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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

2 **1. Introduction**

3 Nowadays, landfilling is still the most commonly used method for municipal
4 solid waste (MSW) treatment in many countries. Taking China as an example, 100
5 million tonnes of MSW were disposed of in landfills during 2011, which accounted
6 for 77% of the total amount of treatable waste (National Bureau of Statistics of China,
7 2012). Life cycle assessment (LCA) can be used to evaluate the environmental
8 impacts associated with all stages of a product/service's life cycle, and through this
9 assessment it provides useful insights into improving the whole process from an
10 environmental perspective. Therefore, the LCA of MSW landfilling is important in
11 supporting decision-making in integrated MSW management. The impacts of
12 generating and treating landfill gas (LFG) and leachate have been the primary
13 concerns of researchers as the major environmental issues with regards to MSW
14 landfilling (El-Fadel et al., 1997; Kirkeby et al., 2007; Niskanen et al., 2009).
15 Nevertheless, approaching landfill sites as products, their construction and operation
16 (C&O) consume certain amounts of materials and energy, and the manufacturing and
17 utilization of these materials could lead to environmental burdens. Frischknecht et al.
18 (2007) investigated the contributions of capital goods in the LCA of a large number of
19 product/service systems. It was argued that the lower the pollutant content of the
20 assessed waste, the higher the environmental burden contribution from capital goods.
21 Their study also demonstrated that the burden from capital goods was important for
22 landfilling, but not as significant for other waste treatment technologies such as waste
23 incineration, especially when considering climate change, acidification, and
24 eutrophication.

25 The majority of published works on the LCA of MSW landfilling employ an
26 energy consumption amount (e.g. as megajoules of energy or liters of diesel) to
27 represent the environmental impacts of the landfill C&O process (Damgaard et al.,
28 2011; Khoo et al., 2012; Manfredi et al., 2009). Although Manfredi et al. (2010) and

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

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

57 much as possible.

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

64 **2. Approach and Method**

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

83 **2.1 Life cycle inventory of landfill construction and operation**

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

96 2.1.1 Quantification of materials and energy

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

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

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

$$111 \quad M_i = \sum_j (h_{ij} \times A \times \rho_i) \quad (1)$$

112 where M_i represents the consumption amount of mineral material i used in the
113 construction of the landfill body, ($\text{kg}\cdot\text{t-waste}^{-1}$); h_{ij} represents the thickness of material
114 i used in the j^{th} layer (m) (**Table 1**); A , the projected area for one tonne of disposed
115 waste in the landfill, (m^2); and ρ_i represents the density of material i ($\text{kg}\cdot\text{m}^{-3}$) (**Table**
116 **2**). The consumption amounts of GCL, geomembrane, geotextiles and geonets, except
117 for those used for LFG and leachate collection systems, were calculated based on their
118 quality requirements by **Equation 2**.

$$119 \quad M_i = n \times A \times \rho'_i \quad (2)$$

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

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

$$125 \quad M_i = L \times \rho''_i \quad (3)$$

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

$$132 \quad L = \frac{H}{D^2} \times A \quad (4)$$

133
$$L = \frac{A}{D} \quad (5)$$

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

138

139 Table 1 is here

140 Table 2 is here

141

142 Through personal communication with design engineers working for a landfill
143 design company (Fu, 2012), combined with searching the existing literature (Cong,
144 2012), seven design reports for landfill sites located at Jimo, Hexian, Songyuan,
145 Shaoyang, Yulin, Jiuquan and Leshan were collected. These landfills have daily
146 receiving capacities of 150–300 tonnes and a designed height of 10 to 30 m. By
147 comparison, material consumptions during the CM of the typical landfill calculated in
148 this paper were within the ranges found in the design reports (**Table 3**), which
149 demonstrates that the generalized calculation method above is reliable. It has to be
150 noted that the sand amounts obtained from the design reports are the ones purchased
151 at specific landfill sites rather than the actual used values (including also the sands
152 obtained from site preparation which are already at the sites), which induced
153 significantly lower values compared to those estimated by this study.

154

155 Table 3 is here

156

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

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

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

$$180 \quad M_{Diesel\ on\ site} = \sum_j (CF_j \times \sum_i M_{ij}) \quad (6)$$

181 where $M_{Diesel\ on\ site}$ represents the consumption amounts of diesel used for on-site
 182 landfill C&O (kg·t-waste⁻¹); CF_j is the diesel consumption factor to handle per cubic

183 meters of materials by machine j ($\text{kg}\cdot\text{m}^{-3}$); and M_{ij} is the amount of material i handled
184 by machine j corresponding to landfilling of one tonne of waste, ($\text{m}^3\cdot\text{t}\cdot\text{waste}^{-1}$).

