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

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Abstract

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

Keywords: garden waste, composting, integrated waste management, LCA, EASEWASTE.

Abbreviations:

C&D: Constructions & Demolition

CHP: Combined Heat and Power

GHG: Greenhouse Gases

GWP: Global Warming Potential

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LHV: Lower Heating Value

MFA: Material Flow Analysis

PAH: Polycyclic Aromatic Hydrocarbons

PE: Person Equivalent

RS: Recycling Station

SFA: Substance Flow Analysis

SNCR: Selective Non-Catalytic Reduction

VOC: Volatile Organic Compounds

VS: Volatile Solids

TS: Total Solids

U-O-D: Upstream-Operation-Downstream

WTE: Waste-To-Energy

ww: wet waste

1. Introduction

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

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

Environmental assessment studies comparing alternatives for garden waste management are almost non-existing in literature. Systematic environmental evaluations are thus needed to support rational decision-making processes at the local level concerning garden waste. LCA (Life Cycle Assessment) is a fairly exhaustive tool for collecting and evaluating data about the generation, collection and treatment of waste. LCA has been used in several studies for assessing waste management both at the system level (e.g. Kirkeby et al., 2006a; Zhao et al., 2009) and at the technology level (e.g. Manfredi & Christensen, 2008; Damgaard et al., 2009).

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

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

2. Materials and methods

Garden waste treatment can be considered as a service system, working in respect of the legislation and the environment. The primary service is thus the treatment of a given quantity of garden waste. As suggested by Bjarnadottir et al. (2002), the functional unit of this study was thus defined as: “Handling and treatment of 16,220 Mg of garden waste produced in Aarhus municipality and treated at the Aarhus garden waste composting plant in 2007”. The time horizon of the assessment is 100 years. Eventual allocations were done on a weight basis. The “zero burdens” assumption was made, since garden waste does not imply any production phase.

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

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

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

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

The Life Cycle Impact Assessment (LCIA) was performed based on the EDIP97 methodology (Wenzel et al., 1997). Results are presented as normalised impact potentials calculated according to normalization factors reported in Table 1 (Stranddorf et al., 2005), where 1 person equivalent (PE) represents the potential impact of an average person for one year including all aspects of life (housing, food, transport, etc.). Emissions of biogenic CO_2 are reported in the emission inventory, but accounted as neutral to global warming (GWP = 0) during the characterisation phase of the LCA, as suggested by Christensen et al. (2009).

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

3. Scenarios description

As shown in Figure 1, the compositing facility in the Municipality of Aarhus received and treated in 2007 16,220 tons of garden waste originating from public collection of private garden waste (2%), from private households delivered to collection stations (recycling stations, RSs) (64%), and from public areas and parks (34%). The composition of the garden waste is described in Boldrin & Christensen (2010) and the material fractions are shown in Figure 1.

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

- *Scenario 1 - Current management.* After the initial sorting, all the collected garden waste is composted (15,540 Mg). The screen residue >25 mm are sent to incineration (597 Mg), the residues with size between 8 mm and 25 mm are re-entered in the compost process (recirculated) as structure material. This fraction is estimated to be approximately 1,300 Mg, or about 10%. Large items of wood screened out during shredding operations and sent to incineration amounts to 501 Mg.
- *Scenario 2 - Composting and incineration of rejects.* After the initial sorting, all the collected garden waste is composted (15,540 Mg), but the screen residues >8mm (1,749 Mg) are in this scenario sent to incineration in Aarhus WTE plant (in Scenario 1 screen residues were recirculated).
- *Scenario 3 - Composting and seasonal incineration of waste*. All garden waste received during the winter months (December, January, and February) is incinerated – only hard materials are removed. Boldrin & Christensen (2010) showed that

