THE USE OF LIFE CYCLE ASSESSMENT FOR THE COMPARISON OF BIOWASTE COMPOSTING AT HOME AND FULL SCALE

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Abstract

Environmental impacts and gaseous emissions associated to home and industrial composting of the source-separated organic fraction of municipal solid waste have been evaluated using the environmental tool of Life Cycle Assessment (LCA). Experimental data of both scenarios were experimentally collected. The functional unit used was one ton of organic waste. Ammonia, methane and nitrous oxide released from home composting (HC) were more than 5 times higher than those of industrial composting (IC) but the latter involved within 2 and 53 times more consumption or generation of transport, energy, water, infrastructures, waste and Volatile Organic Compounds (VOCs) emissions than HC. Therefore, results indicated that IC was more impacting than HC for four of the impact categories considered (abiotic depletion, ozone layer depletion, photochemical oxidation and cumulative energy demand) and less impacting for the other three (acidification, eutrophication and global warming). Production of composting bin and gaseous emissions are the main responsible for the HC impacts, whereas for IC the main contributions come from collection and transportation of organic waste, electricity consumption, dumped waste and VOCs emission. These results suggest that HC may be an interesting alternative or complement to IC in low density areas of population.

Keywords: life cycle assessment; environmental impacts; organic fraction of municipal solid waste; gaseous emissions; home composting; industrial composting.

1. Introduction

At present, waste management is becoming a global problem in developed countries due to the rapid collapse of landfills and the high impacts related to biowaste dumping. In view of these problems the European Union (EU) published in 1999 the Landfill Directive (Council of the European Union, 1999), which requires the member states to reduce the amount of biodegradable waste being dumped by promoting the adoption of measures to increase and improve sorting activities at the origin, recovery and recycling. The overall annual food and garden waste included in mixed municipal solid waste in the European Union is within 76.5-102 Mt that represents 30-40% of the total annual municipal waste generation (European Commission, 2009).

Composting, which can be defined as the aerobic biological degradation and stabilization of organic substrates under controlled, thermophilic and aerobic conditions (Haug, 1993), has been presented as an environmental friendly and sustainable alternative to manage and recycle organic solid wastes, with the aim of producing a quality product known as compost, to be used as organic amendment in agriculture (European Commission, 2009). For these reasons, exhaustive and systematic evaluations about its environmental performance are necessary. Potential environmental impacts, positive and negative, of municipal waste treatments should be considered including their potential pollution and their contributions to climate change, among other environmental impacts.

Industrial composting, in-vessel composting or windrow composting, imply the consumption of energy for waste transport and processing, the emission of odours and other contaminants, the proliferation of insects, birds and rodents and the mixture of different quality materials (Haug, 1993). The organic fraction of municipal solid waste (OFMSW) or biowaste usually has a percentage of non-biodegradable materials, which in Catalonia (northeast of Spain) can account for 1 to 30% (Catalan Waste Agency, 2009). Collection and separation of waste according to its different fractions (organics, metals, glass, papers, aluminum, fabrics, wood) is one of the best ways to obtain a good quality final compost product that may be used without great concerns (Barreira et al., 2008). Therefore the non-biodegradable material in the initial OFMSW affects the normal composting process by reducing the available capacity of composting plants and increasing the metal contamination of compost. Notwithstanding these disadvantages, biowaste composting at industrial scale presents great benefits such as a proper control of composting process variables (temperature, moisture, oxygen content, etc.) or the treatment of the exhaust gases.

Home composting or backyard composting, which means the self-composting of the biowaste as well as the use of the compost in a garden belonging to a private household (European Commission, 2009), presents some potential benefits when compared to the industrial process: it avoids the collection of the OFMSW; it considerably reduces the economic, material and energetic investments; and finally, it allows a direct control of the process and the organic materials input by avoiding or reducing the inclusion of impurities (McGovern, 1997; Ligon and Garland, 1998; Jasmin and Smith, 2003; Martínez-Blanco et al., 2009a, Boldrin et al., 2009). However, home composting also presents some problems: compost obtained often is not homogeneous; odours and other pollutants such as methane, ammonia or nitrous oxide are emitted directly to the atmosphere during the decomposition process (Amlinger et al., 2008; Ansorena, 2008), etc.

As observed, these two composting technologies present important differences and each one can be appropriate for different situations. For instance, home composting can be a good alternative to industrial composting in low density urban areas where a large investment in transport is required for the separate collection of the OFMSW. On the contrary, it is difficult to substitute industrial composting in high density urban areas, because of site, hygienic and monitoring requirements. The present study is intended to improve the knowledge about the environmental concerns of composting facilities and to help in the regional planning of organic waste management, since specific real and quantitative environmental data about the different alternatives available for the management of the OFMSW is scarce. Hence, the aim of this study is to quantify material requirements, energy consumption and gaseous and waste emissions associated to home and industrial composting and to determinate their environmental impacts using the environmental tool of Life Cycle Assessment, LCA (Rebitzer et al., 2004; International Organisation for Standardisation, 2006).

2. Materials and methods

2.1. Data origin

Data from home composting system were obtained from an experimental composter controlled and managed by the authors and located at the *Universitat Autònoma de Barcelona* (Barcelona, Spain) following the practices recommended by some local Catalan municipalities (Catalan Waste Agency, 2008). In relation to industrial composting, data were obtained in an industrial composting facility located in the Barcelona province (Spain): gaseous emissions were experimentally determined by the authors, whereas the rest of the inventory data were supplied by plant managers. This composting facility was selected because its steady state, its adequate technical and environmental characteristics and because it generates a compost of an agronomic quality within the legal regulations in Spain (Martínez-Blanco et al., 2009b).

2.2. Organic fraction of municipal solid waste

The organic material treated in both composting processes was the source-separated organic fraction of the municipal solid waste (OFMSW) that is defined as household waste that because of their nature or composition is capable of undergoing anaerobic or aerobic decomposition (leftovers of raw fruits and vegetables, food scraps and raw fish or meat and other similar waste), excluding pruning waste from gardens and parks. In fact, pruning waste (PW), which includes tree cuttings, branches, grass and wood (European Commission, 2009), was used as bulking agent in home and industrial composting to provide enough porosity and to prevent leachate generation.

2.3. Home composting experimental set-up

The organic waste was poured to the upper part of the composter and was extracted through the lower panels. The composter has a lateral system of natural ventilation to guarantee an aerobic process. The composter (70x70x103 cm) was made of recycled plastic from source separated municipal collection.

The composter was fed once a week following the next methodology, similar to that reported by Colón et al. (2010). First, the PW was shredded by means of an electric garden chipper (BOSCH AXT 2500 HP, Barcelona, Spain). Then, the OFMSW and PW were mixed in an average volume ratio of 0.8:1 (OFMSW:PW), the mixing ratio was slightly variable at each load depending on the moisture content of the material in the composter (the moisture content was determined using the fist test according to the US Department of Agriculture and the US Composting Council (2001)). An average of 11.4 kg of mixture (8.3 kg of OFMSW and 3.1 kg of PW) were added to the composter each week. This amount corresponds to the average quantity of the OFMSW produced by a Spanish two-member family (Ministerio de Medio Ambiente, 2008). In order to aerate the mixture, upper layers of the composter were weekly mixed with a commercial tool specially designed for this purpose (mixing tool, Compostadores SL, Barcelona, Spain). Also, the moisture content of the material was adjusted by direct tap water addition (to increase moisture) or by adding pruning waste (to reduce moisture), when necessary. The organic material was composted for approximately 12 weeks and finally the compost was extracted (0.05 m^3) through the lower panel and it was immediately analyzed. No sieving was necessary since it was considered that all the obtained product could be directly applied to soil.

