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Determination of the energy and environmental burdens associated to the biological treatment of source-separated Municipal Solid Wastes

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Abstract

Environmental burdens of four different full-scale facilities treating source-separated organic fraction of Municipal Solid Wastes (OFMSW) have been experimentally evaluated. The studied facilities include different composting technologies and also anaerobic digestion plus composting. Home composting, as an alternative to OFMSW management, was also included in the study. Energy (electricity and diesel), water consumption and emissions of volatile organic compounds (VOC), ammonia, methane and nitrous oxide have been measured for each process. Energy consumption ranged between 235 and 870 MJ Mg $OFMSW^{-1}$ while the emissions of the different contaminants considered per Mg OFMSW ranged between 0.36-8.9 kg VOC, 0.23-8.63 kg NH_3, 0.34-4.37 kg CH_4 and 0.035-0.251 kg N_2O, respectively. Environmental burdens of each facility are also analyzed from the point of view of process efficiency (i.e. organic matter stabilization degree achieved, calculated as the reduction of the Dynamic Respiration Index (DRI) of the waste treated). This study is performed through two new indices: Respiration Index Efficiency (RIE), which includes the reduction in the DRI achieved by the treatment process and Quality Respiration Index Efficiency (QRIE), which also includes the quality of the end product. Finally, a Life Cycle Assessment is performed using the Respiration Index Efficiency (RIE) as novel functional unit instead of the classical LCA approach based on the total mass treated.

Keywords: Life Cycle Assessment, Environmental Impact, Energy Consumption, Municipal Solid Waste, Composting, Anaerobic digestion, Dynamic Respiration Index.

1. Introduction

Waste management, a complex system involving at least waste collection and waste treatment, has been analyzed in many publications from different points of view. Obviously, the economics of waste management systems[1,2] are mainly required by the authorities while engineers also appreciate technical/engineering information on the system. However, in the last years, a number of authors have been also studying waste management systems by focusing on their environmental impact (mainly energy consumption and environmental burdens). The main question arising from such works is: which is the most environmentally friendly way to manage organic wastes?

The broad number of technologies, waste collection systems and types of waste make necessary to focus on this issue. Regarding Municipal Solid Wastes (MSW) some literature can be found on waste management systems modeling: for example: EASEWASTE,[3] ORWARE[4] and WASTED,[5] are simulation tools that include the environmental burdens associated to waste management. Also, Life Cycle Assessment (LCA) has been applied to generic waste management systems[6] and to MSW management systems of different cities or regions such as Wales,[7] Ankara,[8] Phuket,[9] Corfu[10] or Delaware[11]. Other authors have focused their research on the environmental impact and energy requirements of the different waste collection options[12].

Waste treatment technologies applied to waste stabilization have been also analyzed from the environmental point of view. Composting and anaerobic digestion, which have been widely studied as biological processes[13,14], are the main biological treatments applied to biowaste, that is, the organic fraction of MSW, especially in source-selection collection systems, which are being implemented all over the world. Regarding the environmental impact of such technologies, some studies have been mainly focused on atmospheric emissions (ammonia, methane, nitrous oxide and volatile organic compounds); however, most of them have been performed at pilot or laboratory scale and only a few at real scale.[15-20] A small number of these studies were performed by means of LCA.[21,22] In conclusion, limited literature can be found on the global impact of a specific technology or facility by using in situ measurements (especially with biowaste). This is the case, for example, of Blengini,[23] who used LCA to evaluate the environmental impacts of a composting plant in Italy.

The objective of the present study is to analyze the environmental impacts and energy consumptions of four full-scale source-separated biowaste biological treatment facilities based on different technologies. According to previous studies, home composting has been also considered in the study. Life Cycle Assessment is used to evaluate the environmental burdens and energy consumptions of each technology. A new functional unit is proposed to perform the LCA. This new functional unit includes the real performance of each plant based on the level achieved of organic matter stabilization, which permits to establish novel environmental and energy performance indices related to the biological treatment of organic solid wastes.

2. Materials and methods

2.1. Treatment facilities studied

Four industrial plants located in Catalonia (Spain) treating the source-separated Organic Fraction of Municipal Solid Wastes (OFMSW) were studied over a period of two to three months each, resulting in a global study of two years. The technologies applied in the treatment plants are widely used for biowaste treatment all over the world both in developing and developed countries. The processes studied have been named: Composting in-vessel (CT), composting in confined windrows (CCW), anaerobic digestion plus composting (ADC) and composting in turned windrows (TW). Besides, home composting (HC), as an alternative way to manage household OFMSW has also been included. The main characteristics of each technology are shown in Table 1.

The studied plants (Table 1) can be classified into two categories. On one hand, CCW and TW facilities are based on low technology processes. No pre-treatment step is used in CCW and in TW only a screening process is used after decomposition. Compost in CCW and TW facilities is finally processed in a trommel screen.

On the other hand, CT and ADC are plants based on more technologically complex processes. Both plants include pre-treatment of the OFMSW prior to the curing phase in CT and prior to anaerobic digestion in ADC. The anaerobic digestion process in the ADC plant is based on thermophilic Dranco® technology (Organic Waste Systems, Belgium). In the CT plant the decomposition phase is performed in aerated in-vessel tunnel systems as is the composting of digestate in the ADC plant. Also, a post-treatment based on two steps (trommel screen and refining in a ballistic separator) is used after the composting process.

Due to the low capacity of the CCW plant (91 Mg OFMSW y^{-1}) it is necessary to explain the technology used in this plant in more detail to explain why the results obtained are representative of a larger capacity plant. In the CCW plant[24] the waste to be composted is disposed of in open trapezoidal containers made of concrete with three perforated tubs in their floors to provide aeration and to collect leachate that is stored in a separate tank. The waste is partially covered with a textile linen to prevent water losses (evaporation) and protect it from rainfall. Each container is considered a confined aerated windrow. The studied plant consists of one single container. Considering that the scale up of the process would simply consist of increasing the number of containers but maintaining the same process conditions (amount of waste in each container, shape and dimensions of the windrow, aeration rate, bulking agent:OFMSW ratio, etc.), the CCW plant can be considered representative of any plant capacity using this technology. In fact, at the time of writing this study, the plant has been scaled-up and four containers are now used, with a global capacity of 1500 Mg OFMSW y^{-1}.