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

- *Scenario 4 – Maximum incineration of garden waste*. Garden waste received in winter period, screen residues >8 mm and large items of wood are incinerated (5,907 Mg including 1,276 Mg of screen residues >8 mm). Remaining waste is composted (11,410 Mg). No recirculation is assumed in this scenario.
- *Scenario 5 - Home composting*. A part of the generated garden waste is treated in private gardens (home composting). It is assumed that 25% of the "small stuff" fraction (small branches, leaves, grass, soil etc.) will be composted in private gardens (3,039 Mg) – i.e. the total mass of waste undergoing central composting is decreased by 19%. This implies reduced transportation of waste (both to recycling stations (RSs) by citizens and between RSs and the composting facility). Large items of wood (502 Mg) and screen residues >25 mm (604 Mg) are incinerated.
- *Scenario 6 – Home composting and maximum incineration*. 25 % of the "small stuff" fraction is composted in private gardens (3,039 Mg) and transportation is reduced. Garden waste received in winter period, screen residues > 8 mm and large items of wood are incinerated (5,052 Mg, of which 1,035 Mg are screen residues). The remaining waste is composted (9,233 Mg).

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

FIGURE 1 - LCA system boundaries for scenario 1.

FIGURE 2 - LCA system boundaries for scenario 5.

4. Inventory and modelling of relevant data

The following sections describe how the collected data are modelled in the assessment. Loads and savings are described as "direct", when they originate directly from the operation of the garden waste treatment facilities, and "indirect" when they, although associated with garden waste management, take place outside the actual treatment facility. The indirect aspects are further distinguished in upstream (e.g. provision of energy to the treatments facilities) or downstream (e.g. substitution of inorganic fertilizers by compost) contributions. An overview of different aspects included in the assessment is summarized in Table 3 according to the Upstream-Operation-Downstream (U-O-D) concept (Gentil et al., 2009).

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

4.1 Collection and transportation distances

In the Municipality of Aarhus, citizens deliver garden waste by car to six recycling stations (RSs). The average distance between households and the RSs is 4.5 km and it was estimated from a user survey that was carried out at one of the RSs (Lystrupvej). Including a return trip (delivery of garden waste is in many cases not combined with other activities), the average driven distance is thus 2*4.5 km (9 km in total). The gasoline consumption for waste delivery (collection) is hence estimated to be 8.9 l Mg^{-1} of wet waste (ww) (Andersen et al., 2010a).

The average transportation distance between the RSs and the composting plant was calculated considering the amount of waste (number of loads) delivered from each

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

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

4.2 Garden waste composition

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

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

4.3 Modelling of the composting treatment

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

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

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

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

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

The substitution of commercial fertilizers is modelled according to the nutrient contents in compost and their utilization rate (Hansen et al., 2006). The complete chemical-physical characterization of compost produced in Aarhus composting plant is reported in Andersen et al. (2010a). Utilization rates are assumed to be 30% for N and 100 % for P and K (Hansen et al., 2006). Hence, the amount of substituted mineral fertilizers per Mg of compost is: 1.64 kg N, 1.08 kg P, and 10.8 kg K. The study also accounts for carbon still bound in the soil at the end of the 100 years time horizon. This amounts to 14 % of the carbon inputs with compost, according to the modelling done by Bruun et al. (2006) for Danish conditions. Bound carbon is credited to the system as avoided CO_2 emissions.

From an LCA perspective, the use of compost in replacement of peat is modelled on a 1:1 volume basis (Boldrin et al., 2010b). Thus, assuming that the average densities of peat and compost in the Danish context are 200 kg/m^3 and 760 kg/m^3 respectively (Boldrin et al., 2010b), 1 Mg of compost substitutes 263 kg peat. All the benefits and burdens of substituting peat with compost have been accounted for in EASEWASTE according to Boldrin et al. (2010b). The substituted peat-profile includes the four phases of peat life cycle: peatland preparation, extraction, transportation, and use. The two materials (compost and peat) are compared taking into account the different chemical compositions and the different leaching characteristics. Carbon emitted as CO_2 from degradation of peat - during 100-years time frame of the assessment – is considered a greenhouse gas (Boldrin et al., 2010b).

The actual use of compost by private citizens was reported by Andersen et al., 2010c) based on interviews with compost users. Less than 50 % of the citizens using compost in their garden were replacing peat or mineral fertilizers with compost. In an LCA context, this means that the benefits from peat replacement are in reality smaller than what is potentially possible if the compost is used in rational way. A 50% substation is modelled in EASEWASTE by assuming that 1 Mg of compost substitutes 131.5 kg peat (instead of 263 kg) and that only 50% of the N,P,K nutrients contained in compost replace mineral fertilizers.

