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Environmental impact assessment of leachate recirculation in landfill of municipal solid waste by comparing with evaporation and discharge (EASEWASTE)

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ABSTRACT

In some arid regions where landfill produces minimal amount of leachate, leachate recirculation is suggested as a cost-effective option. However, its long-term impacts to environment remain disputed. For the purpose of revealing the environmental impacts of leachate recirculation in landfill, four scenarios were modeled using EASEWASTE, comparing the strategies of leachate recirculation (with or without gas management), evaporation and discharge. In the current situation (Scenario A), a total of 280 t of waste was generated and then transported to a conventional landfill for disposal. A number of contaminants derived from waste can be stored in the landfill for long periods, with 11.69 person equivalent (PE) for stored ecotoxicity in water and 29.62 PE for stored ecotoxicity in soil, considered as potential risks of releasing to the environment someday. Meanwhile, impacts to ecotoxicity and human toxicity in surface water, and those to groundwater, present relatively low levels. In Scenario B, leachate evaporation in a collecting pool has minimal impacts on surface water. However, this strategy significantly impacts groundwater (1055.16 PE) because of the potential infiltration of leachate, with major contaminants of As, ammonia, and Cd. A number of ions, such as Cl^-, Mg^{2+}, and Ca^{2+}, may also contaminate groundwater. In Scenario C, the direct discharge of leachate to surface water may result in acidification (2.71 PE) and nutrient enrichment (2.88 PE), primarily attributed to soluble ammonia in leachate and the depositional ammonia from biogas. Moreover, the direct discharge of leachate may also result in ecotoxicity and human toxicity via water contaminated by heavy metals in leachate, with 3.96 PE and 11.64 PE respectively. The results also show that landfill gas is the main contributor to global warming and photochemical ozone formation due to methane emission. In Scenario D, landfill gas flaring was thus be modeled and proven to be efficient for reducing impacts by approximately 90% in most categories, like global warming, photochemical ozone formation, acidification, nutrient enrichment, ecotoxicity, and human toxicity. Therefore, leachate recirculation is considered a cost-effective and environmentally viable solution for the current situation, and landfill gas treatment is urgently required. These results can provide important evidence for leachate and gas management of landfill in arid regions.

1. Introduction

Over the past decades, landfills, which have been developed from being open dumps into engineer facilities with special controls for leachate and gas, has always been the dominant technology for municipal solid waste (MSW) disposal (Manfredi and Christensen, 2009; Manfredi et al., 2010). Landfills enable the cost-effective and efficient treatment of MSW, making it widely used in developing countries and areas. Similar to other MSW treatment technologies, a landfill should be managed properly to help protect human health and environmental quality in surrounding and even global areas, as well as to preserve natural resources (Al-Maaded et al., 2012). Therefore, in waste management and technology alternatives, authorities, communities, researchers, and waste management companies should consider environmental aspects in addition to the technical and economic aspects based on local conditions (Banar et al., 2009).

The conventional municipal landfill is considered suitable for most climates, normally producing a highly contaminated leachate and a significant amount of landfill gas (Damgaard et al., 2011). Leachate generation in landfills is affected by several parameters, including water content in waste, precipitation, evaporation, biochemical reaction of organic waste, operational mode, and even groundwater inflow (Kjeldsen et al., 2002). Landfill leachate is recognized to be mainly produced when rainwater infiltrates into the

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landfill, permeates through the waste, and then leaches out with contaminants (Shim et al., 2012). Commonly used leachate control technologies include bottom liners, collection systems, as well as treatment processes prior to the discharge to surface water (Damgaard et al., 2011). However, in some special areas with dry climate, the amount of leachate is normally minimal, thus making the construction and operation of leachate treatment plants infeasible. In such case, the recirculation of leachate in landfills, which can enhance waste degradation via moisture regulation and can prevent leachate discharge via liquid storage, is suggested as a cost-effective management option (Bilgili et al., 2007; Sanphoti et al., 2006). However, the long-term sustainability and environmental impacts of such a practice remain disputed and must be verified (Calabro and Mancini, 2012).

This paper aims to assess the environmental impacts of leachate recirculation in a conventional landfill via the life-cycle-assessment (LCA) methodology. The benefit of using LCA in the analysis of waste management systems is that it allows for a comprehensive view of the processes and impacts involved from an environmental perspective (Del Borghi et al., 2009). Furthermore, LCA has been applied in assessment of MSW management systems at different levels (Bernstad and Jansen, 2011; Cherubini et al., 2009; Zhao et al., 2009). Based on an MSW system serving a Chinese city located in an arid region, the environmental impacts of leachate recirculation in a landfill were investigated using Environmental Assessment of Solid Waste Systems and Technologies (EASEWASTE), an LCA-model-based software. Results were analyzed and compared with landfills utilizing leachate evaporation and discharge to reveal how the leachate recirculation process affects the overall environmental impacts of such systems.