185

186 Table 4 is here

187

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

205 2.1.2 Combination of LCI data

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

207
$$LCI_{C\&O} = \sum_i LCI_i \times M_i \quad (7)$$

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

212 According to the data quality indicators suggested by Weidema and Wesnaes
213 (1996), the LCI data for materials and energy used in this paper (**Table 2**) are of good
214 quality in terms of reliability and completeness. Nevertheless, their relevance to this
215 study is not good because most of the processes are based on European data, due to
216 their availability. However, this does not influence the results critically because the
217 manufacturing technologies for many goods, especially plastics, are similar all over
218 the world.

219 **2.2 Life cycle impact assessment of landfill construction and operation**

220 The life cycle impact assessment (LCIA) is the evaluation of potential
221 environmental impacts associated with emissions identified during the LCI. Generally,
222 LCIA comprises three main elements, namely characterization, normalization, and
223 weighting. In this study, characterization, which is considered mandatory by ISO
224 14044 (International Standardization Organization, 2006), and normalization were
225 conducted by means of EASETECH (Clavreul et al., 2013), while weighting was not
226 performed as it depended on government policies. EASETECH, the new update to
227 EASEWASTE (Kirkeby et al., 2007; Kirkeby et al., 2006) developed by the Technical
228 University of Denmark, is a professional tool used for life cycle assessment in the
229 fields of solid waste treatment and energy production.

230 The LCIA was based mainly on the Environmental Development of Industrial
231 Products (EDIP) 2003 method (Hauschild and Potting, 2004). The impact categories
232 considered included five non-toxic categories (i.e. global warming (GW),
233 stratospheric ozone depletion (SOD), acidification (AC), nutrient enrichment (NE),
234 and photochemical ozone formation (POF)) and five toxic categories (i.e. human

235 toxicity via air (HTa), via water (HTw) and via soil (HTs), eco-toxicity in
236 water-chronic (ETwc), and eco-toxicity in soil (ETs)). To compare the environmental
237 burdens among these impact categories, all the characterized impact potentials were
238 divided by their individual normalization references (**Table 5**) to achieve a unified
239 unit, milli Person Equivalent (mPE)·t-waste⁻¹ (Stranddorf, et al. 2005). The
240 normalized unit “mPE·t-waste⁻¹” means the environmental burdens caused by one
241 tonne of waste equal to how much environmental burdens caused by one milli Person.
242 The normalization references in EU-15, instead of those found in China or elsewhere
243 worldwide, were utilized in this study in order to be able to compare the results to
244 other studies using the same normalization references. Normalization reference data
245 from 1994 were used for the same reason. It should be noted that a great deal of
246 uncertainty still existed in some impact categories, especially in the toxic categories
247 (Moberg et al., 2005).

248

249 Table 5 is here

250

251 **3. Results and Discussion**

252 **3.1 Materials and energy used for the construction and operation of a landfill site**

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

261 materials. Therefore, the amounts of mineral materials and diesel used were crucial
262 parameters in evaluating the environmental impacts of landfill C&O.

263 By comparing the values in the present study with those reported in studies
264 concentrating on developed countries (Brogaard et al., 2013; Cherubini et al., 2009;
265 Ecobalance Inc., 1999; Menard et al., 2004) (**Table 6**), it was found that the quantities
266 of concrete and asphalt used in Chinese landfills were more than three times higher
267 than those in developed countries. Concrete is mainly used to construct the monitor
268 wells, leachate tanks, roads and buildings in a landfill site. However, in the study done
269 by Ecobalance Inc. (1999), building constructions were not taken into account.
270 Brogaard, et al. (2013) did not count the concrete consumption for building
271 construction. In the case of asphalt, it is often used for road construction. Ecobalance
272 Inc. (1999) summarized the values from 6 landfill sites with the reliable range from
273 0.06 to 0.25 kg·t-waste⁻¹. The Chinese data in this study was obtained from one
274 specific design report, which may induce high uncertainty. Diesel consumption in this
275 study was comparable to the values reported by Ecobalance Inc. (1999), which seem
276 higher than those in Menard et al. (2004) and Brogaard et al. (2013) because the latter
277 two studies did not take into account the landfilling operation. Although Menard et al.
278 (2004) stated that daily operations fell within its system boundary, it only included the
279 installation of horizontal trench and vertical gas collection systems, which are
280 considered construction activities in this study. Hence, the research scope has to be
281 identified clearly when researchers plan to obtain from the literature data on the
282 consumption of materials. In the case of this study, misapplication of the data would
283 underestimate diesel consumption by 60 to 80%.