4.4 Modelling of the thermal treatment

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

4.5 Modelling of hard materials recycling

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

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

4.6 Modelling of home composting

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

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

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

5. Results

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

Figure 3 presents results for potential non-toxic impacts from the current management of garden waste in Aarhus (Scenario 1). The composting facility is the main potential source of environmental impacts (positive PE values). Contributions to Global Warming come from greenhouse gases (GHGs) generated from combustion of fuel (fossil CO_2) in heavy machineries (for example front loaders, excavators, shredder, etc.) or during the composting process (CH_4 and N_2O). Significant contributions arise also during collection (emissions of fossil CO_2) of garden waste because of the high fuel consumption per Mg of waste in private cars. Potential impacts on Photochemical Ozone Formation also originate mainly from the composting process, collection and transportation, because of Volatile Organic Compounds (VOC), NO_x and CO emissions during fuel combustion in engines.

The composting process is the main contributor to Nutrient Enrichment (eutrophication). NO_x are emitted to air from fuel combustion during the use of heavy machineries and ammonia (NH_3) evaporates from composting windrows. NO_x and NH_3 (together with SO_2 from engines) are also the main contributors to Acidification. The use of compost in gardens results in some credits in Acidification due to savings in use of peat. Replacement of mineral P fertilizer production by the use of compost results in important savings in Nutrient Enrichment category (almost counterbalancing detrimental impacts) as large discharges of P to freshwater are avoided.

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

The incineration of wood and foreign items also contributes with credits to the system together with the stones that are routed to the C&D facility. The credits are due to the electricity and heat produced by the WTE plant, offsetting the production of coal-based energy elsewhere in the energy system. The credits exceed the loads to Global Warming, meaning that the system “saves” approximately 98 PE (853 Mg CO_2-eq.) with respect to global warming. All other non-toxic categories show net (loads) impacts.

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

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

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

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

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

Compared to the current scenario, the introduction of home composting has benefits in all non-toxic categories, mainly because of the avoided waste collection by means of private cars, but they are small. The small contribution by home composting is due to the small amount of garden waste being home-composted. Space availability in backyards, size of the materials (large wood items may be too big for backyard composters) and people's attitudes influence the actual amounts diverted. Another second issue concerns the quality (e.g. maturation) and use (e.g. gardening) of compost which could be very variable in case of home-composting and thus difficult to model.

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

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

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

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

In absolute terms, toxic categories show relatively high potential impacts on human toxicity (via water and via soil) for all the scenarios. The dominant factor is the content of heavy metals in compost. The LCA methodology estimates the potential toxic effects based on the amount of heavy metals, without taking into account effective concentrations. As presented in Andersen et al. (2010a), the compost produced in Aarhus composting plant respects legal and quality standards regarding potential pollutants (it is actually suitable for organic farming), meaning that compost can be used on land without any significant risks. Seen from another perspective, most of the heavy metals contained in compost were originally contained in the soil fraction (Boldrin & Christensen, 2010) and therefore do not contribute to an increase of the background concentration of heavy metals in the soil when the compost is spread on land. Therefore, less emphasis should be put on the results for the toxic categories and it may be needed in the future to develop another approach for characterization of the impact of heavy metals in soils (Christensen et al., 2007).

5.1. Sensitivity and uncertainty analysis

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

- The substitution rate between compost and peat is considered highly uncertain because it is based on a precautionary assumption extrapolated from the user survey.
- The CH_4 emission during composting is based on precise and repeated measurements, supported with a mass balance. The uncertainty is low.
- Nitrogen losses during composting (determining N_2O and NH_3 emissions) are uncertain: the NH_3 measurements were inaccurate and the N balance was imprecise.
- Distance driven by means of private cars for delivery of garden waste to the recycling stations was considered having medium level of uncertainty.

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

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

TABLE 5 - Sensitivity test for different parameters and scenarios.

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

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

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

TABLE 6 - Results of the sensitivity and uncertainty analysis.