The composter was placed outdoors in the *Escola d'Enginyeria* (Barcelona, Spain) of the *Universitat Autònoma de Barcelona* in shady conditions on a paved surface. The experiment was carried out during 100 days from November 2008 to March 2009. This corresponds to typical winter Mediterranean mild conditions (temperature from 5 to 20ºC and scarce rainfall).

2.4. Industrial composting operation

The composting plant studied has the capacity to treat 15,000 ton of organic waste a year (OFMSW and PW) using the in-vessel (“tunnel”) decomposition technology with a curing phase in turned windrows in an enclosed building. The plant has different biofilters for the treatment of the exhaust gases. Such characteristics are the most widely established in closed industrial composting facilities in Spanish populated areas.

The industrial composting process in the studied plant lasts for 10 weeks and includes four main steps. During the pre-treatment step, OFMSW and PW are prepared and mixed, at a volume ratio of 1:1 (OFMSW:PW). The decomposition phase takes place in-vessel (composting tunnels) with forced aeration and irrigation systems. The decomposed material is then disposed in composting windrows for the curing phase as third step. Windrows are weekly turned. Finally, during the post-treatment final step, the processed material is screened to separate the mature compost from the pieces of pruning waste that are not totally decomposed and other impurities. Recovered pruning waste is used again in the composting process and the impurities (mainly glass, metals and plastics) are dumped in a sanitary landfill. A more comprehensive description of the process was previously described by Martínez-Blanco et al. (2009b).

2.5. Determination of gaseous emissions

Although during the composting process more than 100 types of gaseous compounds can be emitted (Chung, 2007), only NH_3, CH_4, N_2O and volatile organic compounds (VOC) have been considered in this study as they represent together with CO_2, 99% of the total emission (Beck-Friis et al., 2000; Pagans et al., 2006a; Amlinger et al., 2008). CO_2 emitted from composting is not fossil-derived, and therefore, it was not considered as a greenhouse gas emission (Amlinger et al., 2008), in accordance to the European Commission (Smith et al., 2001).

The methodology developed by Colón et al. (2009) and Cadena et al. (2009) for the sampling and determination of gaseous emissions in industrial composting facilities was used to calculate gaseous emissions from the composting plant. This methodology was also adapted to determine the home composting emissions. In this case, measures were taken in only one point on the upper surface area of the composter assuming a homogeneous emission in all the composter small emission surface area (0.31 m^2) at each sampling time. The covered area for this sampling point corresponds to 25 % of the total home composting emission area, and it was considered representative of the whole system after checking that the emission velocity was highly uniform in the entire surface as described by Colón et al. (2009) and Cadena et al. (2009).

Air velocity on the emission surface was determined using a thermo-anemometer (VelociCalc Plus mod. 8386, TSIAirflow Instruments, Buckinghamshire, UK) and a specially designed Venturi tube to increase airflow velocity (Veeken et al., 2002). Ammonia was determined on site using a multigas sensor (model iTX-T82, Industrial Scientific, Vertex, Barcelona, Spain) with an ammonia detection range 0 to 200 mL m^{-3}. Gaseous samples were taken in Tedlar® bags for the laboratory determination of VOCs, methane and nitrous oxide. Total VOCs were analyzed as stated in Colón et al. (2009). Methane was analyzed by gas chromatography using a Flame ionization detector (FID) and a HP-Plot Q column with a detection limit of 1 ppmv (home composting) and by gas chromatography in a certified external laboratory with a detection limit of 10 ppmv (industrial composting). Nitrous oxide was analyzed by gas chromatography in a certified external certified laboratory with a detection limit of 50 ppbv (home composting) and by gas chromatography using a Thermal Conductivity Detector (TCD) and a GS-CarbonPlot column with a detection limit of 10 ppmv (industrial composting).

2.6. Organic waste and compost analytical methods for both systems

Moisture and organic matter content, pH, electrical conductivity, N-Kjeldhal, heavy metals content and bulk density of input materials and compost were determined following the standard methodology proposed by the US Department of Agriculture and the US Composting Council

(2001). Porosity was assessed by air pycnometry (Ruggieri et al., 2009). The static respirometric index (SRI), which was used as a measure of the biological stability of the material, was determined following the methodology proposed by Barrena et al. (2005).

3. Life cycle assessment

3.1. General methodology

LCA is a methodology for the determination of environmental impacts associated to a product, process or service from cradle to grave, in other words, from production of the raw materials to ultimate disposal of waste. According to ISO 14040-14044 (International Organisation for Standardisation, 2006), there are four main steps in a LCA study: the goal and scope definition, the inventory analysis, the impact assessment and the interpretation.

In this study, the software SimaPro v. 7.1.8 (PRé Consultants, 2008) was used to evaluate the environmental impacts of home and industrial composting. Only the obligatory phases defined by the ISO 14040-14044 regulation for the impact assessment (International Standardisation Organisation, 2006), namely classification and characterization, were performed as they are the more objective ones (Martínez-Blanco et al., 2009b).

The impact assessment method used was CML 2001, which was based on the CML Leiden 2000 method developed by the Center of Environmental Science of Leiden University (Guinée, 2001). The impact categories considered were: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (OLDP), photochemical oxidation potential (POP) and a flow indicator, the cumulative energy demand (CED).

3.2. Goal and scope definition

3.2.1. Goal of the study

There were three main objectives in this environmental study: firstly, to evaluate the overall environmental impacts of home and industrial composting; secondly, to detect the environmental critical phases of each composting system; and finally, to compare home and industrial composting environmental performances.

3.2.2. Functional unit

The key functions for the two composting technologies considered were the management of the OFMSW and the production of an organic fertilizer or amendment, the compost. The functional unit (FU) in LCA provides a reference to which the inputs and outputs of the inventory are related and allows the comparison between systems (International Organisation for Standardisation, 2006). In this study the functional unit (FU) selected was the management by composting of one ton of OFMSW.

3.2.3. Composting system burdens

The two systems considered are home composting (HC) and industrial composting (IC). Both systems include the steps from the OFMSW and PW collection to the final compost use, for instance in decorative gardening and in productive courtyards (Figure 1).

Home composting system: The home composting system, which is represented in Figure 1a, includes: (i) the kitchen bin for the OFMSW storage; (ii) the tools and infrastructures used during the process; (iii) electricity and water consumption; (iv) transport and management of the waste dumped generated by the system (bags, gloves, etc.); and (v) gaseous emissions and leachate generated during home composting.

Industrial composting system: The industrial composting system, represented in Figure 1b included (i) the OFMSW and PW generation that includes their transport and kitchen bin production; (ii) the building and other infrastructures of the facility; (iii) diesel, electricity and water consumption; (iv) the transport and management of the waste generated by the system that was dumped (solid waste fraction and building waste); (v) gaseous emissions and leachate generated during industrial composting; and (vi) transport of compost from the plant to the final user.

3.2.4. Main hypothesis

An average house of two people was considered as OFMSW and PW producer, compost consumer and, additionally for home composting system, as compost producer. A composter made of municipal collected and recycled plastic (plastic mix) was considered, according to the actual industrial manufacture of this product. In home composting, no transport was considered for organic waste collection and compost distribution from and to the household. The aforementioned standard house was supposed to be located at 10 km from the industrial composting facility, which was nearly the average distance from the collection areas to the composting facilities in the Barcelona metropolitan area. In relation to the presence of impurities, it has been considered that a family spending time and efforts on home composting and using the compost obtained is presumably concerned for a well sorted organic waste. Therefore for home composting this material was not considered.