It is the authors' opinion that these four plants represent practically all the available options in the industrial market for the biological treatment of biowaste.

Finally, environmental burdens regarding HC of kitchen wastes (i.e. including leftovers of raw fruits and vegetables, food scraps and raw fish or meat and other similar wastes) have also been studied and compared to full-scale plants. Complete details of this study can be found in Martínez-Blanco *et al.*[25] HC was performed in a composting bin (70 $\times$70 $\times$103 cm) placed outdoors in the Escola d'Enginyeria of the Universitat Autònoma de Barcelona (Bellaterra, Spain).

In all the processes the waste was mixed with bulking agent (wood chips or pruning wastes) prior to the composting decomposition phase. Ratio bulking agent:waste used in the studied facilities was 1:2, 2:3, 4:1, 1:2 and 1:1.3 for CT, CCW, ADC, TW, and HC respectively.

2.2 Analytical Methods

The Dynamic Respiration Index (DRI) was used as a measure of the biological activity of the material. This measure is related to the biodegradable organic matter present in the sample and it is widely used in scientific literature. In this study, DRI was determined following the methodology proposed by Adani *et al*.[26] Details of the respirometer can be found in Ponsá *et al.*[27] Briefly, it consists of three Erlenmeyer glass flask reactors, a thermostatic bath at 37°C, a control cabinet, an oxygen sensor, an air supply system based on mass flow-meters and a personal computer unit. Tests were performed by setting airflow constant and sufficient to preserve the oxygen concentration in the outlet airflow above 10% v/v. This value was maintained by a manual control to adapt the airflow rate as a function of the oxygen concentration in the exhaust gases. A 100 g waste sample was placed in each 500 ml reactor that contained a plastic net to support the organic waste and provide an air distribution chamber. The degree of biological stability measured by DRI was calculated by the average value of 24 instantaneous respiration indices obtained during the most active 24 h of biological activity. DRI was expressed as mg of oxygen consumed per g of organic matter and per hour (mg O_2 g^{-1} OM h^{-1}). DRI is presented as an average of a triplicate measurement. As commented before, more detailed explanations about the respiration specific measurement can be found in Ponsá *et al.*,[27] whereas a general explanation about respiration measurements can be consulted in Barrena *et al.*[28]

2.3. Determination of input and output flows

A combination of a questionnaire addressed to plant managers and a systematic sampling work was used to obtain the data for the Life Cycle Inventory. Data on amounts on the treated OFMSW, refuse and compost production, electricity and water consumption were obtained through the questionnaire. Emissions of NH_3, N_2O, CH_4 and VOC were determined in situ or in the laboratory, as explained below.

A specific methodology was developed to calculate gaseous emissions from the composting process[25,28,29] and from biofilters[30]. In brief, airflow velocity and ammonia, nitrous oxide, methane and VOC concentrations on the surface of the composting pile, composting bin or the biofilter were simultaneously measured on the material surface of the composter in order to calculate the gas outlet emission rate (mg/s). Air velocity was determined using a thermo-anemometer (VelociCalc Plus mod. 8386, TSI Airflow Instruments, UK) and a Venturi tube.[31] The product of each pollutant concentration (mg m^{-3}) and air velocity (m s^{-1}) results in the mass flow of a given compound released per surface area unit studied (mg s^{-1} m^{-2}). The pollutant mass flow per area unit (mg s^{-1} m^{-2}) was multiplied by the entire emitting surface area resulting in the outlet mass flow emission (mg s^{-1}) at the moment of measurement for each compound.

Ammonia concentration in gaseous emissions was determined in situ using an ammonia sensor ITX T82 with a measurement range of 0 to 200 ppmv. Gaseous samples were also collected in Tedlar bags for the laboratory determination of VOC, methane and nitrous oxide. Total VOC were analyzed as stated in Colón *et al.*[30] Briefly, total VOC content from gaseous samples was determined as total carbon content using a gas chromatograph equipped with a flame ionization detector (FID) and a dimethylpolysiloxane 2 m×0.53 mm×3.0 μm column (Tracsil TRB-1, Teknokroma, Barcelona, Spain). This column permits the determination of total VOC as a unique peak. The injected volume was 250 μL and the analysis time was 1 min. The gas chromatography operating conditions were as follows: oven temperature isotherm at 200ºC, injector temperature 250ºC, FID temperature 250ºC;

carrier gas helium at 1.5 psi pressure. Methane was also analyzed by gas chromatography using a Flame Ionization Detector (FID) and a HP-Plot Q column (30m x 0.53 mm x 40 μm) with a detection limit of 1 ppmv. The gas chromatography operation conditions were as follows: oven temperature isothermal at 60°C, injector temperature 240°C, FID temperature 250°C; carrier gas N_2 at 4 psi pressure. Nitrous oxide was analyzed by gas chromatography using an Electron Capture Detector (ECD) and a HP-Plot Q column (30m x 0.53 mm x 40 μm) with a detection limit of 50 ppbv. The gas chromatography operation conditions were as follows: oven temperature isothermal at 60°C, injector temperature 120°C, ECD temperature 345°C; carrier gas N_2 at 4 psi pressure. Measurement data for all gases studied were acquired and quantified by the Empower® 2 software (Waters Associates Inc., Milford, USA).

2.4. Life Cycle Assessment

LCA was performed on the waste treatment process, excluding both the transportation of the OFMSW, compost and refuse to their final destinations and wastewater treatment. Fuel, electricity and water consumption as well as atmospheric emissions were completely studied.

The emissions from diesel and electricity consumption in plant were derived from the Ecoinvent v2 database in Simapro 7.1.8.[32] The electricity model considers the consumption of electricity produced in Spain including production and transport of primary energy sources. The energy mix in Spain is mainly composed by: coal (24.3%), nuclear (22.8%), natural gas (19.6%), hydropower (12.7%) and oil (8.4%).