6. Discussion and recommendations

The current garden waste management system in Aarhus is finely organised and has good environmental performances. Emissions and impacts rising from the current garden waste treatment in Aarhus are quite small, in the order of few mPE per Mg of waste treated. The environmental burdens of the current management are in the range -6 to 8 mPE/Mg of ww for the non-toxic categories and up to 100 mPE/Mg of ww for the toxic categories. The potential impacts for non-toxic categories are much smaller than what found for other types of municipal solid waste (e.g. Kirkeby et al., 2006a).

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

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

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

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

7. Conclusion

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

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

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

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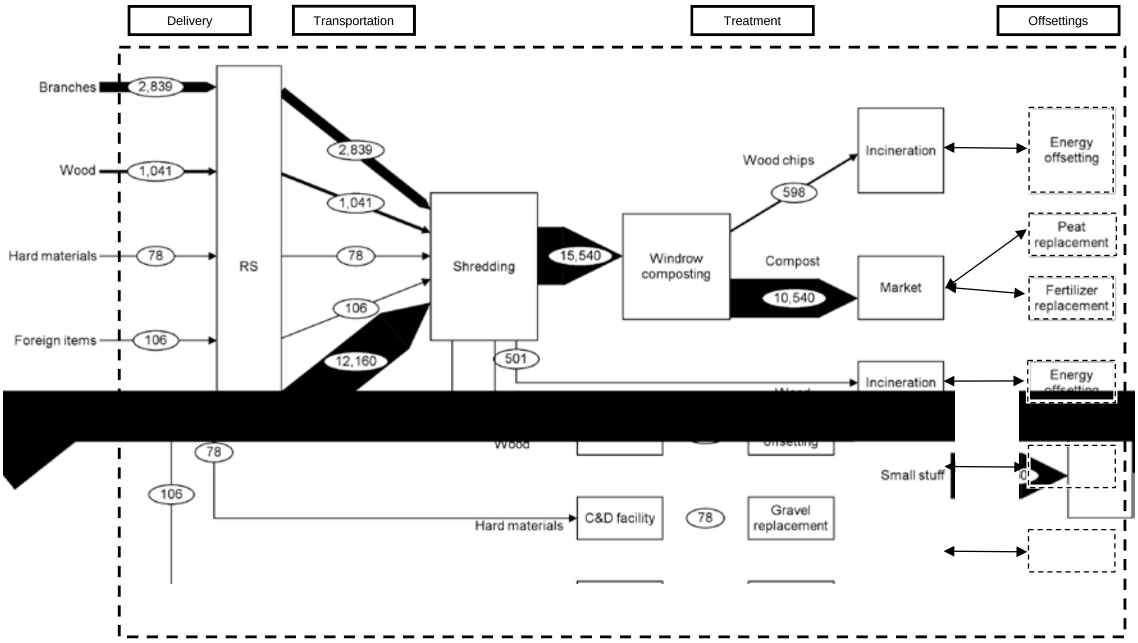
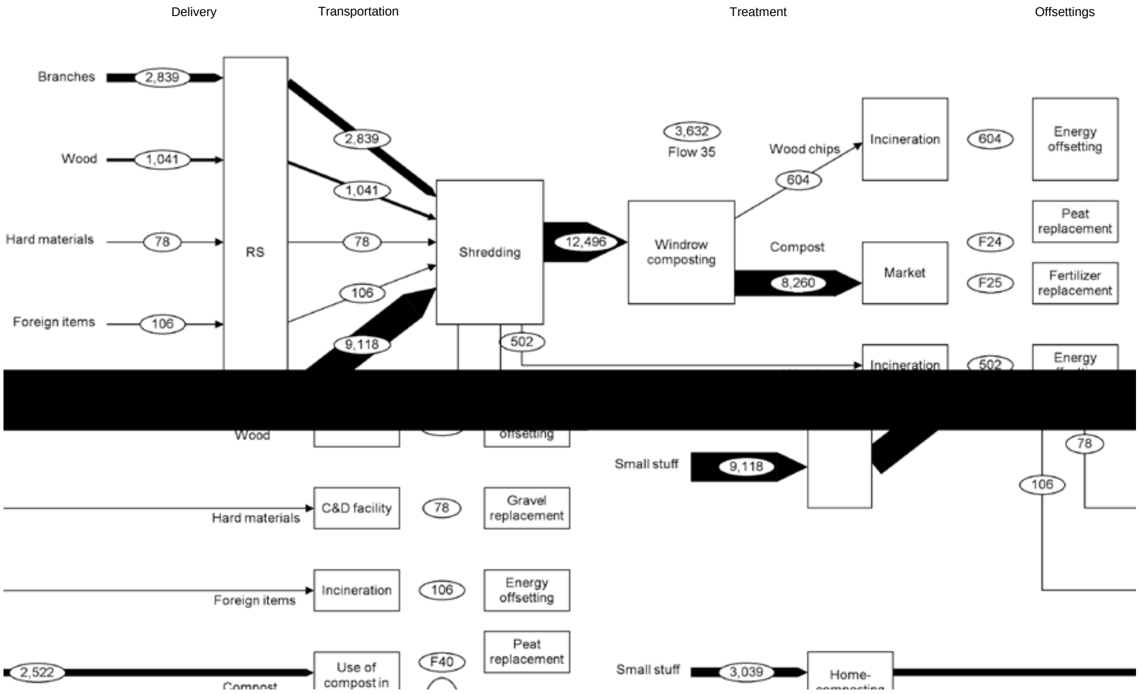