284

285 Table 6 is here

286

287 3.2 Contributions to individual impact categories

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

303

304 Figure 2 is here

305

306 3.3 Normalized impact potentials

307 **Figure 3** shows the normalized impact potentials for landfill C&O compared
308 with ‘total landfill processes’, a term which herein represents three (out of nine)
309 landfilling scenarios with different leachate and LFG treatment technologies, obtained
310 from a study by Damgaard et al. (2011). In the case of landfill C&O, HTs was the
311 predominant impact category, followed by ETwc, with impact potentials of 8.7 and
312 7.1 mPE·t-waste⁻¹, respectively. The impact potentials of GW, AC, NE, and HTa were

313 between 1 and 2 mPE·t-waste⁻¹, and those of SOD, POF, and ETs were less than 0.2
314 mPE·t-waste⁻¹. In terms of total landfill processes, energy recovery from LFG and
315 carbon sequestration reduced environmental impacts effectively, sometimes even with
316 negative values. When comparing the absolute ratios of landfill C&O impact
317 potentials to total landfilling technologies, the ratios were between 0.2 and 1.0 for AC,
318 NE, HTw, HTs, ETwc, and ETs. The ratios were as high as 15 to 60 for HTa. This
319 highlights clearly that the C&O process contributes significantly to the environmental
320 impacts of landfilling technology.

321

322 Figure 3 is here

323

324 **3.4 Scenario uncertainty**

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

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

354 A LCA was conducted for the six alternative approaches, and the differences
355 between each one and the Baseline were calculated and shown in **Figure 4**. Most of
356 the alternative approaches would decrease the environmental impact potentials of
357 C&O; however, *A3* and *A4*, both of which use more clay than the other options,
358 increased impact potentials in several categories—*A3* on NE, POF, and ETwc, and *A4*
359 on SOD, AC, NE, HTw, and ETwc. The replacement of mineral materials with
360 synthetic materials (*A1* and *A2*) was the most effective method for mitigating
361 environmental burdens, with a reduction efficiency of 2 to 28%. The saved
362 consumptions of mineral materials when using synthetic materials are important on
363 burden reduction from both material manufacturing and transportation (i.e. diesel
364 consumption). From **Figure 4** it is clear that *A1* is more effective than *A2*, while the
365 mitigation efficiencies are more significant on toxic impacts than on non-toxic ones.
366 Comparatively, switching to a single composite liner system (*A5*) would only decrease

367 impact potentials by less than 5%, and the absence of LFG collection system (A6)
368 would make no difference from Baseline. On the other hand, reducing the functional
369 systems (A5 and A6) would induce the higher probability of leachate and LFG release
370 than using alternative synthetic materials (A1 and A2), which, according to Damgaard
371 et al. (2011), is critical for the performance of integrated landfilling technology. If
372 landfill managers plan to minimize the environmental impacts of C&O, they could
373 use synthetic materials to replace mineral materials, but one should always be
374 cautious about reducing a functional system.

375

376 Figure 4 is here

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

382 **4. Conclusions**

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

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

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

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

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

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

408 **Acknowledgements**

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412 **References**

413 Brogaard, L.K., Stentsøe, S., Willumsen, H.C., Christensen, T.H., 2013.
414 Quantifying capital goods for waste landfilling. *Waste Manage. Res.* 31, 55–598.

415 Camobreco, V., Ham, R., Barlaz, M., Repa, E., Felker, M., Rousseau, C., Rathle,
416 J., 1999. Life-cycle inventory of a modern municipal solid waste landfill. *Waste*
417 *Manage. Res.* 17, 394–408.

418 Caterpillar Inc., 2009. *Caterpillar Performance Handbook*, Edition 42, Peoria,
419 Illinois, U.S.A.

420 Cherubini, F., Bargigli, S., Ulgiati, S., 2009. Life cycle assessment (LCA) of
421 waste management strategies: Landfilling, sorting plant and incineration. *Energy* 34,
422 2116–2123.