To assess the impacts included in this study the CML 2001 method was used. This method is based on the CML Leiden 2000 method developed by the Centre of Environmental Science of Leiden University.[33] Impact categories considered in the analysis were global warming (GWP), acidification (AP), photochemical oxidation (POP), eutrophication (EUP), human toxicity (HTP), abiotic depletion (ADP) and ozone layer depletion (ODP), which are commonly used in waste management LCA studies.[7,23] Energy consumption was also analyzed in detail. In the context of this study the main contributors to these impact categories were: greenhouse gases emissions for GWP (mainly methane, nitrous oxide and non-biogenic carbon dioxide); ammonia, nitrogen and sulphur oxides emissions for AP; VOC and nitrogen oxides emissions for POP; nitrogen and phosphorous compounds released to the environment for EUP; any human toxic compound released for HTP and compounds affecting ozone layer depletion for ODP. Finally, ADP is mainly related to non-biotic resource consumptions (fossil fuels, metals and minerals).

3. Results and discussion

3.1 Input and output flows

Main input and output material and energy flows for each facility are presented in Table 2. All values are referred to the treatment of 1 Mg of OFMSW processed in each facility.

3.1.1. Energy

Regarding electricity consumption, this issue is highly dependent on the type of machinery used in each plant and the technology applied. Electricity is mainly consumed in in-vessel and windrows aeration. In general, low technology plants that base their process on turned windrows (TW) consume less electricity (Table 2) than more complex plants (CT and ADC). This lower electricity consumption coincides with higher diesel use. Diesel is mainly used in waste transportation and handling within the treatment plant limits and it strongly depends on the distance that the transporting equipment must cover between process steps. This is particularly important in the case of CCW, where the decomposition zone and the curing zone are separated by 200 m, resulting in the highest diesel consumption. In addition, CCW plant also uses diesel machinery in the post-treatment processes.

Total energy consumption can be calculated assuming that 1L of diesel produces 38.16 MJ of energy.[34] Then, the total energy consumption will range between 235 and 870 MJ Mg $OFMSW^{-1}$ (in the full scale facilities). The lowest value corresponds to TW (low technology process). Fricke *et al.*[35] reported a range (including electricity, heat generation and diesel) between 200 and 430 MJ Mg $OFMSW^{-1}$ for MSW treatment plants with anaerobic treatment and aerobic post-treatment. Blengini[23] reported a total energy consumption of 297 MJ Mg $OFMSW^{-1}$ in an aerated windrow composting plant.

The CT plant was improved few months before the study due to neighbors complaining about bad odors. The re-design consisted of closing the maturation area (which was previously open to atmosphere) and installing new gaseous emissions mitigation measures. The re-designed plant has three wet scrubbers and a 1560 m^3 biofilter (divided into three units), while the old plant had only one scrubber and 720 m^3 of biofilter.[24,29] These changes in the gaseous emissions mitigation measures involved a 45% increase in energy consumption, but obviously a better performance regarding atmospheric emissions.

HC was characterized by a low energy consumption (33.7 MJ Mg $OFMSW^{-1}$), which exclusively corresponded to the electricity used in the garden-chipper to prepare the bulking agent.

In the case of the ADC facility, which includes an anaerobic digestion process, energy is recovered from the produced biogas. During the studied period the plant produced 98.9 Nm^3 biogas Mg of input $OFMSW^{-1}$. This value is in the range reported by Fricke *et al.*[35] (60-110 Nm^3 biogas Mg $OFMSW^{-1}$). Biogas is converted to energy in the same treatment plant yielding 717.12 MJ Mg $OFMSW^{-1}$, as it was reported by plant managers. Part of this self-produced electricity is consumed in the plant (167.04 MJ Mg $OFMSW^{-1}$) and the rest is sold to an external electricity company. This means that 21% of the produced energy is consumed in the plant. This value is in the lower range of values (20-40%) reported by Braber[36] for this type of facilities. As a result, the gross positive energy yield in ADC facility is 216.72 MJ Mg $OFMSW^{-1}$ (Table 3).

3.1.2. Water

In the same way as energy, water consumption is also dependent on the level of technology used in the facility. In low technology facilities, using aerated or turned windrow technologies without exhaust gas treatment, leachate is typically recirculated to the material during the decomposition phase, thus reducing water consumption. In fact, water consumption in CCW and TW plants is negligible. Also HC reported low water consumption (0.051 m^3 Mg $OFMSW^{-1}$). However, complex facilities, which include gas wet treatment processes (CT and ADC), are expected to have higher water requirements. Water consumption in the CT facility (0.56 m^3 Mg $OFMSW^{-1}$) should be considered as an extreme value, since in this particular plant the scrubber used in the gas treatment process operates in an open loop mode. In general, the water consumption ranges, approximately, between 0 and 0.5 m^3 Mg $OFMSW^{-1}$, the lower values being those corresponding to low technology processes. It must be remarked that, although leachates can be used for watering during the decomposition phase, they cannot be used during maturation to avoid pathogen re-colonization. Then, no water consumption means that no watering is performed during maturation, a situation that is not always adequate for the composting process. Fricke *et al.*[35] reported a water consumption ranging between 0.1 and 0.17 m^3 Mg $OFMSW^{-1}$ for MSW treatment plants with anaerobic treatment and aerobic post-treatment and Blengini[23] reported a water consumption of 0.09 m^3 Mg $OFMSW^{-1}$ in an aerated windrow composting plant.

3.1.3. Gaseous emissions

During the study of the four plants and the HC process, measurements of the atmospheric emissions of NH_3, VOC, N_2O and CH_4 were undertaken. CO_2 from biogenic sources, that is, coming from the decomposition of organic matter, has not been considered. In the closed facilities (CT and ADC) gaseous emissions were evaluated on the biofilter external surface.[29] In open facilities (CCW, TW and HC), emissions were evaluated on the surface of the composting windrows.[25,29]

Ammonia emissions are important due to its environmental impact as an atmospheric contaminant, but also due to the possible loss of nitrogen in the final compost and the impact that this phenomenon produces on the use of chemical fertilizers. Since in all plants the waste treated (OFMSW) has the same organic characteristics, the final nitrogen content in the compost could be related to the treatment technology used. For example, ammonia emissions to the atmosphere or leachate generation and management, which are related to process technology and plant management, can affect nitrogen content in the end product. In terms of total nitrogen, the final compost from the CT plant presented the highest content (2.7%, dry matter basis), while CCW presented the lowest content (1.08%, dry matter basis). Total nitrogen content in compost from ADC, HC and TW were 1.54%, 1.71% and 2.65%, respectively.

