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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, ( $\text{kg}\cdot\text{t}\cdot\text{waste}^{-1}$ );  $h_{ij}$  represents the thickness of material  
114  $i$  used in the  $j^{\text{th}}$  layer (m) (**Table 1**);  $A$ , the projected area for one tonne of disposed  
115 waste in the landfill, ( $\text{m}^2$ ); and  $\rho_i$  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;  $\rho'_i$  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,  $\rho''_i$  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<sup>-1</sup> (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<sup>-1</sup>);  $CF_j$  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<sup>-1</sup> (Stranddorf, et al. 2005). The  
240 normalized unit “mPE·t-waste<sup>-1</sup>” 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<sup>-1</sup>. 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<sup>-1</sup>, respectively. The impact potentials of GW, AC, NE, and HTa were



313 between 1 and 2 mPE·t-waste<sup>-1</sup>, and those of SOD, POF, and ETs were less than 0.2  
314 mPE·t-waste<sup>-1</sup>. 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.

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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 <sup>a</sup>
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 <sup>-2</sup>
	L4	Geomembrane	N.A.	Thickness > 1 mm
	L5	GCL <sup>b</sup>	N.A.	Thickness > 5 mm
	L6	Clay	0.2	Thickness > 20 cm <sup>c</sup>
	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 <sup>c</sup>
	L10	Perforated HDPE pipe	N.A.	Diameter > 250 mm <sup>c</sup> , 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 <sup>-2</sup>
	L15	Gravel	0.3	Thickness > 30 cm
	L16	Woven geotextile	N.A.	Covering HDPE pipes, qualification > 200 g·m <sup>-2</sup>



	L17	Perforated HDPE pipe	N.A.	Diameter of main pipe > 250 mm, with the distance < 50 m <sup>c</sup> ; Diameter of branch pipe > 200 mm, with the distance < 10 m <sup>c</sup>
	L18	Coarse sand	0.15	Thickness > 15 cm <sup>c</sup>
Double liner system	L19	Nonwoven geotextile	N.A.	Qualification > 600 g·m <sup>-2</sup>
	L20	Geomembrane	N.A.	Thickness > 1.5 mm
	L21	Nonwoven geotextile	N.A.	Qualification > 600 g·m <sup>-2</sup>
	L22	Gravel	0.3	Thickness > 30 cm
	L23	Nonwoven geotextile	N.A.	Qualification > 600 g·m <sup>-2</sup>
	L24	Geomembrane	N.A.	Thickness > 1.5 mm
	L25	GCL <sup>b</sup>	N.A.	Thickness > 5 mm
	L26	Clay	0.5	Thickness > 50 cm <sup>c</sup>
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 <sup>a</sup> 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 <sup>b</sup> 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 <sup>c</sup> 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 <sup>-3</sup>	Mastic asphalt, at plant, CH
Concrete	2374	kg·m <sup>-3</sup>	Cement, unspecified, at plant, CH
Clay	1842	kg·m <sup>-3</sup>	Clay, at mine, CH
Diesel	0.84	kg·L <sup>-1</sup>	Diesel combustion in industrial equipment, RER
Electricity			Electricity, production mix, CN
HDPE	955	kg·m <sup>-3</sup>	
HDPE geomembrane (1 mm thick)	0.955	kg·m <sup>-2</sup>	Polyethylene, HDPE, granulate, at plant, RER
HDPE geomembrane (1.5 mm thick)	1.432	kg·m <sup>-2</sup>	
Geonet	0.55	kg·m <sup>-2</sup>	Polyethylene, HDPE, granulate, at plant, RER
GCL	4.8	kg·m <sup>-2</sup>	Bentonite, at processing, DE
Gravel	2200	kg·m <sup>-3</sup>	Gravel, unspecified, at mine, CH
Nonwoven geotextile	0.6	kg·m <sup>-2</sup>	Polypropylene, granulate, at plant, RER
Sand	1562	kg·m <sup>-3</sup>	Sand at mine, CH
Steel	7880	kg·m <sup>-3</sup>	Chromium steel product manufacturing, average metal working, RER
Woven geotextile	0.2	kg·m <sup>-2</sup>	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 <sup>-1</sup>	This study <sup>b</sup>	Landfill design reports <sup>c</sup>	
		Average	Range
HDPE <sup>a</sup>	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 <sup>d</sup>
Clay	53.7	48.6	48.6 <sup>e</sup>

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

531 <sup>a</sup> Including HDPE geomembranes, HDPE pipes and geonets.

