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Environmental impact assessment on the construction and operation of municipal solid waste sanitary landfills in developing countries: China case study

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Abstract

An inventory of material and energy consumption during the construction and operation (C&O) of a typical sanitary landfill site in China was calculated based on Chinese industrial standards for landfill management and design reports. The environmental impacts of landfill C&O were evaluated through life cycle assessment (LCA). The amounts of materials and energy used during this type of undertaking in China are comparable to those in developed countries, except that the consumption of concrete and asphalt is significantly higher in China. A comparison of the normalized impact potential between landfill C&O and the total landfilling technology implies that the contribution of C&O to overall landfill emissions is not negligible. The non-toxic impacts induced by C&O can be attributed mainly to the consumption of diesel used for daily operation, while the toxic impacts are primarily due to the use of mineral materials. To test the influences of different landfill C&O approaches on environmental impacts, six baseline alternatives were assessed through sensitivity analysis. If geomembranes and geonets were utilized to replace daily and intermediate soil covers and gravel drainage systems, respectively, the environmental burdens of C&O could be mitigated by between 2 and 27%. During the LCA of landfill C&O, the research scope or system boundary has to be declared when referring to material consumption values taken from the literature; for example, the misapplication of data could lead to an underestimation of diesel consumption by 60 to 80%.

Key words

Municipal solid waste landfill, life cycle assessment, liner system, intermediate cover, alternative materials

1 Abbreviations

AC	Acidification
C&O	Construction and Operation
CM	Construction of the Main parts of the landfill body
COF	Construction of Other Facilities in the landfill site
EDIP	Environmental Development of Industrial Products
ETs	Eco-Toxicity in soil
ETwc	Eco-Toxicity in water-chronic
GCL	Geosynthetic Clay Liner
GW	Global Warming
HDPE	High-density Polyethylene
HTa	Human Toxicity via air
HTs	Human Toxicity via soil
HTw	Human Toxicity via water
ISO	International Standardization Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFG	Landfill Gas
MSW	Municipal Solid Waste
NE	Nutrient Enrichment
OL	Operation of the Landfill
POF	Photochemical Ozone Formation
SOD	Stratospheric Ozone Depletion
SP	Site Preparation

1. Introduction

Nowadays, landfilling is still the most commonly used method for municipal solid waste (MSW) treatment in many countries. Taking China as an example, 100 million tonnes of MSW were disposed of in landfills during 2011, which accounted for 77% of the total amount of treatable waste (National Bureau of Statistics of China, 2012). Life cycle assessment (LCA) can be used to evaluate the environmental impacts associated with all stages of a product/service's life cycle, and through this assessment it provides useful insights into improving the whole process from an environmental perspective. Therefore, the LCA of MSW landfilling is important in supporting decision-making in integrated MSW management. The impacts of generating and treating landfill gas (LFG) and leachate have been the primary concerns of researchers as the major environmental issues with regards to MSW landfilling (El-Fadel et al., 1997; Kirkeby et al., 2007; Niskanen et al., 2009). Nevertheless, approaching landfill sites as products, their construction and operation (C&O) consume certain amounts of materials and energy, and the manufacturing and utilization of these materials could lead to environmental burdens. Frischknecht et al. (2007) investigated the contributions of capital goods in the LCA of a large number of product/service systems. It was argued that the lower the pollutant content of the assessed waste, the higher the environmental burden contribution from capital goods. Their study also demonstrated that the burden from capital goods was important for landfilling, but not as significant for other waste treatment technologies such as waste incineration, especially when considering climate change, acidification, and eutrophication.

The majority of published works on the LCA of MSW landfilling employ an energy consumption amount (e.g. as megajoules of energy or liters of diesel) to represent the environmental impacts of the landfill C&O process (Damgaard et al., 2011; Khoo et al., 2012; Manfredi et al., 2009). Although Manfredi et al. (2010) and

Niskanen et al. (2009) considered the C&O process during the LCA of landfilling, they did not include the original data in their papers, which limited the applicability of these data for further research. Of studies that did cover C&O in detail, Ecobalance Inc. (Camobreco et al., 1999; Ecobalance Inc., 1999) collected and summarized the consumption of materials and energy for more than 20 landfill sites in the United States as a life cycle inventory (LCI) report. Menard et al. (2004) demonstrated that differences in materials and energy inputs between an engineered landfill and a bioreactor landfill were due to different waste density. A detailed quantification of the capital goods used for constructing a typical hill-type landfill (Brogaard et al., 2013) indicated that gravel and clay were used in the greatest amounts. In addition, an environmental impact assessment by Brogaard et al. (2013) revealed that the potential impacts of capital goods consumption were low-to-insignificant compared to the overall impacts of landfill processes (direct and indirect emissions), except for the impact category of resource depletion. In China, researchers usually refer to energy consumption figures published in developed countries during LCA of waste treatment processes (Hu, 2009; Xu, 2003). The only published paper possessing original data, to the authors' knowledge, was by Wei et al. (2009), who reported the usage of water, soil, pesticide, diesel, and electricity in a landfill located in the city of Suzhou.

In China, a representative developing country, the national industrial standard for MSW sanitary landfill management is still under development and has been updated twice in the last two decades (Ministry of Construction of the People's Republic of China, 2001, 2004). This could make landfill C&O in China different from that in developed countries. If a study refers to the literature data reported in developed countries directly, it may thus lead to wrong assessment results. In addition, from a spatial aspect, China is a large country with diverse geographic and economic conditions, which could induce lots of different choices regarding landfill C&O approaches. When researchers conduct a LCA of waste landfilling, they would be more precise in the assessment if they considered the aforementioned differences as much as possible.

The present study will provide a comprehensive LCI of materials and energy consumption and evaluate environmental impacts through a LCA for the C&O process in a typical landfill site in China. The other purposes of this study are to estimate whether the diverse approaches to landfill C&O affect the studied environmental impacts significantly and to identify relatively better approaches with the intention of mitigating environmental burdens in a Chinese context.

2. Approach and Method

In this study, the C&O process in a typical sanitary landfill site was taken as the object for a LCA. The functional unit was one tonne of waste disposed of in the landfill site. According to the “Chinese Technical Code for Municipal Solid Waste Sanitary Landfill” (CJJ17-2004) (Ministry of Construction of the People’s Republic of China, 2004), in combination with engineering experience, the bulk density of waste buried in the landfill site was assumed to be 1.0 $t \cdot m^{-3}$ and the overall height of the landfill body, including the liner and cover system, was assumed to be 30 m. The system boundary in this study is shown in **Figure 1**, which consists of four stages: 1) Site preparation (SP), for example, excavation and backfilling of soil and stone; 2) Construction of the main parts of the landfill body (CM), including groundwater drainage, barrier layer, bottom liner, leachate and LFG collection, and top cover systems; 3) Construction of other facilities in the landfill site (COF), such as monitoring wells, onsite roads, and official buildings; and 4) Operation of the landfill (OL), for example, the placement and compaction of waste and intermediate soil covers. The treatment facilities for leachate and LFG were not considered in this paper, as they are closely associated with the pollution control features and treatment efficiencies of leachate and LFG. The C&O for leachate and LFG facilities will be analyzed together with the leachate and LFG associated emissions, in future works.