Scenario 1 – LCA system boundaries

Figure 1 - LCA system boundaries for scenario 1 - Current management of garden waste. Material flows are expressed in Mg of ww. RS = recycling station



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

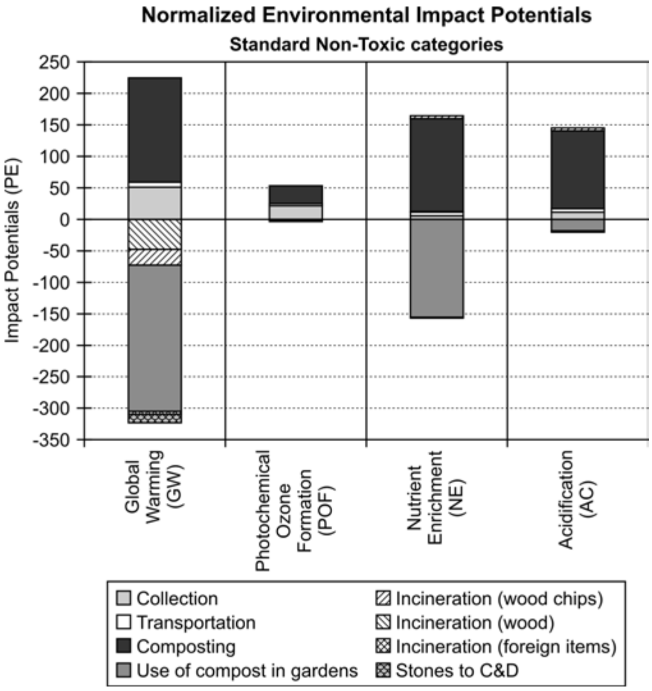


Figure 3 - Potential non-toxic environmental impacts from the current management of garden waste (16,220 Mg).

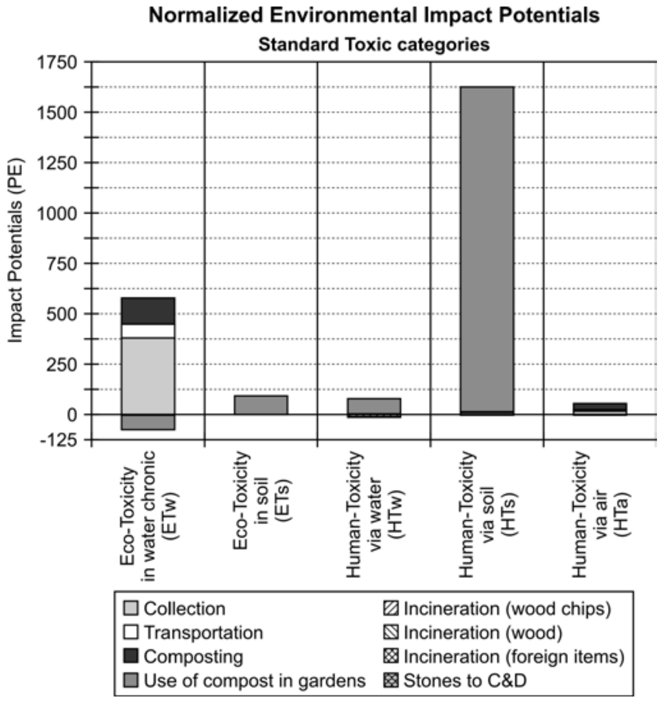


Figure 4 - Potential toxic environmental impact from the current management of garden waste (16,220 Mg).