423 Clavreul, J., Baumeister, H., Christensen, T.H., Damgaard, A., 2013.
424 EASETECH - an environmental assessment system for environmental technologies.
425 Submitted to *Environ. Modell. Softw.*

426 Cong, X., 2012. Project design of municipal solid waste landfill site in Songyuan
427 Jiangnan district (in Chinese), College of Environment and Resource. Jilin University,
428 Changchun.

429 Damgaard, A., Manfredi, S., Merrild, H., Stens, S., Christensen, T.H., 2011. LCA
430 and economic evaluation of landfill leachate and gas technologies. *Waste Manage.* 31,
431 1532–1541.

432 Ecobalance Inc., 1999. Life cycle inventory of a modern municipal solid waste
433 landfill. Environmental Research and Education Foundation, Washington DC.

434 Ecoinvent, 2005. Excavation, hydraulic digger, RER. Swiss Centre for Life
435 Cycle Inventories, St-Gallen, Switzerland.

436 Ecoinvent, 2010. Swiss centre for life cycle inventories, Ecoinvent, V2/2, in:
437 (TSL), c.o.E.T.S.L. (Ed.), Lerchenfeldsrasse 5, 9014 St-Gallen, Switzerland.

438 El-Fadel, M., Findikakis, A.N., Leckie, J.O., 1997. Environmental impacts of
439 solid waste landfilling. *J. Environ. Manage.* 50, 1–25.

440 Frischknecht, R., Althaus, H.J., Bauer, C., Doka, G., Heck, T., Jungbluth, N.,
441 Kellenberger, D., Nemecek, T., 2007. The environmental relevance of capital goods in
442 life cycle assessments of products and services. *Int. J. Life Cycle Assess.* 12, 7–17.

443 Fu, Q., 2012. In discussion with the author, Shanghai municipal engineering
444 design institute Co., LTD., Shanghai, China.

445 Gong, D., Sun, D., Xie, M., Mu, X., Ding, W., 2008. LCA comparison between
446 Incineration and integrated treatment patterns of municipal domestic waste.
447 *Environmental Sanitation Engineering (in Chinese)* 16, 52–55.

448 Hauschild, M., Potting, J., 2004. Spatial differentiation in life cycle impact
449 assessment - the EDIP2003 methodology, Guidelines from the Danish Environmental
450 Protection Agency, Copenhagen.

451 Hu, G., 2009. Integrated municipal solid waste management and life cycle 3E
452 assessment decision - a case study of Chongqing (in Chinese), College of Resource
453 and Environmental Science of Chongqing. Chongqing University, Chongqing, China,
454 p. 117.

455 International Standardization Organization, 2006. Environmental management -

456 Life cycle assessment - Requirements and guidelines, ISO 14044: 2006, Geneva,
457 Switzerland.

458 Kirkeby, J.T., Birgisdottir, H., Bhandar, G.S., Hauschild, M., Christensen, T.H.,
459 2007. Modelling of environmental impacts of solid waste landfilling within the
460 life-cycle analysis program EASEWASTE. *Waste Manage.* 27, 961–970.

461 Kirkeby, J.T., Birgisdottir, H., Hansen, T.L., Christensen, T.H., Bhandar, G.S.,
462 Hauschild, M., 2006. Environmental assessment of solid waste systems and
463 technologies: EASEWASTE. *Waste Manage. Res.* 24, 3–15.

464 Khoo, H.H., Tan, L.L.Z., Tan, R.B.H., 2012. Projecting the environmental profile
465 of Singapore's landfill activities: Comparisons of present and future scenarios based
466 on LCA. *Waste Manage.* 32, 890–900.

467 Manfredi, S., Christensen, T.H., Scharff, H., Jacobs, J., 2010. Environmental
468 assessment of low-organic waste landfill scenarios by means of life-cycle assessment
469 modeling (EASEWASTE). *Waste Manage. Res.* 28, 130–140.

470 Manfredi, S., Tonini, D., Christensen, T.H., Scharff, H., 2009. Landfilling of
471 waste: accounting of greenhouse gases and global warming contributions. *Waste
472 Manage. Res.* 27, 825–836.

473 Ministry of Construction of the People's Republic of China, 2001. Technical
474 code for municipal solid waste sanitary landfill (CJJ17-2001) (in Chinese), Chinese
475 Industrial Standard. China Architecture & Building Press, Beijing, China.

476 Ministry of Construction of the People's Republic of China, 2004. Technical
477 code for municipal solid waste sanitary landfill (CJJ17-2004) (in Chinese), Chinese
478 Industrial Standard. China Architecture & Building Press, Beijing, China.