In the OFMSW input stream of the industrial composting facility, 8% of impurities were measured. However, with the aim of studying comparable composting systems, the burdens of the treatment of these impurities (by recycling, landfilling, incineration or other methods) were not considered, although the losses of the treatment capacity in industrial facility due the presence of this material were considered.

Throughout the inventory three average distances were considered for the transportation required: local distance (10 km), with a van of 3.5 ton MAL (maximum authorised load); regional distance (50 km), with a van of 3.5 ton MAL or a lorry of 3.5-16 ton MAL; and national distance (500 km), with a lorry of 3.5-16 ton MAL. In addition, for the municipal solid waste collection a specific lorry of 21 ton MAL was taken into account.

3.2.5. Allocation procedure

When LCA is applied to complex systems (i.e. involving multiple products and recycling systems), the burden allocation procedures must be defined. For the system studied the “cut-off” methodology defined by Ekvall and Tillman (1997) was used. Accordingly, environmental burdens should be assigned to the system that it is directly responsible for them. Thus, impacts of waste dumping, for example, are fully attributable to the systems being studied; whereas burdens of recycled or reused waste should not be accounted since it is considered that they should be attributed to the system that uses such waste as a material source (Ekvall and Tillman, 1997; Finnveden, 1999; Johns et al., 2008).

3.2.6. Quality and origin of the data in the inventory

In this study, data inventories for home and industrial systems were elaborated including energy, water and material resources, emissions and waste. The majority of these figures were experimentally obtained from both systems. Regarding the industrial composting, data previously collected on energy and materials inputs and outputs in the composting plant were used (Martínez-Blanco et al., 2009b). These data correspond to average amounts calculated during the 2003-2006 period. Data on gaseous emissions obtained in the same industrial composting plant were also considered (Colón et al., 2009). Regarding the home composting system, the data were collected specifically for the present study, which is based on Colón et al. (2010). To complete the life cycle inventories (LCI), bibliographical sources and the Ecoinvent database (Swiss Centre for Life Cycle Inventories, 2007) were used. The specific data sources used are compiled in Tables 1 and 2 (last column).

3.3. Life cycle inventory (LCI)

In this section the two composting systems are widely described and quantified with regard to the functional unit.

3.3.1. LCI of home composting system

The home composting process has been previously described. In order to express the results based on the functional unit, the flows were related to one ton of OFMSW (Table 1).

Generation of OFMSW and PW: It was considered that both the OFMSW and the PW were generated in the same household where the composter was set up and collected in a polypropylene kitchen bin (8 L). No transport or collectively collection infrastructure were considered neither for OFMSW nor PW. In addition no shredding was considered for the OFMSW, but it was necessary for PW in order to adjust the particle size (Ruggieri et al., 2009).

Building, machinery and tools: Environmental loads associated to the procurement of primary materials, the manufacture and the transport of the tools and the composter were considered. The data needed for the environmental inventory were obtained from local producers and distributors of the devices and from the database Swiss Centre for Life Cycle Inventories (2007), considering their lifespan. The composter and the rest of building, machinery and tools were represented as separate stages in the inventory and in the results.

Altogether, six tools were currently used for the home composting process: a polyethylene bag to collect the shredded PW; a shovel of steel and wood; an iron-made mixing tool; a watering can made of polypropylene used to maintain the moisture of the composting material; a pair of cotton gloves and an electric garden chipper (2500 W), which was supposed to be used collectively (i.e. by a community of 10 neighbours). It was considered that the shovel, the watering can and the cotton gloves were also used in the garden for other purposes (only a 15% of their total burdens where finally allocated to the home composting process).

The composter used was made of plastic mix, which is a mixture of several recycled plastics, such as HDPE (high density polyethylene) or PP (polypropylene), with a capacity of 0.4 m^3 and a weight of 28 kg. Collection and transport of the household source separated plastic waste (Iriarte et al., 2009) and the fabrication process (melting and moulding) were accounted.

For the garden chipper, the mixing tool and the composter, transport in a lorry of 3.5-16 ton MAL and a distance of 500 km from the producer to the house were considered (national distance), since they were specific tools. The rest of the tools (bag PW, shovel, watering can and gloves) were transported by van of 3.5 ton MAL at a distance of 50 km from the producer (regional distance).

Energy consumption: Pruning waste shredding was the only stage where electricity was necessary. Technical characteristics of the equipment indicated that the garden chipper consumes 28 kWh per ton of PW, corresponding to 4.2 h/t OFMSW.

Water consumption and leachate production: Occasionally, watering of the organic material in the composter was necessary due to its low moisture content. Overall, 51 L of water were used during the experimental period per ton of OFMSW. Leachate was not generated during the experiment.

Gaseous emissions: Gaseous compounds generated during the home composting process were directly emitted to the atmosphere as it typically occurs in home composting. NH_3, VOCs, CH_4 and N_2O emissions were considered and measured as previously described.

Waste dumped: According to the cut-off methodology (Ekvall and Tillman, 1997) and considering that HDPE, polypropylene, steel and iron should be recycled or recovered, only the dumping of the wooden shovel, the gloves and the plastic mix composter were considered. The landfill was placed at a regional distance from the home composter (50 km) and the waste was transported with a municipal solid waste collection lorry (21 ton MAL).

3.3.2. LCI of industrial composting system

The inventory flows and values for the industrial composting plant are summarized in Table 2.

Generation of OFMSW and PW: OFMSW and PW were obtained by source-separated collection systems from six nearby municipalities and the main Barcelona market suppliers, both located at 10 km of the composting plant (local distance). Transport of the organic waste, production and cleaning of the street collection containers and production of the kitchen bin were considered following the studies by Iriarte et al. (2009) and Martínez-Blanco et al. (2009b). The average content of non-organic impurities (plastics, glass, fabrics and metals, among others) in the OFMSW was 8% (Catalan Waste Agency, 2009). Such materials were not sorted at the beginning of the composting process and they implied a reduction in the plant treatment capacity, as commented previously.

Building, machinery and tools: The building and the machinery of the facility entailed materials production, transport and waste management that were accounted by Martínez-Blanco et al. (2009b). According to Washington State Office of Financial Management (2008) a lifespan of 25 years was accounted for the plant.

Energy consumption: The types of energy consumed by the composting plant were electricity, used in the aeration system, plant lighting and some machineries, and diesel oil, used by tractors and trucks. The average energetic consumption was of 383.5 MJ per ton of OFMSW.

Water consumption and leachate production: 426.8 l of water were consumed per ton of OFMSW. The water was used for cleaning and for irrigating the organic material in active decomposition during the composting process. Approximately 20% of this water was rainfall water collected in biofilters and reused. Leachates generated in the composting process were also completely reused in the composting process.

Gaseous emissions: The exhaust gases generated in the composting tunnels and in the pre-treatment and curing areas of the composting plant were treated using biofilters before being released to the atmosphere. Biofilters consist of a 1 m layer of vegetal material previously used as bulking agent in the composting process, in which the gaseous contaminants are biodegraded by microorganisms. The emissions were determined according to the methodology previously explained (Colón et al., 2009). Null emissions of N_2O and CH_4 were detected according to the analytical methods applied that have a detection limit of 10 ppmv in both cases. For such compounds we considered an average emission value of 5 ppmv.

Waste dumped: Two types of waste were generated in the composting plant: the solid waste fraction that was dumped and the machinery and building waste at the end of their useful life. Regarding the former, an amount equivalent to the weight of the improper material content (8% of the OFMSW treated) was not considered as previously mentioned and according to the allocation procedure. The transport and landfill disposal of the rest of solid waste fraction was included in the inventory. For machinery and building waste, only management of dumped waste was considered in the case of concrete and cement, whereas steel recycling was not accounted.

