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Environmental performance evolution of municipal solid waste management by life cycle assessment in Hangzhou, China

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ABSTRACT

There is a significant increase in the volume of Municipal Solid Waste (MSW) that is being generated across the world. Faced with this challenge and the associated environmental issues, MSW management (MSWM) in Hangzhou, China has made various positive changes in order to adapt. During the last 10 years, MSW source-separated collection was launched, which was accompanied by estimations of a new waste-to-energy (incineration) plant and food waste separate treatment methods. The aim of this study is to investigate the related evolution of the environmental performance of MSWM system in Hangzhou from 2007 to 2016 by using life cycle assessment (LCA). LCA is a scientific tool to quantify factors such as environmental impacts from a life cycle perspective and provides valuable inputs to decision-makers, thus leading to proper strategy determination. Results illustrate that the annual environmental performance has an overall downward trend with some minor fluctuations. The MSWM system in 2010 had the lowest weighted result of 0.0349 PE/t-MSW due to the highest incineration rate and implementation of source-separated collection. Incineration shows better environmental performance than landfill, while source-separated collection can benefit the MSWM. While the importance of source-separated collection is significant, it is also essential to concentrate on the food waste treatment technology. It is suggested that anaerobic digestion (AD) can be considered as a primary option for food waste treatment.

1. Introduction

The amount of municipal solid waste (MSW) in China has increased rapidly in the last few decades and China now is the largest MSW generator in the world (Zhou et al., 2018). In 2015, the annual generated MSW has reached 191.4 million tonnes, with a ten-year cumulative growth rate of 122.9% (CSYCC, 2016). The increasing amount and complex components of MSW impose the evolution of municipal solid waste management (MSWM). Source-separated collection is considered as a desirable option to achieve the principle of “reducing quantity” “harmless” “reclamation” for waste management (Han and Zhang, 2017; Ma et al., 2017; Ripa et al., 2017). In 2017, an implementation plan regarding MSW source-separated collection was launched by China's national development and reform commission. At present, source-separated collection has been implemented in many cities, and several corresponding regulations and facilities have been established. New policies and standards on waste treatment enable the formal and scientific management. In general, various strategies aiming at enhancing MSWM have been adopted in the last few years, but their realistic effects on environmental improvement need to be examined.

To assess the environmental performance scientifically, life cycle assessment (LCA) is widely adopted. LCA is a systematic methodology considering all inputs and outputs of materials and energy ‘from cradle to grave’ (ISO, 2006a,b; Jeswani and Azapagic, 2016). LCA can quantify the environmental impacts and support the decision-makers to identify the appropriate strategy.

Until now, LCA has been conducted in various waste management systems. Dong et al. (2014) compared the incineration, landfill with and without energy recovery and concluded the incineration was more suitable for MSWM. Havukainen et al. (2017) suggested that refuse derived fuel (RDF) production could improve the environmental impacts on waste incineration based on LCA results. Advanced WtE technologies, for instance pyrolysis, gasification and plasma, also have been examined by LCA in recent years. Evangelisti et al. (2015) utilized LCA to compare the two-stage gasification and plasma with conventional WtE technology. Arena et al. (2015) evaluated a vertical shaft

gasifier coupled with direct melting and suggestions for improvement in technological solutions were put forward for further development. Pyrolysis–gasification was also modeled and assessed in toxic impacts and non-toxic impacts (Zaman, 2013).

Based on the WtE case-study LCA scenarios from 1995 to 2013, a concrete overview of assumptions and modeling choices for WtE was provided and some practical recommendations were put forward for the further LCA study (Astrup et al., 2015). Zhou et al. (2018) also summarized the ranges of the environmental results of different WtE techniques worldwide. Othman et al. (2013) analyzed the LCA scenarios in Asian MSW management systems and the results were used as a reference for decisions on strategies for waste management.

However, most researches focus on the environmental impacts of waste treatment technologies, but little attention has been paid to the evolution of the MSWM system with time. Ibáñez-Forés et al. (2018) assessed the temporal evolution of the environmental performance of MSWM system in João Pessoa, Brazil, and focused on the effect of door-to-door selective collection of recyclable waste; however, its evolution was mainly caused by the change of MSW composition and the population served by each sorting unit; besides, recycle and landfill were the only treatment methods in the system. Nowadays, WtE technologies play an important role in MSWM (Zhou et al., 2018). The integrated MSWM system with WtE technologies is more complex and its environmental performance evolution can reflect meaningful results for decision-makers.

The goal of this study is to analyze the environmental performance evolution of integrated MSWM system during the last decade (i.e., from 2007 to 2016) in Hangzhou, China. The evolution of MSWM is modeled and annual MSWM strategies are included. The changes of environmental performance with each passing year are evaluated by LCA. The results could give a better understanding of the environmental performance of the MSWM system and reflect effects of MSWM strategies. Source-separated collection and food waste treatment technologies are further analyzed in sensitivity analysis and the results can be served as a support for the future MSWM development.

2. MSWM system in Hangzhou

Hangzhou, one of the most developed coastal cities with advanced economy and dense population in China, is chosen for this study. Hangzhou has an urban area of 16,596 km^2 and a population of 9.18 million (HSYCC, 2017), and its GDP reached 1.17 trillion CNY in 2016, which ranks the tenth in China. However, like the most cities in China, Hangzhou faces the MSW treatment challenges. Fig. 1 shows the amount of MSW generated and treatment from 2007 to 2016 in Hangzhou. Hangzhou generated 1,703,450 tonnes and 3,684,946 tonnes in 2007 and 2016 respectively, with an annual growth rate of 9.0% (HMSWDSC, 2016). Landfill was the main MSW treatment method, while incineration got much attention and developed rapidly these years. However, the amount of MSW generated grew quickly while the capacity of incineration factories was limited. Therefore, the MSW incineration rate decreased from 2011 to 2015 after the rise from 2007 to 2010. A new waste-to-energy (incineration) plant was put into operation in December 2015 and the incineration rate grew sharply from 2015 to 2016. At the end of 2016, there were five MSW incineration plants and one landfill plants (see in Table 1).

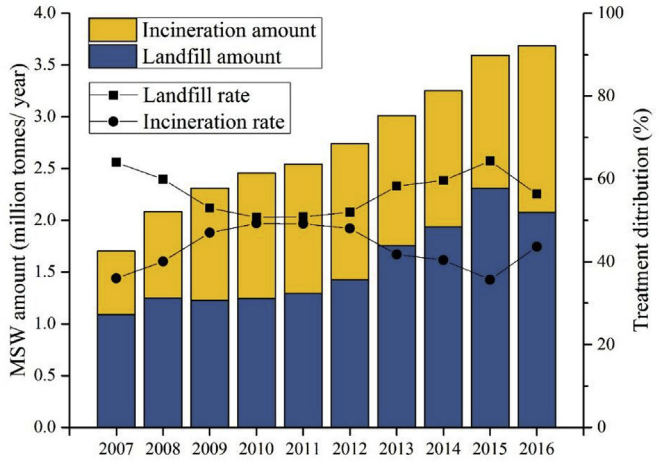


Fig. 1. Amount of MSW generated and treatment distribution in Hangzhou from 2007 to 2016 (HMSWDSC, 2016).