Ammonia emissions ranged between 0.23 and 8.63 kg NH_3 Mg $OFMSW^{-1}$, the highest values being those corresponding to facilities that did not include exhaust gas treatment equipment (CCW and TW). The ammonia emission range obtained is consistent with values reported by other authors. Blengini[23] estimated 0.6 kg NH_3 per Mg biowaste in an aerated windrow composting plant with a gas treatment process. Gronauer *et al.*[37] reported 0.67 kg NH_3 Mg $OFMSW^{-1}$ in an aerated pile composting process.

Process VOC emissions ranged between 0.36 and 6.22 kg VOC Mg $OFMSW^{-1}$. The highest values, as in the case of ammonia, being those corresponding to facilities without gas treatment steps, especially in the case of the TW facility. HC reported VOC emission in the lowest range determined for the industrial facilities (0.56 kg VOC Mg $OFMSW^{-1}$). To our knowledge, few data on total VOC emissions in full scale facilities treating biowaste are reported in literature.[30] Smet *et al.*[19] and Baky and Eriksson[38] reported VOC emission factors in pilot-scale composting experiments of 0.59 and 1.7 kg VOC Mg $OFMSW^{-1}$, respectively. Diggelman[1] reported 4.3 kg VOC Mg $OFMSW^{-1}$ from bibliographic data.

Emissions of N_2O and CH_4 during waste biotreatment are acquiring major relevance due to their effect on global warming. Both gaseous compounds are related to a lack of oxygen during the composting process or, obviously, to the presence of an anaerobic digestion step. In this study, N_2O emissions in full scale facilities ranged between 0.035 and 0.251 kg N_2O Mg $OFMSW^{-1}$, while HC revealed the highest value (0.676 kg N_2O Mg $OFMSW^{-1}$). The high N_2O emissions measured during TW and HC indicate that the waste was insufficiently aerated using these technologies. In this context, Boldrin *et al.*,[39] in a literature review, reported N_2O emissions ranging between 0.0075 and 0.252 kg N_2O Mg $OFMSW^{-1}$ and Amlinger *et al.*[40] reported a range from 0.192 to 0.454 kg N_2O Mg $OFMSW^{-1}$ for home composting.

CH_4 emissions ranged between 0.34 and 4.37 kg CH_4 Mg $OFMSW^{-1}$ in the full scale facilities. The highest values were those corresponding to facilities without gas treatment steps, especially in the TW facility. Boldrin *et al.*[39] reported CH_4 emissions in biowaste composting ranging from 0.02-1.8 kg CH_4 Mg $OFMSW^{-1}$ and Amlinger *et al.*[40] reported a range from 0.788 to 2.18 kg CH_4 Mg $OFMSW^{-1}$ for home composting. Nevertheless, few studies are available for these last two gases in literature, especially when dealing with full-scale processes.

It is worthwhile to pay special attention to the ADC facility, where the sludge from anaerobic digestion (digestate) is in-vessel composted. It is supposed that the digestate is mostly saturated with CH_4 that will be released during the mixing operation with the bulking agent and the in-vessel aeration. However, all these operations are performed in closed areas and emissions are treated (wet scrubber plus biofilter) leading to an emission of 2.39 kg CH_4 Mg $OFMSW^{-1}$.

In the case of HC the obtained value was lower than those obtained in full scale facilities (0.16 kg CH_4 Mg $OFMSW^{-1}$) while Amlinger *et al.*[40] reported 0.8 to 2.2 kg CH_4 Mg

OFMSW^{-1}. Observing CH_4 and N_2O emissions, it can be assumed that in the HC process there was a lack of aeration that did not lead to the formation of strictly aerobic areas, while in the TW (reporting the highest emissions of N_2O and CH_4) the lack of aeration lead to the formation of anoxic and anaerobic zones in the windrow.

Table 3 presents the electricity balance in the ADC facility. A net electricity generation of 216.72 MJ Mg OFMSW^{-1} was estimated. According to IPCC,[41] electricity produced from biogas does not account for CO_2 emissions. Then, this electricity surplus sold to the electric external company can be considered as an avoided impact regarding the Life Cycle Assessment of this facility.

3.1.4. Compost and refuse

The compost yield (Mg compost Mg OFMSW^{-1}) ranges between 0.03 and 0.52, the mean yield being 0.21. Blengini[23] reported a yield of 0.28 Mg compost Mg OFMSW^{-1} for an aerated windrow composting plant. The compost yield of a treatment plant depends mainly on several parameters; on one hand, the real content of biodegradable organic matter in each Mg of OFMSW (impurities or refuse content, Table 1). In this sense the ADC facility, which reported the lowest yield, had the highest refuse content per Mg of OFMSW. On the other hand, the efficiency of the pre- and post-treatment steps used to separate unwanted materials and residual bulking agent from biowaste and, finally, the type of biological process used (aerobic or anaerobic/aerobic steps) are crucial for the compost yield. OFMSW in the ADC facility is treated by two consecutive biological processes (anaerobic and aerobic) yielding a lower quantity of compost by the previous transformation of the organic matter into biogas.

3.2 Exploring energy and environmental burdens related to real process performance

The main objective of the OFMSW treatment plants is to stabilize the organic matter content of the waste to a level that allows its use as compost or, in general, as organic amendment. The biological stability is defined as the measure of the degree of decomposition of biodegradable organic matter contained in a matrix.[42] The degree of biological stability of waste materials can be directly measured by means of respirometric indices.[26,28,43] In the European legislation drafts[44] ‘stabilization’ means the reduction of the decomposition properties of biowaste to such an extent that offensive odors are minimized and that the Dynamic Respiration Index (DRI) is below 1.0 g O_2 kg^{-1} OM h^{-1}. Consequently, the efficiency of the OFMSW treatment plants can be calculated through the difference between the degrees of stability for input and output materials (DRI reduction). However, the traditional LCA approach to study waste management environmental impacts only considers the amount of mass treated, which often results in partial conclusions.