479 Ministry of Construction of the People's Republic of China, 2007a. Technical
480 code for liner system of municipal solid waste sanitary landfill (CJJ113-2007) (in
481 Chinese), Chinese Industrial Standard. China Architecture & Building Press, Beijing,
482 China.

483 Ministry of Construction of the People's Republic of China, 2007b. Technical
484 code for municipal solid waste sanitary landfill closure (CJJ112-2007) (in Chinese),
485 Chinese Industrial Standard. China Architecture & Building Press, Beijing, China.

486 Menard, J.F., Lesage, P., Deschenes, L., Samson, R., 2004. Comparative life
487 cycle assessment of two landfill technologies for the treatment of municipal solid
488 waste. *Int. J. Life Cycle Assess.* 9, 371–378.

489 Ministry of Housing and Urban-Rural Development of the People's Republic of
490 China, 2009. Construction standard for municipal solid waste sanitary landfill
491 (CJJ124-2009) (in Chinese), Chinese Industrial Standard. China Planning Press,
492 Beijing, China.

493 National Bureau of Statistics of China, 2012. China Statistical Yearbook 2012.
494 China statistical press, Beijing, China.

495 Niskanen, A., Manfredi, S., Christensen, T.H., Anderson, R., 2009.
496 Environmental assessment of Ammassuo landfill (Finland) by means of
497 LCA-modeling (EASEWASTE). Waste Manage. Res. 27, 542–550.

498 Stranddorf, H.K., Hoffmann, L., Schmidt, A., 2005. Impact categories,
499 normalization and weighting in LCA-Update on selected EDIP97-data,
500 Environmental news No. 78. Danish Environmental Protection Agency, Copenhagen,
501 Denmark.

502 Stripple, H., 2001. Life Cycle Assessment of Road, A Pilot Study for Inventory
503 Analysis, Second Revised Edition. The Swedish Environmental Research Institute,
504 Gothenburg, Sweden.

505 Wei, B., Wang, J., Tahara, K., Kobayashi, K., Sagisaka, M., 2009. Life cycle
506 assessment on disposal methods of municipal solid waste in Suzhou. China
507 Population, Resources and Environment (in Chinese) 19, 93–97.

508 Weidema, B.P., Wesnaes, M.S., 1996. Data quality management for life cycle
509 inventories - an example of using data quality indicators. J. Cleaner Prod. 4, 167–174.

510 Xu, G., 2003. Research on applying LCA to municipal solid waste management -
511 a case study of Guangzhou (in Chinese), College of Environmental Science and
512 Engineering. Sun Yat-sen University, Guangzhou, China, p. 94.

513 **List of Tables**

514 Table 1 Vertical profile of the materials used in a typical landfill body. Assumed thickness based on technical code requirement, if not
 515 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·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·m ⁻²
	L15	Gravel	0.3	Thickness > 30 cm
	L16	Woven geotextile	N.A.	Covering HDPE pipes, qualification > 200 g·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·m ⁻²
	L20	Geomembrane	N.A.	Thickness > 1.5 mm
	L21	Nonwoven geotextile	N.A.	Qualification > 600 g·m ⁻²
	L22	Gravel	0.3	Thickness > 30 cm
	L23	Nonwoven geotextile	N.A.	Qualification > 600 g·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

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

517 ^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.

518 ^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
519 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
520 construction approaches, the combination of GCL and clay in the liner systems were calculated in this study as the example.

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

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

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

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

527

528 Table 3 Material consumption during construction of the main parts in a landfill
 529 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

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

531 ^a Including HDPE geomembranes, HDPE pipes and geonets.

532 ^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
 533 considering the comparable benefits.

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

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

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

538

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

Usage		Diesel (kg·m ⁻³)	Handled materials (m ³ ·t-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·t-waste ⁻¹)	
OL			
Excavator	To handle waste	0.218 ^e	
Bulldozer	To handle waste	0.540 ^e	
Compactor	To compact waste	0.185 ^e	

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

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

544 ^b Ecoinvent (2005).

545 ^c Stripple (2001).

546 ^d Caterpillar Inc. (2009).

547 ^e Gong et al. (2008).

548 ^f Volume of sand soils excavated during site preparation.

549 ^g Volume of mineral materials used for landfill construction.

550 ^h The sum of the volume of sand and clay used as daily and intermediate covers.