Compost distribution: The transport of the compost produced to the households, where it is used, was considered in the industrial system. A distance of 10 km was covered with a van of 3.5 ton MAL.

4. Results and discussion

This section has been divided into three parts: first, analytical results of the gaseous emissions and compost are shown; next, the input and output flow inventories for the two composting systems are compared; and finally, the impact assessment is presented.

4.1. Experimental results

4.1.1. Physicochemical characterization of compost in home and industrial systems

The most important properties for compost obtained in the industrial composting facility were found within the quality proposed limits (Giró, 1994; Giró, 2001; California Compost Quality Council, 2001) as shown in Table 3. Compost obtained from home composting was near or within the legislation limits, and only moisture and nitrogen content were slightly above and below these limits, respectively. The compost obtained in home composting was not sieved for the analysis presented in Table 3 because it was considered that the obtained compost is directly used as soil amendment. However, if home compost had been sieved at 10 mm (as in the industrial plant), the nitrogen content of the home compost would increase to 2.25%.

Regarding the respirometric index, values between 0.5 and 1.5 mg O_2 g OM^{-1} h^{-1} were obtained in both technologies. These values correspond to a high level of stability according to California Compost Quality Council (2001) and the European Commission (2001).

Metal concentrations in the final compost obtained from industrial composting and home composting were lower than the limits proposed by the European Commission (2001) (Table 3). Such concentrations were in agreement to the careful selection of input materials for home composting and the relative low presence of impurities in the OFMSW used for industrial composting.

4.1.2. Gaseous emissions and leachate in home and industrial systems

Ammonia, VOCs, methane and nitrous oxide were measured during the studied period for both composting systems.

According to Tables 1 and 2, the VOCs emissions of home composting process were lower than industrial composting ones (0.559 and 1.210 kg C-VOC ton^{-1} OFMSW, respectively). Regarding ammonia, emissions in home composting were eight times higher than in industrial composting (0.842 kg and 0.110 kg NH_3 ton^{-1} OFMSW, respectively). This difference was obviously related to the high ammonia removal efficiency during the biofiltration process in the composting facility with removal efficiencies close to 90% (Colón et al., 2009). In the case of VOCs the biofilter removal efficiency was close to 70%. On the other hand, methane and nitrous oxide were only detected in home composting. The emissions of these compounds were 0.158 kg CH_4 ton^{-1} OFMSW and 0.676 kg N_2O ton^{-1} OFMSW respectively. These higher emissions of methane and nitrous oxide during home composting can be explained by the lower oxygen availability due to passive aeration.

Amlinger et al. (2008) reported similar values of ammonia (0.474 to 0.972 kg NH_3 ton^{-1} OFMSW) and nitrous oxide (0.192 to 0.454 kg N_2O ton^{-1} OFMSW) during home composting of OFMSW. On the contrary methane emissions detected in this study were between 5 and 14 times lower than those reported by these authors. In relation to VOCs emissions, several authors presented emissions ranging from 0.590 to 0.430 kg C-VOC ton^{-1} OFMSW for IC (Smet et al., 1999; Muñoz and Rieradevall, 2002; Diggelmand and Ham, 2003; Diaz and Warith, 2005), which are similar to the values found in this work. Recently, Boldrin et al. (2009) have collected the most significant works published on IC emissions, showing a high level of dispersion. Nevertheless, it is important to highlight that the level of emissions will be highly dependent on the aeration system used, that is, natural convective aeration for home composting and forced-aeration for the case analysed of industrial composting (Barrington et al., 2003; Pagans et al., 2006b; Amlinger et al., 2008).

During the experimental period of the home composting, no leachate generation was observed. It must be pointed that other authors reported leachate generation from 0.01 to 0.07 m^3/t of biowaste with home composting technology (Amlinger et al., 2008). In the industrial composting plant the leachates were totally reused (Martínez-Blanco et al, 2009b). Generation of leachate is a possible source of nitrogen losses, normally in the form of ammonia and an environmental load associated to eutrophication.

4.2. Main input and outputs flows

Table 4 presents a summary of the main input and output flows of energy, materials and emissions for the two composting systems. Data corresponds to the functional unit (1 ton of OFMSW). Unfortunately, no other data have been found in literature to compare both composting systems.

Values for industrial composting are generally higher than those of home composting apart from ammonia, methane and nitrous oxide emissions, and land required. The differences were especially significant for waste dumped and transport, with ratios of 53 and 19, respectively. Such high difference in waste production was mainly due to the solid waste rejects produced during the industrial composting process. Regarding transport, industrial composting included the transport of the OFMSW and the PW collection, the transport of the solid waste rejected, the transport of the plastic waste for the composter production, the transport of the materials and the waste of the building and the transport of the compost distribution, having the two first the major contribution to the total transport burdens. For home composting the transport flows included were only the transport of the composter and the tools from the producer and the transport of waste derived from some tools to landfill.

Home composting land requirements were nearly twice than that of industrial composting. As previously mentioned in relation to gaseous emissions, ammonia, methane and nitrous oxide emissions for home composting were 8, 5 and 7 times higher than for industrial composting, respectively.

4.3. Environmental impacts assessment

4.3.1. Environmental assessment of the home composting process

The environmental impacts attributable to each stage considered for the home composting are summarised in Table 5. In general, the composter and the NH_3, VOCs and N_2O emissions were the four main impacting items.

Particularly, for abiotic depletion potential (ADP), ozone layer depletion potential (OLDP) and cumulative energy demand (CED), the composter presented the highest impacts (40%, 79% and 41% of the total impact, respectively). As shown in Table 6, the main responsible for the impact produced by the composter was the manufacturing process, which includes between 63 and 95% to the total composter impact for all the categories studied.

Returning to Table 5, the ammonia emissions contributed in a percentage of 93% and 91% to the acidification (AP) and the eutrophication potentials (EP), respectively. Nitrous oxide emissions were the main contributor (91%) to global warming potential (GWP), while VOCs were the major contributors (98%) to photochemical oxidation potential (POP). It is important to highlight that the release of gaseous contaminants to atmosphere is an important concern in the environmental impact assessment of home composting, as it has been reported by other authors (Amlinger et al., 2008).

Regarding the rest of elements or stages considered, the electricity consumption represented 33 and 30% of the impact for CED and ADP, respectively; whereas for these categories the contribution of the building, machinery and tools was also relevant, 21 and 24%, respectively. For the rest of elements and categories the contributions were lower than 8%.

4.3.2. Environmental assessment of the industrial composting process

The contributions of the industrial composting elements or stages to the total environmental impact of the process are presented in Table 7. The three stages that presented a major impact were the collection of OFMSW and PW, the electricity supply and the solid dumped wastes, for all the categories considered except for photochemical oxidation potential. For POP, VOCs emissions presented the highest contribution (94%). The collection of the OFMSW and PW was the most impacting stage for ADP, GWP and OLDP categories, contributing between 27-46%, and it also had a relevant contribution for AP and EP (23 and 16%, respectively), being the transport the main responsible. For CED the electricity consumption together with the collection of the OFMSW and PW had the higher contributions (32% each item). Electricity consumption was also the most impacting stage (37%) for AP and it contributed to a 29, 20 and 12% for ADP, GWP and OLDP, respectively. In EP category, the solid waste dumped was the most impacting item that represented 55% of the total impact, while for GWP, OLDP and CED their contribution were higher than 11%. The high amount of solid wastes that were landfilled was related to the difficulty of a perfect separation of the compost obtained from the impurities, which is usual in industrial composting (Ruggieri et al., 2008).

