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Environmental assessment of different management options for individual waste fractions by means of life-cycle assessment modelling

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ABSTRACT

Several alternatives exist for handling of individual waste fractions, including recycling, incineration and landfilling. From an environmental point of view, the latter is commonly considered as the least desirable option. Many studies based on life-cycle assessment (LCA) highlight the environmental benefits offered by incineration and especially by recycling. However, the landfilling option is often approached unjustly in these studies, maybe disregarding the remarkable technological improvements that landfills have undergone in the last decades in many parts of the world.

This study, by means of LCA-modelling, aims at comparing the environmental performance of three major management options (landfilling, recycling and incineration or composting) for a number of individual waste fractions. The landfilling option is here approached comprehensively, accounting for all technical and environmental factors involved, including energy generation from landfill gas and storage of biogenic carbon. Leachate and gas emissions associated to each individual waste fraction have been estimated by means of a mathematical modelling. This approach towards landfilling emissions allows for a more precise quantification of the landfill impacts when comparing management options for selected waste fractions.

Results from the life-cycle impact assessment (LCIA) show that the environmental performance estimated for landfilling with energy recovery of the fractions "organics" and "recyclable paper" is comparable with composting (for "organics") and incineration (for "recyclable paper"). This however requires high degree of control over gas and leachate emissions, high gas collection efficiency and extensive gas utilization at the landfill. For the other waste fractions, recycling and incineration are favourable, although specific emissions of a variety of toxic compounds (VOCs, PAHs, NO_x, heavy metals, etc.) may significantly worsen their environmental performance.

1. Introduction

Since the early 1990s, life cycle thinking (LCT) based models have been applied to the assessment of waste management systems (Morrisey and Browne, 2004; Björklund et al., 2010) and are nowadays regarded as major decision support tools, also within this sector. Some of these can model the environmental performance of complete waste management systems (from waste generation to final disposal), as for instance EPIC/CSR (Haight, 1999, 2004), ISWM DST (Weitz et al., 1999; Solano et al., 2002a, b), IWM2 (Mc Dougall, 2000), LCA-IWM (Den Boer et al., 2005a,b, 2007), ORWARE (Dalemo et al., 1997; Eriksson et al., 2002), WISARD (jointly developed by the UK EPA and Ecobilan: www.ecobalance.com/uk_wisard.php), WRATE (Thomas and McDougall, 2005; Gentil et al., 2005; Coleman, 2006) and EASEWASTE (Kirkeby et al., 2006, 2007). EASEWASTE (Environmental Assessment of Solid Waste Systems and Technologies), which is one of the few models that can assess individual waste fractions, has been used to perform the LCA calculations included in this study.

A growing issue in waste management is the identification of the best treatment and disposal option for individual waste fractions as source separation of material fractions like paper, glass, plastic, metals and organics are introduced in many cities around the world. A comprehensive international review of studies using life-cycle-assessment (LCA) for comparison of recycling, incineration and landfilling of individual waste fractions was carried out by the "Waste & Resources Action Program" and the Technical University of Denmark (DTU) and was published in a report titled "Environmental benefits of recycling" (WRAP, 2006). It was found that, in most cases, recycling is the best options (156 out of 188 scenarios included), as it typically offers more environmental benefits and lower impacts than other options. However, several of the studies were some years old and the incineration technology and the landfilling technology represented in the studies were not necessarily

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Table 1
Waste fractions and sub-fractions included in the study, mass distribution in the mixed waste (%), water content (H_2O, % of wet waste) decomposition factor (*D*, as % of wet waste fraction), biogenic carbon (Bio-C, as kg C/tonne wet waste fraction) and methane potential (M, as Nm^3 CH_4/tonne wet waste fraction) (Manfredi et al., 2009; US EPA, 2006).

Fraction	Waste sub-fractions	H_2O	D	Bio-C	M
Organics	Vegetable waste, animal waste, kitchen tissues	70	86.5	110	117
Recyclable paper	Magazines, advertisements, books and phonebooks, office paper, other clean paper, paper and carton containers, cardboard	8	40	340	115
Recyclable plastic	Soft plastic, hard plastic, plastic bottles	12	1	Negligible	Negligible
Aluminium	Al containers, Al trays/foil	8	50	Negligible	Negligible
Glass	Clear glass, green glass, brown glass, other glass	5	1	Negligible	Negligible

reflecting up-to-date technologies and thus may not offer justice to the alternatives to recycling. Global warming potentials are often a key impact category in LCA-studies and optimal energy recovery from incineration and from utilization of landfill gas (LFG) are crucial for the performance of these two technologies. In addition, not all LCA-studies assuming biogenic CO_2 as neutral with respect to global warming, paid attention to the fact that this assumption tacitly demands that stored biogenic carbon should be considered a saving with respect to global warming and thus assigned a negative global warming potential (Christensen et al., 2009a). This fact would *per se* improve the global warming profile of the landfill.