551

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

Impact categories	Acronyms	Physical basis	Normalization references		Reference year
			EU-15	Units	
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 ₂ H 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 ^c	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.	N.A.	0.096
Electricity ⁱ	0	0	0	0.173	0.173	N.A.	0.963	N.A.	N.A.

554

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.

555

^a Including HDPE geomembranes, HDPE pipes, geonets.

556

^b The sum of HDPE and PVC.

557

558

^c The sum of GCL and bentonite.

559

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

560

^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.

561

^f The sum of sand and soil.

562

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

563

^h Unit: L·t-waste⁻¹.

564

ⁱ Unit: kWh·t-waste⁻¹.

565 **Figure captions**

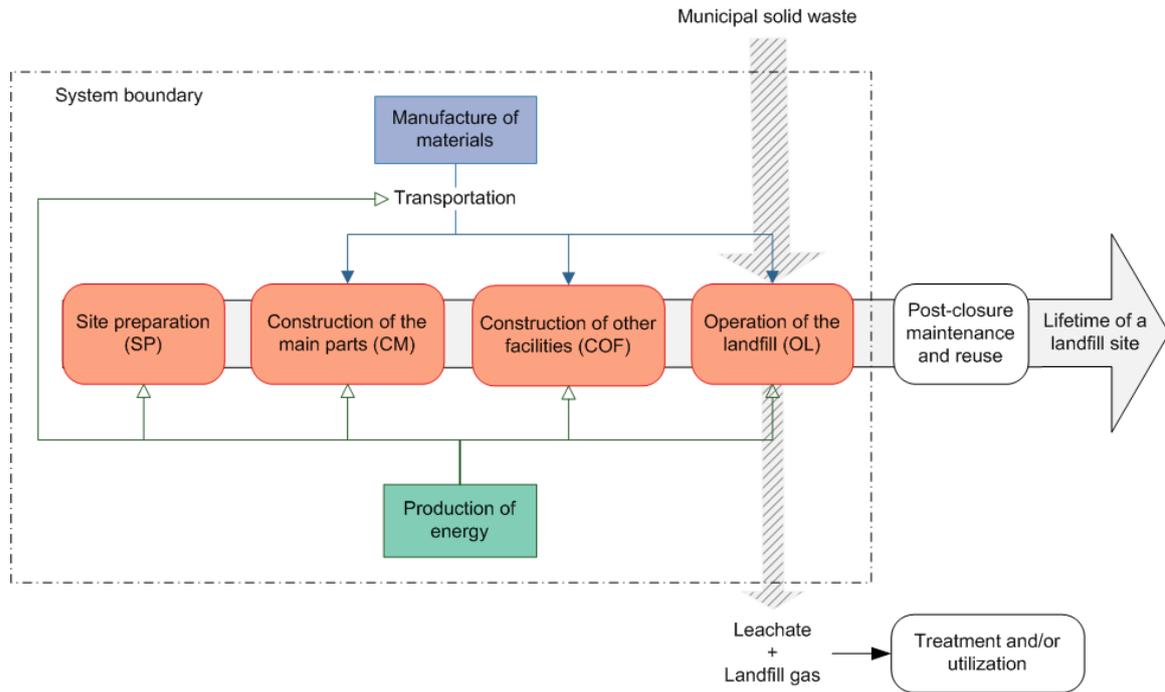
566 Figure 1 System boundary for the construction and operation process of a landfill site.