Table 1
MSW treatment plants at the end of 2016 in Hangzhou.

Name	Technology	Energy recovery	Capacity (t/d)	Start date
Tianziling	Landfill	Electricity	–	Jan. 2007
Tianziling (for food waste)	Anaerobic digestion	Electricity	200	Jun. 2014
Binjiang	Incineration (Grate)	Electricity	600	Oct. 2004
Yuhang	Incineration (fluidized bed)	Electricity	600	Oct. 1998
Qiaosi	Incineration (fluidized bed)	Electricity	800	Jun. 2002
Xiaoshan	Incineration (fluidized bed)	Electricity	1200	Jul. 2007
Jiangdong	Incineration (fluidized bed)	Electricity	1200	Dec. 2015

The physical composition of mixed waste generated in Hangzhou is given in Table 2. MSW generated in Hangzhou has high moisture content due to its high proportion of food waste. As shown in Table 2, the food waste accounts for 55.6% of the total mixed waste. Besides, the mixed waste has rather low LHV (low heating value), which effects the incineration process and energy recovery. Therefore, the separate collection and treatment of food waste are essential.

Hangzhou is the pioneer regarding MSW source-separated collection in China and started it in 2010. Food waste is separately collected and then the mixed waste after source-separated collection is sent to landfill or incineration. After separate collection, the mixed waste has higher LHV and is suitable for effective incineration. The food waste is sent for separate landfill in Tianziling. For the purpose of better food waste management, an anaerobic digestion (AD) pilot project was put into operation in Tianziling in June 2014. In Hangzhou, most recyclables, for instance cardboard, plastic and metal bottles, are collected and sold by residents before the formal collection organized by the government.

Table 2
Physical composition of mixed waste before and after source-separation in Hangzhou (HMSWDSC, 2016).

Composition	Mixed waste before source-separated collection[a]	Mixed waste after source-separated collection
Food waste	55.79%	41.06%
Dust	3.50%	4.67%
Bricks	1.85%	2.47%
Paper	12.14%	16.19%
Plastics	13.67%	18.23%
Rubber	1.37%	1.82%
Textiles	4.12%	5.50%
Glass	2.81%	3.75%
Metals	2.49%	3.32%
Wood	1.53%	2.05%
Others	0.71%	0.94%
Moisture (wt.%)	62.05%	59.40%
LHV (kJ/kg)	5551.81	6402.42

[a] The data are obtained from the average of MSW compositions from 2012 to 2016.

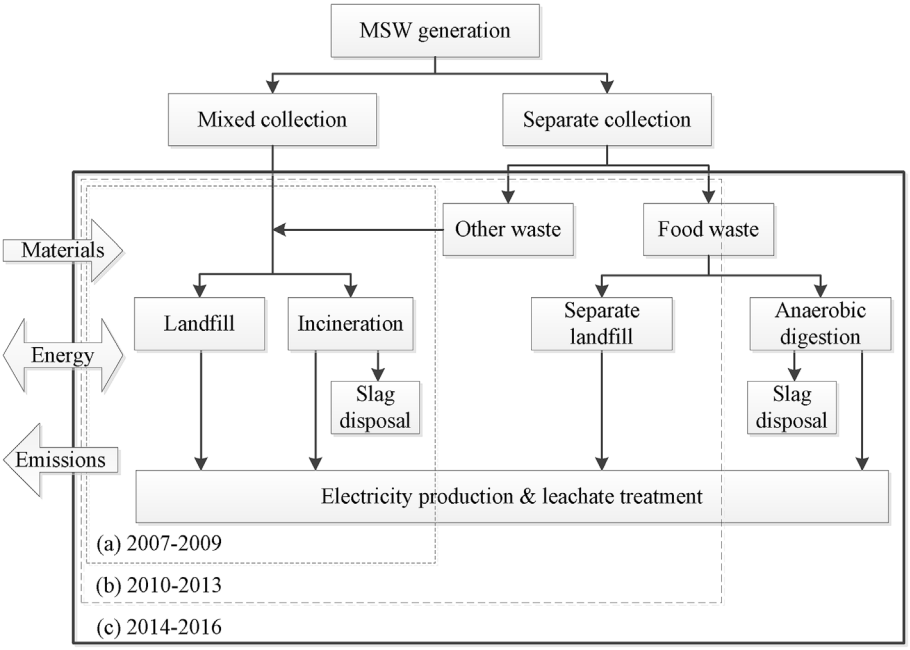


Fig. 2. System boundary of the study: (a) during 2007–2009, 100% mixed collection (dotted box); (b) during 2010–2013, 25% source-separated collection and food waste was treated by separate landfill (dashed box); (c) during 2014–2016, 25% source-separated collection and food waste was treated by AD and separate landfill (solid box).

Thus, only a small proportion of recyclables flow into the municipal collection system. This informal collection is common in China (Steuer et al., 2017; Zhang and Wen, 2014). Therefore, source-separated collection for recyclables is not considered in this study.

3. Methodology

According to ISO 14040 standards, the LCA consists of four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (ISO, 2006a,b).

3.1. Goal and scope definition

This study aims to evaluate the environmental impact evolution of MSWM system in Hangzhou, China over the last decade. Fig. 2 shows system boundary of the study and the system is divided into three periods: (a) during 2007–2009, MSW was unsegregated and was sent for landfill or incineration (in dotted box); (b) during 2010–2013, part of food waste was separately collected and transported for separate landfill, while the rest mixed waste was diverted for landfill or incineration (in dashed box); (c) during 2014–2016, 73 thousand tonnes of food waste was treated by AD (36.5 thousand tonnes in 2014), and the rest was sent to separate landfill (in solid box). The system involves 6 MSW treatment scenarios and the information of the scenarios is illustrated in Table 3.