532 <sup>b</sup> 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 <sup>c</sup> 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 <sup>d</sup> The amount of sand were those need to be purchased in specific landfill sites rather than the actual usage.

537 <sup>e</sup> 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 <sup>-3</sup> )	Handled materials (m <sup>3</sup> ·t-waste <sup>-1</sup> )
<b>SP</b>			
Excavator	To excavate soils	0.130 <sup>b</sup>	0.238 <sup>f</sup>
Front loader	To move soils on site	0.102 <sup>c</sup>	0.238 <sup>f</sup>
Truck	To transport soils on site	0.193 <sup>c</sup>	0.238 <sup>f</sup>
<b>CM</b>			
Bulldozer	To handle the mineral materials <sup>a</sup>	0.232 <sup>d</sup>	0.164 <sup>g</sup>
<b>OL</b>			
Bulldozer	To handle the daily and intermediate soil covers	0.232 <sup>d</sup>	0.125 <sup>h</sup>
Usage		Diesel (kg·t-waste <sup>-1</sup> )	
<b>OL</b>			
Excavator	To handle waste	0.218 <sup>e</sup>	
Bulldozer	To handle waste	0.540 <sup>e</sup>	
Compactor	To compact waste	0.185 <sup>e</sup>	

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 <sup>a</sup> The on-site transportation of imported mineral materials was not considered in this study.

544 <sup>b</sup> Ecoinvent (2005).

545 <sup>c</sup> Stripple (2001).

546 <sup>d</sup> Caterpillar Inc. (2009).

547 <sup>e</sup> Gong et al. (2008).

548 <sup>f</sup> Volume of sand soils excavated during site preparation.

549 <sup>g</sup> Volume of mineral materials used for landfill construction.

550 <sup>h</sup> 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	
<b>Non-toxic impacts</b>					
Global Warming (100 yrs)	GW	Global	8,700	kg CO <sub>2</sub> -eq·person <sup>-1</sup> ·yr <sup>-1</sup>	1994
Stratospheric Ozone Depletion	SOD	Global	0.103	kg CFC-11-eq·person <sup>-1</sup> ·yr <sup>-1</sup>	1994
Acidification	AC	Regional	74	kg SO <sub>2</sub> -eq·person <sup>-1</sup> ·yr <sup>-1</sup>	1994
Nutrient Enrichment	NE	Regional	119	kg NO <sub>3</sub> -eq·person <sup>-1</sup> ·yr <sup>-1</sup>	1994
Photochemical Ozone Formation	POF	Regional	25	kg C <sub>2</sub> H <sub>4</sub> -eq·person <sup>-1</sup> ·yr <sup>-1</sup>	1994
<b>Toxic impacts</b>					
Human Toxicity via air	HTa	Regional	2.09×10 <sup>9</sup>	m <sup>3</sup> air·person <sup>-1</sup> ·yr <sup>-1</sup>	1994
Human Toxicity via water	HTw	Regional	1.79×10 <sup>5</sup>	m <sup>3</sup> water·person <sup>-1</sup> ·yr <sup>-1</sup>	1994
Human Toxicity via soil	HTs	Regional	1.57×10 <sup>2</sup>	m <sup>3</sup> soil·person <sup>-1</sup> ·yr <sup>-1</sup>	1994
Eco-Toxicity in water-chronic	ETwc	Regional	3.52×10 <sup>5</sup>	m <sup>3</sup> water·person <sup>-1</sup> ·yr <sup>-1</sup>	1994
Eco-Toxicity in soil	ETs	Regional	9.64×10 <sup>5</sup>	m <sup>3</sup> soil·person <sup>-1</sup> ·yr <sup>-1</sup>	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 <sup>-1</sup>	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)
<b>Materials</b>									
HDPE	0	0.211 <sup>a</sup>	0	0	0.204 <sup>a</sup>	0.090 <sup>b</sup>	0.186	1.40 <sup>b</sup>	0.241 <sup>b</sup>
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 <sup>c</sup>	N.A.
Sand	-372+136 <sup>d</sup>	114 <sup>c</sup>	0	117	231	257	N.A.	130 <sup>f</sup>	169 <sup>f</sup>
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 <sup>g</sup>
Water <sup>h</sup>	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
<b>Energy</b>									
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 <sup>i</sup>	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

<sup>a</sup> Including HDPE geomembranes, HDPE pipes, geonets.