2. Materials and methods

2.1. Waste generation and composition

The MSW management system under study serves a typical medium-sized city located in North China, which normally has a dry climate throughout the year. MSW generation in the study area amounts to 102,200 t annually, which corresponds to 280 t per day. Considering that the resident population is 0.22 million, the unit generation rate of MSW is approximately 1.27 kg per person per day. Similar to other waste systems in China, most recyclables are collected by individuals and are then managed in other systems (approximately 20% of all the generated waste, according to statistical data). Therefore, the waste generation is considered as waste managed by the municipal system and does not include the source-separated recyclables.

The composition of the waste was divided into eight fractions, namely, food waste, ash and dust, plastics and rubbers, paper and cardboard, textiles, metals, glass, and organic yard waste. The detailed composition information, including the element percentages of waste composition, was described in our previous work (Zhao et al., 2012) and is briefly listed in Table 1.

Table 1 shows that although food waste with high water content (approximately 55%) comprised half of the waste portions, the overall water content was only 32.5%. One reason is that ash and dust, which have very low water content, accounted for 30% of the waste portions. The high percentage of ash and dust, along with the relatively low percentage of water content, makes the waste suitable for landfilling. The methane-producing potential was calculated as 294 m^3 per ton of volatile solid (99 m^3 per ton of mixed waste), in accordance with the methane potentials of food waste, paper and cardboard, and organic yard waste.

2.2. Waste transportation and landfilling

The generated MSW (102,200 t annually) was mixed and collected using 280 metal containers (car containers covering 6 m^3). These car containers served as transfer stations that conducted container exchange with transport trucks having 5 t loads. According to the operational data provided by the system operator, the average fuel consumption per ton of waste for collection was 0.2 L of gasoline. The average transportation distance was 7 km. The transport trucks consumed 3.3×10^4 L of gasoline annually, indicating that the unit fuel consumption of transportation was 0.046 L per ton of waste per km. All trucks used for waste collection and transportation meet the emission standards of Euro III. After transportation, the mixed waste was finally disposed in a simple and conventional landfill.

The landfill has a storage capacity of 3 million m^3, providing an annual treatment capacity of 127,000 t. Compared with the generation amount (102,200 t annually), the capacity was sufficient to treat all the generated waste. The operation technology was that of a conventional landfill without energy recovery. The average landfill height was 20 m, and the bulk density was 0.8 t/m^3. Detailed information on material and energy inputs is listed in Table 2. The landfill gas was released through landfill gas wells without organized treatment. Specially, the studied area has dry climate, with an average annual precipitation of only 409.1 mm. Moreover, approximately 50% of the precipitation is concentrated in July (100.5 mm) and August (110.1 mm). On the contrary, the average annual evaporation is 1981.6 mm, almost four times higher than the precipitation. Therefore, the amount of landfill leachate generated was as small as 300 mm/a to 400 mm/a according to temporal variation, corresponding to 2000 m^3/a to 2500 m^3/a in terms of the landfill area. The leachate was thus collected using a collecting pool and recirculated. The recirculation strategy was performed as follows: leachate was pumped and sprinkled onto the surface of the landfilled waste on sunny days just after generation from rain. According to the operational data, the energy consumption for landfill operation was approximately 0.2 kW h/t including leachate recirculation. Leachate recirculation can accelerate the degradation of degradable compounds to a certain extent. On the other hand, leachate recirculation can promote evaporation to reduce leachate generation. Therefore, no further treatment technology was applied for the leachate.

Table 1
Fractions of MSW in the studied system (% by wet weight).

Fractions	Percentage (%)	Water content (%)	Volatile solid (%TS)	Methane potential (CH_4 m^3/t VS)
Food waste	47.49	54.51	94.8	450
Ash and dust	30.85	10.56	0.0	–
Plastics and rubbers	8.40	15.46	87.5	–
Paper and cardboard	6.22	25.92	86.6	170
Textiles	3.13	6.48	96.4	–
Metals	1.88	1.38	0.0	–
Glass	1.45	1.67	0.0	–
Organic yard waste	0.58	29.93	76.0	100
Overall	100	32.48	50.08	294

Table 2
Detailed information on material and energy inputs in the landfill.

Material or energy	Amount	Unit	Transportation distance (km)	Fuel consumption L/(kg km)
External soil	0.05	t/t waste	1	0.0008
External clay	0.08	t/t waste	1	0.0008
Electricity	0.2	kW h/t waste	–	–
Gasoline	0.4	kg/t waste	–	–

Table 3
Information on scenario settings of Scenarios A to D.