2.1 Life cycle inventory of landfill construction and operation

The environmental burdens associated with the C&O process were attributed wholly to the usage of materials and energy. However, the problems associated with waste degradation (e.g. the odour compounds released during waste placement) were not taken into account in this study. The LCI of C&O firstly quantified the materials and energy used, and then associated emissions from the manufacturing and consumption of these materials were aggregated to a total. The manufacturing of mineral materials (e.g. sand) is related to the excavation of the materials. In this study, a typical sanitary landfill body with a double liner system was investigated as the baseline. The original data on materials and energy consumption were obtained mainly from China's national industrial standards and design reports. Emission figures for the manufacturing and consumption of materials and energy were obtained from existing LCI database (Ecoinvent, 2010).

2.1.1 Quantification of materials and energy

As shown in Figure 1, materials are used in three processes during landfill C&O (i.e. CM, COF and OL), while energy is used for all the on-site processes as well as transportation of materials. In accordance with the usage places, the consumption amounts of materials and energy are classified into five types with their specified calculation methods.

1) Materials used for the construction of the main parts of the landfill body (CM) include sand, clay, gravel, geosynthetic clay liners (GCL), geomembranes, geonets and geotextiles used for groundwater drainage, barrier layer, bottom liner, leachate and LFG collection, and top cover systems. The vertical profile of the CM material utilization is shown in **Table 1** which is in accordance with the technical standards issued by Ministry of Construction of the People's Republic of China (2004, 2007a, b). The consumptions of mineral materials (i.e. sand, clay and gravel), except for those used in LFC and leachate collection system, were calculated by their typical

thicknesses of individual layer using **Equation 1**.

$$M_i = \sum_j (h_{ij} \times A \times \rho_i) \quad (1)$$

where M_i represents the consumption amount of mineral material i used in the construction of the landfill body, (kg·t-waste^{-1}); h_{ij} represents the thickness of material i used in the j^{th} layer (m) (**Table 1**); A, the projected area for one tonne of disposed waste in the landfill, (m^2); and ρ_i represents the density of material i (kg·m^{-3}) (**Table 2**).The consumption amounts of GCL, geomembrane, geotextiles and geonets, except for those used for LFG and leachate collection systems, were calculated based on their quality requirements by **Equation 2**.

$$M_i = n \times A \times \rho'_i \quad (2)$$

where n is the numbers of layers for material i, which could be GCL, geomembrane, geotextiles, or geonets; ρ'_i is the quality of material i, representing the weight per square meter (kg·m^{-2}) (**Table 2**).

With regards to LFG and leachate collection systems, the material consumption amounts could be calculated by **Equation 3**.

$$M_i = L \times \rho''_i \quad (3)$$

where, ρ''_i represents the weight of material i used for per meter of collection system (kg·m^{-1}), which could be calculated by the material density (**Table 2**) and collection system diameters (**Table 1**). The length of LFG collection wells corresponding to one tonne of landfilled waste were calculated according to the distance demands by **Equation 4**. In case of the leachate collection system, a modified Equation is used (**Equation 5**).

$$L = \frac{H}{D^2} \times A \quad (4)$$

$$L = \frac{A}{D} \quad (5)$$

where, L represents the length of collection systems for per tonne of waste (m·t-waste^{-1}); H is the height of LFG collection wells in the landfill body (m), which is considered the same as the landfill height; D is the distance requirement for collection pipes (m).

Table 1 is here

Table 2 is here

Through personal communication with design engineers working for a landfill design company (Fu, 2012), combined with searching the existing literature (Cong, 2012), seven design reports for landfill sites located at Jimo, Hexian, Songyuan, Shaoyang, Yulin, Jiuquan and Leshan were collected. These landfills have daily receiving capacities of 150−300 tonnes and a designed height of 10 to 30 m. By comparison, material consumptions during the CM of the typical landfill calculated in this paper were within the ranges found in the design reports (**Table 3**), which demonstrates that the generalized calculation method above is reliable. It has to be noted that the sand amounts obtained from the design reports are the ones purchased at specific landfill sites rather than the actual used values (including also the sands obtained from site preparation which are already at the sites), which induced significantly lower values compared to those estimated by this study.

Table 3 is here

2) Materials used for the construction of other facilities in the landfill site (COF) represent concrete used for roads, storm drainage and storage systems, monitoring wells, asphalt used for the road, gravel or stone used as hard core for the road, embankment and flood control channels, and steel used for fencing and drainage pipes. The average consumption amounts summarized from the aforementioned seven design reports were 3.10 kg of concrete (with the range of 0.7−6.8 kg, n=7), 0.930 kg of asphalt (n=1), 6.79 kg of gravel (with the range of 2.5−13 kg, n=7) and 0.051 kg of steel (with the range of 0.012−0.15 kg, n=4) for every one tonne of waste disposed.

3) Materials used for operation of the landfill (OL) include sand and clay used for daily cover and intermediate cover, respectively, as well as water used for truck washing. The diesel required for OL is calculated in the next paragraph. The consumption of sand and clay can be calculated by **Equation 1** based on the thicknesses of cover layers (**Table 1**). Water usage for every one tonne of waste was reported at 47 L (Wei et al., 2009).

4) Energy used for on-site landfill C&O means diesel and electricity. The consumption of diesel can be calculated by **Equation 6**, and the original values for calculations are displayed in **Table 4**. The machine types considered in this paper are in accordance with practical experience of landfill engineers in China, whilst diesel consumption for each machine refers to existing literature in developed countries (Caterpillar Inc., 2009; Ecoinvent, 2005; Stripple, 2001), as the machine manufacturers are international. The amounts of materials handled by each machine were calculated in the three subsections above. Electricity consumption at a practical landfill site located in Suzhou was reported as 0.173 kWh·t-waste^{-1} (Wei et al., 2009).

$$M_{Dieselonsite} = \sum_j (CF_j \times \sum_i M_{ij}) \tag{6}$$

where $M_{Dieselonsite}$ represents the consumption amounts of diesel used for on-site landfill C&O (kg·t-waste^{-1}); CF_j is the diesel consumption factor to handle per cubic meters of materials by machine j ($kg \cdot m^{-3}$); and M_{ij} is the amount of material i handled by machine j corresponding to landfilling of one tonne of waste, ($m^3 \cdot$t-waste^{-1}).

