



Environmental assessment of garden waste management in the Municipality of Aarhus, Denmark

Boldrin, Alessio; Andersen, Jacob Kragh; Christensen, Thomas Højlund

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6 **Environmental assessment of garden waste management in the Municipality of**
7 **Aarhus, Denmark**

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13 Alessio Boldrin*, Jacob K. Andersen, Thomas H. Christensen
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19 Department of Environmental Engineering
20 Technical University of Denmark
21 Kongens Lyngby, Denmark
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23
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25
26
27
28 *Corresponding author
29 Department of Environmental Engineering,
30 Technical University of Denmark,
31 Miljoevej
32 DK-2800 Kongens Lyngby, Denmark
33 Phone: (+45) 4525 1585,
34 Fax: (+45) 4593 2850,
35 e-mail: aleb@env.dtu.dk
36

37 **Abstract**

38 An environmental assessment of six scenarios for handling of garden waste in the
39 municipality of Aarhus (Denmark) was performed from a life cycle perspective by
40 means of the LCA-model EASEWASTE. In the first (baseline) scenario, the current
41 garden waste management system based on windrow composting was assessed, while in
42 the other five scenarios alternative solutions including incineration and home
43 composting of fractions of the garden waste were evaluated. The environmental profile
44 (normalised to Person Equivalent, PE) of the current garden waste management in
45 Aarhus is in the order of -6 to 8 mPE Mg⁻¹ ww for the non-toxic categories and up to
46 100 mPE Mg⁻¹ ww for the toxic categories. The potential impacts on non-toxic
47 categories are much smaller than what is found for other fractions of municipal solid
48 waste. Incineration (up to 35% of the garden waste) and home composting (up to 18%
49 of the garden waste) seem from an environmental point of view suitable for diverting
50 waste away from the composting facility in order to increase its capacity. In particular
51 the incineration of woody parts of the garden waste improved the environmental profile
52 of the garden waste management significantly.

53

54

55 **Keywords:** garden waste, composting, integrated waste management, LCA,
56 EASEWASTE.

57

58

59 **Abbreviations:**

- 60 C&D: Constructions & Demolition
- 61 CHP: Combined Heat and Power
- 62 GHG: Greenhouse Gases
- 63 GWP: Global Warming Potential
- 64 LCA: Life Cycle Assessment
- 65 LCI: Life Cycle Inventory
- 66 LHV: Lower Heating Value
- 67 MFA: Material Flow Analysis
- 68 PAH: Polycyclic Aromatic Hydrocarbons
- 69 PE: Person Equivalent
- 70 RS: Recycling Station
- 71 SFA: Substance Flow Analysis
- 72 SNCR: Selective Non-Catalytic Reduction
- 73 VOC: Volatile Organic Compounds
- 74 VS: Volatile Solids
- 75 TS: Total Solids
- 76 U-O-D: Upstream-Operation-Downstream
- 77 WTE: Waste-To-Energy
- 78 ww: wet waste
- 79

80 **1. Introduction**

81 Garden waste is a mixture of organic (e.g. grass clippings, flowers, branches, wood) and
82 inorganic (e.g. soil) materials generated during maintenance of private gardens and
83 public parks (Boldrin & Christensen, 2010). The amount of garden waste generated has
84 been steadily increasing in Denmark in the last decade. The generation of garden waste
85 was 67 kg person⁻¹ year⁻¹ in 1994, while 143 kg person⁻¹ year⁻¹ were produced in 2006
86 (Boldrin & Christensen, 2010), representing more than 18% of municipal waste
87 generation in 2006 (Miljøstyrelsen, 2010). The increasing generation of garden waste is
88 a major contributor to the increasing generation of residential waste in Denmark
89 (Skovgaard et al., 2005). Capacity of plants treating garden waste is thus high on the
90 agenda of many municipalities.

91 Collected garden waste is almost exclusively treated by central composting in
92 Denmark (Miljøstyrelsen, 2010). Often only big roots and tree trunks are combusted
93 (<2%). However, garden waste was recently partly re-classified in Denmark and is
94 currently regulated by the Biomass Ordinance, meaning that branches, wood and roots
95 from garden and park waste can be combusted for energy production without being
96 taxed (Miljøministeriet, 2010). This may potentially make it attractive to recover a
97 woody fraction from the garden waste to be used as a biomass fuel in waste-to-energy
98 (WTE) incineration plants for start up operations. However, not all the garden waste is
99 useful as a fuel, and implementation of home- composting could also be considered an
100 option in finding solutions for the treatment of the increasing amounts of garden waste.

101 Environmental assessment studies comparing alternatives for garden waste
102 management are almost non-existing in literature. Systematic environmental evaluations
103 are thus needed to support rational decision-making processes at the local level
104 concerning garden waste. LCA (Life Cycle Assessment) is a fairly exhaustive tool for

105 collecting and evaluating data about the generation, collection and treatment of waste.
106 LCA has been used in several studies for assessing waste management both at the
107 system level (e.g. Kirkeby et al., 2006a; Zhao et al., 2009) and at the technology level
108 (e.g. Manfredi & Christensen, 2008; Damgaard et al., 2009).

109 The goal of the present study is to provide an environmental evaluation of a range of
110 waste management options for dealing with garden waste generated in the Municipality
111 of Aarhus (Denmark). The Municipality of Aarhus has about 300,000 inhabitants is
112 facing a severe capacity problem of the current garden waste composting plant, which
113 only receives about half the garden waste generated in the municipality. The goal is
114 achieved by assessing the environmental profile of:

- 115 • The current garden waste management having a minimum of wood and reject
116 recovery for combustion (about 6% of the garden waste)
- 117 • Potential increases in the amount of wood and reject recovered for combustion (up
118 to 35%)
- 119 • Potential increases in the amount of wood and reject recovered for combustion (up
120 to 35%) in combination with increased home composting of garden waste (about
121 18%)

122

123 **2. Materials and methods**

124 Garden waste treatment can be considered as a service system, working in respect of the
125 legislation and the environment. The primary service is thus the treatment of a given
126 quantity of garden waste. As suggested by Bjarnadottir et al. (2002), the functional unit
127 of this study was thus defined as: “Handling and treatment of 16,220 Mg of garden
128 waste produced in Aarhus municipality and treated at the Aarhus garden waste
129 composting plant in 2007”. The time horizon of the assessment is 100 years. Eventual

130 allocations were done on a weight basis. The “zero burdens” assumption was made,
131 since garden waste does not imply any production phase.