Scenario	Waste generation, collection and transportation	Landfilling	Landfill gas	Landfill leachate	Energy input for leachate pump
A	Same as the current system	Conventional landfill without energy recovery	Direct release	Recirculation	Yes
B	Same as the current system	Conventional landfill without energy recovery	Direct release	Collection and natural evaporation	No
C	Same as the current system	Conventional landfill without energy recovery	Direct release	Collection and direct discharge	No
D	Same as the current system	Conventional landfill without energy recovery	Flaring	Recirculation	Yes

2.3. Scenarios

To evaluate the environmental impacts of the entire waste system, as well as the technology of leachate recirculation, four scenarios (Scenarios A to D), including the current MSW system and hypothetical systems focusing on leachate or landfill gas, were modeled in EASEWASTE. Scenario A presents the current system in which leachate was recirculated and landfill gas was released. Leachate recirculation modeled here is based on surface sprinkling according to the actual situation. Recirculation with horizontal or vertical wells, which may have clogging problems and thus cause accident pollution, is not taken into account in this study. Scenarios B and C are both focused on the landfill leachate. In Scenario B, the leachate is assumed to be guided into the collecting pool and mainly relies on natural evaporation. In Scenario C, the leachate is assumed to be collected and directly discharged to the surface water. Considering the potential impact of landfill gas on global warming, Scenario D presents a hypothetical system with landfill gas flaring based on the current system. Detailed information on the scenario settings is listed in Table 3.

2.4. LCA method and EASEWASTE model

EASEWASTE is an LCA-based model developed by the Technical University of Denmark for the assessment of the environmental impacts of MSW systems and technologies. Details on EASEWASTE can be found in previous work (Christensen et al., 2007; Bhander et al., 2008) and in the Web site www.easewaste.dk. EASEWASTE utilizes the Danish environmental design of industrial products (EDIP) method as a default method for impact assessment (Wenzel et al., 1997). EASEWASTE provides LCA results, including life cycle inventory, characterization of impacts, normalized impact profile, and weighted impact profile (Kirkeby et al., 2006). Normalization results (person equivalent, PE) are calculated with normalized environmental impact potential references, providing a relative expression of the environmental impact or resource consumption compared with the impact from one average person in a reference year (kg eq/(per a)). EASEWASTE includes 13 categories of environmental impacts in the LCA method (Kirkeby et al., 2006). However, only six major environmental impact categories are available in China's normalization reference (Zhao et al., 2011). Therefore, the assessment in this study was performed based on the 13 default categories updated according to Chinese data, as shown in Table 4 (Li et al., 2007; Wenzel et al., 1997). In this instance, the results calculated with Chinese and Danish normalization references are incomparable, and thus discussed separately in the following text to avoid cross-comparison.

3. Results and discussion

3.1. Environmental impacts of the current MSW system (Scenario A)

In the current MSW system, mixed waste is collected and transported to the landfill with leachate recirculation. Evidently, the environmental impacts from landfilling are more important than those from waste collection and transportation, except for zero values of OD due to no related substances detected such as chlorofluorocarbon and chlorohydrocarbon in all the processes (Table 5). For instance, the environmental impacts on AC and NE from landfilling are approximately 20 times greater than those from collection and transportation. Moreover, the impact on GW100 from landfilling is even 700 times greater than that from collection and transportation. Pollutants in collection and transportation are mainly from fuel combustion, which hardly affect the stored ecotoxicity in water or soil. However, some ecotoxic pollutants remain stored in the landfill for a relatively long period, and such pollutants may be released to the environment someday. Therefore, in EASEWASTE, impacts of SETw and SETs are introduced and utilized to evaluate such risks of landfilled pollutants (Hauschild et al., 2008).

The life cycle inventory of the MSW system shows that 168.85 t and 271.85 t of CO_2 are released annually because of fossil fuel consumption during collection and transportation, respectively. However, the fossil CO_2 released from the landfill is only 118.17 t/a compared with 57329.80 t/a of biological CO_2 released, primarily because the former is mainly derived from power and fuel consumption during landfilling, and the latter is totally derived from the degradation of organic waste. During collection and transportation, 1.84 t and 2.97 t of NO_x, which is generated during fuel combustion, are annually released to the atmosphere, as opposed to 0.76 t from the landfill. The environmental impacts from collection and transportation are omitted in the following discussion because of their marginal contribution to the environment and because they have the same situation in all the scenarios.

Fig. 1 shows the normalization impacts with Chinese references from the landfill with leachate recirculation and landfill gas release. The results are presented in substance style, showing that

Table 4
Normalized environmental impact potential reference applied in this study.