556

<sup>b</sup> The sum of HDPE and PVC.

557

<sup>c</sup> The sum of GCL and bentonite.

558

<sup>d</sup> The amounts of excavated and backfilled sand soil were 372 and 136 kg·t-waste<sup>-1</sup>, respectively.

559

<sup>e</sup> 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.

560

<sup>f</sup> The sum of sand and soil.

561

<sup>g</sup> The sum of steel, stainless steel, copper, cable (most weight is attributed to copper) and aluminum.

562

<sup>h</sup> Unit: L·t-waste<sup>-1</sup>.

563

<sup>i</sup> Unit: kWh·t-waste<sup>-1</sup>.

564

565 **Figure captions**

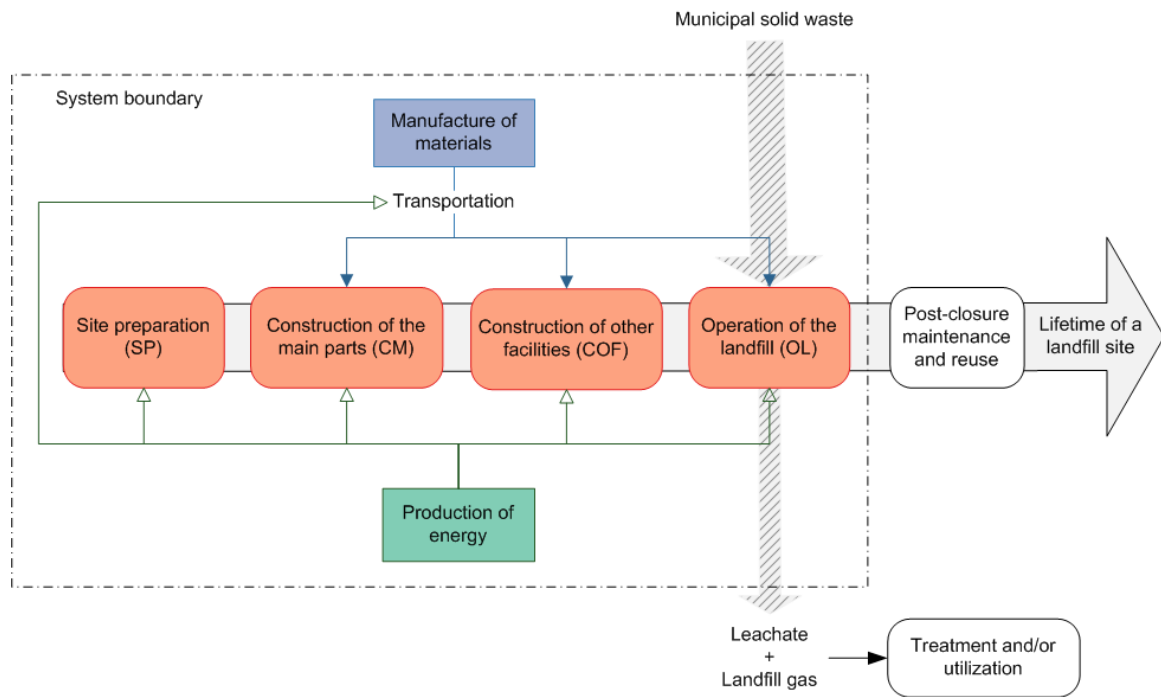
566 Figure 1 System boundary for the construction and operation process of a landfill site.

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.