Ammonia emissions and nitrous oxide emissions were responsible for more than 17% of the impact in the categories of AP, EP and GWP. For ADP, OLDP and CED, diesel consumption contributed to more than 14% to the total impacts. For the rest of elements and categories the contributions were lower than 11%.

4.3.3. Comparison of the environmental impacts between home and industrial composting

In general, the industrial composting system implied higher consumption of energy during the process, larger transport requirements for the biowaste collection and higher generation of waste compared to the home composting system, as it was previously discussed (Table 4). As a result of these environmental items the former was more impacting than the latter (between 4 and 6 times higher) for ADP, OLDP and CED categories (Figure 2). Additionally, industrial composting doubled POP impacts, whose main contributor was the VOCs emissions, in comparison to home composting.

For the categories of AP, EP and GWP, in spite of the higher consumptions of energy and materials and the waste generated in industrial composting system, the significantly higher emissions of nitrous oxide and ammonia in home composting resulted in higher impacts in this system (between 31-46% higher).

The home composting system entailed the consumption of 351 MJ eq and the emission of 220 kg CO_2 eq ton^{-1} OFMSW, whereas for industrial composting, the energy consumption was 1908 MJ eq and 153 kg CO_2 eq were emitted per ton of OFMSW. In addition, it has to be pointed out that in the global warming context, composting contributes to produce emissions as well as to avoid emissions. For instance, Boldrin et al. (2009) show that when the final use of compost is also taken into account the overall emission factor for composting can vary between significant savings (-900 kg CO_2 eq ton^{-1} OFMSW) to a net load (300 kg CO_2 eq ton^{-1} OFMSW). It is evident that the benefits of compost use from the environmental point of view should be the focus of future studies.

4.3.4. Sensitivity analysis of the results

As the results obtained correspond to a quite particular situation, environmental impacts for several hypothetical scenarios obtained by modifying relevant assumptions of the industrial composting system were assessed and compared with initial scenario studied (IC1) to perform the sensitivity analysis of the results. Three new assumptions were assessed: the distance between the composting facility and the household, the emissions of nitrous oxide and methane and the impurities content in the OFMSW. Results are illustrated in Table 8. Sensitivity analysis for home composting was performed by Colón et al. (2010) reporting as sensitive assumptions: whether recycled or raw plastic was considered as composter material and variations in nitrous oxide and ammonia emissions.

A distance of 10 km between the composting facility and the standard house has been considered in the inventory (IC1). Such situation may change as a function of the local distribution and restrictions of this kind of facilities. Impacts in scenario IC2 considered half reduced distance (5 km) and were significantly lower for all the impact categories (10-30%), apart from POP. For scenario IC3 that doubled the initial distance (20 km) impacts were significantly higher (15-38%), apart from POP. Such distance modifications presented more important effects on ADP, OLDP and CED because, as it is shown in Table 7, the collection of the OFMSW and PW supposed the maximum contribution of these categories.

Since the emissions of N_2O, VOCs and NH_3 are reported to have a relevant contribution in some of the impact categories considered and nitrous oxide is not detected within the detection limits of the analytical methods used, a sensitivity analysis was performed for these emissions. To study this point, in IC4 scenario minimum emissions of N_2O (0 ppmv) were considered, whereas in IC5 scenario maximum emissions of N_2O (10 ppmv) were considered. As seen in Table 8, the only impact category affected relevantly was GWP (increasing or decreasing 18%), according to the results of Table 7.

In relation to methane, although the low impact of its emissions in our study, considerable higher emissions were reported in Amlinger et al. (2008) than in our experimental results (26 times higher). Therefore in the IC6 scenario an average emission of 900 g of CH_4 per ton of OFMSW was considered for industrial composting. Even though the high difference between the emission factors considered, an increase of only 13 % was measured in IC6 with respect to IC1 for GWP (Table 8).

Finally, scenarios IC7 and IC8 considered high and low values of the impurities content of the OFMSW that the composting facility received (0-30%), according to the characterizations reported for the OFMSW in Catalonia (Catalan Waste Agency, 2009). Such modification had moderate effects on all the impact categories apart from POP that was mainly affected by VOCs emissions. For IC7 scenario impacts were reduced between 5-6% depending on the category. For IC8 scenario impact, an increase between 26-33% was measured for the categories studied except for POP. The main reason for this behaviour is that high impurities content reduced the treatment capacity of the industrial composting plant and therefore the energy, materials, transport and waste required to process 1 ton of OFMSW are increased. To our knowledge, no studies have been reported on the environmental impact that the impurities present in the OFMSW in source-separated collection systems produces in the full-scale composting process.

5. Conclusions

A life cycle analysis was carried out in order to compare two types of composting systems: industrial and home composting. The physicochemical properties of the final composts obtained indicate that they were stable and according to the European standards.

NH_3, N_2O and CH_4 emitted were between 5 and 8 times higher in home composting than in the industrial process. Biofiltration of exhaust gases and forced aeration during the composting process in industrial composting could be the main reasons to explain these differences. On the contrary, volatile organic compounds (VOCs) emissions in the industrial process doubled that of the home composting.

The composter production, and particularly the manufacturing process, and the ammonia, VOCs and nitrous oxide emissions were the four main impacting elements in the home composting system. In the industrial composting, the major impact contributions were related to obtaining of OFMSW and PW (mainly due to the requirements of the collection transport), electricity consumption and solid waste management for all the categories except for the photochemical oxidation potential. For such category VOCs emissions presented the higher contribution. As a result of the relevant consumptions, industrial composting was more impacting (between 2 and 6 times) than the home composting process for ADP, OLDP and POP and CED. However, the significantly higher emissions of nitrous oxide and ammonia in the home system meant higher impacts for AP, EP and GWP categories for this system.

In reference to the sensitivity test performed, the impacts were proportional to the distance from the composting facility to the household being especially dependent in the case of ADP, OLDP and CED. In relation to the impurities content, their modification had moderately proportional effects on all the impact categories.

In conclusion, the incorporation of gas treatment systems for home composting and the use of low-impact materials in the composter construction appears to be the main issues to minimize the environmental impact of this system, whereas the improvement in the biofiltration of VOCs, jointly with the minimization of the energy use and the presence of impurities in the source-separated collection systems of the OFMSW, should be the main focus of research for the implementation of industrial composting programmes. Another important point of future research should be the comparison of home composting from the environmental point of view in different seasons of the year and, if possible, under very different climate conditions.

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Table 1. Summary of compost production inventory for the home composting system. Values are related to 1 ton of OFMSW (functional unit).