Environmental impact category	Normalization	Standard unit	Resource
Global warming (GW100)	8.70×10^3	$kgCO_2$ eq/(per a)	China
Stratospheric ozone depletion (OD)	2.00×10^{-1}	kgCFC-11 eq/(per a)	China
Acidification (AC)	36.0	$kgSO_2$ eq/(per a)	China
Nutrient enrichment (NE)	62.0	$kgNO_3$ eq/(per a)	China
Photochemical Ozone formation (POF)	6.50×10^{-1}	kgC_2H_4 eq/(per a)	China
Ecotoxicity in soils (ETs) [a]	9.64×10^5	m^3 soil/(per a)	Denmark
Ecotoxicity in water (ETw)	3.52×10^5	m^3 water/(per a)	Denmark
Human toxicity via air (HTa)	6.09×10^{10}	m^3 air/(per a)	Denmark
Human toxicity via water (HTw)	5.00×10^4	m^3 water/(per a)	Denmark
Human toxicity via soils (HTs)	1.27×10^2	m^3 soil/(per a)	Denmark
Stored ecotoxicity in water (SETw)	1.14×10^7	m^3 water/(per a)	Denmark
Stored ecotoxicity in soils (SETs)	5.06×10^2	m^3 soil/(per a)	Denmark
Spoiled groundwater resource (SGR)	1.40×10^2	m^3 water/(per a)	Denmark

[a] Normalized reference of ecotoxicity in soil is available in China (358 m^3 soil/(per a)). However, to maintain the consistency on ecotoxicity assessment, a Danish number is applied to this category in this study.

Table 5
Normalized environmental impacts from Scenario A (PE).

Impact category	Collection	Transportation	Landfilling	In total	Major contaminant	PE of major contaminant
GW100	0.0201	0.0323	34.4978	34.5502	CH_4	39.4439
OD	0.0000	0.0000	0.0000	0.0000	–	0.0000
AC	0.0392	0.0632	2.0051	2.1075	NH_3	1.8315
NE	0.0403	0.0649	2.0761	2.1814	NH_3	2.0590
POF	0.3667	0.5940	149.7121	150.6692	CH_4	147.8236
ETs	0.0000	0.0000	0.0000	0.0000	–	0.0000
ETw	0.1523	0.2452	0.3694	0.7669	Polycyclic Aromatic Hydrocarbon (PAH)	0.6079
HTa	0.0204	0.0329	0.0494	0.1027	VOC from fuel	0.0529
					H_2S	0.0473
HTw	0.0012	0.0019	0.0139	0.0170	Hg	0.0139
HTs	0.0020	0.0033	0.5437	0.5490	Benzene	0.5277
SETw	0.0000	0.0000	11.6908	11.6908	As	7.4286
SETs	0.0000	0.0000	29.6224	29.6224	As	29.0685
SGR	0.0000	0.0000	0.0000	0.0000	–	0.0000

methane is the major pollutant in both photochemical ozone formation and global warming. This is because the large amount of biogas from the landfill was not collected efficiently, and methane contributes 25 kg CO_2-eq per kg and 0.007 kg C_2H_4-eq per kg. Considering the normalization references of 0.65 kg C_2H_4-eq/(per a) and 8700 kg CO_2-eq/(per a), as shown in Table 4, POF and GW100 are the major categories of the environmental impacts of the landfill. Moreover, ammonia as air emission, which is also from landfill gas, is a main contributor to acidification and nutrient enrichment. Carbon sequestered in the landfill can save some impacts (−4.96 PE) of global warming, although it may be released into the environment hundreds of years later. Therefore, biogas management can be concluded as the most pressing environmental problem and should thus be improved immediately.

The results on ecotoxicity, human toxicity, and other categories with Danish references are shown in Fig. 2. The stored ecotoxicity in soil is the most noticeable impact, with As stored in soil as the major contributor. Furthermore, the stored ecotoxicity in water is also remarkable, and the dissoluble As and Pb contaminants have the greatest potential for ecotoxicity (7.43 PE and 3.97 PE, respectively), along with other heavy metals, such as Cd and Cr(III). However, the impacts to SETw and SETs cannot be considered as subsistent pollution because these contaminants are supposed to settle in the landfill for a long period despite the risk of being released into the environment. Moreover, benzene, Hg, and H_2S are the major substances impacting HTs, HTw, and HTa, respectively. Furthermore, potential impacts on ETw and ETs are relatively small compared with those on other categories.

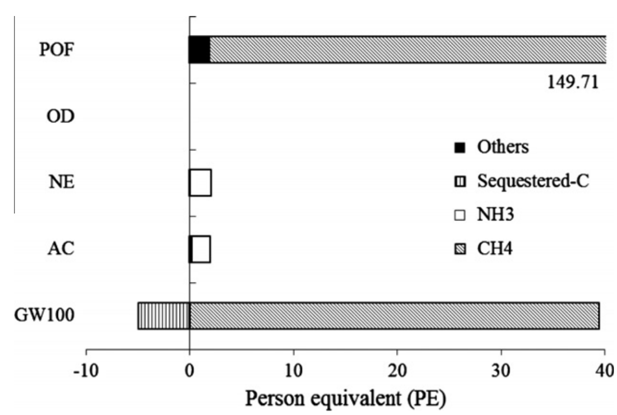

Fig. 1. Normalization impacts with Chinese references from the landfill in Scenario A. GW100: global warming (100 years); AC: acidification; NE: nutrient enrichment; OD: ozone depletion; POF: photochemical ozone formation.