From these considerations, some crucial questions arise: are the energy and environmental impacts related to process performance (waste stabilization)? Did all the studied plants produce a stabilized material? Were the input materials equivalent from the point of view of stability? Was the effort to produce a stabilized material the same in each plant?

Answering these questions will provide a fair approach of the studied plants, both from the efficiency and the environmental point of view. To undertake this new approach, each facility must be analyzed using the degree of stabilization achieved in each process treatment. Table 4 presents DRI values of the input and output materials for each studied plant as well as values of this index within the main process steps. The initial DRI value used is the mean of the OFMSW DRI obtained for all plants. This value was selected because the variability found among the plants analyzed is similar to that found for the input waste in a single plant analyzed at different times. For instance, the average DRI value used in this study for the OFMSW is 4.83 (confidence interval within 4.25 and 5.42, using α=0.05), which is acceptable for raw organic solid wastes.[27] The variability observed for this value in a single plant was approximately 20%.

In the case of final compost DRI, the variability found in each plant was minimal (lower than 5%), so the value can be fully attributed to the plant performance. As can be seen in Table 4, final compost DRI was in the range 0.7 to 2.7 g O_2 kg OM^{-1} h^{-1}. According to the legislation draft value stated above, compost from the TW and CT facilities (2.7 and 1.45 g O_2 kg OM^{-1} h^{-1}, respectively) does not fulfill the stability criteria.

Gaseous emissions or total energy consumption could be normalized if they are expressed as a ratio referred to DRI reduction achieved in each plant. This ratio could be called the Respiration Index Efficiency (RIE) and can be calculated according to Equation 1. RIE (Table 5) reports the environmental impact and the energy consumption related to the stabilization of the waste per one unit of DRI reduction. Then, at the same initial waste composition, RIE could be used for the comparison of different plants from an environmental and energy point of view including its performance, even when different technologies are used.

$$\mathrm{RIE} = \frac{\text{Environmental burden or energy consumption}}{\mathrm{DRI}_{\text{reduction}}} \qquad \text{Eq. 1}$$

where: environmental burden is referred to any specific emission factor (i.e. VOC, ammonia, etc.) and energy consumption is the amount of energy necessary to carry out the process.

However, the reduction of DRI achieved in each plant does not completely reflect its real performance. For example, a facility could consume low energy (electricity or fossil fuel) in its operation (i.e. low CO_2 emissions) but its final product (compost) might have a low quality (i.e. DRI > 1.0 g O_2 kg^{-1} OM h^{-1}). In order to consider the real performance of a facility another index can be proposed: the Quality and Respiration Efficiency Index (QRIE), that can be calculated (Equation 2) by multiplying the RIE by the quality of the final compost expressed as DRI. The QRIE (Table 5) provides information on the environmental burdens to treat 1 Mg OFMSW and to reduce 1 unit the DRI taking into account the quality of the final product. Thus, the QRIE value is specific for each plant and its operation goodness in terms of organic matter stabilization.

$$\mathrm{QRIE} = \frac{\text{Environmental burden or energy consumption}}{\mathrm{DRI}_{\mathrm{reduction}}}\,\mathrm{DRI}_{\mathrm{compost}} \qquad \text{Eq. 2}$$

As can be seen in Table 5, the environmental performance of TW is clearly affected when RIE and QRIE are used. TW consumed 236.8 MJ Mg $OFMSW^{-1}$, that was the lowest energy consumption obtained at full-scale, and it was attributed to the low technology process used in this plant. However, when RIE is calculated the differences of TW with CCW and ADC are reduced and when applying the QRIE, TW facility becomes the second least efficient plant in terms of energy consumption. This is due to the low DRI reduction achieved (44.4%) in this plant and to the end-product high DRI value (2.7 g O_2 kg OM^{-1} h^{-1}). In fact, during the study of the TW plant the authors realized that few turnings were performed during the decomposition phase. Furthermore, no turnings were performed during the curing phase. To increase the DRI reduction and obtain stable compost, a minimal number of windrow turnings should be performed, both in the decomposition phase and in the maturation phase, which would lead to an increase in diesel consumption considering the energy requirements. Accordingly, it seems that an optimal operation should be designed by considering the stabilization achieved and the related energy requirements. Further research in this field is necessary to obtain these optimal values for the different technologies that are being applied to biowaste.

In conclusion, the value of the final compost DRI is only a measure of product quality regardless the waste origin, plant performance, etc., whereas DRI reduction is an intermediate value that considers all these factors and permits the calculation of advanced environmental impact indices such as RIE and QRIE. These novel indices permit to compare plants with different technologies and size or even treating different wastes and are proposed as a tool to help policy makers and stakeholders in the decision making for selecting appropriate biowaste treatment technologies.

3.3. Life Cycle Assessment applied to solid waste treatment plants

The LCA methodology includes the selection of a functional unit to relate the results obtained during the inventory step. When an OFMSW treatment system is studied, a defined amount of waste treated (typically 1 Mg of OFMSW) has been traditionally selected as functional unit. However, according to the arguments stated above, the LCA functional unit should include the degree of stabilization measured during the biological treatment process. This is achieved by using the new functional unit proposed (RIE, Eq. 1) i.e. the reduction of 1 DRI unit in 1 Mg of OFMSW. In consequence, all the environmental impacts will be related to RIE.

Table 6 shows the values of impact categories for a conventional function unit (1 Mg OFMSW) and for the novel proposed functional unit (RIE, reduction of 1 DRI unit in 1 Mg of OFMSW). Analyzed impact categories include: global warming (GWP), acidification (AP), photochemical oxidation (POP), eutrophication (EUP), human toxicity (HTP), abiotic depletion (ADP) and ozone layer depletion (ODP). In an ADC plant, in which biogas is used to produce electricity (self-consumed and sold to an electric company), this electricity was considered an avoided impact, leading to negative values on the different impact categories. In these cases, when the RIE is considered as functional unit, the values are multiplied by DRI reduction instead of divided.