132 System boundaries were defined according to the cradle-to-grave principle, thus
133 including all stages and treatments in the life cycle of garden waste. Furthermore,
134 system boundaries were expanded to include benefits/burdens from disposal or purchase
135 of products/services directly linked to waste treatment activities (ash, energy, compost,
136 etc.) (Bjarnadottir et al., 2002). We did not include the environmental loads of the
137 capital goods (construction and demolition of waste treatment facilities and equipment),
138 the treatment and disposal of any solid outputs from the waste-to-energy plant
139 receiving wood and rejects (i.e. bottom ash, fly ash, APC residues, gypsum), and any
140 wastewater generated in different facilities. These aspects were excluded because they
141 were considered of minor importance and for the sake of keeping the comparison of the
142 many scenarios as simple as possible.

143 Only direct consequences (environmental burdens) of the analysed scenarios
144 were accounted for. If, for example, a scenario assesses the diversion of some waste
145 from a current plant, the consequences of available capacity (e.g. other types of waste
146 could be potentially treated) in a specific facility were not evaluated. The report aimed
147 to address future strategies to be implemented when increasing waste generation
148 exceeds the treatment capacity available in current facilities and new installations
149 potentially need to be built.

150 The MFA (Material Flow Analysis)-model STAN was used for setting up the
151 mass flows and the substance flows of the various scenarios (Cencic and Rechberger,
152 2008). STAN was also used to estimate Volatile Solids (VS) degradation and Total
153 Solids (TS) transfer coefficients used in technology modules involved on the LCA-
154 modelling.

155 The environmental assessment is performed by means of EASEWASTE
156 Kirkeby et al. (2006b). EASEWASTE allows the user to assess the environmental
157 performance of a scenario and to compare different management systems and
158 technologies. The model includes a standard package of datasets, but specific databases
159 for garden waste were entered for this study. Descriptions of specific modules used in
160 the present assessment are available in the literature: biotreatment (Boldrin et al.,
161 2010a), incineration (Riber et al., 2008) and use-on-land of treated organic waste
162 (Hansen et al., 2006).

163 The Life Cycle Impact Assessment (LCIA) was performed based on the EDIP97
164 methodology (Wenzel et al., 1997). Results are presented as normalised impact
165 potentials calculated according to normalization factors reported in Table 1 (Stranddorf
166 et al., 2005), where 1 person equivalent (PE) represents the potential impact of an
167 average person for one year including all aspects of life (housing, food, transport, etc.).
168 Emissions of biogenic CO₂ are reported in the emission inventory, but accounted as
169 neutral to global warming (GWP = 0) during the characterisation phase of the LCA, as
170 suggested by Christensen et al. (2009).

171

172 TABLE 1 - Normalisation references for environmental impact categories in EDIP1997.

173

174 **3. Scenarios description**

175 As shown in Figure 1, the composting facility in the Municipality of Aarhus received
176 and treated in 2007 16,220 tons of garden waste originating from public collection of
177 private garden waste (2%), from private households delivered to collection stations
178 (recycling stations, RSs) (64%), and from public areas and parks (34%). The

179 composition of the garden waste is described in Boldrin & Christensen (2010) and the
180 material fractions are shown in Figure 1.

181 Six different scenarios for handling and treatment of garden waste in Aarhus
182 municipality were compared. The scenarios are here briefly described. System
183 boundaries for Scenarios 1 and Scenario 5 (including diversion of waste at the source)
184 are presented in Figure 1 and Figure 2. System boundaries for the remaining scenarios
185 are specified in Boldrin et al. (2009). An overview of waste routing for the analysed
186 scenarios is provided in Table 2. For all scenarios it is estimated that the amount and
187 treatment of hard materials and foreign items is the same (described later). In all
188 scenarios foreign items, hard materials and wood is removed prior to the actual
189 composting process.

190 • *Scenario 1 - Current management.* After the initial sorting, all the collected garden
191 waste is composted (15,540 Mg). The screen residue >25 mm are sent to
192 incineration (597 Mg), the residues with size between 8 mm and 25 mm are re-
193 entered in the compost process (recirculated) as structure material. This fraction is
194 estimated to be approximately 1,300 Mg, or about 10%. Large items of wood
195 screened out during shredding operations and sent to incineration amounts to 501
196 Mg.

197 • *Scenario 2 - Composting and incineration of rejects.* After the initial sorting, all the
198 collected garden waste is composted (15,540 Mg), but the screen residues >8mm
199 (1,749 Mg) are in this scenario sent to incineration in Aarhus WTE plant (in
200 Scenario 1 screen residues were recirculated).

201 • *Scenario 3 - Composting and seasonal incineration of waste.* All garden waste
202 received during the winter months (December, January, and February) is incinerated
203 – only hard materials are removed. Boldrin & Christensen (2010) showed that

204 during winter the soil content of the garden waste was low and the calorific value
205 high. The rest of the year garden waste is managed as usual: large wood items are
206 sorted out during shredding and sent to incineration, screen residues >25 mm are
207 sent to incineration, screen residues between 8 and 25 mm are recirculated. The
208 amount of material composted is 11,410 Mg, 4,631 Mg are sent to incineration
209 (winter waste + large wood items), 935 Mg are recirculated, and reject > 25 mm
210 amounts to 440 Mg.

211 • *Scenario 4 – Maximum incineration of garden waste.* Garden waste received in
212 winter period, screen residues >8 mm and large items of wood are incinerated
213 (5,907 Mg including 1,276 Mg of screen residues >8 mm). Remaining waste is
214 composted (11,410 Mg). No recirculation is assumed in this scenario.

215 • *Scenario 5 - Home composting.* A part of the generated garden waste is treated in
216 private gardens (home composting). It is assumed that 25% of the “small stuff”
217 fraction (small branches, leaves, grass, soil etc.) will be composted in private
218 gardens (3,039 Mg) – i.e. the total mass of waste undergoing central composting is
219 decreased by 19%. This implies reduced transportation of waste (both to recycling
220 stations (RSs) by citizens and between RSs and the composting facility). Large
221 items of wood (502 Mg) and screen residues >25 mm (604 Mg) are incinerated.

222 • *Scenario 6 – Home composting and maximum incineration.* 25 % of the “small
223 stuff” fraction is composted in private gardens (3,039 Mg) and transportation is
224 reduced. Garden waste received in winter period, screen residues > 8 mm and large
225 items of wood are incinerated (5,052 Mg, of which 1,035 Mg are screen residues).
226 The remaining waste is composted (9,233 Mg).