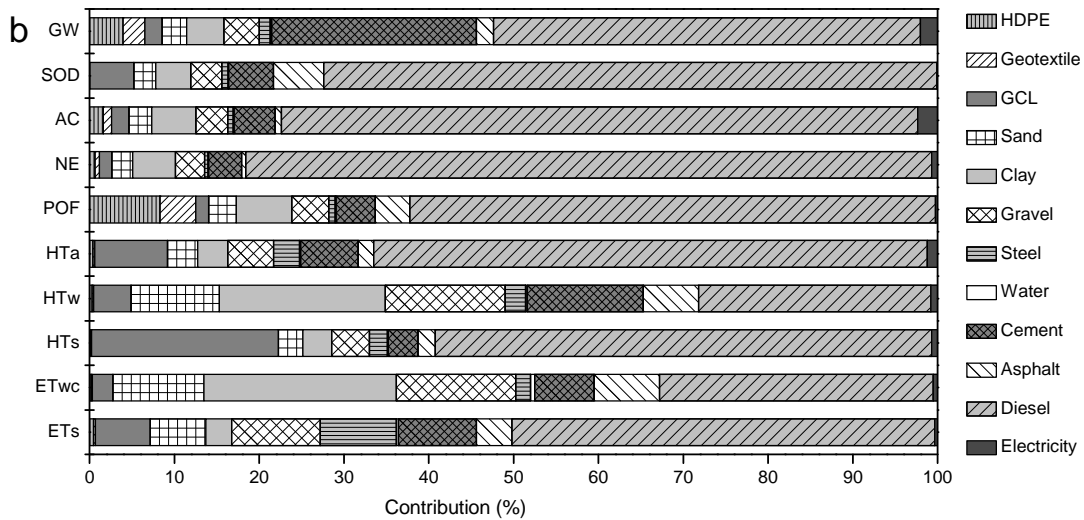
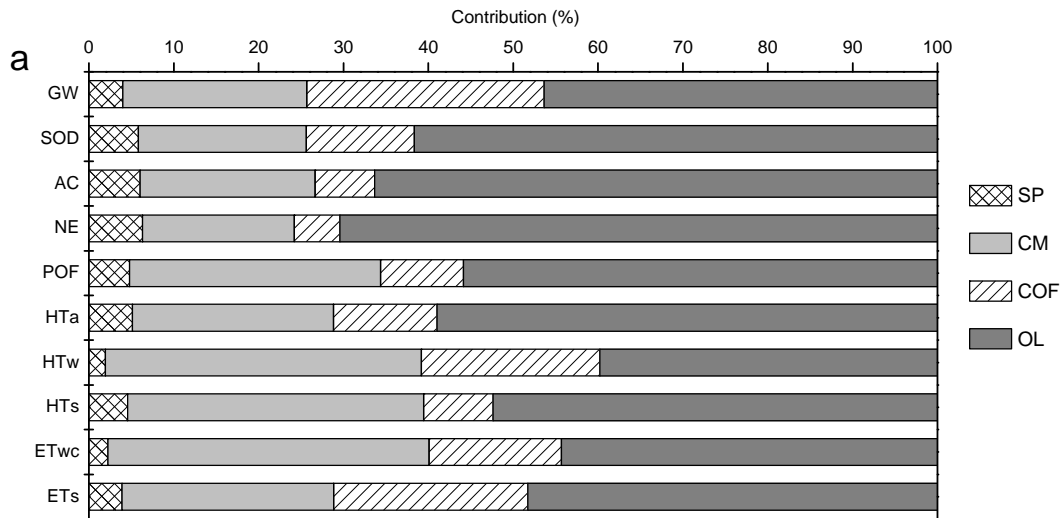
580 **Figures**