To evaluate the environmental impacts, some assumptions are made:

(1) The fractions of MSW composition are assumed to keep same in these ten years, since the variation of MSW compositions in Hangzhou is little (HMSWDSC, 2016). The deviation caused by this assumption can be ignored realizing the fact that the aim is focused on evolution of MSWM system.
(2) According to the Hangzhou Municipal Solid Waste Disposal Supervision Center, the source-separated collection efficiency reached 25% (Dong et al., 2013). The efficiency is assumed to keep 25% in the assessment and the effect of source-separated collection efficiency is discussed in sensitivity analysis. Thus, Fig. 3 presents the evolution of MSW treatment distribution in this study and Table A.1**SM** (available as supplementary available online) illustrates the associated MSW mass (HMSWDSC, 2016).
(3) Collection process and transportation from collection point to treatment plant are not considered in this system boundary. However, disposal of bottom ash and fly ash is the necessary part of incineration. Thus, transportation for bottom ash and fly ash is contained in the system boundary.
(4) Electricity produced is sent to the electricity grid and is assumed to displace same amount of electricity produced from China's mixed power grid.
(5) Because of the unavailable of investigation data, emissions to the soil are assumed not to be contained in this study, and emissions to the water only consider the NH_3-N and T-P in leachate.

Table 3
The description of treatment scenarios.

Scenario	Method	Waste type
Scenario 1.1	Landfill	Mixed waste before separate collection
Scenario 1.2	Landfill	Mixed waste after separate collection
Scenario 2.1	Incineration	Mixed waste before separate collection
Scenario 2.2	Incineration	Mixed waste after separate collection
Scenario 3.1	Landfill	Food waste
Scenario 3.2	Anaerobic digestion	Food waste

3.2. Inventory analysis

Collecting and establishing inventory data is one of the most labor- and time-intensive work. The inventory includes the material flow and energy flow that cross the system boundary.

3.2.1. Landfill

More than half of the MSW in Hangzhou is sent to the Tianziling for landfill. Intergovernmental Panel on Climate Change (IPCC) proposed the calculation method to estimate the CH_4 emission from landfill. The equations are listed as follows (IPCC, 2006):

$$CH_4 Emissions = \left[\sum_x CH_4 generated_{x,T} - R_T \right] \times (1 - OX_T) \quad (1)$$

$$CH_4 generated_{x,T} = DDOC_{m,x} \times F \times 16/12 \quad (2)$$

$$DDOC_{m,x} = W_x \times DOC_x \times DOC_f \times MCF \quad (3)$$

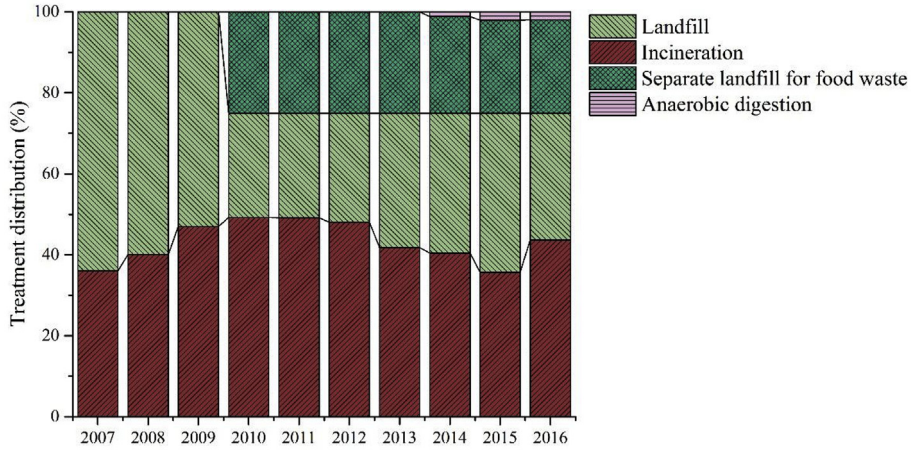


Fig. 3. The evolution of MSW treatment distribution in this study during 2007–2016.

$CH_4 Emissions$: CH_4 emitted in year T (Gg);
$CH_4 generated_{x,T}$: CH_4 generated from waste type x in year T (Gg);
R_T: Recovered CH_4 in year T (Gg);
OX_T: Oxidation factor in year T (%);
$DDOC_{m,x}$: Mass of decomposable degradable organic carbon in waste type x (Gg);
F: Fraction by volume of CH_4 in landfill gas (%);
W_x: Mass of waste type x deposited (Gg);
DOC_x: Fraction of degradable organic carbon in waste type x (Gg C/Gg waste);
DOC_f: Fraction of degradable organic carbon that can decompose;
MCF: CH_4 correction factor.

Based on IPCC default value, the CH_4 oxidation factor and correction factor is set at 0.1 and 0.77 (IPCC, 2006). The carbon content of different waste types is summarized in Table A.2**SM** and the DOC_f is assumed to be 1. In Tianziling landfill, 54.5% volume of the landfill gas is CH_4 (CO_2 45%) and 65% of generated CH_4 is recovered and converted into electricity at an efficiency of 39.1% by a gas engine (Dong et al., 2014). A set of wastewater treatment equipment is installed and leachate is directly discharged to the city's sewage treatment system after purification.

3.2.2. Incineration

The data of incineration are mainly from the long-term on-site visit to a 1200 t/day incineration plant utilized fluidized bed technology and Hangzhou municipal solid waste disposal supervision center. According to the MSW composition, LHV and the fossil carbon content of MSW are calculated to be 5551.81 MJ/t-MSW and 11.7%. Coal, with LHV of 21 MJ/kg and fossil carbon content of 44.5%, is taken as an auxiliary fuel at a ratio of 50 kg/t-MSW. The electricity generation efficiency is estimated to be 23%. Among the generated electricity, 80% is sent to power grid and 20% is for self-consumption. Advanced air pollution control system is equipped for flue gas purification and its input materials are illustrated in Table 4. Bottom ash and fly ash, accounting for 17% and 3% of total mass, are solidified by cement and sent for special landfill 45.8 km away from the incineration (Dong et al., 2014). Source-separated collection changes the LHV and fossil carbon proportion of the mixed MSW and leads to the variation of electricity generation and CO_2 emissions.

3.2.3. Food waste treatment

The food waste is separately collected and sent to Tianziling for landfill. The calculation method regarding CH_4 generation is similar as that of mixed waste landfill. In June 2014, an AD pilot project with a capacity of 200 t/day was put into trial operation in Tianziling and part of the food waste was treated by AD. The yield of biogas is estimated to be 108 Nm^3/tonne food waste, with CH_4 content of 63% volume. CH_4 emitted in the digestion process is assumed to 2% of CH_4 generated (Fruergaard and Astrup, 2011). The AD slag, with moisture content of 80%, accounts for 15% of total mass. However, the slag is not suitable for composting due to high salt content, and hence, the slag is treated by landfill after dewatering. Since the AD facility is only in trial operation and its data cannot be obtained, the energy consumption and emission data are from Danish plants based on the literatures (Fruergaard and Astrup, 2011; Jungbluth et al., 2007).