227

228 TABLE 2 – Routing of primary and secondary waste flows for the analysed scenarios.

229 FIGURE 1 - LCA system boundaries for scenario 1.

230 FIGURE 2 - LCA system boundaries for scenario 5.

231

232 **4. Inventory and modelling of relevant data**

233 The following sections describe how the collected data are modelled in the assessment.

234 Loads and savings are described as “direct”, when they originate directly from the

235 operation of the garden waste treatment facilities, and “indirect” when they, although

236 associated with garden waste management, take place outside the actual treatment

237 facility. The indirect aspects are further distinguished in upstream (e.g. provision of

238 energy to the treatments facilities) or downstream (e.g. substitution of inorganic

239 fertilizers by compost) contributions. An overview of different aspects included in the

240 assessment is summarized in Table 3 according to the Upstream-Operation-Downstream

241 (U-O-D) concept (Gentil et al., 2009).

242

243 TABLE 3 - Overview of different aspects considered in the assessment.

244

245 *4.1 Collection and transportation distances*

246 In the Municipality of Aarhus, citizens deliver garden waste by car to six recycling

247 stations (RSs). The average distance between households and the RSs is 4.5 km and it

248 was estimated from a user survey that was carried out at one of the RSs (Lystrupvej).

249 Including a return trip (delivery of garden waste is in many cases not combined with

250 other activities), the average driven distance is thus 2*4.5 km (9 km in total). The

251 gasoline consumption for waste delivery (collection) is hence estimated to be 8.9 l Mg⁻¹

252 of wet waste (ww) (Andersen et al., 2010a).

253 The average transportation distance between the RSs and the composting plant

254 was calculated considering the amount of waste (number of loads) delivered from each

255 RS in 2007. The weighted average distance from RS to Aarhus composting plant is 12.7
256 km – i.e. the total transportation distance is 2*12.7 km (25.4 km). The diesel
257 consumption for covering such distance is estimated to be 0.06 l km⁻¹ Mg⁻¹
258 (EASEWASTE, 2008).

259 Both the WTE plant and the Construction & Demolition (C&D) waste recycling
260 centre are located next to the composting plant, so these transportation distances are
261 assumed to be negligible.

262

263 *4.2 Garden waste composition*

264 Monthly generation, material fraction composition and chemical characterization of
265 garden waste is thoroughly reported in Boldrin & Christensen (2010). A representative
266 sampling and mass reduction method - described in Boldrin et al. (2009) – was used for
267 seasonal characterization (8 samples during one year, twice per season) of garden waste
268 and its classification into five material fractions (i.e. small stuff, branches, wood, hard
269 materials, foreign objects).

270 As described in Andersen et al. (2010a), foreign items (e.g. plastic bags), hard
271 materials (e.g. stones, rocks, bricks) and large items of wood are removed prior to or
272 during the shredding operations. Foreign items are sent to incineration, hard materials
273 are recycled in a C&D waste facility and the wood is sent to incineration after being
274 dried together with roots. In total 16,220 Mg of garden waste were treated at Aarhus
275 composting plant in 2007 (15,540 Mg of shredded waste + 500 Mg of wood to
276 incineration + 78 Mg of hard materials + 106 Mg of foreign items to incineration).

277

278 *4.3 Modelling of the composting treatment*

279 Composting of garden waste in Aarhus composting plant is performed in outdoor
280 windrows. The process lasts typically 55-60 weeks. The piles have a trapezoidal cross
281 section (4.5 m high, 9 m wide in the bottom and 1 m wide at the top) and are turned
282 infrequently, approximately every 6-8 weeks. Gaseous emissions produced during the
283 decomposition of waste are not controlled nor treated.

284 In the modelling, a diesel consumption of 3.04 litre Mg^{-1} ww and an electricity
285 consumption of 0.2 kWh Mg^{-1} ww were considered (details available in Andersen et al.,
286 2010a); in both cases, inventories of upstream processes were taken from the EDIP
287 database. Gaseous emissions included in the assessment are reported in Table 4,
288 according to Andersen et al. (2010b). A detailed description of the data collection
289 process and all available data for Aarhus composting plant are collected in Andersen et
290 al. (2010a). Such inventory comprises all energy and material consumptions at the
291 facility, mass balances for the process (including estimation of transfer coefficients and
292 VS degradation values), measured emissions (mainly gaseous) to the environment, and
293 characterization and use of the outputs.

294

295 TABLE 4 - Estimated values for gaseous emissions from the composting process.
296

297 In normal operations, at the end of the composting process the material is
298 processed in a trommel screen with 8 mm and 25 mm sieves. The material with particle
299 size >25 mm (approximately 5 % ww) is incinerated in the nearby WTE plant. The
300 material with particle size between 8 and 25 mm (~10% ww) is recirculated and used as
301 structure material when establishing new windrows. The main fraction is compost
302 (particle size < 8 mm, ~85% ww), which is transported back to the RSs and sold to
303 citizens – either as compost or mixed with sandy soil. According to a user's survey

304 (Andersen et al., 2010c), compost is mainly used in private gardens partly substituting
305 for peat-based growth media and commercial N, -P, -K fertilizers.

306 The substitution of commercial fertilizers is modelled according to the nutrient
307 contents in compost and their utilization rate (Hansen et al., 2006). The complete
308 chemical-physical characterization of compost produced in Aarhus composting plant is
309 reported in Andersen et al. (2010a). Utilization rates are assumed to be 30% for N and
310 100 % for P and K (Hansen et al., 2006). Hence, the amount of substituted mineral
311 fertilizers per Mg of compost is: 1.64 kg N, 1.08 kg P, and 10.8 kg K. The study also
312 accounts for carbon still bound in the soil at the end of the 100 years time horizon. This
313 amounts to 14 % of the carbon inputs with compost, according to the modelling done by
314 Bruun et al. (2006) for Danish conditions. Bound carbon is credited to the system as
315 avoided CO₂ emissions.

316 From an LCA perspective, the use of compost in replacement of peat is
317 modelled on a 1:1 volume basis (Boldrin et al., 2010b). Thus, assuming that the average
318 densities of peat and compost in the Danish context are 200 kg/m³ and 760 kg/m³
319 respectively (Boldrin et al., 2010b), 1 Mg of compost substitutes 263 kg peat. All the
320 benefits and burdens of substituting peat with compost have been accounted for in
321 EASEWASTE according to Boldrin et al. (2010b). The substituted peat-profile includes
322 the four phases of peat life cycle: peatland preparation, extraction, transportation, and
323 use. The two materials (compost and peat) are compared taking into account the
324 different chemical compositions and the different leaching characteristics. Carbon
325 emitted as CO₂ from degradation of peat - during 100-years time frame of the
326 assessment – is considered a greenhouse gas (Boldrin et al., 2010b).

327 The actual use of compost by private citizens was reported by Andersen et al.,
328 2010c) based on interviews with compost users. Less than 50 % of the citizens using

329 compost in their garden were replacing peat or mineral fertilizers with compost. In an
330 LCA context, this means that the benefits from peat replacement are in reality smaller
331 than what is potentially possible if the compost is used in rational way. A 50%
332 substitution is modelled in EASEWASTE by assuming that 1 Mg of compost substitutes
333 131.5 kg peat (instead of 263 kg) and that only 50% of the N,P,K nutrients contained in
334 compost replace mineral fertilizers.