Table 4 is here

5) Fuels used for the transportation of materials external to the site, depending on the quantities of materials and travel distances. The quantities of materials required for transportation from offsite locations were calculated in the previous subsections. However, one assumption regarding soil usage has to be mentioned here. Based on the aforementioned landfill design reports, the average quantities of soils for excavation and backfilling during site preparation (SP) were 372 and 136 kg·t-waste^{-1}, respectively. It was assumed that the remaining soils after SP could provide the sandy soils used for CM, which means that the manufacturing (or excavation) and transportation of the remaining soils were not considered in this paper. In the case of transport distances, the return distances between the places of supply for specific individual materials and the place of consumption (or the landfill site in this paper) were taken into account and assumed to be 30 km for mineral materials (i.e. gravel, clay, and sand), 50 km for plastics (i.e. HDPE geomembranes, HDPE pipes, geonets, and geotextiles) and GCL, and 100 km for other materials (i.e. concrete, asphalt, and diesel). It was hypothesized that 5−30 t-lorries were used for transportation, with diesel consumption amounting to 0.008−0.016 $kg \cdot t^{-1} \cdot km^{-1}$ (Ecoinvent, 2010). The average value of diesel consumption, at 0.012 $kg \cdot t^{-1} \cdot km^{-1}$, was used for computation.

2.1.2 Combination of LCI data

The LCI data for C&O were calculated by **Equation 7**.

$$LCI_{C\&O} = \sum_i LCI_i \times M_i \quad (7)$$

where $LCI_{C\&O}$, represents the LCI data during C&O, namely a row vector of environmental emission quantities [Q_1, Q_2,…]; LCI_i is the LCI data for the manufacturing and consumption of materials or energy *i*, which were obtained from the Ecoinvent database (Ecoinvent, 2010), see **Table 2** for details.

According to the data quality indicators suggested by Weidema and Wesnaes (1996), the LCI data for materials and energy used in this paper (**Table 2**) are of good quality in terms of reliability and completeness. Nevertheless, their relevance to this study is not good because most of the processes are based on European data, due to their availability. However, this does not influence the results critically because the manufacturing technologies for many goods, especially plastics, are similar all over the world.

2.2 Life cycle impact assessment of landfill construction and operation

The life cycle impact assessment (LCIA) is the evaluation of potential environmental impacts associated with emissions identified during the LCI. Generally, LCIA comprises three main elements, namely characterization, normalization, and weighting. In this study, characterization, which is considered mandatory by ISO 14044 (International Standardization Organization, 2006), and normalization were conducted by means of EASETECH (Clavreul et al., 2013), while weighting was not performed as it depended on government policies. EASETECH, the new update to EASEWASTE (Kirkeby et al., 2007; Kirkeby et al., 2006) developed by the Technical University of Denmark, is a professional tool used for life cycle assessment in the fields of solid waste treatment and energy production.

The LCIA was based mainly on the Environmental Development of Industrial Products (EDIP) 2003 method (Hauschild and Potting, 2004). The impact categories considered included five non-toxic categories (i.e. global warming (GW), stratospheric ozone depletion (SOD), acidification (AC), nutrient enrichment (NE), and photochemical ozone formation (POF)) and five toxic categories (i.e. human toxicity via air (HTa), via water (HTw) and via soil (HTs), eco-toxicity in water-chronic (ETwc), and eco-toxicity in soil (ETs)). To compare the environmental burdens among these impact categories, all the characterized impact potentials were divided by their individual normalization references (**Table 5**) to achieve a unified unit, milli Person Equivalent (mPE)·t-waste^{-1} (Stranddorf, et al. 2005). The normalized unit "mPE·t-waste^{-1}" means the environmental burdens caused by one tonne of waste equal to how much environmental burdens caused by one milli Person. The normalization references in EU-15, instead of those found in China or elsewhere worldwide, were utilized in this study in order to be able to compare the results to other studies using the same normalization references. Normalization reference data from 1994 were used for the same reason. It should be noted that a great deal of uncertainty still existed in some impact categories, especially in the toxic categories (Moberg et al., 2005).

Table 5 is here

3. Results and Discussion

3.1 Materials and energy used for the construction and operation of a landfill site

The consumption of materials and energy during C&O is presented in **Table 6**, where the 12 kinds of materials and energy used are allocated into the four stages mentioned above, namely SP, CM, COF, and OL. From the perspective of weight, mineral materials (i.e. sand, clay, and gravel), which were predominantly consumed, were for the most part used for the construction of liner and cover systems. In the case of energy, diesel was used mainly for the operation of onsite equipment, accounting for 88% of the overall consumption of diesel, where 77% for OL, 8% for SP and 3% for CM. During offsite transportation, diesel was used primarily for carrying mineral materials. Therefore, the amounts of mineral materials and diesel used were crucial parameters in evaluating the environmental impacts of landfill C&O.

By comparing the values in the present study with those reported in studies concentrating on developed countries (Brogaard et al., 2013; Cherubini et al., 2009; Ecobalance Inc., 1999; Menard et al., 2004) (**Table 6**), it was found that the quantities of concrete and asphalt used in Chinese landfills were more than three times higher than those in developed countries. Concrete is mainly used to construct the monitor wells, leachate tanks, roads and buildings in a landfill site. However, in the study done by Ecobalance Inc. (1999), building constructions were not taken into account. Brogaard, et al. (2013) did not count the concrete consumption for building construction. In the case of asphalt, it is often used for road construction. Ecobalance Inc. (1999) summarized the values from 6 landfill sites with the reliable range from 0.06 to 0.25 kg·t-waste^{-1}. The Chinese data in this study was obtained from one specific design report, which may induce high uncertainty. Diesel consumption in this study was comparable to the values reported by Ecobalance Inc. (1999), which seem higher than those in Menard et al. (2004) and Brogaard et al. (2013) because the latter two studies did not take into account the landfilling operation. Although Menard et al. (2004) stated that daily operations fell within its system boundary, it only included the installation of horizontal trench and vertical gas collection systems, which are considered construction activities in this study. Hence, the research scope has to be identified clearly when researchers plan to obtain from the literature data on the consumption of materials. In the case of this study, misapplication of the data would underestimate diesel consumption by 60 to 80%.