3.2. Environmental impacts from a landfill with leachate evaporation (Scenario B)

The leachate amount from the landfill is minimal and sporadic, making a special water treatment plant uneconomical because the landfill is located at a typically dry area with very low precipitation and high evaporation. Therefore, the landfill operators suggested and implemented the method of leachate recirculation, in which a collecting pool collects the leachate during rainy days, and a

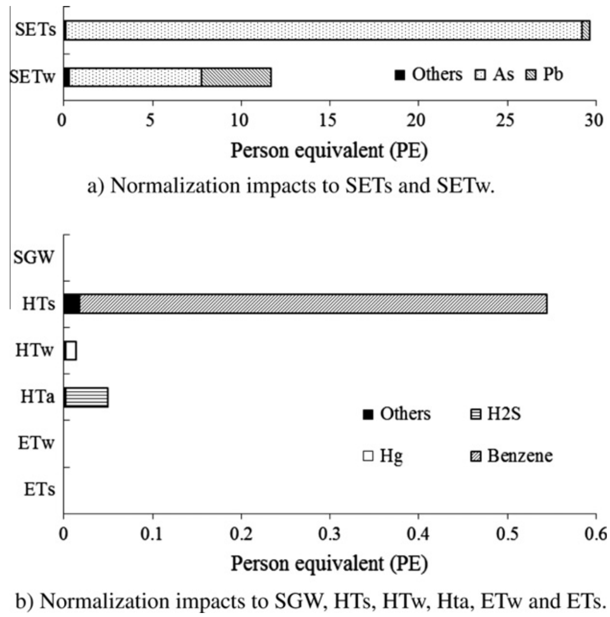

Fig. 2. Normalization impacts with Danish references from the landfill in Scenario A. ETs: ecotoxicity in soil; ETw: ecotoxicity in water; HTa: human toxicity via air; HTw: human toxicity via water; HTs: human toxicity via soil; SETw: stored ecotoxicity in water; SETs: stored ecotoxicity in soil; SGW: spoiled groundwater resource.

pump is used to sprinkle the leachate back to the surface of the landfill during sunny days. However, the environmental benefit of leachate recirculation remains unclear, especially in terms of its impacts on ecotoxicity and human toxicity via water and soil, as well as groundwater.

To evaluate the environmental impacts of leachate recirculation, two contrasting scenarios were designed and modeled. In Scenario B, the leachate is assumed to be collected by the collecting pool, and is then evaporated in the pool without any manual intervention. The normalized environmental impacts on ecotoxicity, human toxicity, and groundwater were calculated by EASEWASTE with Danish references, as shown in Table 6.

Compared with the results obtained in Scenario A, the potential environmental impacts derived from leachate collection and evaporation are slightly smaller in most impact categories. For instance, the impacts on HTw and HTs are respectively 0.0083 PE and 0.0103 PE smaller than those in Scenario A, and the reduction values on SETw and SETs are 0.0550 PE and 0.1849 PE, respectively. However, the impact on SGR is approximately 1055 PE when leachate evaporation is applied. These findings can be explained by the LCA inventories of contaminants. Fig. 3 shows the distribution amounts of major contaminants in groundwater for Scenarios A and B. In Scenario A, heavy metals are mainly stored in water and soil in the landfill, whereas ammonia is mainly released into the air. However, when the leachate naturally evaporates from the collecting pool, the contaminants may infiltrate and pollute the groundwater under the collection and evaporation system. Therefore, the distribution proportion of ammonia in groundwater increases to 16.5% (6.93 kg/a), and that of Cd increases to 8.3% (0.0017 kg/a), with most of Mg^{2+} (15.86 kg/a) infiltrating the groundwater. As (0.5561 kg/a), Cr (0.0017 kg/a), and Pb (1.35×10^{-5} kg/a) also contribute to the groundwater resource spoilage to different extents. Given the sensitivity of groundwater, even a small amount of contaminants can contaminate a large resource area (for instance, 2×10^5 m^3/kg As and 5×10^5 m^3/kg Cd).

Thus, although leachate collection and evaporation can reduce energy consumption because the process does not require a water pump, this process may place considerable pressure on groundwater resources. Aside from heavy metals, a number of common ions, such as Cl^-, Mg^{2+}, and Ca^{2+}, may result in groundwater contamination. Therefore, seepage prevention during evaporation is very important.

3.3. Environmental impacts from a landfill with leachate discharge (Scenario C)

For purposes of comparison, a contrast scenario (Scenario C) was built to model the environmental impacts from a landfill, which was assumed to discharge the leachate into surface water after collection. The results on the normalized environmental impacts on AC, GW100, POF, OD, and NE showed marginal differences on GW100, POF, and OD between Scenarios A and C primarily because the pollutants in leachate hardly affect the air environment. Fig. 4 presents the normalized results on AC and NE, in comparison with Scenario A. Evidently, ammonia in leachate contributes the most to the impact increment (by approximately 1/3) on AC and NE when it is discharged into surface water. Compared with the impacts in Scenario A, impacts derived from NO_x and SO_2 (air emission) in Scenario C are relatively lower (0.0096 PE and 0.0116 PE for AC, respectively). The same phenomena are observed in the results on NE. These are primarily because leachate recirculation can enhance both the degradation of dissolved contaminants and air emission. These contaminants are thus distributed more in the liquid phase without leachate recirculation, resulting in greater impacts on both AC and NE.