3.2.4. Life cycle inventory

In this study, the inventory data are obtained from long-term on-site visit of the treatment plants and reports by Hangzhou MSW disposal supervision center. Background data on raw material production and electricity production are from Gabi 8.0 software database (Thinkstep, 2018). The life cycle inventory of each scenario is summarized in Table 4.

3.3. Impact assessment methodology

Gabi 8.0 software and the EDIP 97 are adopted for environmental impact assessment (Thinkstep, 2018). Danish EDIP 97 is in accordance with the requirements of the ISO framework and widely recognized by LCA-researchers (Dong et al., 2014). According to EDIP97, global warming potential (GWP), acidification potential (AP), nutrient enrichment potential (NEP), photochemical oxidant potential (POP) are considered as the environmental impact categories in this study. The impact assessment includes characterization, normalization and weighting steps.

4. Results and discussion

4.1. Environmental results of each scenario

The environmental results caused by the study scenarios are presented as Fig. 4, including the contributions of main stages to each impact category. For a reasonable comparison, one tonne of corresponding waste is taken out as the basis. The main stages are divided into avoided electricity, direct emissions, input materials and energy. The negative value means a benefit to the relevant environmental impact.

The main contribution substances for GWP are CH_4, CO_2 and N_2O. Biogenic CO_2 emission is not considered as it is carbon neutral to atmosphere, but will be further analyzed in the “Sensitivity analysis” (Dong et al., 2013). As shown in Fig. 4a, greenhouse gas emissions are

Table 4
Life cycle inventory of each scenario (basis = one tonne of corresponding waste) (Chi et al., 2015; Dong et al., 2013; Fruergaard and Astrup, 2011; Havukainen et al., 2017; Jungbluth et al., 2007).

1t-MSW	Unit	Scenario					
		1.1	1.2	2.1	2.2	3.1	3.2
Input							
Diesel for mechanical operation	kg	1.07	1.07	1.96	1.96	1.07	1.07
Diesel for transportation of fly ash and bottom ash	kg	0	0	0.27	0.27	0	0
Electricity	kWh	1.56	1.56	83.99	89.10	1.56	49.48
HDPE	kg	0.45	0.45	0	0	0.45	0.10
Limestone	kg	0.77	0.77	0	0	0.77	0
Clay	kg	59.7	59.7	0	0	59.7	0
NaCl	kg	0.37	0.37	0	0	0.37	0
Calcium hydroxide	kg	0	0	18.14	18.14	0	0
Ammonia water	kg	0	0	8.94	8.94	0	0
Coal	kg	0	0	50	50	0	0
Lubricating oil	kg	0	0	0.04	0.04	0	0
Cement	kg	0	0	14.70	14.70	0	0
Direct emissions to air							
CH_4-bio	kg	26.98	27.17	0.00	0.00	18.85	0.97
CO_2-fossil	kg	0	0	509.68	652.38	0	0
CO_2-bio	kg	488.04	491.58	562.23	566.31	498.16	547.33
N_2O	kg	0	0	0.05	0.05	0	0
CO	kg	0.07	0.07	0.20	0.20	0.07	0.12
NH3	kg	0.08	0.08	0	0	0.08	0
H2S	kg	0.17	0.17	0	0	0.17	0
VOCs	kg	0.05	0.05	0	0	0.05	0.11
HCl	kg	0	0	0.023	0.023	0	0
HF	kg	0	0	0.009	0.009	0	0
NO_x	kg	0.06	0.06	0.48	0.48	0.06	0.15
SO_2	kg	0.03	0.03	0.09	0.09	0.03	0
PM10	kg	0	0	0.094	0.094	0	0
PCDD/DFs	kg	0	0	2.40E-09	2.40E-09	0	0
Mercury	kg	3.41E-08	3.41E-08	2.16E-05	2.16E-05	3.41E-08	0
Lead	kg	0	0	9.62E-06	9.62E-06	0	0
Cadmium	kg	0	0	9.62E-06	9.62E-06	0	0
Direct emissions to water							
NH_3-N	kg	0.2	0.2	3.27E-04	3.27E-04	0.2	0.2
T-P	kg	2.38E-03	2.38E-03	1.62E-05	1.62E-05	2.38E-03	2.38E-03
Output							
Electricity	kWh	217.05	218.62	419.95	474.06	244.99	260.10
Leachate	kg	200	192.05	60	57.62	223.85	223.85

the main contribution to GWP results. Landfill scenarios (scenarios 1.1 and 1.2) have the worst performance of GWP due to the high amount of CH_4 emitted, which accounts for high level of GWP equivalent factor. However, for incineration scenarios (scenarios 2.1 and 2.2), more electricity is produced and more avoided GWP from electricity production can be obtained. Separate landfill of food waste (scenario 3.1) has a better performance due to less CH_4 released. AD (scenario 3.2) is the only scenario that has a negative value and much better than other scenarios. This is mainly because of the decrease in emitted CH_4 by enclosed type of AD reactor and high CH_4 recovery rate.

In view of AP, all the scenarios have the negative values and benefit the environment. The burden from acid gases, for instance H_2S, HCl, SO_2, NO_x, and so on, is well counterbalanced by the offsets of electricity production. Because of good performance on “avoid electricity”, scenario 2.2 has the lowest value of AP.

NH_3-N and T-P in leachate are main contributing elements for NEP and leachate pollutants from landfill and food waste treatment have higher concentration. More NO_x is discharged during incineration and NO_x is another main contributor to NEP, but its NEP effect is offset by the electricity generation. Thus, regarding NEP, scenario 2.2 has the only negative value.

VOCs, CO and CH_4 are main source causing POP. POP for high NOx is chosen for the environment assessment in Hangzhou (Dong et al., 2014; Du et al., 2011). Landfill scenarios have the highest POP, mainly owing to the emission of CH_4 and VOCs during landfill. Negative values appear in both incineration scenarios due to the recovered energy and the control the POP emission.

Source-separated collection changes the composition of MSW and affects the environmental impacts of the waste treatment technologies. The environmental impacts of mixed MSW landfill before and after source-separated collection almost remain unchanged. However, source-separated collection can reduce the amount of mixed MSW deposited by landfill, which is equal to the amount of food waste by separate treatment. Compared to scenario 1.2, scenario 3.1 could reduce the GWP, AP, NEP and POP by 45.9%, 33.4%, 11.7% and 36.8% respectively. The main reason is that separate landfill for food waste produces more avoided emissions by electricity generation. The environmental performance can be better if the food waste is treated by AD. Regarding incineration for mixed waste, the AP, NEP and POP after source-separated collection decrease 25.5%, 440.7% and 18.2% respectively, while GWP increases 36.5%. It is because the source-separated collection increases fossil carbon content and LHV of MSW: higher LHV results in a larger amount of electricity production and it can improve all the impact results; for incineration, CO_2 emitted by fossil carbon combustion is the main contributor to GWP and the amount of added “direct emissions” after source-separated collection is higher than the one of added “avoided electricity”, leading to the increase of burden of GWP.