Table 6 is here

3.2 Contributions to individual impact categories

The contributions of the four stages as well as the 12 kinds of materials and energy used in the overall C&O processes are presented in **Figure 2**. It was found that the impact potentials of C&O could be attributed primarily to OL, which accounted for 46 to 70% and 40 to 60% of the non-toxic and toxic impact categories, respectively. It is clear that the consumption of diesel for handling waste and daily and intermediate soil cover is the predominant factor. The contributions of CM to the overall impact potentials ranged from 18 to 38%, where the contributions in toxic impact categories were relatively higher than those in non-toxic ones, due to the usage of mineral materials and GCL. The impact potentials caused by the COF were lower than those as a result of CM except for the impact category GW, where the contribution of COF to the overall potential was 28% owing to the usage of concrete, asphalt, and steel. Moreover, the proportions of impact potentials due to SP to overall potentials were less than 6%. This could change if there was no temporary on-site storage space for excavated soil, which would mean greater use of diesel for soil transportation in the SP stage.

Figure 2 is here

3.3 Normalized impact potentials

Figure 3 shows the normalized impact potentials for landfill C&O compared with 'total landfill processes', a term which herein represents three (out of nine) landfilling scenarios with different leachate and LFG treatment technologies, obtained from a study by Damgaard et al. (2011). In the case of landfill C&O, HTs was the predominant impact category, followed by ETwc, with impact potentials of 8.7 and 7.1 mPE·t-waste^{-1}, respectively. The impact potentials of GW, AC, NE, and HTa were between 1 and 2 mPE·t-waste^{-1}, and those of SOD, POF, and ETs were less than 0.2 mPE·t-waste^{-1}. In terms of total landfill processes, energy recovery from LFG and carbon sequestration reduced environmental impacts effectively, sometimes even with negative values. When comparing the absolute ratios of landfill C&O impact potentials to total landfilling technologies, the ratios were between 0.2 and 1.0 for AC, NE, HTw, HTs, ETwc, and ETs. The ratios were as high as 15 to 60 for HTa. This highlights clearly that the C&O process contributes significantly to the environmental impacts of landfilling technology.

Figure 3 is here

3.4 Scenario uncertainty

The "Construction Standard for Municipal Solid Waste Sanitary Landfill (CJJ124-2009)" (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2009) suggests that landfill managers utilize suitable technologies and materials according to the practical economic and geographic conditions set out under current national technical codes (Ministry of Construction of the People's Republic of China, 2004, 2007a, b). To test the influences of different technical and material usages on the results of LCIA, six alternative approaches to C&O were investigated based on the approach discussed above (named "Baseline"). *A1* represents a scenario where geomembranes are used, instead of soils, as the daily cover and intermediate cover with the layer label of "L11" and "L12" (based on label numbering in Table 1 - all further labels refer to the same table). As the cover geomembranes can be reused several times, the consumption of geomembranes is considered insignificant and is not taken into account in this scenario. *A2* represents a scenario where geonets are used as drainage layers instead of the gravel used in the

Baseline scenario. The upper gravel layer in the top cover system (L2), the two gravel layers in leachate collection system (L15 and L18) and one layer in the groundwater drainage system (L22) are thus replaced with geonets. *A3* represents a scenario in which single clay layers are used below the geomembranes as the protective layers. This scenario may occur in places with abundant soil resources but with the problem of fund shortage. The combinations of GCL and clay layers in top cover system (L5 and L6) and double liner system (L25 and L26) in the Baseline scenario are replaced with 0.25-m and 0.75-m clay layers, respectively. *A4* is a scenario in which single natural component liners are used as the bottom liner system, which may be used in places with extremely low groundwater levels. The composite liners in the top cover system (from L3 to L6) and bottom liner system (from L19 to L26) in the Baseline scenario are replaced by 0.3-m and 2-m clay layers, respectively. *A5* is a scenario using a single composite liner system. The layers from L21 to L24 in the Baseline scenario are omitted. *A6* represents a scenario without LFG collection system (from L8 to L10 in the Baseline scenario), which could be considered in small landfill sites.

A LCA was conducted for the six alternative approaches, and the differences between each one and the Baseline were calculated and shown in **Figure 4**. Most of the alternative approaches would decrease the environmental impact potentials of C&O; however, *A3* and *A4*, both of which use more clay than the other options, increased impact potentials in several categories—*A3* on NE, POF, and ETwc, and *A4* on SOD, AC, NE, HTw, and ETwc. The replacement of mineral materials with synthetic materials (*A1* and *A2*) was the most effective method for mitigating environmental burdens, with a reduction efficiency of 2 to 28%. The saved consumptions of mineral materials when using synthetic materials are important on burden reduction from both material manufacturing and transportation (i.e. diesel consumption). From **Figure 4** it is clear that *A1* is more effective than *A2*, while the mitigation efficiencies are more significant on toxic impacts than on non-toxic ones. Comparatively, switching to a single composite liner system (*A5*) would only decrease impact potentials by less than 5%, and the absence of LFG collection system (*A6*) would make no difference from Baseline. On the other hand, reducing the functional systems (*A5* and *A6*) would induce the higher probability of leachate and LFG release than using alternative synthetic materials (*A1* and *A2*), which, according to Damgaard et al. (2011), is critical for the performance of integrated landfilling technology. If landfill managers plan to minimize the environmental impacts of C&O, they could use synthetic materials to replace mineral materials, but one should always be cautious about reducing a functional system.

Figure 4 is here

It should be kept in mind that this study does not consider the economic costs of materials and energy. If economic costs were a decision parameter, this could change the recommendations from the uncertainty assessment, especially if the additional costs of synthetic materials were higher than the savings made by using conventional materials.

4. Conclusions

The environmental impacts of a typical sanitary landfill site's C&O process were assessed through the LCA of one tonne of disposed waste. Several conclusions were drawn from this study.

1) The consumption of materials and energy during landfill C&O in China was comparable to that recorded in developed countries.

2) The non-toxic environmental impacts induced by landfill C&O were due mainly to diesel consumption for daily operation, followed by mineral materials used for constructing the main parts of the landfill body, whereas toxic environmental impacts were dominated by the manufacturing of mineral materials.

3) When compared with the environmental burdens of integrated landfilling technologies, the contribution of landfill C&O should not be ignored, especially for toxic impacts.

4) Using synthetic materials to replace daily and intermediate soil covers and gravel drainage systems could effectively mitigate environmental burdens resulting from landfill C&O even further. However, withdrawing a liner layer or LFG collection system makes no significant difference. Thus, one should always be cautious to reduce a functional system.