The objective of this study is to compare the environmental performance of the three major management options (landfilling, incineration or recycling/composting) for a number of individual waste fractions, namely: organics, recyclable paper, recyclable plastic, aluminium and glass (Table 1). The leachate and gas emissions from landfilling of the individual waste fractions have been estimated by means of a mathematical model. The results of the modelling have been used as LCIA inputs for the subsequent comparative life cycle assessment. For recycling, composting and incineration representative up-to-date technologies taken from the EASEWASTE database have been used.

2. Life cycle assessment modelling

2.1. Structure, boundary and assumptions

The functional unit of the LCA is treatment (landfilling, incineration and recycling/composting) of 1 tonne of wet individual waste fraction and the environmental aspects were assessed for 100 years, starting from the moment where the individual waste fraction is treated (for incineration, recycling and composting) or landfilled. The waste entering the treatment facilities is assumed to be “burden free” (no-impact is carried on by the waste itself before being treated). Waste collection and subsequent transportation to the treatment facilities (landfill, recycling industry or composting plants, incinerator) were not included. Emissions and avoided emissions for production of electricity were based on data from the International Reference Life Cycle Data System (ILCD, 2008) and considered applicable for the countries of the Union for the Co-ordination of Transmission of Electricity (UCTE).

It has to be pointed out that the waste fractions included in the study were either recyclable (recyclable paper, recyclable plastic, aluminium and glass) or compostable (organics). This was done in order for the LCA comparison to include all 3 treatment options (landfilling, incineration and recycling or composting) for each individual fraction, which otherwise would not have been possible with non-recyclable or non-compostable fractions. The drawback of this choice is that it does not give credit to the treatment options landfilling and incineration that could handle all types of waste fractions, including those not recyclable. Furthermore, this choice also implies that all the individual waste fractions included in the study do not need any pre-treatment or up-grading, since only the recyclable (or compostable) materials are selected and included in the assessment. Table 2 gives an overview of the LCA-scenarios modelled for each fraction.

The environmental evaluation included several impact categories embracing potential burdens to air, soil, surface- and ground-water bodies and also including potential hazards to humans (Table 3). These categories are often divided into two groups: standard environmental impact categories (Global Warming – GW, Photo-chemical Ozone Formation – POF, Stratospheric Ozone Depletion – SOD, Acidification – AC, and Nutrient Enrichment – NE) and toxicity-related environmental impact categories (Ecotoxicity in soil – ETs and in water (chronic) – ETwc, and Human Toxicity via soil – HTs, via water – HTw, and via air – HTa).

In the LCA-modelling it was assumed that emissions of biogenic carbon dioxide are neutral with respect to GW. With respect to landfilling, this dictates that biogenic carbon left in the landfill after the LCA time horizon considered (100-year) is considered as an avoided emission of carbon dioxide and therefore a negative contribution to GW (a saving) was assigned (Christensen et al., 2009a,b). The Global Warming Potential (GWP, as kg $CO_{2\text{-eq}}$/kg C left in the landfill) of the biogenic carbon left undegraded in the landfill is set to $-44/12$ kg $CO_{2\text{-eq}}$/kg $C_{BiogenicLeft}$. Considering biogenic CO_2 emitted as neutral with respect to GW also dictates that non-biogenic C (e.g. in plastic and rubber) left in the landfill is neutral with respect to GW (Christensen et al., 2009a).

Table 2
List of the scenarios included in the LCA comparison.

Waste fraction	Scenario name	Technology used (from the EASEWASTE database)
Organics	Incineration	Grate furnace incinerator
	Landfilling	Conventional landfill (flares)
	Landfilling	Conventional landfill (electricity)
	Recycling	Composting and use on land
Recyclable paper	Incineration	Grate furnace incinerator
	Landfilling	Conventional landfill (FLARES)
	Landfilling	Conventional landfill (electricity)
	Recycling	Coreboard, Skjern Papirfabrik, Denmark
Recyclable plastic	Incineration	Grate furnace incinerator
	Landfilling	Conventional landfill (leachate management only)
	Recycling	Melting of clean PE (LD and HD) plastic to granulated plastic foam (plastic granulation)
Aluminium	Incineration	Grate furnace incinerator
	Landfilling	Conventional landfill (leachate management only)
	Recycling	Melting and alloying of aluminium scrap
Glass	Incineration	Grate furnace incinerator
	Landfilling	Conventional landfill (leachate management only)
	Recycling	Cleaning of reusable glass bottles (35%) and melting of glass cullet and production of new glass products (65%)