (LGRS) (Alzate et al., 2019).

$$\text{Electricity from } CH_4 \text{ combustion (kWh)} = NCV_{CH_4} \times Q_{CH_4} \times \sigma \times \eta_L \quad (\text{Eq. 6})$$

Electricity generation from combustion of CH₄ from LGRS of sanitary landfill is considered as renewable and cleaner energy. Thus, we can avoid the combustion of fossil fuels to create the same amount of energy, and the avoided emission from the combustion of fossil fuels is known as GHG saving. Eq. 7 calculates GHG saving in terms of CO₂ from electricity generation from LGRS as compared to similar amount of electricity generation from conventional power production in Malaysia (Eggleston et al., 2006; Fan et al., 2019).

$$E_{CO_2,SL} = (\text{Electricity from } CH_4 \text{ combustion} \times EF_{mix}) - (\text{amount of } CH_4 \times NCV_{CH_4} \times EF_{CH_4}) \quad (\text{Eq. 7})$$

Inventory data as equation inputs related to sanitary landfill is tabulated in Table 5.

Table 5 Inventory data related to sanitary landfill disposal of plastic waste

Input Parameters	Unit	Data	Sources
Energy and material			
$Electricity_L$	kWh	11.11	(Eriksson and Finnveden, 2009)
Landfill emission			
$EF_{CO_2,L}$	kg CO ₂ -eq/t	271.00	(Eriksson and Finnveden, 2009)
Energy recovery			
σ	-	0.90	(Banister and Sullivan, 2011)
η_L	-	0.38	(Eriksson and Finnveden, 2009)
Landfill gas property			
ρ_{CH_4}	kg/m ³	0.66	(Eggleston et al., 2006)
ρ_{CO_2}	kg/m ³	1.98	
NCV_{CH_4}	kWh/m ³	9.94	(Engineeringtoolbox, 2003)
	MJ/kg	50.00	
GHG saving			
EF_{CH_4}	kg CO ₂ -eq /TJ	54600.00	(Eggleston et al., 2006)
EF_{mix}	kg CO ₂ -eq/kWh	0.87	(Fan et al., 2019)

Data related to WTE Incineration

Scenario B has the plastic waste been sent to WTE incinerator to reduce the dependence on landfills. Eq.8 is obtained from combination of two sources to calculate CO₂ emission from incineration (Eggleston et al., 2006; Fan et al., 2019).

$$E_{CO_2,I} = \left(PW \times Dm \times CF \times FCF \times OF \times \frac{44}{12} \right) + (\Phi_I \times EF_{mix}) + (Fuel_I \times EF_{gas}) \quad (\text{Eq. 8})$$

Eq. 9 calculates N₂O emission from incineration (Eggleston et al., 2006).

$$E_{N_2O,I} = PW \times EF_{N_2O,I} \quad (\text{Eq. 9})$$

The energy recovery from incineration in terms of electricity can be calculated using Eq.10 (Alzate et al., 2019). Based on survey result, all 26 bubble tea vendors in Subang Jaya utilise polypropylene (PP) grade 5 plastic as cup material. Hence, net calorific value of plastic in Eq.10 is the net calorific value of PP plastic.

$$\text{Electricity from Incineration (kWh)} = PW \times NCV_{PP} \times \eta_I \quad (\text{Eq. 10})$$

Eq.11 is to calculate GHG saving in terms of CO₂-eq from electricity generation from WTE incinerator as compared to similar amount of electricity generated from conventional power production (Fan et al., 2019).

$$E_{CO_2,SI} = (\text{Electricity from Incineration} \times EF_{mix}) \quad (\text{Eq. 11})$$

Inventory data as equation inputs related to WTE incineration is tabulated in Table 6.

Table 6 Inventory data related to WTE incineration of plastic waste

Input Parameters	Unit	Data	Sources
Energy and material			
Electricity _I	kWh	70	(Khoo, 2019)
Fuel _I	MJ	9.86	
Incineration emission			
EF _{gas}	kg CO ₂ -eq/TJ	56100.00	(Eggleston et al., 2006)
EF _{N₂O,I}	g N ₂ O/t	47	
Plastic property			
Dm	-	0.93	
CF	-	0.86	
FCF	-	0.69	(Eriksson and Finnveden, 2009)
OF	-	1.00	
Energy recovery			
NCV _{PP}	kWh/kg	11.39	(Tsiamis and Castaldi, 2016)
η _I	-	0.30	(Perrot and Subiantoro, 2018)
GHG saving			
EF _{mix}	kg CO ₂ -eq/kWh	0.87	(Fan et al., 2019)

Life Cycle Impact Assessment

GWP is the only indicator used in this study as the GHGs are the main emission from all phases of LCA. GHGs such as CH₄ and N₂O are converted to CO₂-eq by multiplying with their respective GWP as shown in Table 7.

