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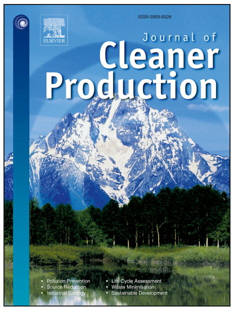

Life Cycle Assessment (LCA) of different municipal solid waste management options: A case study of Asturias (Spain)

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PII: S0959-6526(14)00594-0

DOI: 10.1016/j.jclepro.2014.06.008

Reference: JCLP 4401

To appear in: *Journal of Cleaner Production*

Received Date: 23 October 2013

Revised Date: 28 May 2014

Accepted Date: 2 June 2014

Our reference: JCLP 4401
Editorial reference: JCLP_JCLEPRO-D-13-01662
To be published in: Journal of Cleaner Production

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ABSTRACT

This paper analyses six strategies for managing the MSW generated in Asturias (Spain) in terms of their environmental impacts applying the Life Cycle Analysis methodology. To this end, the effect of these strategies on Human Health, Ecosystem Quality, Global Warming and Resource Depletion is studied. The analysed management options include direct landfill with recovery of biogas (S-0), direct incineration with energy recovery (S-1), biomethanization of the source-separated organic fraction with direct incineration of the mixed fraction (S-2), biomethanization of the source-separated organic fraction, sorting of the mixed fraction and incineration of the rejected fraction (S-3), biomethanization of the source-separated organic fraction, sorting of the mixed fraction and incineration of the rejected fraction following aerobic stabilization of the organic fraction (S-4) and biomethanization of the source-separated organic fraction, sorting of the mixed fraction and landfill of the rejected following aerobic stabilization of the organic fraction (S-5). The Consortium for Waste Management (COGERSA) provide data regarding on transport and collection of waste and consumption of energy, water, oil and reagents at each processes. The results obtained suggest that Scenario S-3 has the least impact on the analysed damage categories while the scenarios including landfilling produces the greatest impact in all the categories analysed. Regarding involved processes in studied scenarios, the transport produces a significant impact in the environment, biomethanization contributes to reducing the impact in all the damage categories and incineration adversely affects the categories of Human Health and Climate Change, but helps to reduce damage in the Resources category.

NUMBER OF WORDS INCLUDING REFERENCES, TABLE AND FINGURE CAPTIONS: 7438

LIFE CYCLE ASSESSMENT (LCA) OF DIFFERENT MUNICIPAL SOLID WASTE MANAGEMENT OPTIONS: A CASE STUDY OF ASTURIAS (SPAIN)

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ABSTRACT

This paper analyses six strategies for managing the MSW generated in Asturias (Spain) in terms of their environmental impacts applying the Life Cycle Analysis methodology. To this end, the effect of different scenarios on four damage categories is studied, namely Human Health, Ecosystem Quality, Global Warming and Resource Depletion. The studied management options include direct landfill with recovery of biogas (S-0), direct incineration with energy recovery (S-1), biomethanization of the source-separated organic fraction with direct incineration of the mixed fraction (S-2), biomethanization of the source-separated organic fraction, sorting of the mixed fraction and incineration of the rejected fraction (S-3), biomethanization of the source-separated organic fraction, sorting of the mixed fraction and incineration of the rejected fraction following aerobic stabilization of the organic fraction (S-4) and biomethanization of the source-separated organic fraction, sorting of the mixed fraction and landfill of the rejected following aerobic stabilization of the organic fraction (S-5). The Consortium for Waste Management (COGERSA) provided data on the transport of waste, amounts of waste collected and distances travelled during collection, as well as data on consumptions (energy, water, oil and reagents) at each processes. The results obtained suggest that Scenario S-3 has the least impact on the analysed damage categories while the scenarios including landfilling (S-0 and S-5) produces the greatest impact in all the categories analysed. Regarding involved processes in studied scenarios, the transport produces a significant impact in the environment. In contrast, biomethanization contributes to reducing the impact in all the damage categories and incineration adversely affects the categories of Human Health and Climate Change, but helps to reduce damage in the Resources category.

Key words: Municipal Waste Management (MWM), Climate Change, Resources, Human Health.

1. Introduction

The management of municipal solid waste (MSW) is currently one of the most serious and controversial issues faced by the local and regional authorities of a country. The member countries of the European Union (EU) are required to propose waste management systems that comply with the hierarchy of options, based on the following order of priority: prevention (in waste generation), preparing for reuse, recycling, other types of recovery (including energy) and, finally, the disposal of waste (Directive 2008/98/EC of the European Parliament and of the Council of 19th November 2008, on Waste). Moreover, sending biodegradable organic matter to landfill must be phased out gradually, in line with the targets set out in Directive 1999/31/EC of the Council of 26th April, on the Landfill of Waste.