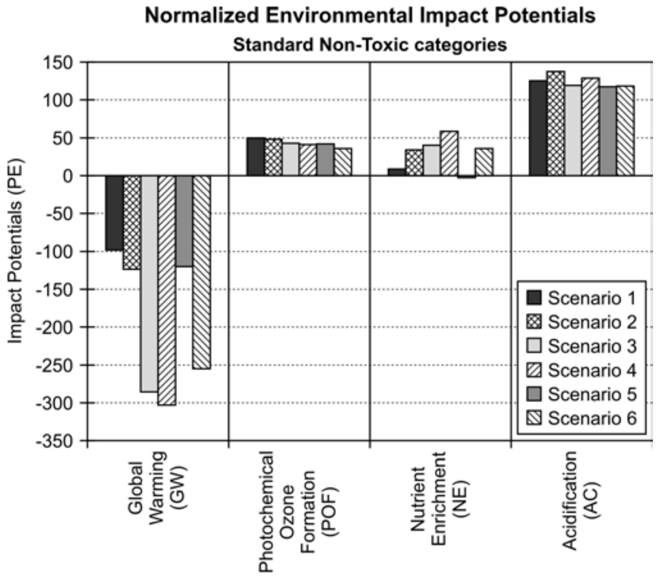


Figure 5 – Comparison of potential non-toxic environmental impacts for analysed scenarios (16,220 Mg of garden waste).

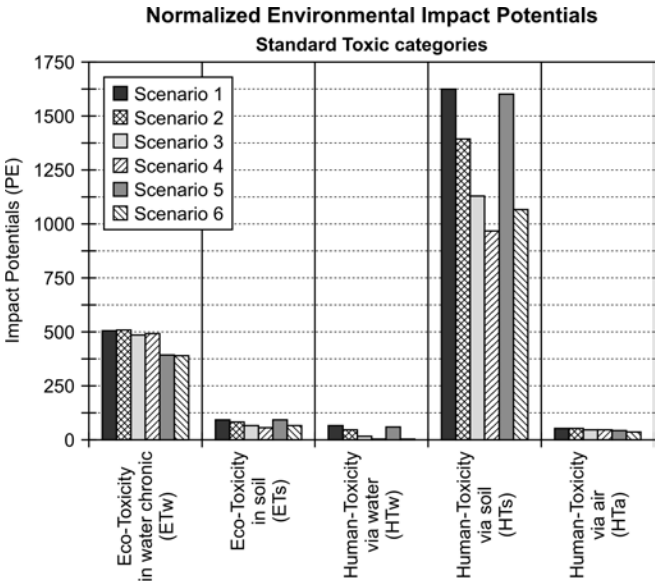


Figure 6 – Comparison of potential toxic environmental impacts for analysed scenarios (16,220 Mg of garden waste).

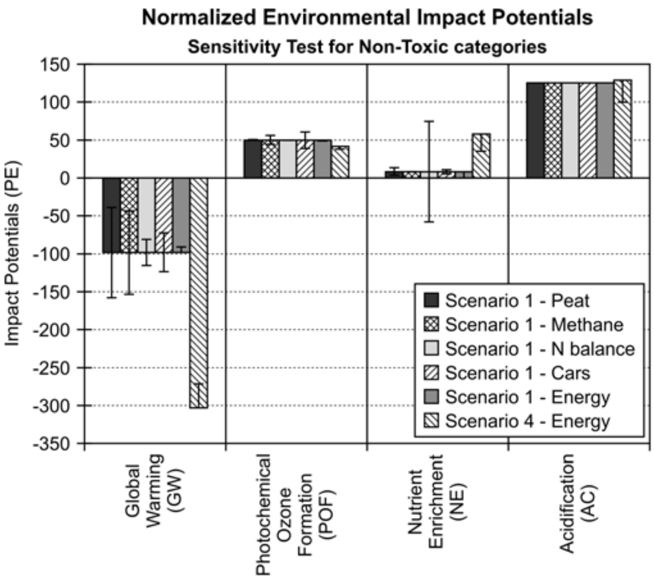


Figure 7 – Results of the sensitivity test for non-toxic impact categories.