Table 7 Equivalency factor for global warming (Pachauri et al., 2014).

GHG	100 year GWP (CO ₂ -eq)
CO ₂	1
CH ₄	28
N ₂ O	265

4. Result and Discussion

Scenario A: Baseline Scenario – Sanitary Landfill

Based on GHG result tabulated in Table 8 and plotted in Fig.4, landfilling has the highest GHG emission as compared to other phases within the system boundary of this LCA study due to potent CH₄ emission. Many sanitary landfills in Malaysia have HDPE geomembrane as bottom liners to achieve landfill gas collection efficiency up to 90 % (Banister and Sullivan, 2011). Despite LGRS has a high efficiency to capture CH₄ combustion purpose, the uncaptured CH₄ is still a main concern as emission of 1 kg of CH₄ is equivalent to emission of 28 kg CO₂ into the environment. The net GWP/GHG emission for sanitary landfill scenario is 566.15 kg CO₂-eq per tonne of plastic waste after taking into consideration the GHG saving of 15.32 kg CO₂-eq achieved from the electricity generation from combustion of captured CH₄.

New study has found out that CH₄ emission from plastic waste has continued at night once the plastic waste is exposed to ambient solar radiation and the exposed aged plastic will release more CH₄ at night (Malekmian, 2018). CH₄ emission from this new study is neither accounted in the journal articles, LCA software nor accounted by the equations listed by IPCC, therefore the actual GHG emission from landfilling is expected to be higher than the predicted value of 280.67 kg CO₂-eq. Electricity consumption from production of bubble milk tea is ranked second in terms of GHG emission which has contributed to 273.34 kg CO₂-eq followed by small amount of GHGs released from mobile combustion of diesel for transportation and stationary combustion of CH₄ for electricity generation. These four activities have combined to give the gross GWP/GHG emission of 581.47 kg CO₂-eq.

Up to date, only 6 % of the landfills in Malaysia are sanitary and as a result, landfilling is still the primary CH₄ emission source in Malaysia. Therefore, the first step for local authorities to implement sustainable plastic waste management plan is to phase out non-sanitary landfills or upgrade these landfills into sanitary ones. With LGRS featured into these upgraded landfills, GHG emission is reduced by 15.32 kg CO₂-eq for every tonne of plastic waste that is disposed into landfill.

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378

Table 8 Net GHG emission for sanitary landfill disposal of 1 tonne of plastic waste (Scenario A)

LCA phases	Unit	Values
A) Production of bubble milk tea		
Electricity consumption for daily operation of bubble tea shops in Subang Jaya	kWh	314.18
Total GHG for production of bubble milk tea	kg CO₂-eq	273.34
B) Transportation		
Diesel consumption for transportation of plastic waste from Bubble Tea Street in Subang Jaya to Jeram Sanitary Landfill for two way distance of 72.4 km	L	10.14
Total GHG for transportation	kg CO₂-eq	27.46
C) Landfilling		
Electricity consumption for compacting the waste	kWh	11.11
CO ₂ emission from electricity consumption	kg CO ₂ -eq	9.67
CO ₂ emission from landfill	kg CO ₂ -eq	26.23
CH ₄ emission (Convert to GWP unit)	kg CO ₂ -eq	244.77
Total GHG for landfilling	kg CO₂-eq	280.67
Gross GHG emission	kg CO₂-eq	581.47
D) Electricity generation		
Electricity generated	kWh	45.03
CO ₂ emission from CH ₄ combustion	kg CO ₂ -eq	23.86
CO ₂ emission based on electricity generation mix	kg CO ₂ -eq	-39.18
Total GHG saving	kg CO₂-eq	-15.32
Net GHG emission (A+B+C+D)	kg CO₂-eq	566.15

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Fig.4 GHG emission of the activities involved in sanitary landfill disposal of 1 tonne of plastic waste for Scenario A

Scenario B: WTE incineration

Based on Table 9 and Fig.5, the GHG emission from production of bubble milk tea, transportation and incineration of plastic waste have combined to generate a gross GWP of 2398.99 kg CO₂-eq. The GHG emission from production phase of bubble milk tea and transportation phase of plastic waste in Scenario B is similar to the values obtained from Scenario A as expected as the input data for LCA study of these two phases are similar for both scenarios.