335

336 *4.4 Modelling of the thermal treatment*

337 Thermal treatment of waste is performed in the Aarhus WTE plant. The facility is
338 equipped with a furnace with a Combined Heat and Power (CHP) energy recovery
339 system. Cleaning of flue gas is done with a semidry (2 lines) and wet (1 line) systems.
340 Activated carbon is used for removal of Dioxin and Hg. NO_x is removed by SNCR. The
341 annual capacity is 240,000 Mg. The input of materials and energy to the process is
342 included. Details can be found in EASEWASTE (2008). The treatments of wastewater,
343 bottom ash, fly ash and sludge are not included in the assessment. The efficiency of the
344 plant is 20.7 % for electricity production and 74 % for heat production, calculated on
345 the Lower Heating Value (LHV) of the feedstock. Coal-based electricity and coal-based
346 heat are the marginal technologies for the energy produced in Aarhus WtE plant (Riber
347 et al., 2008; Fruergaard et al., 2010).

348

349 *4.5 Modelling of hard materials recycling*

350 The flow of materials sent to the C&D recycling is rather small (see later). In the
351 modelling it is assumed that the hard material is undergoing crushing. The use of the
352 resulting material (similar to gravel) is modelled to offset extraction of gravel and
353 crushed rock. The LCI dataset for such process is included in EASEWASTE (2008).

354 The modelling of this part of the system is considered uncertain, but, as seen later, it has
355 very little influence on the results.

356

357 *4.6 Modelling of home composting*

358 Home composting is supposed to be performed in private backyards. For the LCA-
359 modelling it is assumed that:

- 360 • No impurities are entered in the composters;
- 361 • There is only one solid output (compost);
- 362 • The degradation of VS in the waste is 40 %;

363 Because of lack of data, eventual leaching from the composters is not modelled.
364 Therefore, the only direct emissions from the process are in gaseous form (to
365 atmosphere). The magnitude of air emissions is reported in Table 4.

366

367 **5. Results**

368 In this section, results of the assessment are presented and the analysed scenarios are
369 compared. Due to lack of space, disaggregated LCA results are presented only for
370 Scenario 1. Similar results can be found in Boldrin et al. (2009) for the remaining
371 scenarios.

372 Figure 3 presents results for potential non-toxic impacts from the current
373 management of garden waste in Aarhus (Scenario 1). The composting facility is the
374 main potential source of environmental impacts (positive PE values). Contributions to
375 Global Warming come from greenhouse gases (GHGs) generated from combustion of
376 fuel (fossil CO₂) in heavy machineries (for example front loaders, excavators, shredder,
377 etc.) or during the composting process (CH₄ and N₂O). Significant contributions arise
378 also during collection (emissions of fossil CO₂) of garden waste because of the high fuel

379 consumption per Mg of waste in private cars. Potential impacts on Photochemical
380 Ozone Formation also originate mainly from the composting process, collection and
381 transportation, because of Volatile Organic Compounds (VOC), NO_x and CO emissions
382 during fuel combustion in engines.

383 The composting process is the main contributor to Nutrient Enrichment
384 (eutrophication). NO_x are emitted to air from fuel combustion during the use of heavy
385 machineries and ammonia (NH₃) evaporates from composting windrows. NO_x and NH₃
386 (together with SO₂ from engines) are also the main contributors to Acidification. The
387 use of compost in gardens results in some credits in Acidification due to savings in use
388 of peat. Replacement of mineral P fertilizer production by the use of compost results in
389 important savings in Nutrient Enrichment category (almost counterbalancing
390 detrimental impacts) as large discharges of P to freshwater are avoided.

391 The main credit (negative PE values) to the system originates from the use of
392 compost in substitution of peat, especially in terms of Global Warming (peat is
393 considered as fossil carbon, see section 4.3). The credit is mainly due to avoided use of
394 energy for extraction and production of peat.

395 The incineration of wood and foreign items also contributes with credits to the
396 system together with the stones that are routed to the C&D facility. The credits are due
397 to the electricity and heat produced by the WTE plant, offsetting the production of coal-
398 based energy elsewhere in the energy system. The credits exceed the loads to Global
399 Warming, meaning that the system “saves” approximately 98 PE (853 Mg CO₂-eq.)
400 with respect to global warming. All other non-toxic categories show net (loads) impacts.

401

402 FIGURE 3 - Potential non-toxic environmental impacts from the current management.

403

404 Figure 4 shows the potential toxic environmental impacts from the current
405 management of garden waste. The main potential impacts in Ecotoxicity in Water
406 originate from fossil fuel burning during collection, transportation and composting. The
407 main contributors to Ecotoxicity in Water are PAH, which are released when fossil fuel
408 is combusted, and strontium, which is emitted during the production of gasoline
409 (upstream process). Use of compost in gardens is the most important process in the
410 toxic categories. It has large contributions to Human Toxicity via Soil and Human
411 Toxicity via Water, mainly due to chromium and arsenic contained in the compost
412 materials. Smaller contributions originate also from mercury, lead and zinc contained in
413 compost.

414

415 FIGURE 4 - Potential toxic environmental impact from the current management.

416

417 Figure 5 and Figure 6 compare potential impacts arising from the six analysed
418 scenarios. For each of the impact categories, potential impacts originating from the
419 different processes have been aggregated into a single normalised indicator. The base
420 scenario (scenario 1) is the least environmentally favourable of all scenarios regarding
421 non-toxic categories. The introduction of both more incineration and home composting
422 could have potential improvements in all non-toxic impact categories.

423

424 FIGURE 5 – Comparison of potential non-toxic environmental impacts for analyzed
425 scenarios.

426

427 Compared to the current scenario, the introduction of home composting has
428 benefits in all non-toxic categories, mainly because of the avoided waste collection by

429 means of private cars, but they are small. The small contribution by home composting is
430 due to the small amount of garden waste being home-composted. Space availability in
431 backyards, size of the materials (large wood items may be too big for backyard
432 composters) and people's attitudes influence the actual amounts diverted. Another
433 second issue concerns the quality (e.g. maturation) and use (e.g. gardening) of compost
434 which could be very variable in case of home-composting and thus difficult to model.