Figure 1 shows the contribution of process, electricity and fuel consumption to each impact category considered. As stated above, CO_2 from biogenic sources has not been considered in the calculation of GWP.[41,45] In ADC (anaerobic digestion + composting) part of the biogas produced was burned in a flare. Since CO_2 from biogas combustion comes from a biogenic source it was not considered in the GWP calculation. GWP values ranged between 11 and 92 kg CO_2 eq DRI reduction^{-1} Mg OFMSW^{-1}, being the ADC plant the best and the TW plant the worst in this term. In all cases, the biological process contributes more than 50% in GWP category (due to CH_4 and N_2O emissions) except for the CT plant, in which the high electricity consumption caused a 75% contribution (Figure 1).

Contribution to AP is mainly caused by ammonia emissions occurring during the process except for the CT plant, in which the high electricity consumption resulted in 80% contribution (Figure 1). AP ranged between $3.98 \cdot 10^{-2}$ and 6.6 kg SO_2 eq DRI reduction^{-1} Mg OFMSW^{-1}. The low values are related to facilities with gas treatment processes reporting a low effect on AP while, when no gas treatment is used; the reported AP values are significantly higher, except for HC.

The case of GWP can be used as an example to confirm the effect of the application of the new functional unit. It can be seen from Table 6 that, when the conventional functional unit is used, HC is the technology that makes a higher contribution to GWP (209 kg CO_2 eq Mg OFMSW^{-1} (close to that of the TW plant, 196 kg CO_2 eq Mg OFMSW^{-1}). However, when the new proposed functional unit is used (RIE), TW is the category that contributes more to GWP (92.1 kg CO_2 eq DRI reduction^{-1} Mg OFMSW^{-1}) with a significant difference in the case of HC (56.6 kg CO_2 eq DRI reduction^{-1} Mg OFMSW^{-1}).

Process VOC emissions mainly contribute to POP, which ranged between $5.68 \cdot 10^{-2}$ and 1.11 kg C_2H_4 eq DRI reduction^{-1} Mg OFMSW^{-1}. Electricity and fuel consumption suppose a low contribution to this impact category, except for the CT plant. Lower values are obtained in the facilities with gas treatment equipment.

In the same way as AP, EUP is mainly due to process ammonia emissions, except for the CT plant where electricity is the main contribution. EUP ranged between $2.78 \cdot 10^{-2}$ and 1.42 kg PO_4^{-3} eq DRI reduction^{-1} Mg OFMSW^{-1}. The TW facility reported the highest value since it was the facility with the lower DRI reduction and without gas treatment. EUP as well as AP and POP are highly dependent on process emissions (VOC and NH_3). Thus, to reduce these impacts, it should be mandatory to treat wastes in closed facilities with gas treatment equipment.

The contribution to HTP is mainly related to electricity consumption, except for the TW plant where process emissions are supposed to make the main contribution (56%, Figure 1). HTP ranged between -18.9 and 6.95 kg 1.4-DB eq DRI reduction^{-1} Mg OFMSW^{-1}.

Finally ADP and ODP are related in this case to energy consumption (fuel and electricity). ADP ranged between $-6.34\cdot10^{-1}$ and $2.58\cdot10^{-1}$ kg CFC^{-11} eq DRI reduction^{-1} Mg OFMSW^{-1}. The CT plant provides the worst case due to its high electricity consumption. ODP ranged between $-1.09\cdot10^{-6}$ and $2.11\cdot10^{-6}$ kg CFC^{-11} eq DRI reduction^{-1} Mg OFMSW^{-1} being CT plant again the worst case due to the high electricity consumption. Unfortunately, no literature studies have been found to compare these values.

It has to be noted that the definition of the limits of the studied system will have an important influence on the environmental impact of each management solution. For example, the refuse generation has a direct effect on the environmental impact of each plant, since this refuse is normally transported to a sanitary landfill where, during its decomposition, emissions of methane, carbon dioxide and other gases to the atmosphere will occur. This is the case of the AD plant, which is beneficial in terms of energy production, but it will be penalized by the refuse transport to a landfill and its decomposition due to greenhouse gas emissions. Also, compost utilization has a beneficial effect[46] on those plants with the higher productivity per mass of OFMSW. However, in this work, LCA is only used to demonstrate that a new functional unit should be used in the assessment of the environmental impact of the biological treatment of source-separated

Municipal Solid Wastes and the expansion of the system limits could cover the overall environmental burdens directly associated to the biological process.

In summary, to asses the environmental impact of biological waste treatment plants it is necessary to use a functional unit that includes the performance of the biological treatment (waste stabilization). This functional unit has the origin in a novel combination of two well-known techniques in organic waste management science: environmental impacts assessment by LCA and respiration techniques. Both are internationally used and extensively reported in scientific recent literature.[23-29,33] We have proposed and demonstrated that the reduction of the biodegradable organic matter content of the treated materials (measured as the reduction in the Respiration Index) is an effective and meaningful functional unit for this purpose. This functional unit has been used to analyze different biological biowaste treatment facilities using different technologies, including anaerobic digestion and composting. Although the study is focused on the OFMSW, the developed methodology can be applied to any organic waste that is intended to be biologically treated. This approach will be very useful for policy makers and stakeholders when selecting new biowaste treatment technologies especially when the environmental performance or the energy consumption has to be carefully considered.

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Tables

Table 1. Main characteristics of the studied industrial facilities (CT: composting in-vessel; CCW: composting in confined windrows; ADC: anaerobic digestion plus composting, TW: turned windrow composting and HC: home composting).

Facility	CT	CCW	ADC	TW	HC
Main biological process	Composting	Composting	Anaerobic digestion + composting	Composting	Composting
Pre-treatment	Trommel* screen (80 mm)	No	Ballistic separator + Magnetic separator	Trommel* screen (80 mm)	No
Decomposition phase	In-vessel composting	Aerated windrow composting	Anaerobic digestion + in-vessel composting	Turned windrow composting	Composting bin
Curing phase	Aerated windrow	Turned windrow	Turned windrow	Turned windrow	Composting bin
Post-treatment	Trommel screen (10 mm) + ballistic separator	Trommel screen (10 mm)	Trommel screen (12 mm) + ballistic separator	Trommel screen (10 mm)	No
Type of facility	Completely closed	Completely open	Completely closed	Completely open	Completely open
Exhaust gas treatment	Wet Scrubber + biofilter	Not present	Wet Scrubber + biofilter	Not present	Not present
Waste treated (t $year^{-1}$)	7435	91	17715	3000	0.43
Refuse (percentage of weight over input material)	10	1	13	11	0

* The screen process is performed after the decomposition phase.