Stages	Element	Flow	Amount	Units (ton^{-1} OFMSW)	Lifespan (yr)	Source
			Inputs			
Collection of OFMSW and PW	OFMSW kitchen bin	PP	0.082	kg	7	SCLCI (2007), WSOFM (2008) and Colón et al. (2010)
Building, machinery and tools (composter)	Composter	Plastic mix	4.380	kg	12	SCLCI (2007), Compostadores SL (2008), WSOFM (2008), Iriarte et al. (2009) and Colón et al. (2010)
	Plastic collection. Container	HDPE	0.004	kg	-	
	Plastic collection. Cleaning water	Tap water	0.006	L	-	
	Plastic collection. Transport	Transport	0.146	tkm	-	
	Transport national	Transport	2.190	tkm	-	
Building, machinery and tools (others)	Garden chipper	Steel	0.297	kg	10	Compostadores SL (2008), SCLCI (2007), WSOFM (2008), Colón et al. (2010) and own measurements
		HDPE	0.297	kg		
	Bag for PW collection	PP	0.076	kg	3	
	Shovel	Steel	0.029	kg	12	
		Wood	0.016	kg		
	Mixing tool	Iron	0.133	kg	12	
	Watering can	PP	0.003	kg	12	
	Gloves	Cotton	0.011	kg	6	
	Transport national [a]	Transport	0.364	tkm	-	
	Transport regional [b]	Transport	0.013	tkm	-	
Water consumption	Moistening water	Tap water	50.870	L	-	Own measurements
Energy consumption	Electricity consumption (garden-chipper)	Electricity	9.381	kWh	-	Own measurements and Compostadores SL (2008)
			Outputs			
Gaseous emissions	Methane	CH_4	0.158	kg	-	Own measurements
	Volatile organic compounds	VOCs	0.559	kg	-	
	Nitrous oxide	N_2O	0.676	kg	-	
	Ammonia	NH_3	0.842	kg	-	
Waste dumped	Waste management in landfill	Wood	0.016	kg	-	Compostadores SL (2008), SCLCI (2007), WSOFM (2008) and own measurements
		Cotton	0.011	kg	-	
		Plastic mix	4.380	kg	-	
	Transport to landfill [c]	Transport	0.441	tkm	-	

OFMSW, Organic fraction of municipal solid waste; PP, polypropylene; HDPE, high density polyethylene.
[a] It includes garden chipper and mixing tool that were transported from a distance of 500 km by lorry of 3.5-16 ton MAL.
[b] It includes bag for PW collection, shovel, watering can and gloves that were transported from a distance of 50 km by van of 3.5 ton MAL.
[c] A transport of 50 km with a municipal solid waste collection lorry (21 ton MAL) was considered.

Table 2. Summary of compost production inventory for the industrial composting system. Values are related to 1 ton of OFMSW (functional unit).

Stages	Element	Flow	Amount	Units (ton^{-1} OFMSW)	Source
		Inputs			
Collection of OFMSW and PW	OFMSW kitchen bin	PP	0.089	kg	Martínez-Blanco et al. (2009b) and Iriarte et al. (2009)
	Container	HDPE	0.124	kg	
	Container cleaning water	Tap water	10.604	L	
	OFMSW & PW collection [a]	Transport	30.634	tkm	
Building, machinery and tools [b]	Building materials [c]	Building materials	14.171	kg	Althaus et al. (2004), SCLCI (2007), ITeC (2008) and WSOFM (2008).
	Machinery production	Machinery	0.149	kg	
	Diesel oil consumption	Diesel oil	0.001	kg	
	Transport	Transport	0.057	tkm	
Energy consumption	Diesel oil consumption	Diesel oil	4.743	kg	Martínez-Blanco et al. (2009b)
	Electricity consumption	Electricity	50.531	kWh	
Water consumption	Tap water and rainwater	Water	426.778	L	
		Outputs			
Gaseous emissions	Methane	CH_4	0.034 [d]	kg	Colón et al. (2009) and own measurements
	Volatile organic compounds	VOCs	1.210	kg	
	Nitrous oxide	N_2O	0.092 [d]	kg	
	Ammonia	NH_3	0.110	kg	
Waste dumped	Waste management in landfill	Solid waste	0.219	t	ITeC (2008), Martínez-Blanco et al. (2009b) and WSOFM (2008)
		Building waste	0.014	t	
	Transport to landfill [e]	Waste	23.488	tkm	
Compost distribution	Compost distribution	Transport	4.543	tkm	Own measurements

OFMSW, Organic fraction of municipal solid waste; PP, polypropylene; HDPE, high density polyethylene.
[a] Urban transport collection considered by Iriarte et al (2009) and transport intercity to the plant (10 km), with a municipal solid waste collection lorry (21 ton MAL).
[b] Resources entailed in the construction of the compost plant and its infrastructures. Lifespan of the composting plant is the 25 years (WSOFM, 2008).
[c] The building materials required were cement, concrete, steel, gravel and polyester.
[d] Null emissions of CH_4 and N_2O were detected according to the analytical methods applied which have a detection limit of 10 ppmv in both cases. For such compounds we considered an average emission value of 5 ppmv.
[e] It includes solid waste and building waste transport from the plant to the landfill considering a transport of 50 km with a lorry of 3.5-16 ton MAL.

Table 3. Physicochemical properties of final compost obtained from the home composter and from the industrial composting facility. Compost quality standards are also reported for comparison.

Properties	Units	Compost		Compost quality standards
		Home	Industrial[a]	
Moisture	%, wb	43.63	31.85	25-40[b]
Organic matter	%, db	47.96	55.33	≥40[b]
pH (extract 1:5 w:v)	-	7.83	7.88	6.5-8[b]
Electrical conductivity (extract 1:5 w:v)	mS cm^{-1}	4.30	4.90	≤6[b]
N-Kjeldhal	%, db	1.71	2.04	≥2[b]
Respiration index	mg O_2 g^{-1} OM h^{-1}	1.13	0.89	0.5-1.5[c]
Zn	mg kg^{-1}	156	150	200[e]
Cu	mg kg^{-1}	44	47	100[e]
Ni	mg kg^{-1}	9	9	50[e]
Cr	mg kg^{-1}	9	8	100[e]
Pb	mg kg^{-1}	28	32	100[e]
Cd	mg kg^{-1}	0.30	0.24	0.7[e]

wb: wet basis; db: dry basis; w: weight; v: volume; OM: organic matter; na: not analyzed.
[a] Data supplied by plant managers. Average values of the period 2001-2006.
[b] Regulation proposal for municipal solid waste compost in Spain (Giró, 1994).
[c] Range for stable compost according to California Compost Quality Council (2001).
[d] Regulation proposal for municipal solid waste compost in Europe (European Commission, 2001).

Table 4. Life cycle inventory summary for the two composting systems: home (HC) and industrial composting (IC), including the management of all the OFMSW.

Flow	Units (·ton^{-1} OFMSW)	Industrial composting	Home composting	Ratio (IC/HC)
Water	L	437.383	50.876	8.60
Material resources	kg	13.386	5.327	2.51
Electricity	kWh	50.531	9.381	5.39
Diesel oil	L	4.744	0.000	-
VOC	kg	1.210	0.559	2.16
NH_3	kg	0.110	0.842	0.13
CH_4	kg	0.034	0.158	0.21
N_2O	kg	0.092	0.676	0.14
Waste dumped	kg	232.960	4.407	52.86
Transport	tkm	58.718	3.153	18.62
Land surface	m^2	0.042	0.093	0.45

Table 5. Contribution to total environmental impact of the items considered in the home composting process (in percentages).

%	ADP	AP	EP	GWP	OLDP	POP	CED
OFMSW kitchen bin	2.60	0.06	0.03	0.12	1.41	0.02	2.43
Composter	39.90	1.86	0.85	2.95	79.21	0.52	40.54
Building, machinery & tools	24.28	1.18	0.61	1.55	8.16	0.46	21.48
Water consumption	0.08	0.00	0.00	0.01	0.02	0.00	0.09
Electrictiy consumption	30.01	3.71	0.85	2.55	8.44	0.84	32.61
CH_4	0.00	0.00	0.00	1.65	0.00	0.40	0.00
VOCs	0.00	0.00	0.00	0.00	0.00	97.69	0.00
N_20	0.00	0.00	0.00	90.74	0.00	0.00	0.00
NH_3	0.00	92.98	91.02	0.00	0.00	0.00	0.00
Waste dumped	3.13	0.20	6.64	0.43	2.77	0.07	2.85
Total impact	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

11-40 %	41-70 %	71-100 %

Impact categories: ADP, Abiotic depletion potential; AP, Acidification potential; EP, Eutrophication potential; GWP, Global warming potential; OLDP, Ozone layer depletion potential; POP, Photochemical oxidation potential; CED, Cumulative energy demand.