Incineration process has the highest GHG emission as compared to other phases and the emission is greater than the main GHG contributor in Scenario A - landfilling by 1817.52 kg CO₂-eq. The high GHG emission is due to higher net calorific value of the plastic. The PP plastic has a net calorific value of 41 MJ/kg which is about four times greater than the average calorific value of MSW in Malaysia of 10.88 MJ/kg (Tsiamis and Castaldi, 2016; Yong et al., 2019). The higher the calorific value of waste, the greater amount of heat energy can be extracted from the waste and this leads to higher GHG emission. However, the actual GHG emission from incineration is much lower as the equations provided by IPCC guidelines did not take in account of reduction in carbon emission by advanced air pollution control system such as scrubber and activated carbon filter that are featured in the modern WTE incinerators. Nevertheless, the net GWP of WTE incineration is -573.80 kg CO₂-eq and the huge reduction in GWP is contributed by huge GHG saving achieved from electricity generation by the WTE incinerator which is much cleaner than conventional power production practice of Malaysia. Astonishing amount of 3.42 MWh of electricity is generated due to high net calorific value of plastic waste and this has led to a GHG saving of 2972.79 kg CO₂-eq. Higher amount of electricity can be generated and greater GHG saving can be obtained if the electrical conversion efficiency of WTE incinerator is higher than 30 %.

406 *Table 9 Net GHG emission of WTE incineration of 1 tonne of plastic waste for Scenario B*

LCA phases	Unit	Values
A) Production of bubble milk tea		
Electricity consumption for daily operation of bubble tea shops in Subang Jaya	kWh	314.18
Total GHG for production of bubble milk tea	kg CO₂-eq	273.34
B) Transportation		
Diesel consumption for transportation of plastic waste from Bubble Tea Street in Subang Jaya to Jeram Sanitary Landfill for two way distance of 66.4 km	L	10.14
Total GHG for transportation	kg CO₂-eq	27.46
C) Incineration		
Natural gas consumption as auxiliary fuel for process startup	MJ	9.86
CO ₂ emission from fuel consumption	kg CO ₂ -eq	0.55
Electricity consumption for process startup	kWh	70
CO ₂ emission from electricity consumption	kg CO ₂ -eq	60.90
CO ₂ emission from incineration	kg CO ₂ -eq	2023.49
N ₂ O emission (Convert to GWP unit)	kg CO ₂ -eq	13.25
Total GHG for incineration	kg CO₂-eq	2098.19
Gross GHG emission	kg CO₂-eq	2398.99
D) Electricity generation		
Electricity generated	kWh	3417.00
CO ₂ emission based on electricity generation mix	kg CO ₂ -eq	-2972.79
Total GHG saving	kg CO₂-eq	-2972.79
Net GHG emission (A+B+C+D)	kg CO₂-eq	-573.80

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409 *Fig.5 GHG emission of the activities involved in WTE incineration of*

410 *1 tonne of plastic waste for Scenario B*

Overall Result of Plastic Waste Management Scenarios

Based on net GHG emission/GWP for two plastic waste management scenarios as shown in Fig.6, the overall comparison of both scenarios indicates that Scenario B (WTE incineration) is the better option in terms of environmental sustainability where it has a negative net GWP and it is able to achieve GHG reduction of 1139.95 kg CO₂-eq/t of plastic waste being sent to WTE incineration instead of the baseline scenario (sanitary landfill). Besides this, WTE incineration is able to generate 3.42 MWh of electricity per tonne of plastic waste as compared to sanitary landfill where only 45.03 kWh of electricity is generated for every tonne of plastic waste. Moreover, plastic waste disposal phase is the primary hotspot for GWP in both scenarios as waste management technologies and electricity generation are both under plastic waste disposal phase which have significant impacts on net GHG emission.

Fig.6 Comparative of net GWP for different plastic waste management scenarios

It is better to keep GHG emission of N₂O and CH₄ as low as possible because these gases have higher GWP. CH₄ is the main GHG from landfilling whereas N₂O is the main GHG from incineration. Although the GWP of N₂O is 9.46 times greater than CH₄, mass fraction of N₂O only accounts for 0.78 % of the hot flue gas exiting the WTE incinerator as opposed to sanitary landfill where CH₄ accounts for 25 % of total mass fraction of landfill gas. When comparing both GHG emission per tonne of plastic waste in terms of kg CO₂-eq, CH₄ emission from sanitary landfill and N₂O emission from WTE incinerator are 244.77 kg CO₂-eq and 13.25 kg

CO₂-eq respectively. As a result, WTE incineration is more environmental friendly choice if the study is to focus on reduction of GWP attributed by these two potent GHGs.