Table 2. Input and output flows in the studied MSW treatment plants. All parameters are referred to 1 Mg of OFMSW (CT: composting in-vessel; CCW: composting in confined windrows; ADC: anaerobic digestion plus composting, TW: turned windrow composting and HC: home composting).

Facility		CT	CCW	ADC	TW	HC
Inputs	MJ electricity	770.40	235.80	166.32	33.41	33.77
	MJ electricity self generation	0	0	167.04	0	0
	l diesel	2.66	9.00	3.64	5.33	0
	Total MJ (electricity + diesel)	871.90	579.24	472.26	236.80	33.77
	m^3 water in the waste gas treatment process	0.42	n/a	0.12	n/a	n/a
	m^3 water used in the composting process	0.14	0.00	0.00	0.00	0.051
	Total m^3 water	0.56	0.02	0.12	0.00	0.051
Outputs	m^3 leachate	n/e	0.00	0.03	0.00	0
	m^3 biogas condensates	n/a	n/a	0.05	n/a	n/a
	kg NH_3	0.11	2.00	0.23	8.63	0.84
	kg VOC	0.36	6.22	0.86	5.70	0.56
	kg N_2O	0.075	0.076	0.035	0.251	0.676
	kg CH_4	0.34	1.68	2.39	4.37	0.16
	Mg Compost	0.10	0.52	0.03	0.20	0.25
	Mg Refuse	0.13	0.00	0.41	0.26	0
	m^3 biogas	n/a	n/a	98.90	n/a	n/a
	Electricity MJ	n/a	n/a	550.08	n/a	n/a

n/a: not applicable. n/e: not evaluated.

Table 3. Electricity balance in the Anaerobic Digestion plus Composting facility.

Item	Value (MJ Mg $OFMSW^{-1}$)
Electricity consumption	166.32
Self generated electricity from biogas and consumed in the facility	167.04
Self generated electricity from biogas and sold to an electricity distribution company	-550.08
Net balance	**-216.72**

Table 4. Dynamic Respiration Index at different process steps for each studied process (DRI expressed as g O_2 kg OM^{-1} h^{-1}) (CT: composting in-vessel; CCW: composting in confined windrows; ADC: anaerobic digestion plus composting, TW: turned windrow composting and HC: home composting).

Point of the plant	CT	CCW	ADC	TW	HC
OFMSW	4.83	4.83	4.83	4.83	4.83
Anaerobic digestion output	n/a	n/a	1.59	n/a	n/a
Decomposition output	n/e	1.30	n/e	2.96	n/e
Compost	1.45	0.70	0.75	2.7	1.13
DRI reduction (units)	3.38	4.13	4.08	2.13	3.7
DRI reduction (%)	**69.9**	**85.5**	**84.5**	**44.4**	**76.6**

n/a: not applicable. n/e: not evaluated.

Table 5. Impact factor, Respiration Index Efficiency (RIE), Quality and Respiration Index Efficiency (QRIE) for energy consumption and NH_3, VOC, N_2O and CH_4 emissions (CT: composting in-vessel; CCW: composting in confined windrows; ADC: anaerobic digestion plus composting, TW: turned windrow composting and HC: home composting).

	CT	**CCW**	**ADC**	**TW**	**HC**	**Units**
Energy	871.90	579.24	472.26	236.80	33.77	MJ Mg $OFMSW^{-1}$
RIE_{energy}	257.96	140.25	115.75	111.17	9.13	(MJ Mg $OFMSW^{-1}$) (g O_2 kg OM $h^{-1})^{-1}$
$QRIE_{energy}$	374.04	40.08	29.93	42.43	10.11	MJ Mg $OFMSW^{-1}$
NH_3	0.11	2.00	0.23	8.63	0.84	kg NH_3 Mg $OFMSW^{-1}$
RIE_{NH3}	0.03	0.48	0.06	4.05	0.23	(kg NH_3 Mg $OFMSW^{-1}$) (g O_2 kg OM $h^{-1})^{-1}$
$QRIE_{NH3}$	0.05	0.34	0.04	10.96	0.25	kg NH_3 Mg $OFMSW^{-1}$
VOC	0.36	6.22	0.86	5.70	0.56	MJ Mg $OFMSW^{-1}$
RIE_{VOC}	0.11	1.50	0.21	2.67	0.15	(kg VOC Mg $OFMSW^{-1}$) (g O_2 kg OM $h^{-1})^{-1}$
$QRIE_{VOC}$	0.16	1.05	0.16	7.21	0.17	kg VOC Mg $OFMSW^{-1}$
N_2O	0.08	0.08	0.04	0.25	0.68	kg N_2O Mg $OFMSW^{-1}$
RIE_{N2O}	0.02	0.02	0.01	0.12	0.18	(kg N_2O Mg $OFMSW^{-1}$) (g O_2 kg OM $h^{-1})^{-1}$
$QRIE_{N2O}$	0.04	0.01	0.01	0.32	0.20	kg N_2O Mg $OFMSW^{-1}$
CH_4	0.34	1.68	2.39	4.37	0.16	kg CH_4 Mg $OFMSW^{-1}$
RIE_{CH4}	0.10	0.41	0.59	2.05	0.04	(kg CH_4 Mg $OFMSW^{-1}$) (g O_2 kg OM $h^{-1})^{-1}$
$QRIE_{CH4}$	0.15	0.29	0.43	5.55	0.05	kg CH_4 Mg $OFMSW^{-1}$