581

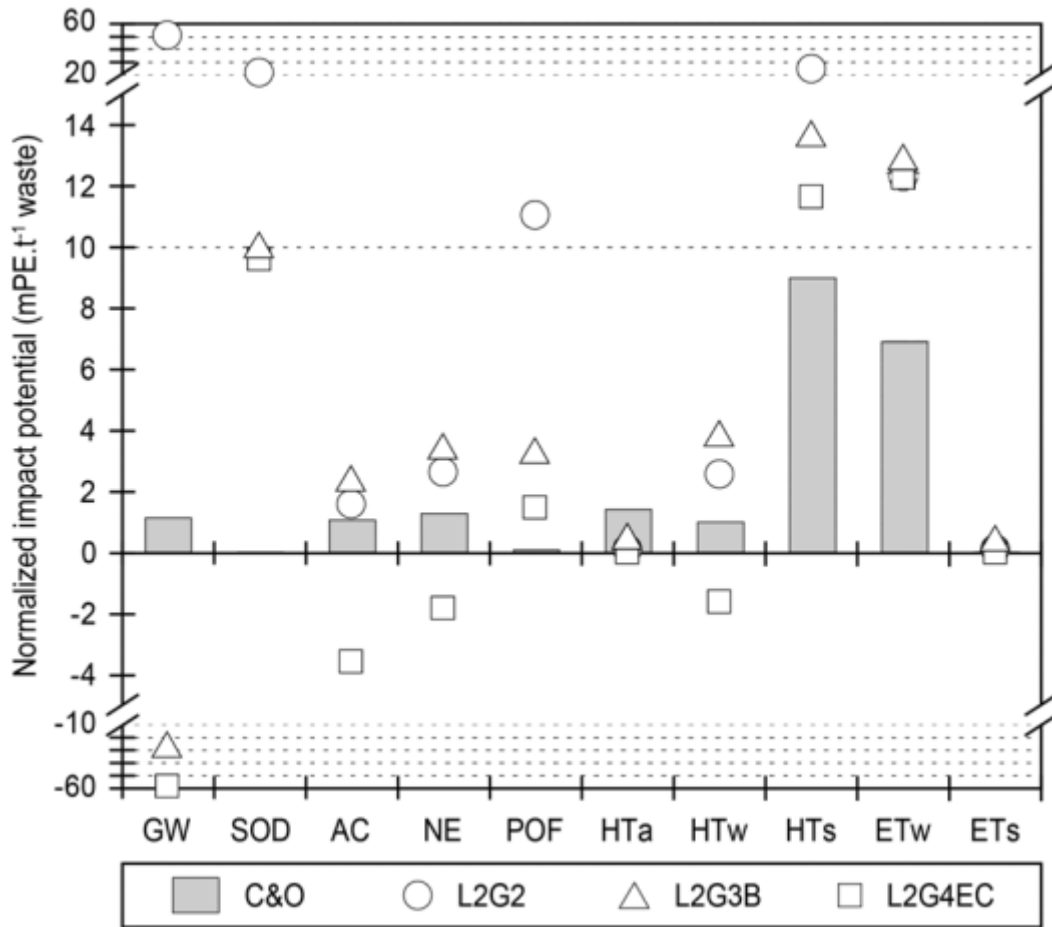
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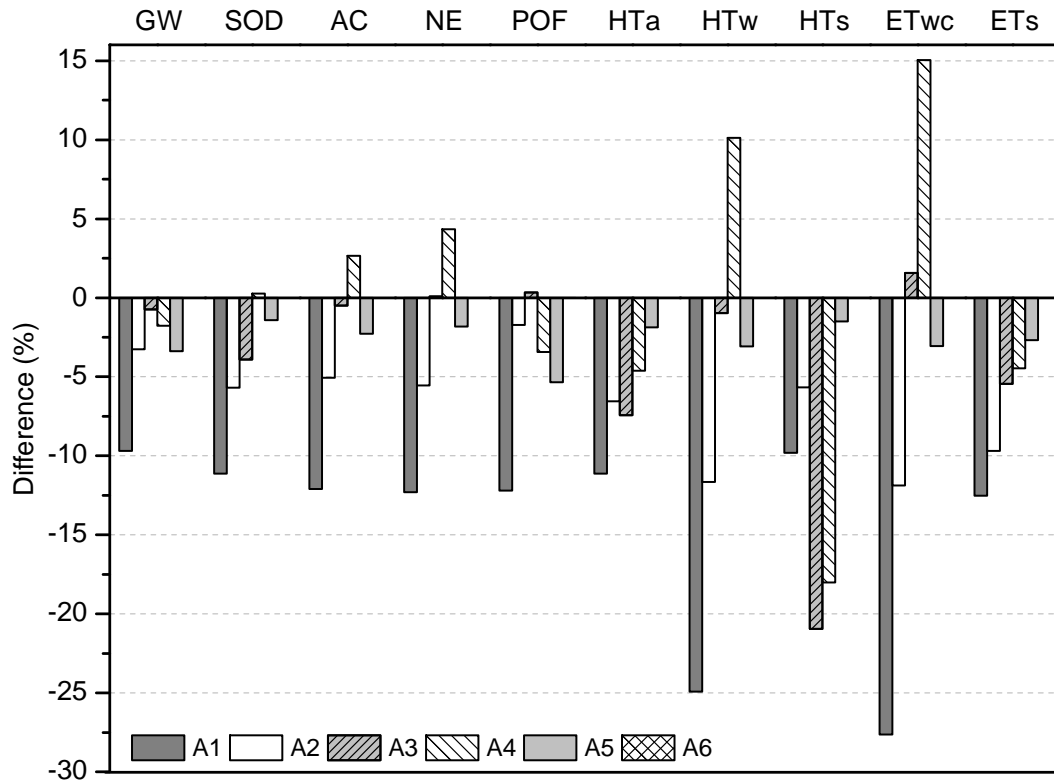
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