In the incineration process, combustion of plastic waste under high temperature generates huge amount of CO₂ which contributes significantly to global warming and rapid climate change. However, the high GWP is compensated by GHG saving via electricity generation from incineration where the emission is lower than conventional power production. While the electricity conversion efficiency of both sanitary landfill and WTE incinerator are within the range of 30 to 40 %, the energy recovery from incineration is much greater than landfill due to higher electricity generation. The recovery difference is mainly due to the amount of fuels being combusted in both energy recovery systems. Energy recovery of WTE incinerator is greater as compared to sanitary landfill as the entire 1 tonne of plastic waste is consumed and converted to heat energy, unlike LGRS of sanitary landfill where only the CH₄ composition of captured landfill gas (8.74 kg) produced from landfill disposal of 1 tonne of plastic waste is consumed and converted to heat energy with remaining CO₂ and uncaptured CH₄ are released to the environment. Moreover, characteristic of CH₄ is almost similar to natural gas in which there is only slight GHG saving when comparing emission from electricity generated from combustion of CH₄ with conventional power production of Malaysia.

Based on the LCA result on GHG emission, WTE incineration can be an effective alternative to improve plastic waste management as it can divert more plastic waste from the sanitary landfill and offer GHG saving through electricity generation from plastic waste. Tsiamis and Castaldi (2016) mentioned that the average net calorific value of all 7 grades of petroleum-based plastic is 35.7 MJ/kg or 9.92 kWh/kg and GHG saving of 2589.12 kg CO₂-eq can be achieved with the net GWP is remained as a negative figure with the amount of -190.13 kg CO₂-eq if average net calorific value of all plastic grades is used for environmental impact assessment of Scenario B instead of using net calorific value of PP plastic alone.

In conclusion, WTE incineration treatment is proven as a carbon negative technology and can be used as the basis of environmental sustainability framework development for plastic waste management that is previously developed based on sanitary landfill to tackle single-use plastic waste from Bubble Tea Streets of Subang Jaya in order to create a cleaner environment and to prevent the increase in global temperature caused by single-use plastics.

Environmental Sustainability Framework for Plastic Waste Management in Bubble Tea Streets of Subang Jaya, Malaysia

Growth of food and beverage industries such as bubble tea industry accelerates the generation of single-use plastic waste. These low quality petroleum based plastics take longer time to degrade as compared to other types of solid waste and thus, taking up more spaces in landfills in the long run. As a result, government is seeking for alternative WTE incineration to replace landfills for plastic waste disposal but the environmental performance of this alternative is still unknown. However, it was proven from LCA study that a negative net GWP of -573.80 kg CO₂-eq is achieved for every tonne of plastic waste being sent to WTE incinerator, a further confirmation that WTE incineration is more environmental friendly than sanitary landfill.

Materialise a plastic waste management framework in a sustainable way is a challenging and difficult task which cannot simply be done by government alone. Besides reducing global warming impact and the dependence on landfill with implementation of WTE incineration, the responsibility to ensure a successful and effective development plastic waste management framework is shared among the government, bubble tea vendors, waste contractors and consumers. This framework assumes bubble tea business is carried out in normal course of business without being affected by coronavirus pandemic.

Government plays an important role in ensuring continuity of a proposed environmental sustainable plastic waste management framework. Besides enforcing stringent regulations on plastic littering, collection and sorting of plastic waste by vendors as well as controlling air emission from incinerators, government can allocate more plastic waste bins around Bubble Tea Streets to provide convenience to customers for disposing the plastic cups after consumption of bubble milk tea. Besides, the government can also encourage these bubble tea vendors to seek alternatives to phase out single-use plastic cups. Alternatively, government can enforce a total ban on single-use plastics which is proven to be very effective to indirectly forcing the vendors to utilise environmental friendlier cup material as soon as possible (Ali et al., 2021). Next, government can appoint reputable sanitation company to collect waste from collection bins to ensure Subang Jaya is always free of plastic waste before transporting it to the waste management company.

Establishing a WTE incinerator requires high capital cost and government can provide assistance in capital in the form of waste management subsidy or grant. The government can then enter into a contract agreement with waste management company, which is the owner of WTE incinerator in this case, to agree on duration of its operation and ensure standard fees are charged for waste disposal. Municipal plastic waste is considered as renewable biomass source and the government pays money directly to the waste management company in exchange for electricity that is being sold to Tenaga Nasional Berhad (TNB) in accordance to the Feed-In Tariff (FIT) rates provided by Sustainable Energy Development Authority (SEDA) Malaysia (SEDA, 2020). Part of these renewable energy can be supplied to the bubble tea vendors in Subang Jaya to run their daily business activities which require an average of 314.18 kWh of electricity. Thus, a conclusion can be made in which more electricity can be generated and greater GHG saving can be achieved if more single-use plastic waste are being incinerated instead of landfilling.