Despite important technological advances, improved legislation and regulatory systems in the field of waste management in addition to more sophisticated health surveillance, public acceptance of the location of new waste disposal and treatments facilities is still very low due to concern about adverse effects on the environment and human health. Health issues are associated with every step of the handling, treatment and disposal of waste, both directly (via recovery and recycling or other activities in the waste management industry, via exposure to hazardous substances in the waste or to emissions from incinerators and landfill sites, vermin, odours and noise) or indirectly (for example, via the ingestion of contaminated water, soil and food) (Giusti, 2009).

Within this context, the application of Life Cycle Assessment (LCA) to sustainable municipal solid waste management has rapidly expanded over the last few years as a tool capable of capturing and addressing the complexities and interdependencies which typically characterise modern integrated waste management systems (Blengini et al., 2012). In fact, numerous studies have been published in recent years in which this tool is applied in the environmental assessment of different scenarios of municipal waste management in different countries, such as Italy (Arena et al., 2003; Cherubini et al., 2009; Blengini et al., 2012), Spain (Güereka et al., 2006; Bovea and Powell, 2006; Montejo et al., 2013), Lithuania (Miliūte and Staniškis, 2009), Brazil (Mendes et al., 2004), Canada (Assamoi and Lawryshyn, 2012), the United States (Vergara et al., 2011), China (Han et al., 2010; Song et al., 2013), Indonesia (Gunamantha and Sarto, 2012) and Australia (Lundie and Peters, 2005).
Cherubini et al. (2009) apply this tool to assess four waste management options in Rome, including: landfilling with and without biogas exploitation, sorting plant to produce electricity via refused derived fuel and biogas via anaerobic digestion and

finally waste incineration. Results show landfill systems as the worst waste management options, while sorting plant coupled with electricity and biogas production is very likely to be the best option for waste management.

Güereka et al. (2006), in the case of biowaste management in Barcelona (Spain), find that as a result of producing electricity, biogas production and incineration are the processes that most contribute to reducing impact.

Montejo et al. (2013) analyze different mechanical biological treatment (MBT) plants in Castile and León (Spain). Their results showed that performance is strongly linked to energy and materials recovery efficiency. To improve the environmental performance of these plants, these authors proposed optimizing materials recovery through increased automation of the selection process and prioritizing biogas-electricity production from the organic fraction over direct composting.

Vergara et al. (2011) studied waste management in California, concluding that biogenic waste management through anaerobic digestion helps reduce the emission of greenhouse gases. The magnitude of the benefits depends strongly on a number of model assumptions: the type of electricity displaced by waste-derived energy, how biogenic carbon is counted as a contributor to atmospheric carbon stocks, and the landfill gas collection rate.

LCA was applied to assess the environmental profile of different solid waste management options for MSW generated in Asturias, a region on the northern coast of Spain, with one million inhabitants. The composition of the MSW generated in the region of Asturias has changed over time, both in terms of volume and composition, on account of population growth and the consequent changes in lifestyle, leading unremittingly towards an unsustainable management system. According to recent confirmed data for 2011, 390.4 kg MSW/capita were generated in Asturias, below the EU average (503 kg/capita for the EU-27) and the Spanish average (531 kg/capita). Currently, landfill is the main destination of mixed household waste in Spain, at 63.1%, presently being the only management option in Asturias for mixed household waste. More than 20 years have passed since the first facilities were commissioned in 1985 and landfilling commenced at the central landfill. The storage capacity of the existing landfill will accordingly reach its limit within the following years, with the mandatory need to redefine the future model for operating the facilities. Therefore, there is a need for evaluating different alternatives for the waste management in this region.

The aim of this paper is to help local decision-makers to design integrated waste management solutions that are optimal from the environmental point of view.

2. Materials and methods

2.1. Case studio area

Asturias is a region on the northern coast of Spain with a population of around 1,100,000 and a surface area of 10,500 km^2. The majority of the MSW (mixed waste or 'black bag' waste, approximately 480,000 t/year) is treated at a centralized plant managed by the Consortium for Waste Management (Spanish acronym, COGERSA). A selective collection system is used for glass, paper/cardboard and packaging waste (recovering around 80,000 t/year). The mixed waste is landfilled with energy recovery, up to 80% of the produced biogas being recovered and used to generate electricity. The composition and properties of the household waste generated in Asturias are shown in Table 1. The landfill has been in operation since January 1986 and occupies a surface area of approximately 250 hectares. The capacity of this landfill will foreseeably be exhausted by 2015.

2.2. Description of the scenarios and principal treatment processes

2.2.1. Waste management scenarios

Six scenarios were chosen, each of which consists of a combination of different options for treating household waste. In addition to the current scenario, five other options for the management of household waste generated in Asturias are proposed which could be implemented in the region once the capacity of the existing landfill has been exhausted. The proposed scenarios are based on the EU hierarchy of options for waste management and aim to meet the targets set out in European regulations to reduce the amount of biodegradable organic matter sent to landfill (Directive 1999/31/EC) and to promote separate collection of waste (Directive 2008/98/EC).