The environmental impacts induced by landfill C&O are important compared with integrated landfilling technology and should not be omitted in future LCA studies. The LCI methods presented in this paper could be utilized by readers according to the actual usage of materials in specific landfills. The consumption amounts of materials and energy obtained in this study could be used directly as the LCI data by researchers in other developing countries with similar conditions. To avoid data misapplication, the system boundary has to be declared when people refer to the data from existing literature.

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List of Tables

Table 1 Vertical profile of the materials used in a typical landfill body. Assumed thickness based on technical code requirement, if not further specified.

Function	Labels	Materials	Thickness (m)	Quality requirements [a]
Top cover system	L1	Sand	0.6	Thickness > 60 cm
	L2	Gravel	0.3	Thickness >30 cm
	L3	Nonwoven geotextile	N.A.	Qualification > 600 $g \cdot m^{-2}$
	L4	Geomembrane	N.A.	Thickness > 1 mm
	L5	GCL[b]	N.A.	Thickness > 5 mm
	L6	Clay	0.2	Thickness > 20 cm [c]
	L7	Gravel	0.3	Thickness > 30 cm
LFG collection system	L8	Geonet	N.A.	Wrapping up the filling gravels
	L9	Gravel	N.A.	Filling around the LFG extraction pipes to form the collection well with the diameter of 1.2m[c]
	L10	Perforated HDPE pipe	N.A.	Diameter > 250 mm[c], distance between two LFG collection well < 50 m
Intermediate cover	L11	Clay	0.9	Set one layer for every 5 m height. Thickness of each layer > 30cm
Daily cover	L12	Sand	1.8	Thickness of each layer: 20–25 cm
Waste	L13	Waste	24	Thickness of each layer: 2–4 m
Leachate collection system	L14	Nonwoven geotextile	N.A.	Qualification > 600 $g \cdot m^{-2}$
	L15	Gravel	0.3	Thickness > 30 cm
	L16	Woven geotextile	N.A.	Covering HDPE pipes, qualification > 200 $g \cdot m^{-2}$

	L17	Perforated HDPE pipe	N.A.	Diameter of main pipe > 250 mm, with the distance < 50 m [c]; Diameter of branch pipe > 200 mm, with the distance < 10 m [c]
	L18	Coarse sand	0.15	Thickness > 15 cm [c]
Double liner system	L19	Nonwoven geotextile	N.A.	Qualification > 600 $g\cdot m^{-2}$
	L20	Geomembrane	N.A.	Thickness > 1.5 mm
	L21	Nonwoven geotextile	N.A.	Qualification >600 $g\cdot m^{-2}$
	L22	Gravel	0.3	Thickness > 30 cm
	L23	Nonwoven geotextile	N.A.	Qualification >600 $g\cdot m^{-2}$
	L24	Geomembrane	N.A.	Thickness > 1.5 mm
	L25	GCL[b]	N.A.	Thickness > 5 mm
	L26	Clay	0.5	Thickness > 50 cm [c]
Barrier layer	L27	Sand	1.0	Thickness > 1 m
Groundwater drainage system	L28	Gravel	0.3	Thickness > 30 cm

HDPE, high-density polyethylene. GCL, geosynthetic clay liner. LFG, landfill gas. N.A. means that data are not available.

[a] Most of the requirements refer to China's national standards for landfill construction (Ministry of Construction of the People's Republic of China, 2004, 2007a, b) if there's no specific statements.

[b] In the "Technical Code for Liner System of Municipal Solid Waste Sanitary Landfill (CJJ113-2007)", it is suggested to use the combination of GCL and clay to substitute the single usage of compacted clay as the protection layers underneath the geomembranes, which could both increase landfill capacity and reduce the cost of liner systems. Recently, the usage of GCL is more and more popular in China. Therefore, to reflect the developing trend of landfill construction approaches, the combination of GCL and clay in the liner systems were calculated in this study as the example.

[c] Those values are obtained by personal communication with the engineers (Fu, 2012).

Table 2 Densities or qualities of the materials and energy associated with the construction and operation process of a landfill site, as well as the life cycle inventory sources

Materials	Density/Quality	Unit	Data source of LCI (Ecoinvent, 2010)
Asphalt	1200	$kg \cdot m^{-3}$	Mastic asphalt, at plant, CH
Concrete	2374	$kg \cdot m^{-3}$	Cement, unspecified, at plant, CH
Clay	1842	$kg \cdot m^{-3}$	Clay, at mine, CH
Diesel	0.84	$kg \cdot L^{-1}$	Diesel combustion in industrial equipment, RER
Electricity			Electricity, production mix, CN
HDPE	955	$kg \cdot m^{-3}$	
HDPE geomembrane (1 mm thick)	0.955	$kg \cdot m^{-2}$	Polyethylene, HDPE, granulate, at plant, RER
HDPE geomembrane (1.5 mm thick)	1.432	$kg \cdot m^{-2}$	
Geonet	0.55	$kg \cdot m^{-2}$	Polyethylene, HDPE, granulate, at plant, RER
GCL	4.8	$kg \cdot m^{-2}$	Bentonite, at processing, DE
Gravel	2200	$kg \cdot m^{-3}$	Gravel, unspecified, at mine, CH
Nonwoven geotextile	0.6	$kg \cdot m^{-2}$	Polypropylene, granulate, at plant, RER
Sand	1562	$kg \cdot m^{-3}$	Sand at mine, CH
Steel	7880	$kg \cdot m^{-3}$	Chromium steel product manufacturing, average metal working, RER
Woven geotextile	0.2	$kg \cdot m^{-2}$	Polypropylene, granulate, at plant, RER

HDPE, high-density polyethylene. GCL, geosynthetic clay liner. CH, CN, DE and RER are the geographical codes of Switzerland, China, Germany and Europe, respectively.

Table 3 Material consumption during construction of the main parts in a landfill site.

Unit: kg·t-waste^{-1}	This study [b]	Landfill design reports [c]	
		Average	Range
HDPE [a]	0.204	0.218	0.127−0.368
Geotextile	0.141	0.068	0.040−0.104
GCL	0.400	0.334	0.037−0.595
Gravel	138	77	35.9−156
Sand	114	4.97	0.07−12.9 [d]
Clay	53.7	48.6	48.6 [e]

HDPE, high-density polyethylene. GCL, geosynthetic clay liner.

[a] Including HDPE geomembranes, HDPE pipes and geonets.

[b] As the materials used for final cover were not given in the seven landfill design reports, those data are not shown in this table considering the comparable benefits.

[c] The seven landfill sites were located in Jimo (Shandong), Hexian (Anhui), Songyuan (Jilin), Shaoyang (Hunan), Yulin (Shaanxi) and Leshan (Sichuan) with the daily landfill capacity of 150−300 t and the designed height of 10−30 m.