Regarding the MSWM system with 50.7% for landfill and 49.3% for incineration in 2010, source-separated collection saves 2.0%, 23.6%, 41.3% and 33.0% impacts of GWP, AP, NEP and POP for treating one tonne of MSW.

Fig. 5 illustrates the weighted environmental impact results of each scenario. Landfill scenarios show the worst environmental

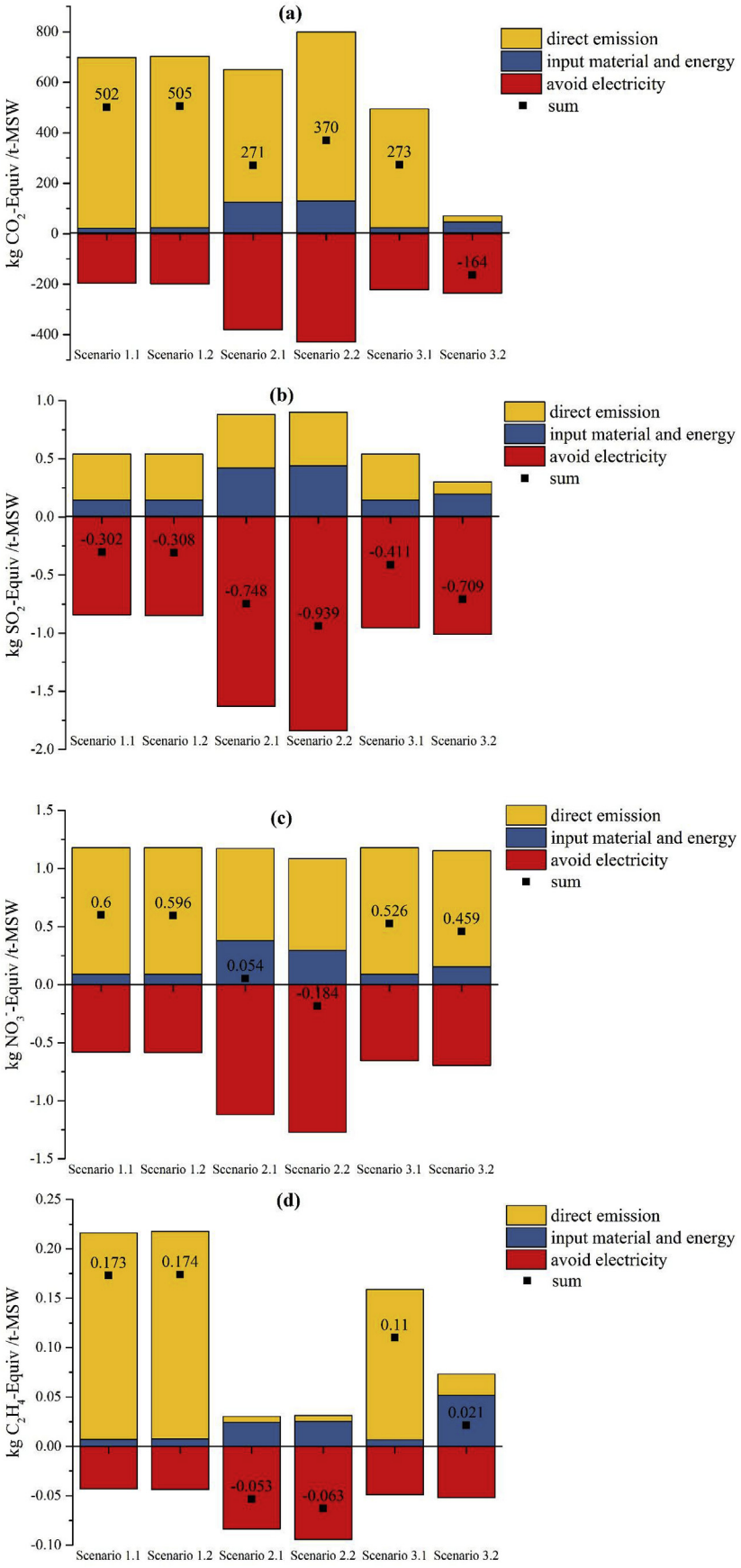


Fig. 4. Contributions of main stages to impact categories in each scenario (basis = one tonne of corresponding waste): (a) GWP; (b) AP; (c) NEP; (d) POP (high NO_x).

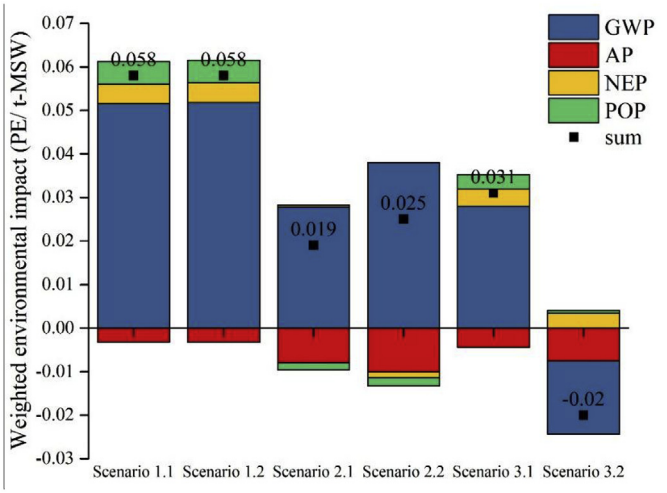


Fig. 5. Weighted environmental impact results of each scenario (basis = one tonne of corresponding waste). PE: One average person equivalent.

performances, while GWP accounting for 88.9% and 89.3%, respectively. Compared to landfill for mixed waste, separate landfill for food waste reduces 46.6% of the weighted result. AD scenario shows the best environmental favorability and is the only one achieving a benefit to environment. Incineration scenarios show the best performances in AP, NEP and POP, but high values of GWP. However, GWP is the principle contributor to its weighted results. Thus, incineration scenarios perform worse than AD scenario, Besides, effective techniques to reduce the GWP are essential for each scenario to the improvement of environmental expression.

4.2. Environmental performance evolution

During 2007 to 2016 in Hangzhou, the annual amount of MSW generated was continually increasing and the MSWM system changed a lot, which resulted in the environmental performance evolution (see in Fig. 6). Because of the increase of MSW generated, the annual weighted environmental performance had an overall downward trend. However, there were two special periods with fluctuations: the weighted result dropped 6.1% from 2009 to 2010 due to implementation of source-separated collection; the second period was from 2015 to 2016, with a decline of 4.3%. During 2015 to 2016, a new incineration plant was put in operation and the growth rate of MSW generated was slow down (only 2.9%), leading to a 22.2% rise of incineration rate. The reduced value by the rise of incineration rate was larger than the added value by the rise of MSW generation. The AD has the only negative value, but merely accounted for 1.98% of waste generated in 2016; thus, the effect by AD was little.