435

436 Figure 6 – Comparison of potential toxic environmental impacts for analyzed scenarios.

437

438 Incineration of a larger fraction of the collected garden waste results in
439 significant improvements in most of the impact categories. The additional waste
440 incinerated results in potential savings in Global Warming from avoided production of
441 electricity and heat from fossil fuels (coal). Photochemical Ozone Formation is
442 improved with the introduction of incineration because of a reduction in VOC emissions
443 from heavy machineries used in the composting plant. On the other side, increased
444 incineration produces larger emissions of NO_x, resulting in a worse environmental
445 profile in Acidification and Nutrient Enrichment.

446 It is worth noting that the amount of garden waste that could be optimally
447 diverted to incineration is limited. For technical reasons, the ash content and the lower
448 heating value (LHV) restrict what can be incinerated (Boldrin & Christensen, 2010):

- 449 • The woody fraction and partly the fraction containing branches (may need sieving);
- 450 • All garden waste collected during winter (may need sieving).

451 In absolute terms, toxic categories show relatively high potential impacts on human
452 toxicity (via water and via soil) for all the scenarios. The dominant factor is the content
453 of heavy metals in compost. The LCA methodology estimates the potential toxic effects

454 based on the amount of heavy metals, without taking into account effective
455 concentrations. As presented in Andersen et al. (2010a), the compost produced in
456 Aarhus composting plant respects legal and quality standards regarding potential
457 pollutants (it is actually suitable for organic farming), meaning that compost can be used
458 on land without any significant risks. Seen from another perspective, most of the heavy
459 metals contained in compost were originally contained in the soil fraction (Boldrin &
460 Christensen, 2010) and therefore do not contribute to an increase of the background
461 concentration of heavy metals in the soil when the compost is spread on land. Therefore,
462 less emphasis should be put on the results for the toxic categories and it may be needed
463 in the future to develop another approach for characterization of the impact of heavy
464 metals in soils (Christensen et al., 2007).

465

466 *5.1. Sensitivity and uncertainty analysis*

467 A number of uncertain/assumed parameters were screened. Their uncertainty level was
468 qualitative assessed:

- 469 • The substitution rate between compost and peat is considered highly uncertain
470 because it is based on a precautionary assumption extrapolated from the user survey.
- 471 • The CH₄ emission during composting is based on precise and repeated
472 measurements, supported with a mass balance. The uncertainty is low.
- 473 • Nitrogen losses during composting (determining N₂O and NH₃ emissions) are
474 uncertain: the NH₃ measurements were inaccurate and the N balance was imprecise.
- 475 • Distance driven by means of private cars for delivery of garden waste to the
476 recycling stations was considered having medium level of uncertainty.

477 • The assumption regarding the type of energy which is substituted by the energy
478 produced in the WTE plant is considered rather robust. The assumption is supported
479 by studies done on the Danish energy systems.

480 A sensitivity test was performed to determine the influence of different parameters on
481 the results. The quantitative results of the sensitivity test are presented graphically in
482 Figure 7 and Figure 8, where variation intervals show the consequences of the changes
483 presented in Table 5.

484

485 TABLE 5 - Sensitivity test for different parameters and scenarios.

486 FIGURE 7 – Results of the sensitivity test for non-toxic impact categories.

487 FIGURE 8 – Results of the sensitivity test for toxic impact categories.

488

489 Critical parameters were determined combining information on their relevance
490 on the final result (according to the LCA results), the uncertainty evaluation and the
491 sensitivity analysis. According to Table 6, the most critical parameters were peat
492 substitution and the N degradation rate.

493

494 TABLE 6 - Results of the sensitivity and uncertainty analysis.

495

496 **6. Discussion and recommendations**

497 The current garden waste management system in Aarhus is finely organised and has
498 good environmental performances. Emissions and impacts rising from the current
499 garden waste treatment in Aarhus are quite small, in the order of few mPE per Mg of
500 waste treated. The environmental burdens of the current management are in the range -6
501 to 8 mPE/Mg of ww for the non-toxic categories and up to 100 mPE/Mg of ww for the

502 toxic categories. The potential impacts for non-toxic categories are much smaller than
503 what found for other types of municipal solid waste (e.g. Kirkeby et al., 2006a).

504 The study showed that the utilization of compost in private gardens in
505 substitution of commercial growth media potentially has important benefits for the
506 environment: actually utilization of compost represents in most cases the major credit to
507 the system. However, the actual substitution obtained by private use of compost in
508 gardens may be much less than the potential and it is critical in the future to obtain better
509 data on this aspects and maybe also educate the compost users so the benefits of using
510 compost are optimized.

511 The comparison of the six analysed scenarios did not show clear and large
512 differences in their environmental profile, so that a clear conclusion on the most
513 preferable solution could not be drawn. However, potential improvements in the current
514 as well as in alternative managements were defined. Emissions of GHG during the
515 composting process are the major contribution to global warming from the current
516 garden waste management. These emissions could potentially be limited with more
517 frequent turnings of the windrows and/or by establishing windrows of smaller size.

518 Incineration of some garden waste showed potential environmental benefits.
519 Anyway, it must be ensured that garden waste with specific characteristics (e.g. high
520 LHV and low ash content) is selected for the thermal treatment. The study showed that
521 if waste can be sorted out, then woody fractions can be incinerated with large benefits.
522 If it is considered to incinerate mixed garden waste, then the suitable waste is that being
523 received during the winter season (sieving may be needed). Increasing the share of
524 screen residues (recirculate) sent for energy recovery was also found to be potentially
525 beneficial. However, this would reduce the amount of structure material available for
526 the composting process.

527 The implementation of home composting could have some benefits (mainly for
528 the avoided collection), but no major improvements were found under the analysed
529 conditions. Also in this case, if home composting is being implemented, a good practice
530 for both process management and use of compost on soil should be ensured to obtain
531 the environmental benefits and reduce the environmental loads.

532

533 **7. Conclusion**

534 An environmental assessment of six scenarios for handling of garden waste in the
535 municipality of Aarhus (Denmark) was performed from a life cycle perspective by
536 means of the LCA-model EASEWASTE. In the first (basic) scenario, the current garden
537 waste management was assessed, while in the other five scenarios alternative solutions
538 including incineration and home composting of waste were evaluated.

539 The current garden waste management in Aarhus has good environmental
540 performances: impacts rising from waste treatment are in the order of a few mPE per
541 Mg of waste treated for non-toxic impact categories, which is several orders of
542 magnitude smaller than what is found for other fractions of municipal solid waste. The
543 environmental burdens of the current management are in the range -6 to 8 mPE Mg⁻¹
544 ww for the non-toxic categories and up to 100 mPE Mg⁻¹ ww for the toxic categories.

545 The study showed that some of the garden waste (may be up to 50%) can
546 potentially be diverted to alternative handling options. Incineration and home
547 composting seem suitable for such purpose, as long as the diverted waste has proper
548 characteristics.