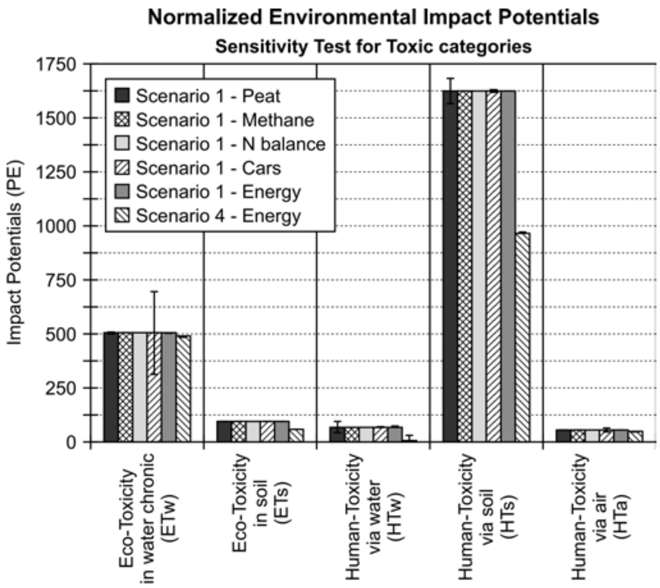


Figure 8 – Results of the sensitivity test for toxic impact categories.

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

Impact category	Geographical scale	Characterisation unit	Normalization reference [Characterisation unit/person/year]
Non-toxic impacts			
Global warming (GW)	Global	kg CO_2-equivalents	$8.7 \cdot 10^{3}$
Acidification (AC)	Regional	kg SO_2-equivalents	$7.4 \cdot 10^{1}$
Nutrient enrichment (NE)	Regional	kg NO_3-equivalents	$1.19 \cdot 10^{2}$
Photochemical ozone formation (POF)	Regional	kg C_2H_4-equivalents	$2.5 \cdot 10^{1}$
Toxic impacts			
Human toxicity via air	Local	m^3 air	$6.09 \cdot 10^{10}$
Human toxicity via water	Regional	m^3 water	$5.22 \cdot 10^{4}$
Human toxicity via soil	Regional	m^3 soil	$1.27 \cdot 10^{2}$
Ecotoxicity via water	Regional	m^3 water	$3.52 \cdot 10^{5}$
Ecotoxicity via soil	Regional	m^3 soil	$9.64 \cdot 10^{5}$

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

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

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

	Indirect: Upstream	Direct: Operation	Indirect: Downstream
Accounted	• Diesel provision. • Electricity provision.	• Combustion of diesel for collection and transportation of garden waste. • Composting plant: - Gas emissions (CO_2-biogenic; CH_4; N_2O, CO, NH_3); - Combustion of diesel. • WTE plant: - Use of materials and energy needed for the combustion process; - Gas emissions from the stack. • C&D facility: - Combustion of diesel. • Home composting: - Gas emissions (CO_2-biogenic; CH_4; N_2O, NH_3).	• Peat substitution: - Substitution of peat; - CO_2-biogenic from compost degradation; - C binding in soil; - N_2O from use-on-land; - Substitution of inorganic fertilizers. • Energy recovery in WTE plant: - Substitution of electricity; - Substitution of heat. • Material recovery in C&D facility: - Substitution of gravel and crushed rock extraction.
Non-accounted	▪ 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.	• Windrow composting plant and home-composting: - Any trace gas release; - Treatment of collected leachate. • WTE plant: - Treatment of wastewater, bottom ash, fly ash, and sludge from WTE plant	• 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 (CH_4)	2.7 % of degraded C *	3 % of degraded C **
Nitrous oxide (N_2O)	1.2 % of total N *	1.05 % of total N **
Ammonia (NH_3)	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
CH_4 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