As regards the environmental impacts on ecotoxicity, human toxicity, stored toxicity, and groundwater, Scenario C is presented differently from Scenarios A and B. Leachate discharge hardly affects groundwater, similar to leachate recirculation. However, normalized impacts on ecotoxicity and human toxicity via surface water became approximately 10 times greater than those in Scenarios A and B. For instance, Fig. 5 shows the impacts on ETw and SETw from the landfill with leachate discharge. According to the LCA inventory analysis, in Scenario C, 44.294 kg/a of As is stored in the liquid phase in the landfill, resulting in 7.38 PE of normalized impacts to SETw. In

Table 6
Normalized environmental impacts with Danish references from the landfill in Scenario B.

Impact category	PE of landfill with leachate evaporation	Major contaminant	PE of major contaminant
ETs	0.0000	–	0.0000
ETw	0.3689	Polycyclic Aromatic Hydrocarbon (PAH)	0.2926
HTa	0.0490	H_2S	0.0473
HTw	0.0056	Hg	0.0041
HTs	0.5334	Benzene	0.5264
SETw	11.6358	As	7.3823
SETs	29.4375	As	28.8872
SGR	1055.1584	As	794.3756
		Ammonia	247.5002
		Cd	5.8938

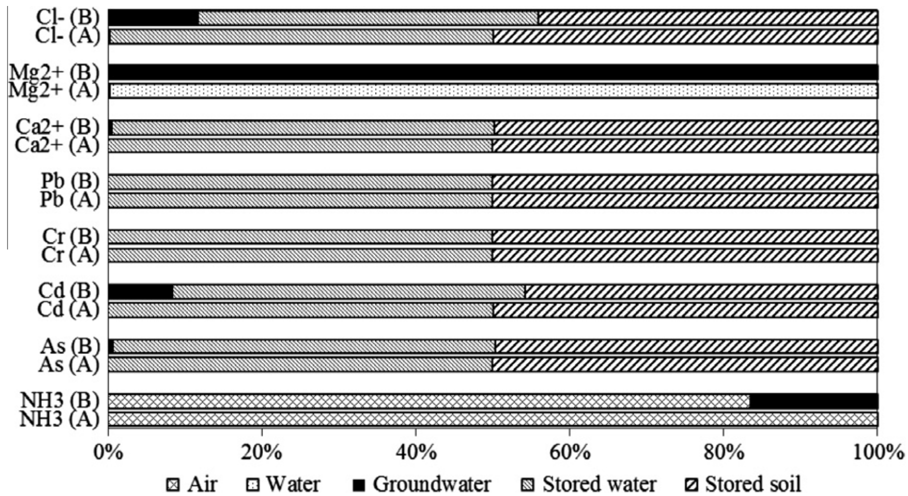

Fig. 3. Amount distribution of major contaminants in groundwater in Scenarios A and B.

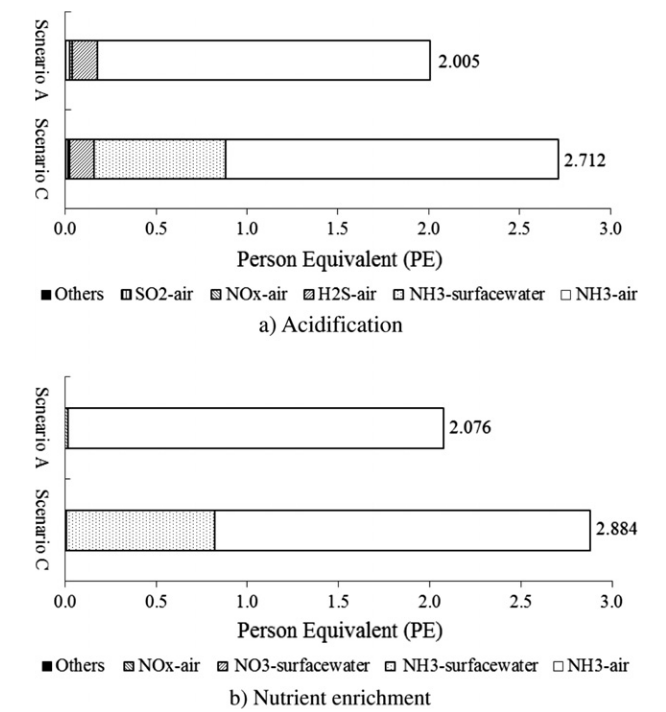

Fig. 4. Normalization impacts on acidification and nutrient enrichment with Chinese references in Scenarios A and C.

contrast, only 0.556 kg/a of As is discharged into surface water, contributing 3.03 PE of normalized impacts to ETw given the relatively low normalization reference value. In contrast, the annual amounts of Cd, Cr, and Pb discharged with leachate into surface water are 1.66×10^{-3} kg, 1.67×10^{-3} kg, and 1.87×10^{-5} kg, respectively, whereas the amounts stored in the liquid phase of the landfill are 9.12×10^{-3} kg, 3.22 kg, and 22.62 kg, respectively. The difference in distribution, which is mainly due to the dissolubility and mobility of the elements, results in the variance in normalized impacts, along with their different toxicity properties.