Fig. 7 provides details of the integrated MSWM system in impact categories during 2007–2016. Annual GWP value climbed with the rise of annual amount of waste generated, because almost all the scenarios (except scenario 3.2) caused global warming. Unlike to GWP, annual AP value fell from 2007 to 2016 due to the negative values of all scenarios. Annual NEP and POP had the same variation with time. The main reason is that incineration scenario is the only scenario can achieve environmental saving in NEP and POP after source-separated collection. Thus, implementation of source-separated collection and a new incineration plant caused the decline from 2009 to 2010 and from 2015 to 2016 respectively. However, regarding POP, incineration before source-separated collection can also benefit to environment and made a decline from 2008 to 2009, with the rise of incineration rate, which is different to NEP.

This study also analyzes the annual environmental behavior of integrated MSWM system for treating one tonne of MSW from 2007 to 2016 (see in Fig. 8). The annual weighted result is closely related to the distribution of waste treatment technologies. As shown in Fig. 8, the result went down sharply with the rise of incineration rate from 2007 to 2010. 2010 was a special year with the highest incineration rate and implement of source-separated collection. Because of the limited capacity of incineration plants, the weighted result grew from 2010 to 2013. An AD pilot project was put into operation in 2014 and the weighted result had a little decline from 2013 to 2014. However, the capacity of AD was so small that its effect was little and the weighted result climbed again with the decline of incineration rate. Then, a new incineration plant resulted in the decline from 2015 to 2016.

The system in 2010 had the best environmental behavior and the weighted result is 0.0349 PE/t-MSW, while GWP 380 $kgCO_2$-Equiv/t-MSW, AP -0.645 $kgSO_2$-Equiv/t-MSW, NEP 0.194 $kgNO_3^-$-Equiv/t-MSW, and POP 0.041 kgC_2H_4-Equiv/t-MSW. Besides, the result evolutions of impact categories for treating one tonne of MSW are presented in Fig. A.1**SM** and they have the similar variation trends as the evolution of weighted result.

4.3. Sensitivity analysis

4.3.1. Capacity of AD

The AD scenario has the best environmental behavior but little effect on the system due to its limited capacity. Therefore, a sensitivity analysis is examined to assess the effect of AD capacity on the environmental results (see in Fig. 9). The system in 2016 is chosen for this analysis and AD is assumed to have the priority for food waste

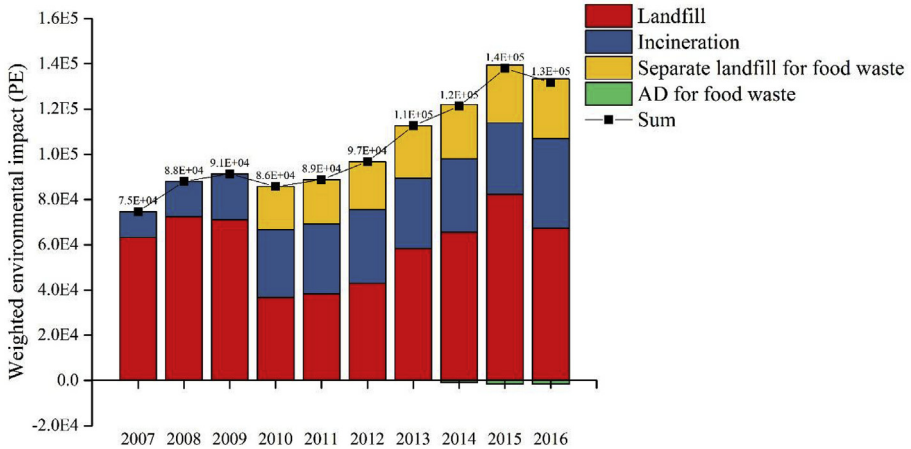


Fig. 6. Evolution of the weighted environmental performance of integrated MSWM system during 2007–2016.