[d] The amount of sand were those need to be purchased in specific landfill sites rather than the actual usage.

[e] The amount of clay was mentioned only in the design report of the landfill sites located in Jimo (Shandong).

Table 4 Diesel consumption during the construction and operation process of a landfill site.

	Usage	Diesel ($kg \cdot m^{-3}$)	Handled materials ($m^3 \cdot t\text{-}waste^{-1}$)
SP			
Excavator	To excavate soils	0.130[b]	0.238[f]
Front loader	To move soils on site	0.102[c]	0.238[f]
Truck	To transport soils on site	0.193[c]	0.238[f]
CM			
Bulldozer	To handle the mineral materials [a]	0.232[d]	0.164[g]
OL			
Bulldozer	To handle the daily and intermediate soil covers	0.232[d]	0.125[h]
	Usage	Diesel ($kg \cdot t\text{-}waste^{-1}$)	
OL			
Excavator	To handle waste	0.218[e]	
Bulldozer	To handle waste	0.540[e]	
Compactor	To compact waste	0.185[e]	

SP, site preparation. CM, construction of the main parts of the landfill body. OL, operation of the landfill. HDPE, high-density polyethylene. GCL, geosynthetic clay liner.

[a] The on-site transportation of imported mineral materials was not considered in this study.

[b] Ecoinvent (2005).

[c] Stripple (2001).

[d] Caterpillar Inc. (2009).

[e] Gong et al. (2008).

[f] Volume of sand soils excavated during site preparation.

[g] Volume of mineral materials used for landfill construction.

[h] The sum of the volume of sand and clay used as daily and intermediate covers.

Table 5 Impact categories used in the life cycle impact assessment.

Impact categories	Acronyms	Physical basis	Normalization references EU-15 Stranddorf et al. (2005)	Units	Reference year
Non-toxic impacts					
Global Warming (100 yrs)	GW	Global	8,700	kg CO_2-eq·person^{-1}·yr^{-1}	1994
Stratospheric Ozone Depletion	SOD	Global	0.103	kg CFC-11-eq·person^{-1}·yr^{-1}	1994
Acidification	AC	Regional	74	kg SO_2-eq·person^{-1}·yr^{-1}	1994
Nutrient Enrichment	NE	Regional	119	kg NO_3-eq·person^{-1}·yr^{-1}	1994
Photochemical Ozone Formation	POF	Regional	25	kg C_2H_4-eq·person^{-1}·yr^{-1}	1994
Toxic impacts					
Human Toxicity via air	HTa	Regional	2.09×10^9	m^3 air·person^{-1}·yr^{-1}	1994
Human Toxicity via water	HTw	Regional	1.79×10^5	m^3 water·person^{-1}·yr^{-1}	1994
Human Toxicity via soil	HTs	Regional	1.57×10^2	m^3 soil·person^{-1}·yr^{-1}	1994
Eco-Toxicity in water-chronic	ETwc	Regional	3.52×10^5	m^3 water·person^{-1}·yr^{-1}	1994
Eco-Toxicity in soil	ETs	Regional	9.64×10^5	m^3 soil·person^{-1}·yr^{-1}	1994

Table 6 Consumption of materials and energy during the construction and operation of a landfill site and comparison with published data.

Unit: kg·t-waste^{-1}	This study					Literature			
	SP	CM	COF	OL	C&O (Total)	Ecobalance Inc. (1999)	Cherubini et al. (2009)	Menard et al. (2004)	Brogaard et al. (2013)
Materials									
HDPE	0	0.211 [a]	0	0	0.204 [a]	0.090 [b]	0.186	1.40 [b]	0.241 [b]
Geotextile	0	0.145	0	0	0.141	0.017	N.A.	0.048	N.A.
GCL	0	0.413	0	0	0.400	N.A.	N.A.	0.455 [c]	N.A.
Sand	−372+136 [d]	114 [e]	0	117	231	257	N.A.	130 [f]	169 [f]
Clay	0	53.7	0	82.3	146	66	44.7	N.A.	82.3
Gravel	0	138	6.79	0	145	N.A	N.A.	105	180
Concrete	0	0	3.10	0	3.10	0.090	N.A.	N.A.	1.01
Steel	0	0	0.051	0	0.051	0.047	0.0004	N.A.	0.141 [g]
Water [h]	0	0	0	47.0	47.0	N.A	N.A.	N.A.	N.A.
Asphalt	0	0	0.930	0	0.930	0.085	N.A.	N.A.	0.12
Energy									
Diesel (on-site)	0.101	0.038	0	0.972	1.11	1.17	0.624	0.522	0.105
Diesel (transportation)	0	0.069	0.007	0.075	0.152	0.085		N.A.	0.096
Electricity [i]	0	0	0	0.173	0.173	N.A.	0.963	N.A.	N.A.

SP, site preparation. CM, construction of the main parts. COF, construction of other facilities. OL, the operation stage of the landfill. C&O, the construction and operation process of a landfill site. HDPE, high-density polyethylene. GCL, geosynthetic clay liner. N.A. means data are not available.

[a] Including HDPE geomembranes, HDPE pipes, geonets.

[b] The sum of HDPE and PVC.

[c] The sum of GCL and bentonite.

[d] The amounts of excavated and backfilled sand soil were 372 and 136 kg·t-waste^{-1}, respectively.

[e] Sands used in CM is considered to be provided by SP rather than from off site, so the manufacturing and transportation of those sands are not taken into account in this study.

[f] The sum of sand and soil.

[g] The sum of steel, stainless steel, copper, cable (most weight is attributed to copper) and aluminum.

[h] Unit: L·t-waste^{-1}.

[i] Unit: kWh·t-waste^{-1}.

Figure captions

Figure 1 System boundary for the construction and operation process of a landfill site.

Figure 2 Contributions of the four stages (a) and 12 materials and energy (b) to individual environmental impact categories during the construction and operation of a landfill site. (SP, site preparation; CM, construction of the main parts of the landfill body; COF, construction of other facilities in the landfill site; OL, operation of the landfill; HDPE, high-density polyethylene; GCL, geosynthetic clay liner)

Figure 3 Comparison of normalized impact potentials between landfill construction and operation (C&O, grey column) and the total landfilling technologies (the scatters represent three scenarios in Damgaard et al. (2011), all of which have leachate collection and treatment. In the case of landfill gas, L2G2 does not collect landfill gas; L2G3B collects landfill gas and flares it; L2G4EC utilizes collected landfill gas to produce electricity, substituting electricity generated from coal combustion).

Figure 4 Difference in normalized impact potentials between Baseline and the six alternative approaches for the construction and operation of a landfill site.