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

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

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

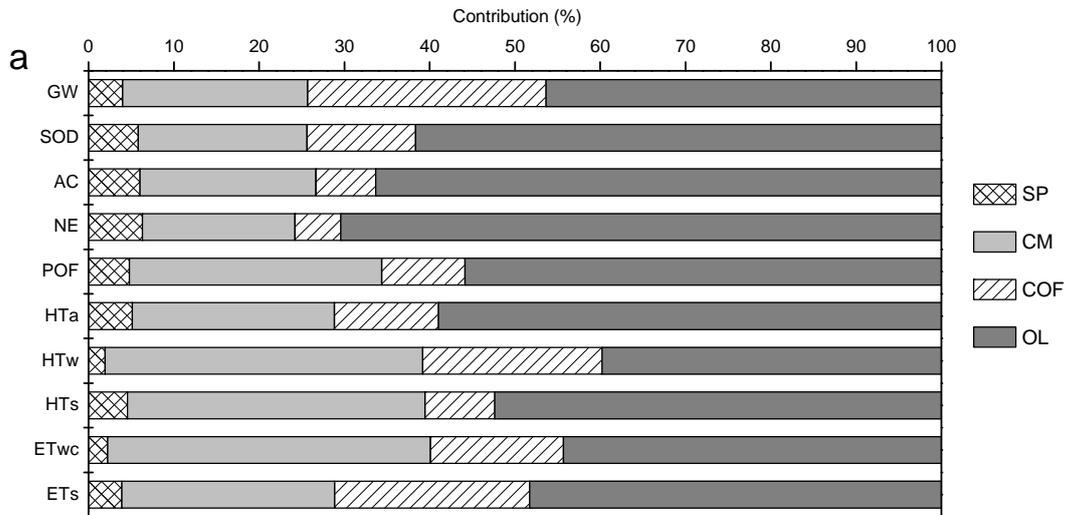
580 **Figures**



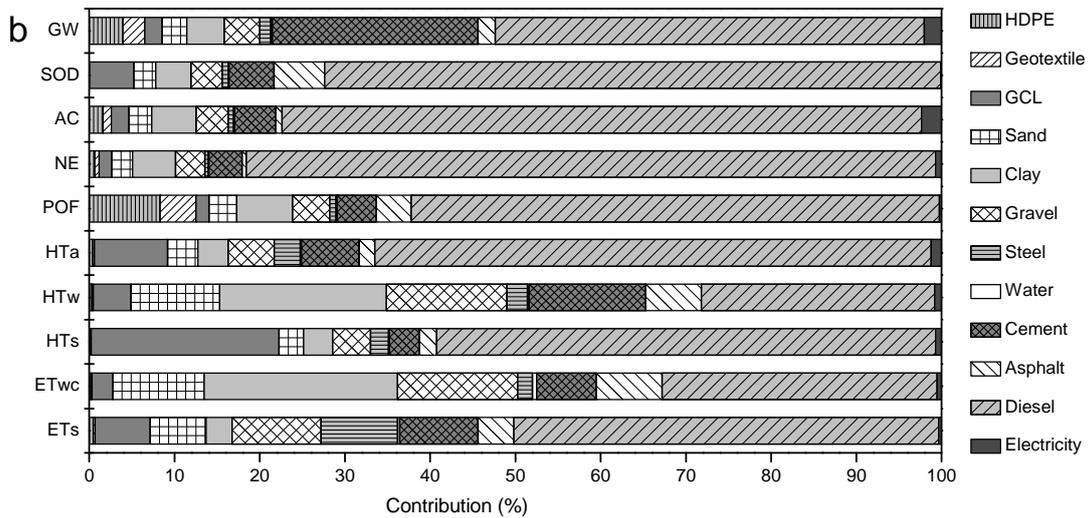
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582 Figure 1 System boundary for the construction and operation process of a landfill site.