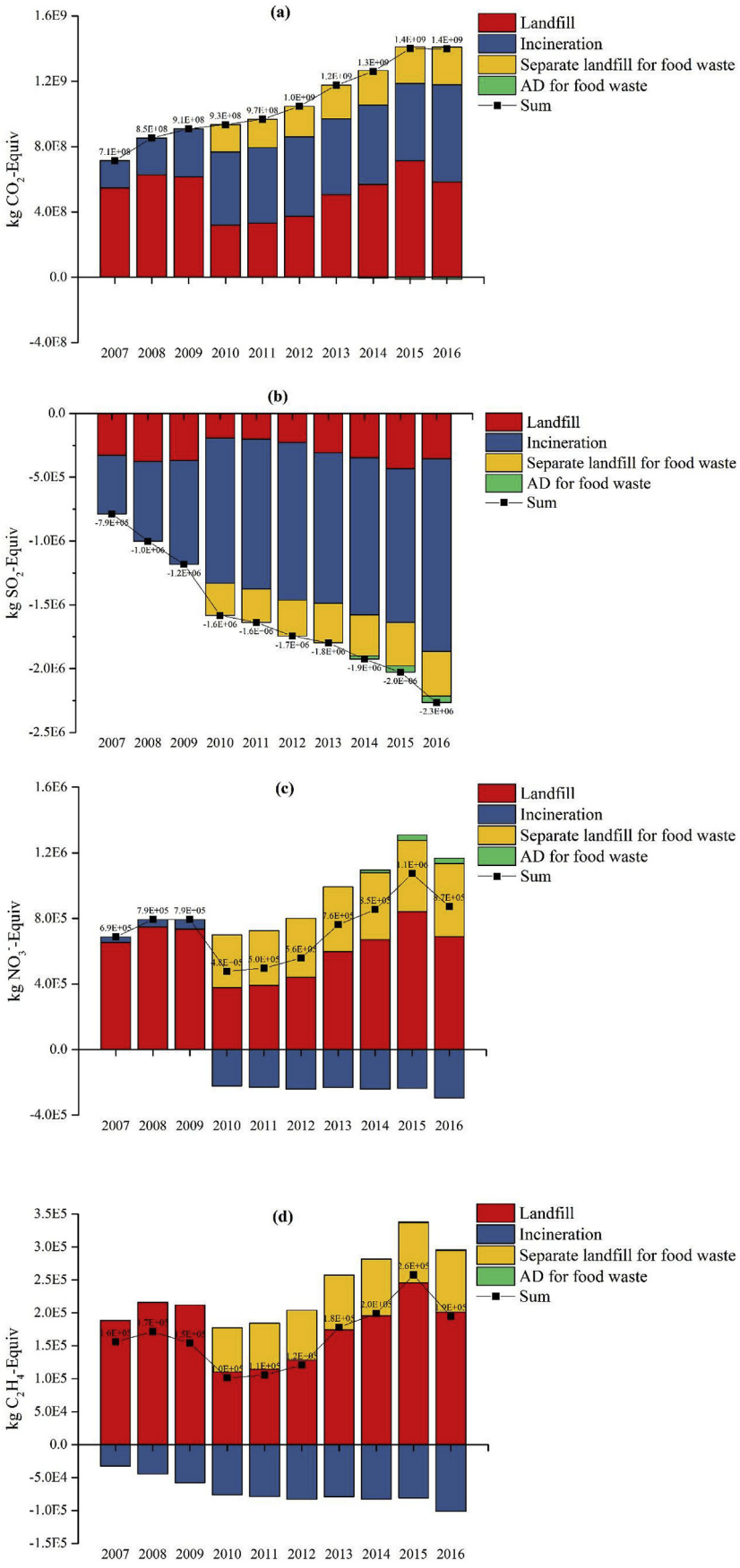


Fig. 7. Evolution of the impact category results of integrated MSWM system during 2007–2016 (a) GWP; (b) AP; (c) NEP; (d) POP.

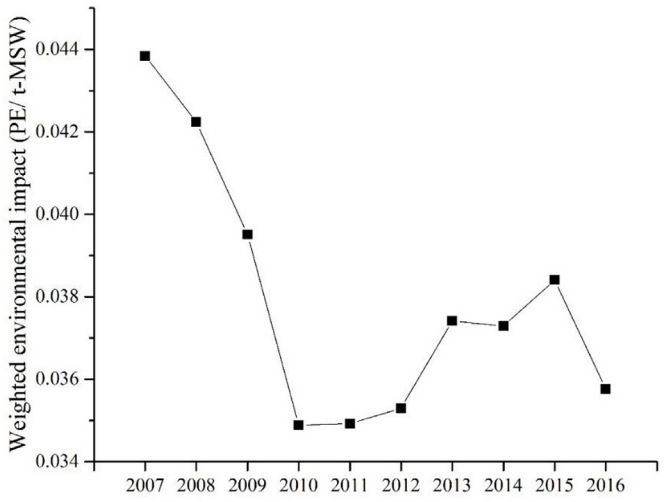


Fig. 8. Evolution of the weighted environmental performance of integrated MSWM system for treating one tonne of MSW during 2007–2016.

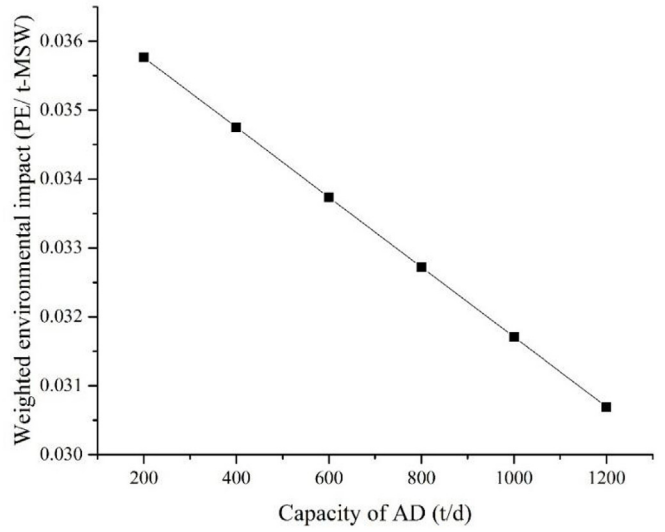


Fig. 9. Environmental performance of integrated MSWM system under different capacities of AD in 2016 (basis = one tonne of MSW).

treatment. The weighted result decreases linearly as the capacity increase. When the capacity of AD reaches 400 t/d, double of current situation, the weighted result is 0.0348 PE/t-MSW, which is lower than that of the system in 2010. Thus, the AD can improve the MSWM and expanding capacity of AD is highly desired.

4.3.2. Source-separated collection efficiency

The environmental performances of MSWM system in 2016 under different source-separated collection efficiencies are examined. As presented in Fig. 10a, weighted result decreases with the source-separation efficiency from 5% to 45%, but turns to rise as the efficiency exceeds 45%. This phenomenon is because source-separated collection increases the environmental burden of incineration, especially in GWP. Increase in the source-separation efficiency leads to more food waste by separate disposition and less mixed waste by landfill. However, this environmental improvement cannot offset the added burden from incineration when the efficiency is above 45%.

To better check the impact of source-separated collection efficiency, the food waste treatment system is improved and AD is chosen to substitute separate landfill. Fig. 10b illustrates the sensitivity analysis result of the improved MSWM system. The weighted result decreases sharply as the efficiency increases. The improved MSWM system with 10% of source-separated collection efficiency show a better environmental performance than the normal system with collection efficiencies from 5% to 50%. Therefore, the improvement of source-separated collection and food waste treatment system should be paid more attention at the same time.

4.3.3. Different impact assessment methods

To check the reliability and robustness of the results, another updated impact assessment method, CML 2001, Jan. 2016 version for world, is adopted. The similar impact categories are considered and both the situations excluding and including biogenic carbon are analyzed. Fig. 11 presents the weighted environmental results of each scenario and the environmental performance evolution by CML 2001 excluding biogenic carbon. It can be concluded that no significant changes are seen between the results by EDIP 97 and CML 2001. Compared to the results by EDIP 97, GWP has smaller proportion of the weighted results by CML 2001 and incineration scenarios become beneficial to environment.

The results by CML 2001 including biogenic carbon are shown in Fig. A.2**SM**. Because biogenic carbon is considered, the GWP results of scenarios are higher, leading to the higher weighted environmental results and greater environmental burdens. There are no differences on the environmental performance rankings of scenarios and the trends of evolution by different impact assessment methods, which supports the reliability of the results.

5. Summary

LCA methodology is adopted in this paper to evaluate the environmental performance evolution of the MSWM system in Hangzhou from 2007 to 2016. The related data in our study are mainly collected from the long-term on-site visit to waste treatment plants and Hangzhou municipal solid waste disposal supervision center.

It is seen that the annual weighted environmental performance had an overall downward trend with the increase amount of MSW. Regarding treating one tonne of MSW, the weighted result is closely related to the distribution of waste treatment technologies. The MSWM system in 2010 had the best environmental behavior, and this phenomenon was mainly caused by the highest proportion of incineration and implementation of source-separated collection.