Figures

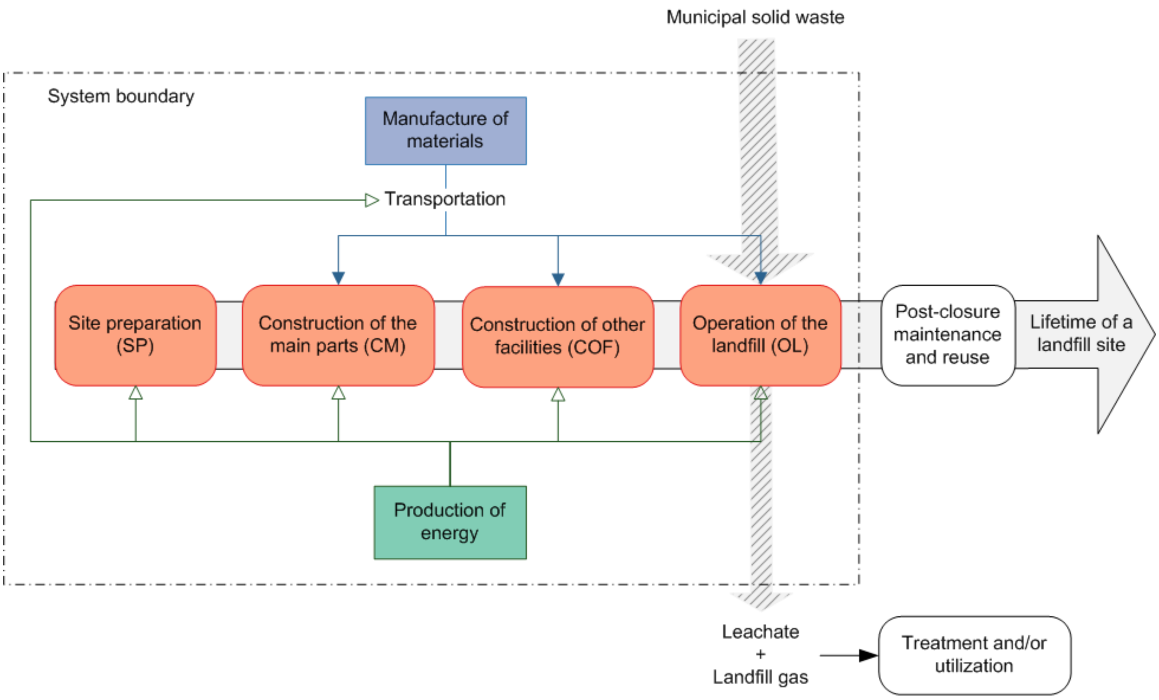

Figure 1 System boundary for the construction and operation process of a landfill site.

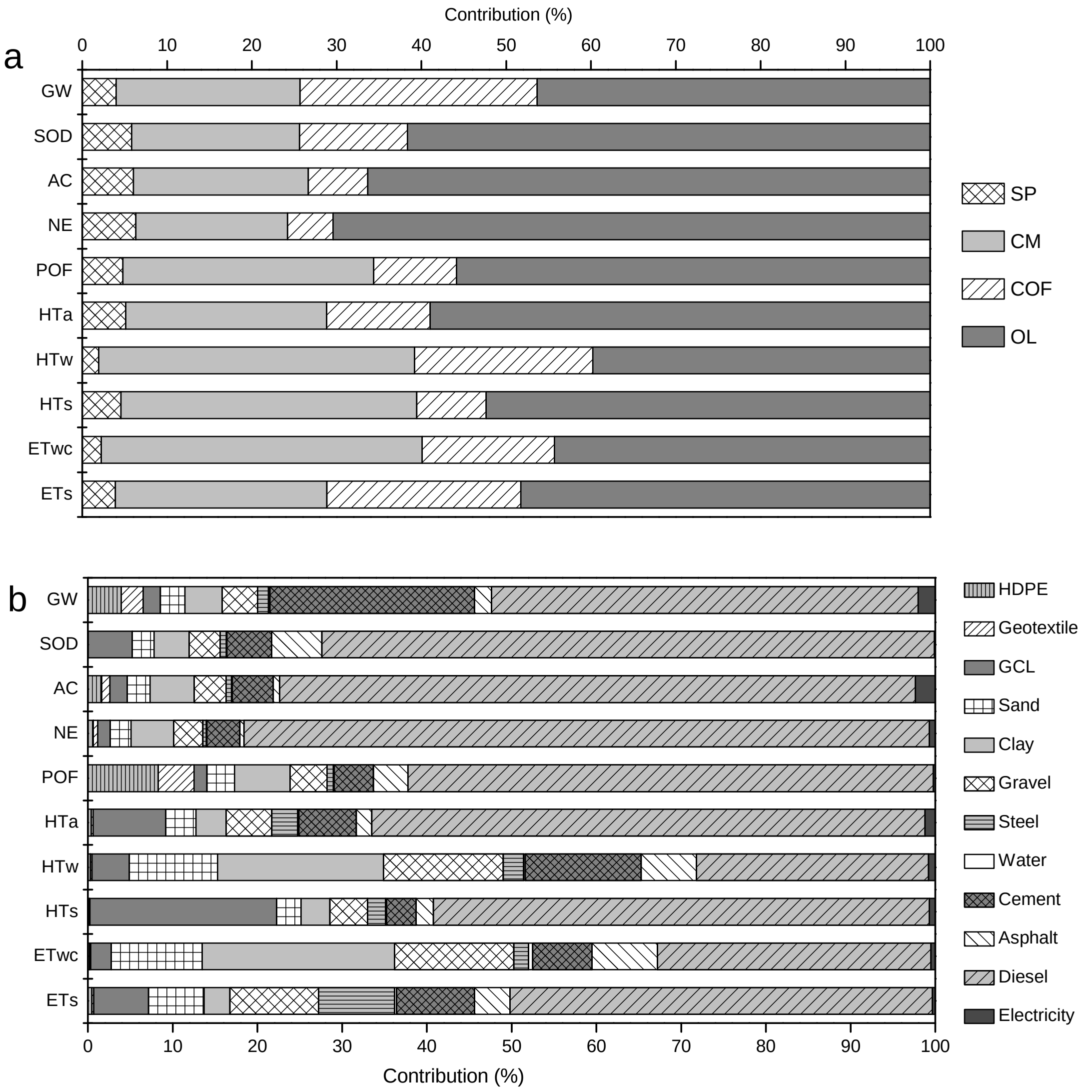

Figure 2 Contributions of the four stages (a) and 12 materials and energy (b) to individual environmental impact categories during the construction and operation of a landfill site. (SP, site preparation; CM, construction of the main parts of the landfill body; COF, construction of other facilities in the landfill site; OL, operation of the landfill; HDPE, high-density polyethylene; GCL, geosynthetic clay liner)