549

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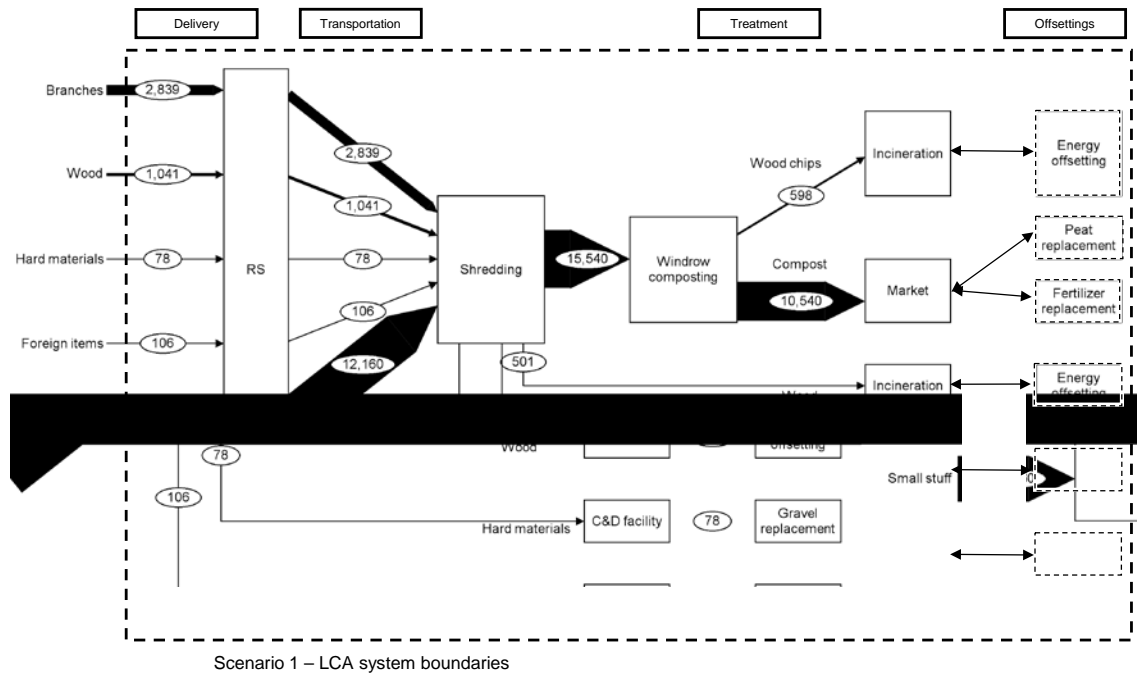
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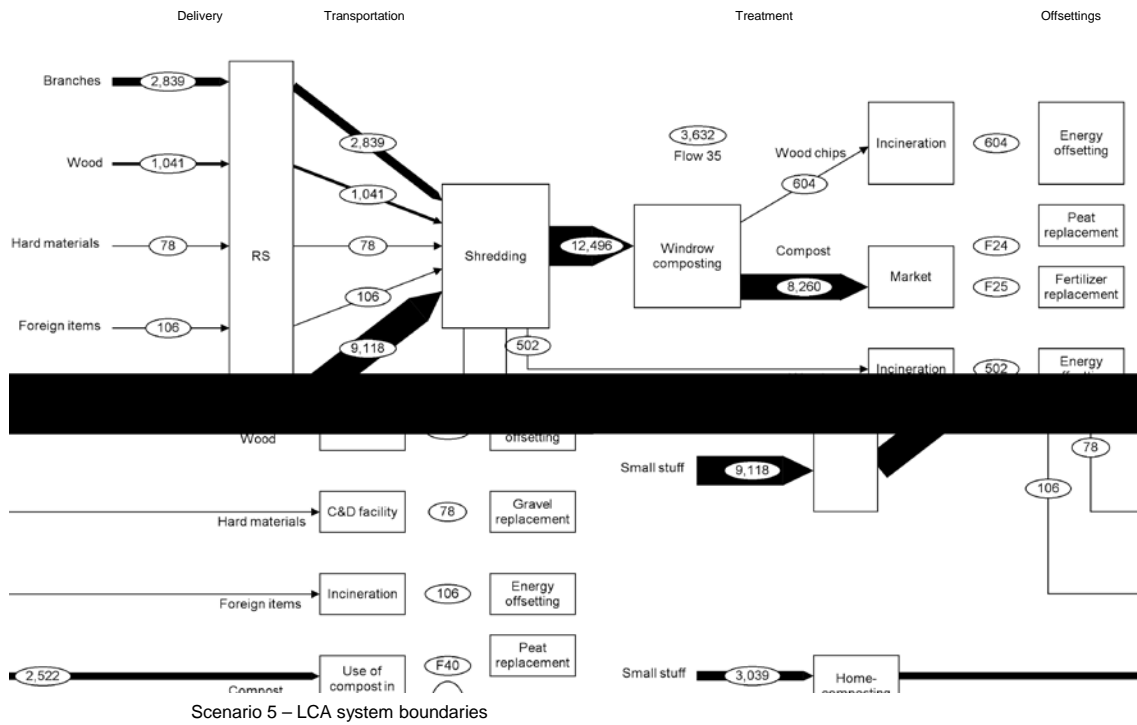
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 666 Figure 1 - LCA system boundaries for scenario 1 - Current management of garden
 667 waste. Material flows are expressed in Mg of ww. RS = recycling station
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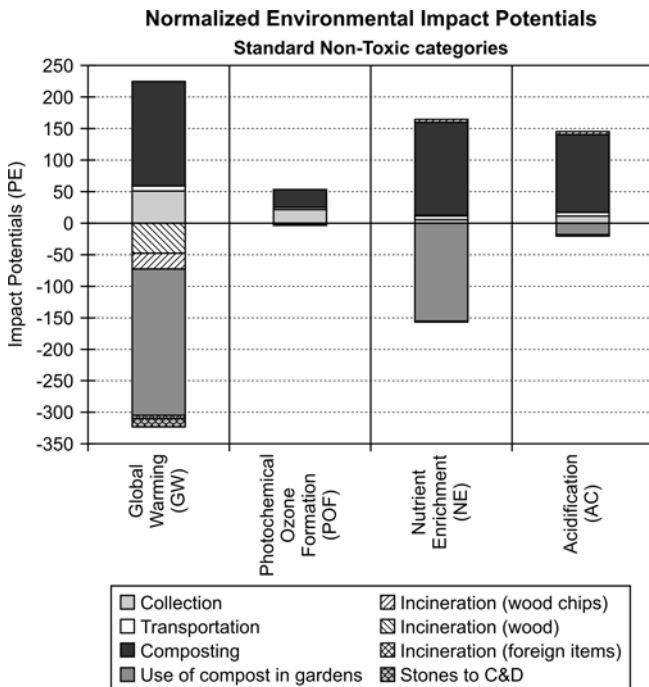
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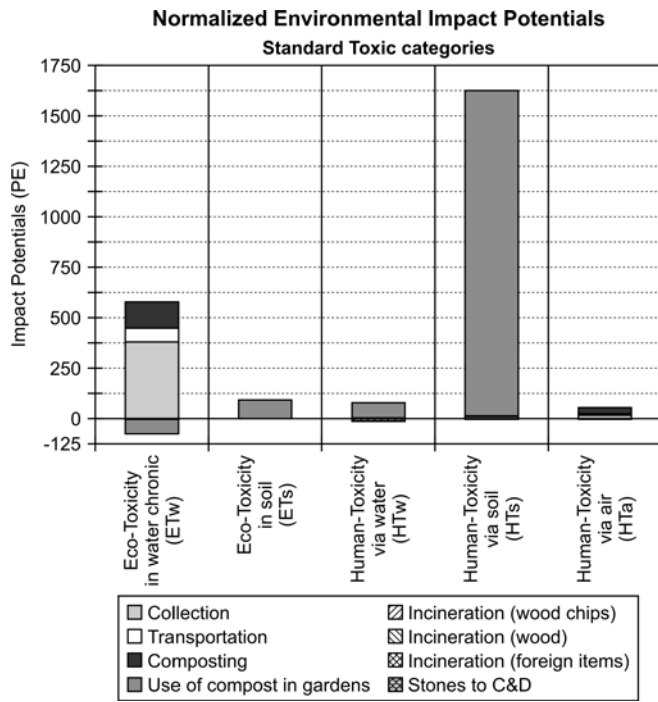
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Scenario 5 – LCA system boundaries
Figure 2 - LCA system boundaries for scenario 5 – Home composting. Material flows are expressed in Mg of ww. RS = recycling station