Incineration has better environmental impacts than landfill in terms of GWP, AP, NEP and POP, no matter before and after source-separated collection. Thus, based on the annual amount of MSW generated, new incineration plants should be built so that the incineration rate can be increased. In Hangzhou, a new waste-to-energy (WtE) plant (Jiufeng incineration plant) with a capacity of 3000 t/d, was put into trial operation in 2017.

Source-separated collection improves the LHV of MSW and benefits the incineration with more electricity production. Besides, the food waste is disposed separately and less MSW is sent for landfill. The environmental performance of the system obtains an obvious improvement after source-separated collection. However, the source-separated collection policy was just started in China and lags behind its western counterparts. Thus, government should attach importance to source-separated collection, and corresponding regulations. Additionally, facilities should be established to enhance the awareness of general public.

Furthermore, sensitivity analysis reveals that food waste treatment plays an important role in the source-separated system. While the importance of source-separated collection is significant, it is also essential to concentrate on the food waste treatment technology. AD can be considered as a primary option for food waste treatment.

In conclusion, this study analyzes the current MSWM system in Hangzhou and the LCA results reflect the effects of MSWM strategies on environmental impacts during 2007–2016. Accordingly, scientific

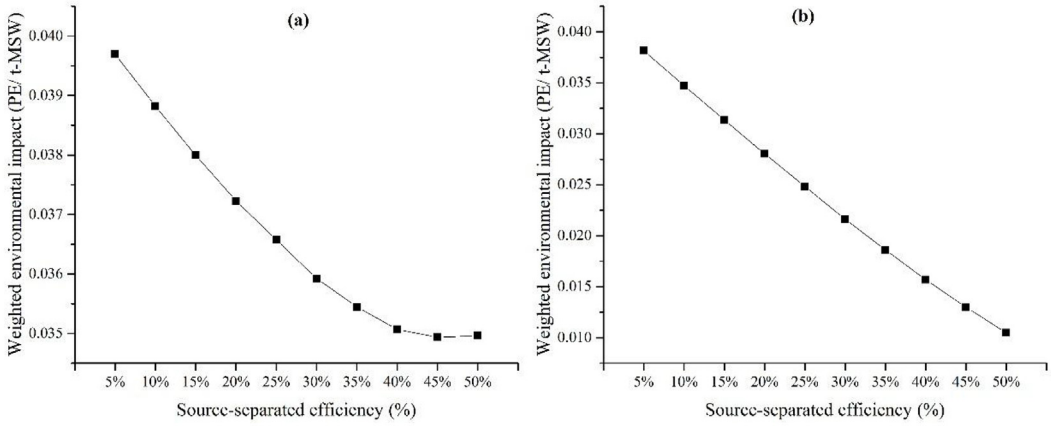


Fig. 10. Environmental performance of integrated MSWM system under different source-separated collection efficiencies in 2016 (basis = one tonne of MSW): (a) the normal MSWM system; (b) the improved MSWM system.

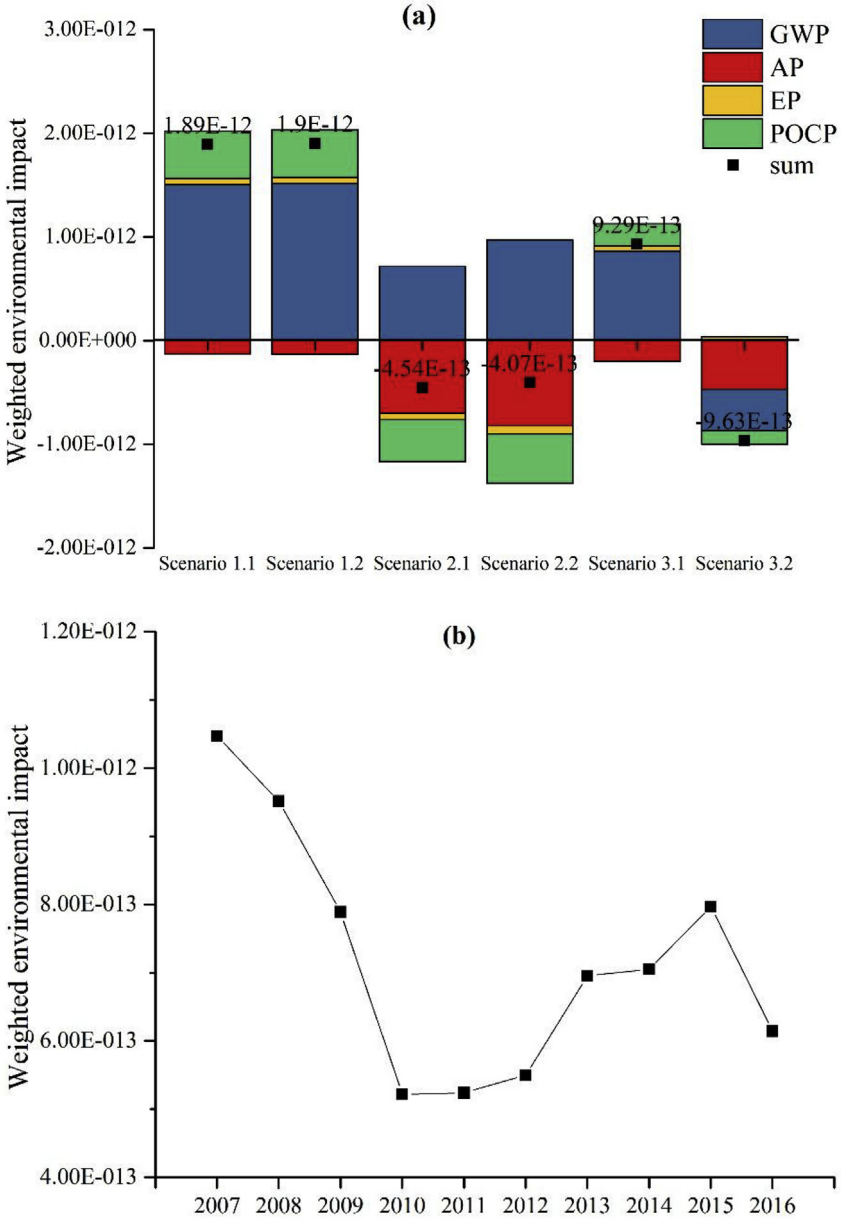


Fig. 11. The environmental results by CML 2001, excluding biogenic carbon (basis = one tonne of MSW): (a) weighted environmental results of each scenario; (b) environmental performance evolution of integrated MSWM system. EP: Eutrophication potential; POCP: Photochem. ozone creation potential; Pt: Point.

suggestions are provided to benefit the environment for the future MSWM development.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2018.08.083.

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