Table 6. Contribution of the recyclable plastic collection, manufacturing process and distribution transport of the home composter (in percentage of total composter burdens).

Impact category	Unit	Plastic collection (%)	Manufacturing process (%)	Transport (%)*
Abiotic depletion potential	kg Sb eq	2.56	88.15	9.29
Acidification potential	kg SO_2 eq	3.29	82.18	14.53
Eutrophication potential	kg PO_4^{3-} eq	6.41	62.83	30.75
Global warming potential	kg CO_2 eq	3.13	85.70	11.17
Ozone layer depletion potential	kg CFC^{-11} eq	1.09	94.96	3.96
Photochemical oxidation potential	kg C_2H_4	2.92	86.52	10.56
Cumulative energy demand	MJ eq	2.29	89.11	8.60

* National transport was considered (500 km)

Table 7. Contribution to total environmental impact of the items considered in the industrial composting process.

%	ADP	AP	EP	GWP	OLDP	POP	CED
Collection of OFMSW and PW	34.62	23.05	16.38	26.70	45.99	1.32	32.26
Water supply	0.12	0.08	0.02	0.09	0.05	0.01	0.14
Building and machinery	2.48	1.25	0.74	2.19	1.41	0.18	1.99
Diesel consumption	14.76	3.73	1.27	1.58	16.43	0.31	13.57
Electricity supply	28.84	37.24	6.62	19.85	12.32	2.00	32.29
CH_4	0.00	0.00	0.00	0.51	0.00	0.04	0.00
VOCs	0.00	0.00	0.00	0.00	0.00	94.09	0.00
N_20	0.00	0.00	0.00	17.84	0.00	0.00	0.00
NH_3	0.00	22.66	17.26	0.00	0.00	0.00	0.00
Solid dumped wastes	10.76	7.42	55.01	25.19	14.07	1.44	11.23
Building dumped wastes	0.43	0.26	0.22	0.24	0.56	0.01	0.41
Compost distribution	7.98	4.32	2.48	5.82	9.17	0.61	8.10
Total impact	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

11-40 % | 41-70 % | 71-100 %

Impact categories: ADP, Abiotic depletion potential; AP, Acidification potential; EP, Eutrophication potential; GWP, Global warming potential; OLDP, Ozone layer depletion potential; POP, Photochemical oxidation potential; CED, Cumulative energy demand.

Table 8. Comparison of the environmental impacts for the seven scenarios considered for industrial composting (IC2 – IC8). Initial scenario (IC1) is considered as the base scenario (100% of contribution of each category), whereas the rest of scenarios are normalized to this base scenario.

Impact category	**Units (ton^{-1} OFMSW)**	**Initial scenario (IC1)**	**Sensitivity analysis of other scenarios (%)**						
			IC2	**IC3**	**IC4**	**IC5**	**IC6**	**IC7**	**IC8**
ADP	kg Sb eq	7.68E-01	77	**127**	100	100	100	94	**133**
AP	kg SO_2 eq	7.77E-01	85	**120**	100	100	100	95	**126**
EP	kg PO_4^{-3} eq	2.23E-01	90	**115**	100	100	100	95	**128**
GWP	kg CO_2 eq	1.53E+02	82	**122**	82	**118**	**113**	95	**126**
OLDP	kg CFC^{-11} eq	1.33E-05	70	**138**	100	100	100	95	**133**
POP	kg C_2H_4 eq	5.35E-01	99	**101**	100	100	101	100	102
CED	MJ eq	1.91E+03	78	**125**	100	100	100	94	**133**

Impact categories: ADP, Abiotic depletion potential; AP, Acidification potential; EP, Eutrophication potential; GWP, Global warming potential; OLDP, Ozone layer depletion potential; POP, Photochemical oxidation potential; CED, Cumulative energy demand.

Scenarios:
IC2: Distance from the household to the composting facility is 5 km.
IC3: Distance from the household to the composting facility is 20 km.
IC4: Emission of N_2O is 0 ppmv.
IC5: Emission of N_2O is 10 ppmv.
IC6: Emission of CH_4 reported by Amlinger et al. (2008).
IC7: Impurities content in the OFMSW is 1%.
IC8: Impurities content in the OFMSW is 30%.

Legends to Figures

Figure 1. Definition and boundaries of the composting systems studied, including the main composting stages and the input and output flows considered. a) Home composting system. b) Industrial composting system. OFMSW, organic fraction of municipal solid waste; PW, pruning waste; IC, impurities material content.

Figure 2. Comparison of the total environmental impacts of the two composting methodologies per ton of OFMSW treated: home composting (HC) and industrial composting (IC).