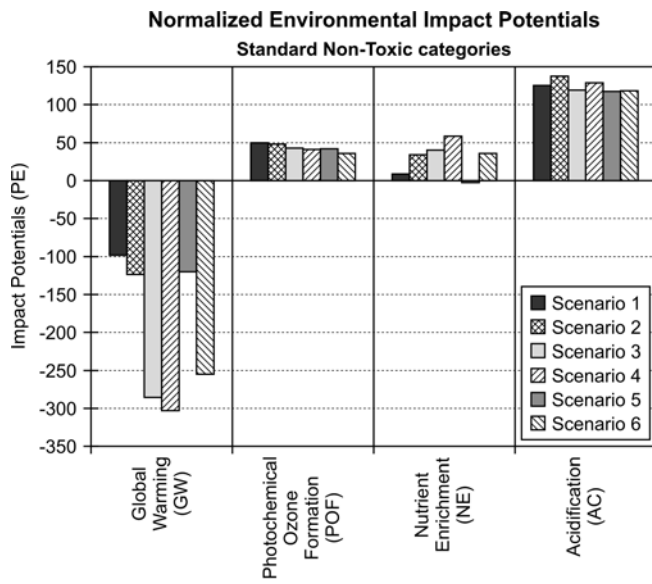


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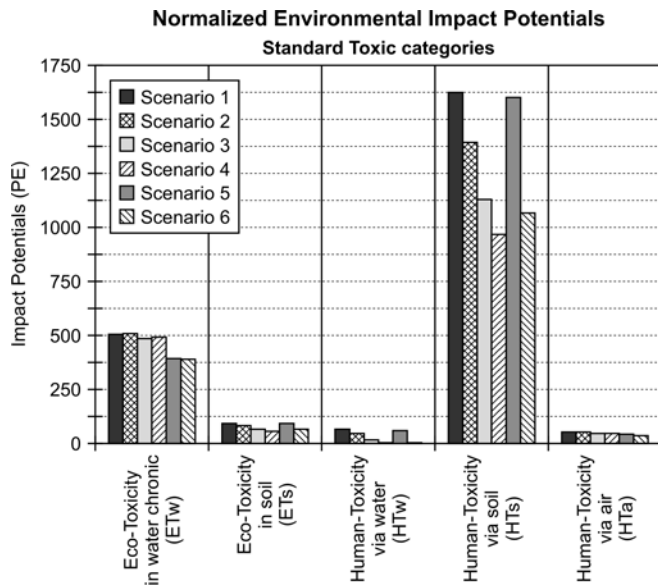
Figure 3 - Potential non-toxic environmental impacts from the current management of garden waste (16,220 Mg).



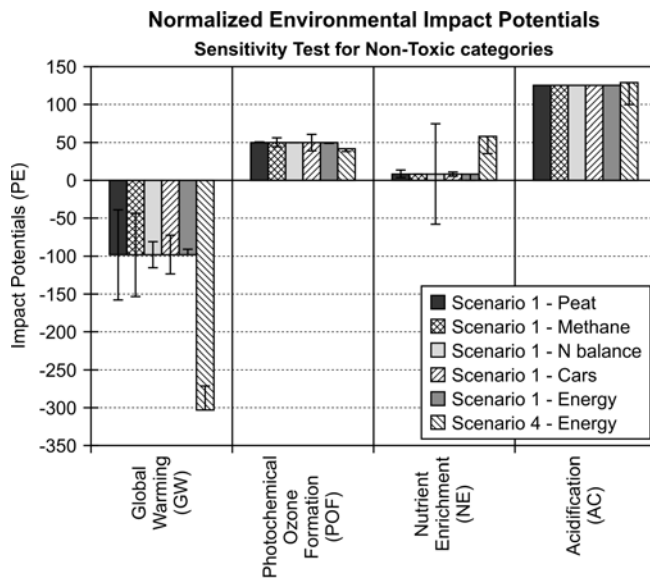
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 690 Figure 4 - Potential toxic environmental impact from the current management of garden
 691 waste (16,220 Mg).
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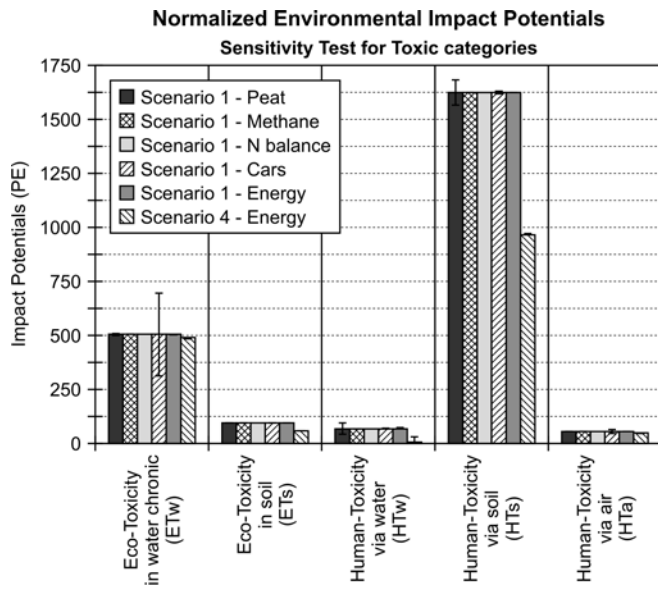
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 694 Figure 5 – Comparison of potential non-toxic environmental impacts for analysed
 695 scenarios (16,220 Mg of garden waste).
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705
 706 Figure 6 – Comparison of potential toxic environmental impacts for analysed scenarios
 707 (16,220 Mg of garden waste).
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712
 713 Figure 7 – Results of the sensitivity test for non-toxic impact categories.
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Figure 8 – Results of the sensitivity test for toxic impact categories.