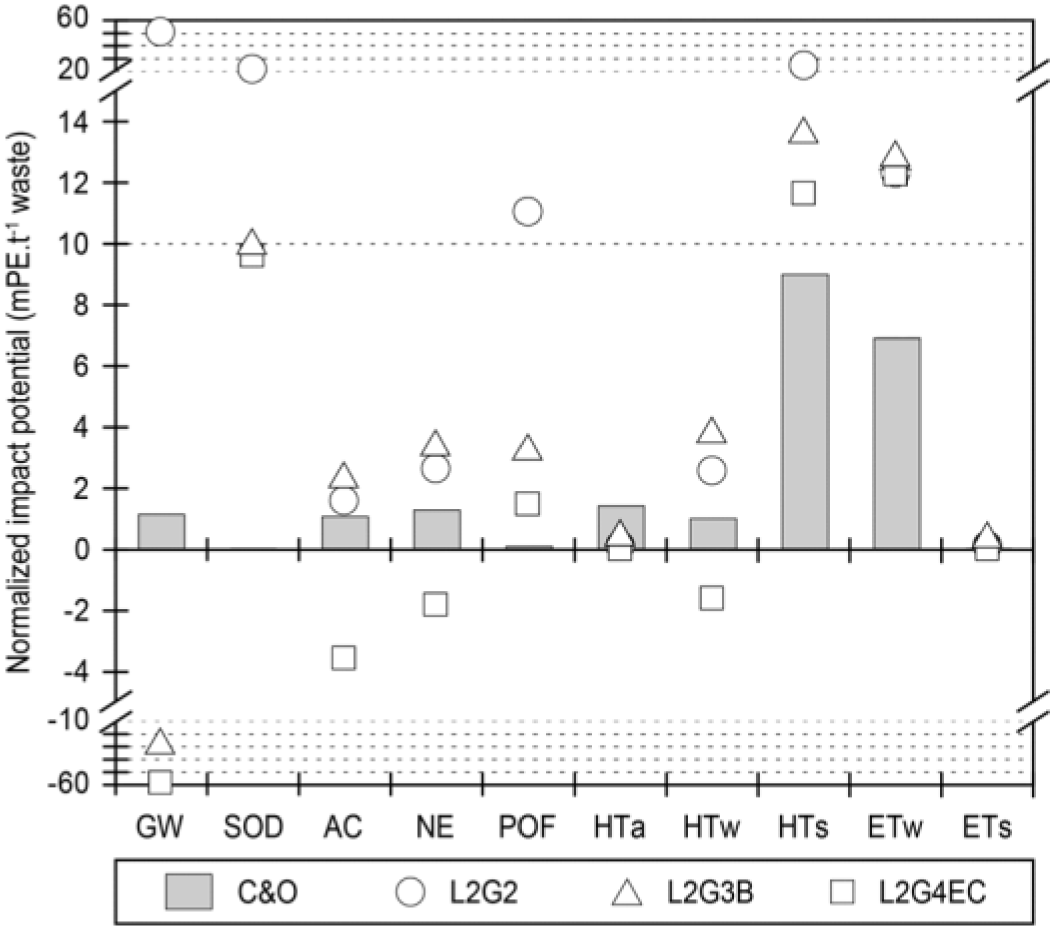

Figure 3 Comparison of normalized impact potentials between landfill construction and operation (C&O, grey column) and the total landfilling technologies (the scatters represent three scenarios in Damgaard et al. (2011), all of which have leachate collection and treatment. In the case of landfill gas, L2G2 does not collect landfill gas; L2G3B collects landfill gas and flares it; L2G4EC utilizes collected landfill gas to produce electricity, substituting electricity generated from coal combustion).

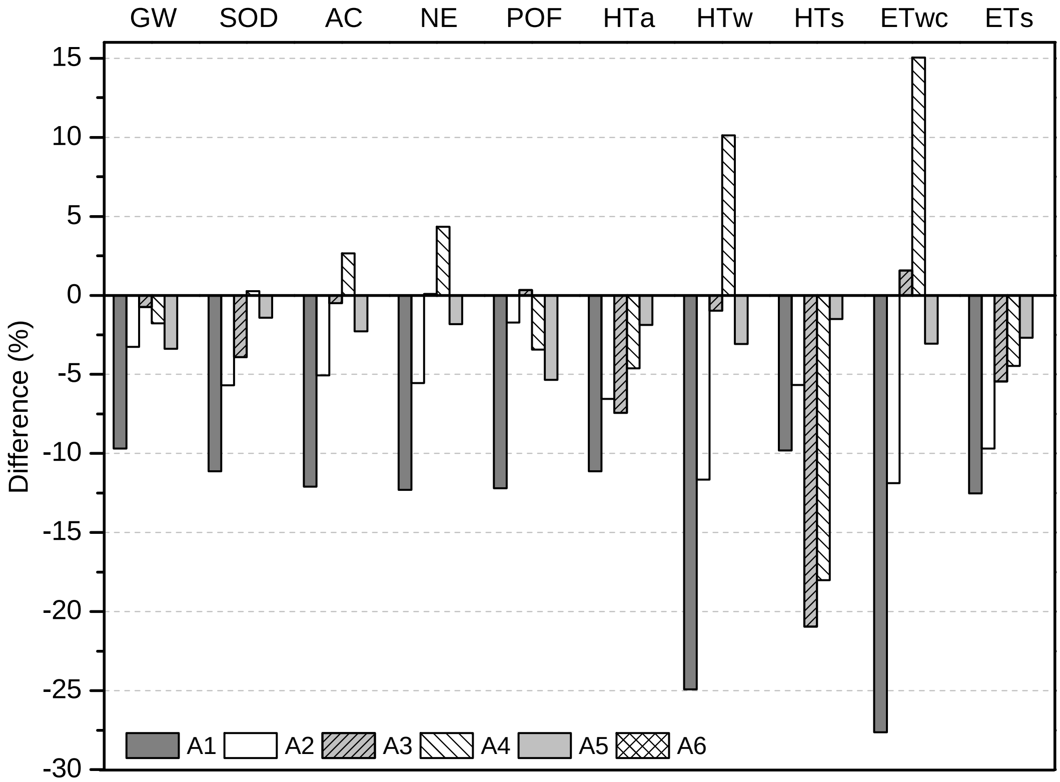

Figure 4 Difference in normalized impact potentials between Baseline and the six alternative approaches for the construction and operation of a landfill site.