Figure 1

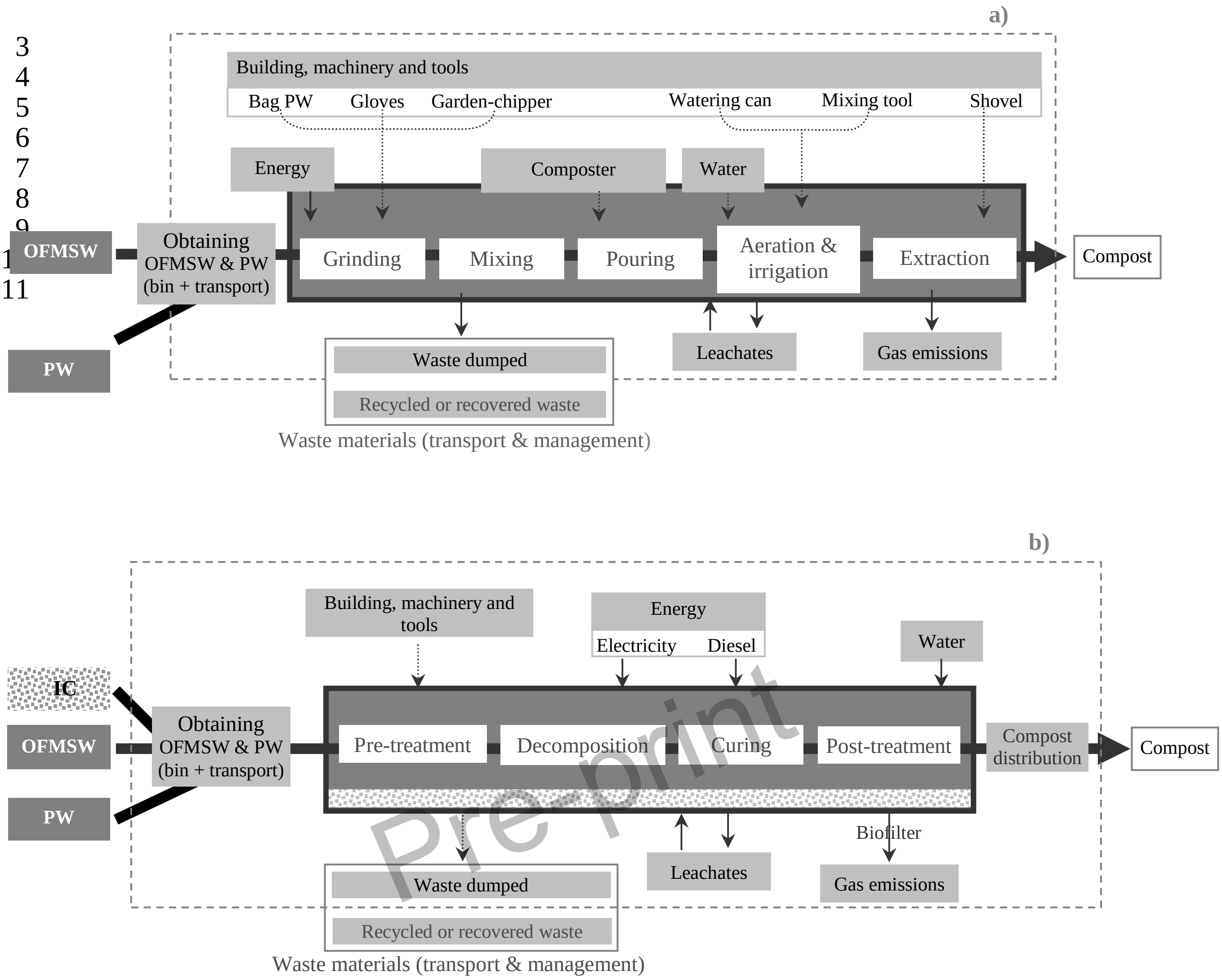
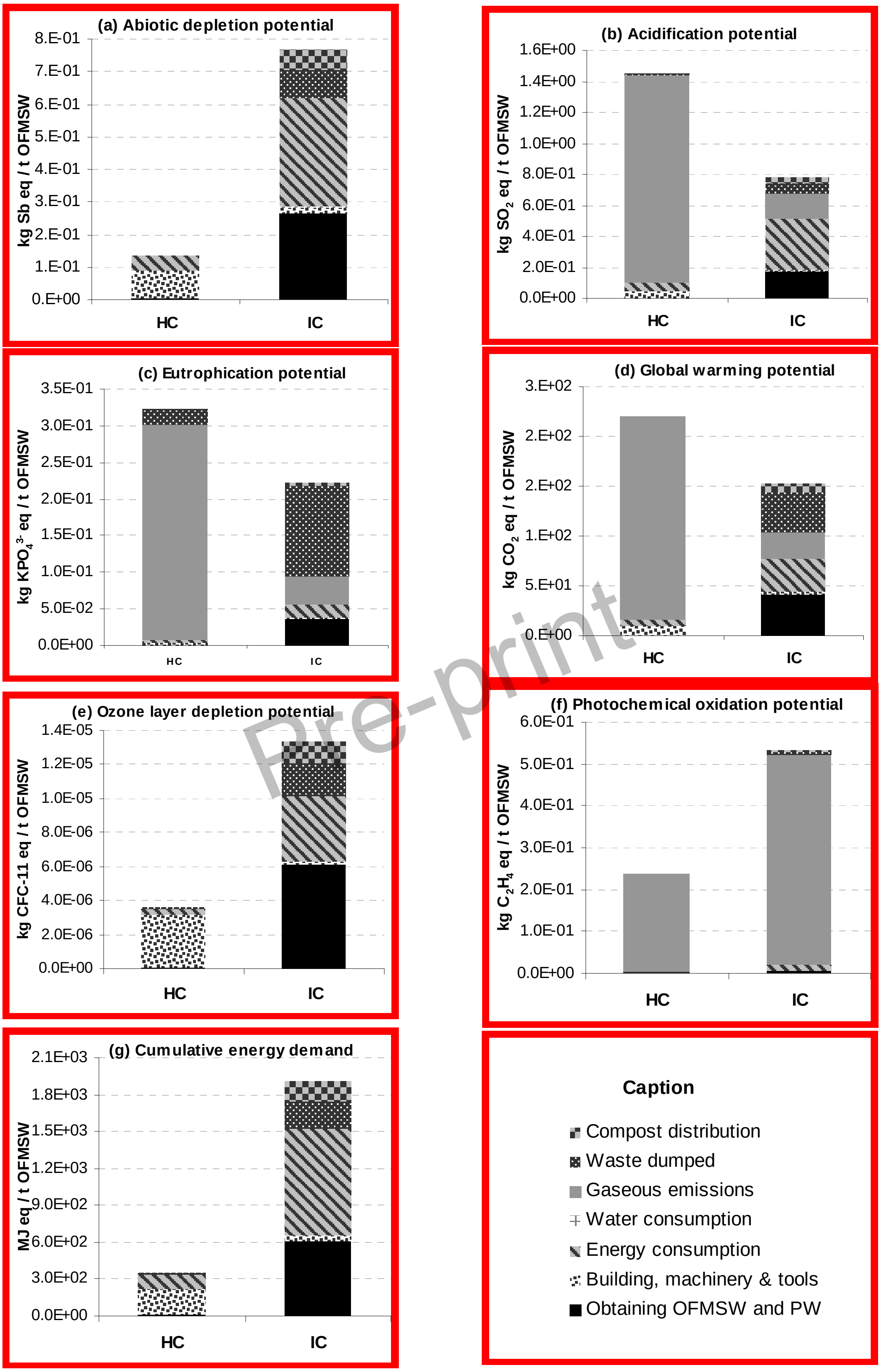

a)
Building, machinery and tools
Bag PW
Gloves
Garden-chipper
Watering can
Mixing tool
Shovel
Energy
Composter
Water
OFMSW
Obtaining OFMSW & PW (bin + transport)
Grinding
Mixing
Pouring
Aeration & irrigation
Extraction
Compost
PW
Waste dumped
Recycled or recovered waste
Leachates
Gas emissions
Waste materials (transport & management)
b)
Building, machinery and tools
Energy
Electricity
Diesel
Water
IC
OFMSW
PW
Obtaining OFMSW & PW (bin + transport)
Pre-treatment
Decomposition
Curing
Post-treatment
Compost distribution
Compost
Biofilter
Leachates
Gas emissions
Waste dumped
Recycled or recovered waste
Waste materials (transport & management)

Figure 2.


(a) Abiotic depletion potential
kg Sb eq / t OFMSW
8.E-01
7.E-01
6.E-01
5.E-01
4.E-01
3.E-01
2.E-01
1.E-01
0.E+00
HC
IC
(b) Acidification potential
kg SO_2 eq / t OFMSW
1.6E+00
1.4E+00
1.2E+00
1.0E+00
8.0E-01
6.0E-01
4.0E-01
2.0E-01
0.0E+00
HC
IC
(c) Eutrophication potential
kg KPO_4^{3-} eq / t OFMSW
3.5E-01
3.0E-01
2.5E-01
2.0E-01
1.5E-01
1.0E-01
5.0E-02
0.0E+00
HC
IC
(d) Global warming potential
kg CO_2 eq / t OFMSW
3.E+02
2.E+02
2.E+02
1.E+02
5.E+01
0.E+00
HC
IC
(e) Ozone layer depletion potential
kg CFC-11 eq / t OFMSW
1.4E-05
1.2E-05
1.0E-05
8.0E-06
6.0E-06
4.0E-06
2.0E-06
0.0E+00
HC
IC
(f) Photochemical oxidation potential
kg C_2H_4 eq / t OFMSW
6.0E-01
5.0E-01
4.0E-01
3.0E-01
2.0E-01
1.0E-01
0.0E+00
HC
IC
(g) Cumulative energy demand
MJ eq / t OFMSW
2.1E+03
1.8E+03
1.5E+03
1.2E+03
9.0E+02
6.0E+02
3.0E+02
0.0E+00
HC
IC
Caption
Compost distribution
Waste dumped
Gaseous emissions
Water consumption
Energy consumption
Building, machinery & tools
Obtaining OFMSW and PW