722 Table 1 - Normalisation references for environmental impact categories in EDIP1997
 723 (Stranddorf et al., 2005)

Impact category	Geographical scale	Characterisation unit	Normalization reference [Characterisation unit/person/year]
<i>Non-toxic impacts</i>			
Global warming (GW)	Global	kg CO ₂ -equivalents	8.7·10 ³
Acidification (AC)	Regional	kg SO ₂ -equivalents	7.4·10 ¹
Nutrient enrichment (NE)	Regional	kg NO ₃ -equivalents	1.19·10 ²
Photochemical ozone formation (POF)	Regional	kg C ₂ H ₄ -equivalents	2.5·10 ¹
<i>Toxic impacts</i>			
Human toxicity via air	Local	m ³ air	6.09·10 ¹⁰
Human toxicity via water	Regional	m ³ water	5.22·10 ⁴
Human toxicity via soil	Regional	m ³ soil	1.27·10 ²
Ecotoxicity via water	Regional	m ³ water	3.52·10 ⁵
Ecotoxicity via soil	Regional	m ³ soil	9.64·10 ⁵

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727 Table 2 – Routing of primary and secondary waste flows for the analysed scenarios.
 728

Scenario	Treatment	Amount (Mg)	Fraction diverted
1	Central composting WTE (wood) WTE (rejects) Home composting	15,540 501 597 -	
2	Central composting WTE (wood) WTE (rejects) Home composting.	15,540 501 1,749 -	Recirculate (>8mm)
3	Central composting WTE (wood) WTE (rejects) Home composting.	11,410 4,631 440 -	Winter waste
4	Central composting WTE (wood) WTE (rejects) Home composting	11,410 4,631 1,276 -	Winter waste Recirculate (>8mm)
5	Central composting WTE (wood) WTE (rejects) Home composting	12,500 502 604 3,039	25% small stuff
6	Central composting WTE (wood) WTE (rejects) Home composting	9,233 4,017 1,035 3,039	Winter waste Recirculate (>8mm) 25% small stuff

Table 3 - Overview of different aspects considered in the assessment.

	Indirect: Upstream	Direct: Operation	Indirect: Downstream
Accounted	<ul style="list-style-type: none"> • Diesel provision. • Electricity provision. 	<ul style="list-style-type: none"> • Combustion of diesel for collection and transportation of garden waste. • Composting plant: <ul style="list-style-type: none"> - Gas emissions (CO₂-biogenic; CH₄; N₂O, CO, NH₃); - Combustion of diesel. • WTE plant: <ul style="list-style-type: none"> - Use of materials and energy needed for the combustion process; - Gas emissions from the stack. • C&D facility: <ul style="list-style-type: none"> - Combustion of diesel. • Home composting: <ul style="list-style-type: none"> - Gas emissions (CO₂-biogenic; CH₄; N₂O, NH₃). 	<ul style="list-style-type: none"> • Peat substitution: <ul style="list-style-type: none"> - Substitution of peat; - CO₂-biogenic from compost degradation; - C binding in soil; - N₂O from use-on-land; - Substitution of inorganic fertilizers. • Energy recovery in WTE plant: <ul style="list-style-type: none"> - Substitution of electricity; - Substitution of heat. • Material recovery in C&D facility: <ul style="list-style-type: none"> - Substitution of gravel and crushed rock extraction.
Non-accounted	<ul style="list-style-type: none"> ▪ Construction of treatment facilities and/or machineries. ▪ Provision of other materials (oil, detergents, lubricants etc.). ▪ Construction of plastic composters and plastic buckets for home composting. 	<ul style="list-style-type: none"> • Windrow composting plant and home-composting: <ul style="list-style-type: none"> - Any trace gas release; - Treatment of collected leachate. • WTE plant: <ul style="list-style-type: none"> - Treatment of wastewater, bottom ash, fly ash, and sludge from WTE plant 	<ul style="list-style-type: none"> • Improved soil quality from use-on-land of compost.

Table 4 - Estimated values for gaseous emissions from the composting process.

	Central composting	Home composting
Methane (CH₄)	2.7 % of degraded C *	3 % of degraded C **
Nitrous oxide (N₂O)	1.2 % of total N *	1.05 % of total N **
Ammonia (NH₃)	6.6 % of total N **	6.3 % of total N **
Carbon monoxide (CO)	0.34 % of degraded C *	0.04 % of total C **
* from Andersen et al. (2010b)		
** from Boldrin et al. (2009)		

Table 5 - Sensitivity test for different parameters and scenarios.

Test name	Tested scenario	Parameter changed	Change	From	To (+/-)	
Scenario 1 – peat	Scenario 1	Peat substitution	± 40 % (± 20 %)	131.5 kg (50%)	79 kg (30 %)	184 kg (70 %)
Scenario 1 – methane	Scenario 1	CH ₄ -C emissions	± 50 %	2.24 %	1.12 %	3.36 %
Scenario 1 – N balance	Scenario 1	N degradation	± 50 %	8 %	4 %	12 %
Scenario 1 – cars	Scenario 1	Gasoline consumption	± 50 %	8.9 l/km	13.4 l/km	4.4 l/km
Scenario 1 – energy	Scenario 1	Marginal electricity mix		Coal	Av. Danish mix	
Scenario 4 – energy	Scenario 4					

Table 6 - Results of the sensitivity and uncertainty analysis.

Parameter changed	Relevance on the LCA results	Uncertainty	Sensitivity
Peat substitution	Large	Large	GW: medium NE, HT: large
CH₄ emissions	Medium	Small	GW: medium
N degradation	Medium	Large	AC, NE: large
Gasoline consumption	Small	Medium	GW,AC,HT: medium POF,ET: large
Marginal electricity mix	Large	Small	AC,NE: medium HT: large