Moreover, a mass of Cl^- (153.82 kg/a), Mg^{2+} (15.87 kg/a), Ca^{2+} (6.40 kg/a) and so on is also released into surface water because of leachate discharge. However, these elements are considered neutral to ecotoxicity and human toxicity and are not assumed to contribute to the normalized impacts on ETw, ETs, SETw, and SETs.

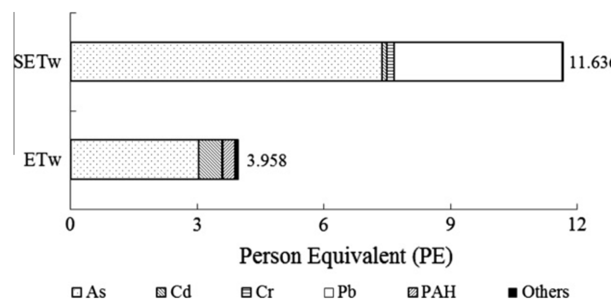

Fig. 5. Normalization impacts on ecotoxicity and stored ecotoxicity in water with Danish references in Scenario C. ETw: ecotoxicity in water; SETw: stored ecotoxicity in water.

3.4. Environmental improvement from landfill gas management (Scenario D)

Considering the huge impact of methane on POF and GW100, the scenario in which landfill gas was treated by direct combustion (Scenario D) was modeled in EASEWASTE. Combustion can remove over 95% methane in the flaring biogas. However, the biogas produced in the late period of landfilling can hardly be ignited given the low concentration of combustive components. Therefore, the amount of methane emitted from the landfill in Scenario D was 1973 kg/a, which is 11753 kg/a less than that from Scenario A. The overall removal efficiency of methane is thus 85.6%. This value indicates that flares can efficiently reduce methane emissions, as reported by other researchers (Damgaard et al., 2011). On the other hand, the amount of CO_2 emission increased to 139005 kg/a (57448 kg/a in Scenario A), and all increments were derived from biological carbon, which is considered a neutral element in global warming. Moreover, combustion can also remove most H_2S, NH_3, and other organic contaminants, resulting in an improvement of acidification and nutrient enrichment. The normalized environmental impacts with Chinese references are shown in Fig. 6.

Comparing Figs. 6 and 1, significant improvements in POF and GW100 were achieved. The normalized impact on POF was reduced from 149.7 PE to 22.0 PE because of methane reduction. Moreover, the normalized impact on global warming was almost totally counteracted by the sequestered carbon, having an overall value of 0.72 PE. The impacts on AC and NE were both reduced by approximately 90%. Moreover, the normalized impacts on HTa and HTs with Danish references were also reduced to a certain

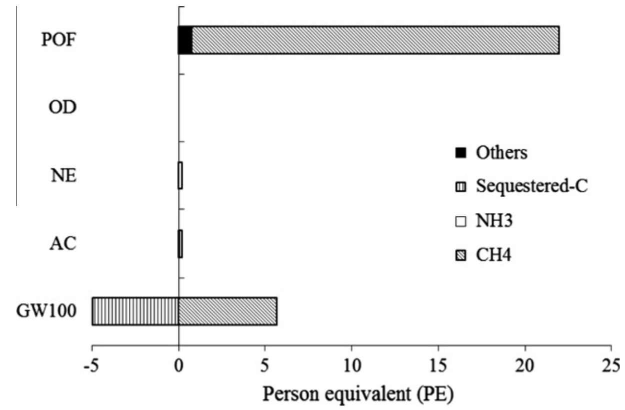

Fig. 6. Normalization impacts with Chinese references from the landfill in Scenario D. GW100: global warming (100 years); AC: acidification; NE: nutrient enrichment; OD: ozone depletion; POF: photochemical ozone formation.

Table 7
Change rates of normalized environmental impacts from the landfills in all the scenarios.