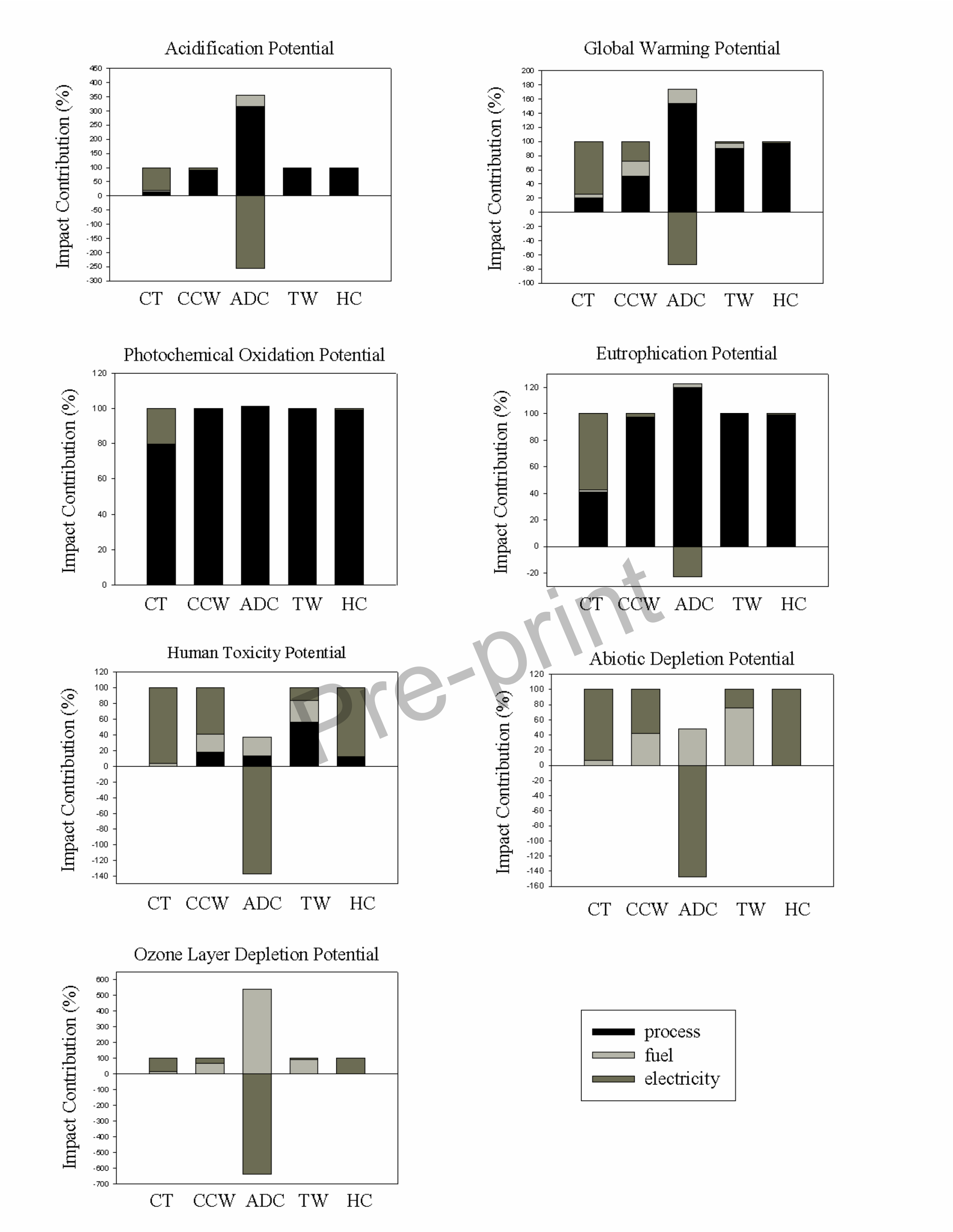
Table 6. Impact categories for the different studied plants, for the conventional unit (Mg OFMSW^{-1}) and for the proposed new functional unit (DRI reduction^{-1} Mg OFMSW^{-1}). For negative values, when RIE is considered as functional unit, the values are multiplied by DRI reduction instead of divided.

Impact category	Units	CT	CT_RIE	CCW	CCW_RIE	ADC	ADC_RIE	TW	TW_RIE	HC	HC_RIE
Acidification	kg SO_2 eq FU	1.30	3.85E-01	3.75	9.08E-01	1.62E-01	3.98E-02	1.40E+01	6.57	1.40	3.78E-01
Global warming	kg CO_2 eq FU	1.50E+02	4.44E+01	1.23E+02	2.99E+01	4.52E+01	1.11E+01	1.96E+02	9.21E+01	2.09E+02	5.66E+01
Photochemical oxidation	kg C_2H_4 FU	1.92E-01	6.68-02	2.59	6.27E-01	3.58E-01	8.77E-01	2.377	1.11	2.33E-01	6.38E-02
Eutrophication	kg PO_4^{3-} eq FU	9.40E-02	2.78E-02	7.21E-01	1.73E-01	6.71E-02	1.77E-02	3.03	1.42	2.97E-01	8.12E-02
Human toxicity	kg 1,4-DB eq FU	2.35E+01	6.95	1.17E+01	2.84	-4.64	-1.89E+01	5.82	4.30	1.94	5.26E-01
Abiotic depletion	kg Sb eq FU	8.72E-01	2.58E-01	4.34E-01	1.05E-01	-1.55E-01	-6.34E-01	1.44E-01	6.78E-02	4.11E-02	1.11E-02
Ozone layer depletion	kg CFC^{-11} eq FU	7.12E-06	2.11E-06	5.42E-06	1.31E-06	-2.67E-07	-1.09E-06	2.37E-06	1.11E-06	3.05E-07	8.23E-08

FU: functional unit

Figure caption

Figure 1. Biological process contribution (black bar), fuel consumption contribution (grey bar) and electricity consumption contribution (white bar). CT: composting in-vessel; CCW: composting in confined windrows; ADC: anaerobic digestion plus composting, TW: turned windrow composting and HC: home composting.


Acidification Potential
Impact Contribution (%)
CT CCW ADC TW HC
Global Warming Potential
Impact Contribution (%)
CT CCW ADC TW HC
Photochemical Oxidation Potential
Impact Contribution (%)
CT CCW ADC TW HC
Eutrophication Potential
Impact Contribution (%)
CT CCW ADC TW HC
Human Toxicity Potential
Impact Contribution (%)
CT CCW ADC TW HC
Abiotic Depletion Potential
Impact Contribution (%)
CT CCW ADC TW HC
Ozone Layer Depletion Potential
Impact Contribution (%)
CT CCW ADC TW HC
process
fuel
electricity