According to waste management hierarchy, reduce and reuse are better waste management options as compared to waste treatment and disposal. Therefore, plastic waste should be reduced instead of sending the waste to incinerator for electricity generation without taking any initiative to reduce the GHG emission from incineration. Bubble tea vendors can do their parts in reducing plastic waste and to spread plastic pollution awareness among the public by utilising paper or biodegradable plastic cups to phase out single-use plastics. Moreover, bubble tea vendors can encourage customers to bring their own tumblers by giving them incentives such as discount or drink rewards thus cutting down plastic waste pollution. Furthermore, bubble tea shops can also introduce reusable tumblers.

The role of waste management company is to keep the discharged CO₂ as low as possible in order to comply with the stringent regulation set by the Department of Environment (DOE). With the financial support from government, further upgrades can be done on the existing advanced air pollution control system which are featured in the WTE incinerator to further reduce the GHG emission coming out from the chimney.

The proposed environmental sustainability framework for plastic waste management in Subang Jaya can be further visualised in Fig.7. The framework highlights on the role of each party to manage and reduce the GHG emission associated with plastic waste. The framework also suggest alternative ways to reduce the use of plastics.

Fig.7 Proposed environmental sustainability framework for plastic waste management in Bubble Tea Streets of Subang Jaya

Conclusion

Based on the study, WTE incineration is proven to be more environmental friendly as compared to sanitary landfill. The GHG emission in terms of CO₂-eq of sanitary landfill and WTE incineration are 566.15 kg CO₂-eq and -573.80 kg CO₂-eq respectively. The main contributor that leads to a negative net GHG emission in overall environmental performance of WTE incineration is the huge GHG saving achieved from the renewable electrical energy generated from incineration. This is because Malaysia is highly depending on fossil fuels for electricity generation and the GHG emission to create useful energy from conventional power production is much greater as compared to WTE incineration. Hence, the power production practice of Malaysia has a significant impact on net GHG emission of WTE incineration. The environmental feasibility of implementing WTE technology might be altered in the future if the renewable energy sources have higher share in power production practice. The result suggests that GHG saving could be further increased if energy conversion efficiency of WTE incineration can be increased to be more than 30 % for greater electricity generation or further improve the technology of advanced air pollution control system to further reduce the GHG emission into the environment.

The proposed environmental sustainability framework for plastic waste management aims to showcase a general idea for the government to deal with increasing solid waste issue, especially on plastic waste caused by heavy usage of single-use plastics from the bubble tea industry. If this framework was deemed to be successful upon its implementation, it can be considered by government to implement on other plastic waste generation hotspots other than bubble tea industry or as a reference to enable policy makers to have a clearer idea on implementing a better and more sustainable Twelfth Malaysia 2021 – 2025 solid waste management plan.

The result of LCA can be improved by obtaining the latest data regarding waste sector of Malaysia from relevant authorities in order to reduce the number of assumptions made. Moreover, LCA software can be used for analysis for more detailed calculations to verify the results obtained from this study. Although GWP is the main environmental impact indicator when dealing with plastic waste, other minor environmental impact indicators should be taken into consideration to assess the overall environmental performance of existing sanitary landfill and alternative WTE incinerator. Furthermore, a more comprehensive study such as economic and social aspects of WTE incineration and sanitary landfill should be taken into consideration to help policy makers to implement better plastic waste management plan that benefits all parties that are dealing with plastic waste issue.

Declaration

Ethics Approval & Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Availability of Data & Materials

The dataset used and/or analysed during the current study are available from the author on reasonable request.

Competing Interests

The authors declare that they have no competing interests.

Funding

No fund/grant is received for the current study.

Authors' Contributions

The first author (CJ) conducted the study and wrote the manuscript. The second author (LC) edited the manuscript. The corresponding author (JT) checked and proofread the manuscript.

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Figures

Figure 1

System boundary of existing plastic waste management for Scenario A

Figure 2

System boundary of plastic waste management for Scenario B

Figure 3

Map showing travel distance from Subang Jaya to Jeram Sanitary Landfill (Maps, 2020) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

GHG emission of the activities involved in sanitary landfill disposal of 1 tonne of plastic waste for Scenario A

Figure 5

GHG emission of the activities involved in WTE incineration of 1 tonne of plastic waste for Scenario B

Figure 6

Comparative of net GWP for different plastic waste management scenarios

Figure 7

Proposed environmental sustainability framework for plastic waste management in Bubble Tea Streets of Subang Jaya

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