583



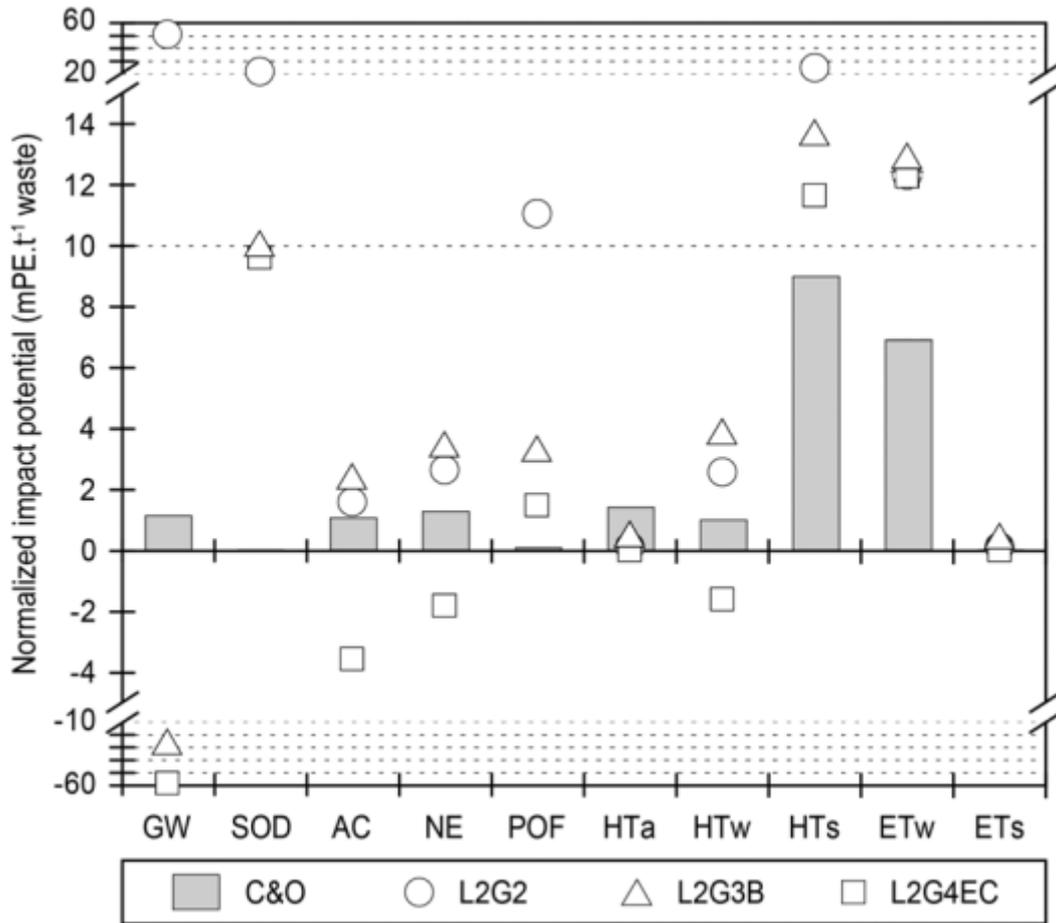
584



585

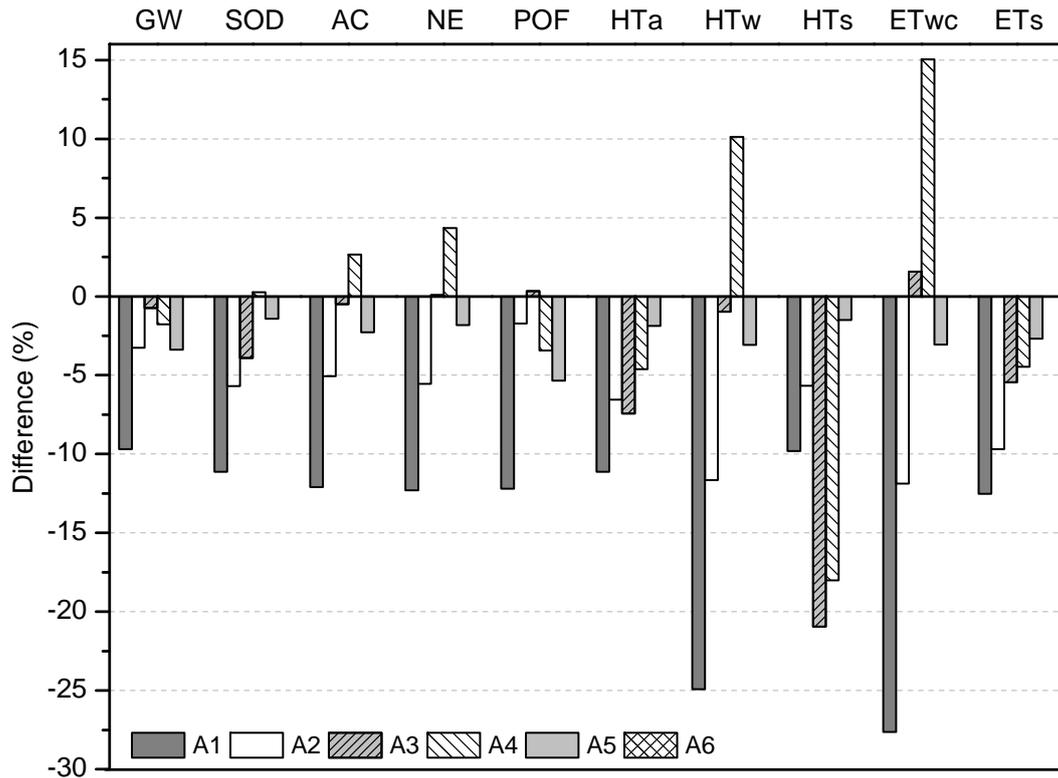
586 Figure 2 Contributions of the four stages (a) and 12 materials and energy (b) to
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588 landfill site. (SP, site preparation; CM, construction of the main parts of the landfill
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591



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 601 alternative approaches for the construction and operation of a landfill site.