Impact category	PE in Scenario C	Change rate		
		Scenario A (%)	Scenario B (%)	Scenario D (%)
GW100	34.4923	+0.02	0.00	−97.91
OD	0.0000	0.00	0.00	0.00
AC	2.7120	−26.07	−26.69	−92.05
NE	2.8839	−28.01	−28.22	−93.16
POF	149.6941	+0.01	0.00	−85.30
ETs	0.0000	0.00	0.00	0.00
ETw	3.9583	−90.67	−90.68	−90.67
HTa	0.0490	+0.82	0.00	−84.29
HTw	0.1339	−89.62	−95.82	−89.77
HTs	0.5334	+1.93	0.00	−90.14
SETw	11.6358	+0.47	0.00	+0.47
SETs	29.4375	+0.63	0.00	+0.63
SGR	0.0000	0.00	$+\infty$	0.00

degree (0.008 PE and 0.053 PE, respectively) because of the combustion of benzene, H_2S, and so on, whereas the impact categories, including SETw, SETs, ETw, and ETs, were hardly influenced by biogas combustion. Biogas treatment is clearly efficient for the avoidance of numerous environmental impacts and is very important in the improvement of the landfill system. However, the instability of landfill gas production and combustion requires that the methods for biogas treatment and management be optimized according to the operational characteristics.

The change rates of environmental impacts among different scenarios were calculated using the results from Scenario C, which is considered as the worst case, as contrast values (Table 7). Evidently, leachate evaporation (Scenario B) can significantly improve the surface water environment (by over 90% for ETw and HTw and by over 25% for AC and NE). Although leachate evaporation has an insignificant influence on the air and soil environments, it results in the serious deterioration of the groundwater environment. Leachate recirculation can also significantly improve the surface water environment to a similar extent as leachate evaporation. However, recirculation of leachate results in the slight deterioration of the air environment because of the enhancement of waste degradation and biogas generation. When landfill gas treatment is applied, the air and soil environments will be significantly improved. Therefore, from an environmental viewpoint, recirculation is considered a reasonable solution to the leachate problem under the current situation, and landfill gas management is urgently needed as an additional measure.

Besides the environmental impacts, economical efficiencies of the alternatives are also concerned. Obviously, direct discharge and natural evaporation of leachate will reduce the economic cost on leachate management to a certain extent, but will result in serious environmental deterioration. Considering the very small amount of leachate, the construction and operation of a special treatment plant are probably uneconomical. In this view, recirculation of leachate presents cost-effectiveness with small increased cost for pumping and sprinkling and great benefit on environment. And gas flaring will probably cost slightly more than direct release. However, this improvement is totally worthy of its environmental benefit. Further evaluation is required to obtain detailed information on economical efficiencies of different alternatives.

4. Conclusions

The environmental impacts of leachate recirculation in an MSW landfill were investigated using EASEWASTE, an LCA-model-based software, by comparing with leachate evaporation and discharge. After collection and transportation, the waste generated in the studied city is disposed in a conventional landfill that has no energy recovery. The life-cycle inventories and normalized environmental impacts of the current MSW management system were analyzed. Particular attention was paid to the landfill processes with different leachate management measures.

Waste landfills can store a massive amount of ecotoxic contaminants for very long periods. Currently, these landfills do not provide subsistent pollution problems. However, these contaminants are at risk of being released to the environment in the future. When the leachate is directly discharged into surface water (Scenario C), soluble ammonia in leachate and depositional ammonia from biogas are key threats to AC (2.56 PE) and NE (2.87 PE). Heavy metals, such as As, Cd, Cr, and Pb, present potential impacts on ETw (3.96 PE) and HTw (0.14 PE) because of the discharge in leachate. When the leachate is collected in a pool and then naturally evaporated (Scenario B), the environmental impacts on surface water are not as significant as that in Scenario C. However, the impact on SGR reaches 1055 PE because of leachate infiltration, which contains such major contaminants as As (794.38 PE), ammonia (247.50 PE), and Cd (5.89 PE). The distribution proportions of contaminants in groundwater, surface water, stored phases, and air were also analyzed. The results indicate that a number of common ions, such as Cl^-, Mg^{2+}, and Ca^{2+}, may also contaminate groundwater. In the current situation where leachate is recirculated (Scenario A), most impacts on ecotoxicity and human toxicity in water can be avoided compared with Scenario C. Moreover, impacts on SGR can also be avoided compared with Scenario B. However, leachate recirculation contributes slightly more to air-related impacts because of greater energy consumption and the enhancement of biogas generation. As and Pb have major potential for stored ecotoxicity in soil and water. In all the above scenarios, landfill gas is not collected or treated, causing huge loads to GW100 and POF mainly due to CH_4, as well as to AC and NE mainly due to NH_3. When flaring of biogas is applied together with leachate recirculation (Scenario D), most combustive components can be efficiently removed, thus avoiding approximately 98% impacts to GW100 (33.78 PE) and approximately 90% impacts to POF (127.7 PE), AC (1.79 PE), NE (1.87 PE), HTa (0.042 PE) and HTs (0.49 PE) compared with the current system. Therefore, leachate recirculation is considered a reasonable solution under the current situation. Moreover, landfill gas treatment can introduce major environmental benefits and is thus urgently required. These results can provide important evidence for leachate and biogas management in conventional landfills in dry areas.

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