Current scenario (S-0)

This scenario describes the current management of household waste in Asturias, according to which the final destination of waste is landfill with energy recovery (biogas) and treatment of leachate. Waste collection is performed in an entirely non-selective way.

Scenario 1 (S-1)

This option describes a management model based on the removal of the mixed waste fraction via incineration, without any pre-treatment. As in scenario S-0, waste collection is performed in an entirely non-selective way and waste is transported as in the previous scenario.

Scenario 2 (S-2)

The management system that this scenario represents combines incineration with anaerobic digestion.

Scenario 3 (S-3)

This scenario is similar to scenario S-2, the difference being that the mixed waste fraction is subjected to a separation process in which recoverable materials are recovered prior to treatment via incineration.

Scenario 4 (S-4)

The management system that this scenario represents is similar to scenario S-3, but with the difference that the stream which is not recovered in the sorting of the mixed waste fraction is subjected to a process of aerobic stabilization in order to reduce its volume before being disposed of via incineration.

Scenario 5 (S-5)

Finally, a scenario has been defined similar to S-4, but in which the waste is finally sent to landfill, rather than incineration. As in scenario S-4, the waste reaching landfill has previously undergone a sorting process and aerobic stabilization. Biomethanization of the source separated organic fraction is also maintained, as in scenarios S-2, S-3 and S-4.

Figures 1 to 4 show the flowcharts of each of the proposed management scenarios.

2.2.2. Waste treatment processes

- *Transportation*

Two systems of transportation are defined: one for the separately collected organic fraction and another for the mixed waste fraction, carried out directly or via transfer stations. The work of collection is considered to finish when the haulage vehicles used for this function return to the place they initially departed from to carry out this work. Twenty-one tonne payload trucks were used to transfer the source separated organic fraction (SSO), while a differentiation was made for the transport of the mixed waste fraction between 21 tonne payload trucks when the transport is carried out directly, and 40 tonne payload trucks when it is carried out via transfer stations.

- *Mixed waste sorting plant*

The considered sorting plant has manual and mechanical separation and is equipped with a trommel and magnetic and ballistic separators. A recovery rate of 7% with respect to the waste entering the plant was considered. The recovered materials are: paper/cardboard (29.54% recovery with respect to the recovered fraction), HDPE (8.73%), PET (10.68%), ferrous metals (29.30%), aluminium (7.45%) and composite packaging (14.30%). The plant has a biofilter for treating the waste gases generated during the sorting process.

- *Plant for producing biogas from organic waste*

Following a prior sorting process, approximately 85% of the organic waste entering the plant is treated in an anaerobic digestion process, 43% of which then goes on to become compost after undergoing a process of aerobic maturation.

In the prior sorting process, 0.95% of the materials are considered recoverable (the same materials and recovery percentages are considered in the case of the mixed waste sorting facility), in addition to a rejected fraction of 14.75%, mostly made up of chunks of wood (FEDEMCO, 2005).

The biogas generated in the process is burned in combustion engines and transformed into electrical energy. A composting process for the digestate obtained in the biomethanization process is also included, aimed at obtaining quality compost for subsequent sale.

Finally, the gases emitted from the plant are treated by means of a biofilter and washing with sulphuric acid. Furthermore, the generated leachate is appropriately decontaminated.

- *Stabilization Plant*

Waste with a high organic load requiring treatment reaches the stabilization plant from the sorting of the mixed waste fraction. The stabilization process basically comprises aeration of this organic matter. Homogenization of the waste is performed by mechanical shovels or drum mixers. Pollutant gas emissions and leachates are treated for decontamination.

According to data provided by the management company, 37% of the waste entering the stabilization process is considered losses due to entrainment of leachate and treatment of the gas that is generated.

- *Incineration Plant*

The different MSW fractions reaching the incineration plant are subjected to a combustion process in a furnace. Combustion engines are used to transform the flue gases into electrical energy. The residual bottom ash from this process (39.24% of the waste for incineration) is taken to a recovery plant which recycles approximately 33.65% of this residue. Its use as a replacement component in aggregates employed in the construction of road surfaces has been considered as a possible application of this waste. The gases emitted by the process receive suitable treatment based on a process of dry adsorption with lime, adsorption with activated carbon, selective non-catalytic reduction and baghouse filtration. The leachate generated in the process of recovering the bottom ash also undergoes physical-chemical treatment.

- *Landfill*

Household waste is landfilled with energy recovery. The leachate treatment consists of a pressurized nitrification-denitrification process followed by ultrafiltration to separate the sludge. After that, treated leachates were send to a wastewater treatment plant. Transportation of the leachate to this plant as well as internal transportation within the COGERSA facilities of leachate collected at the landfill to the in-house treatment plant, were likewise taken into consideration.

2.3. LCA methodology

The LCA methodology was used to quantify and compare the potential environmental impacts of the different municipal waste management scenarios. This study was based on ISO 14040 standards (ISO, 2006 a and b).

2.3.1. Objective

The LCA study was performed to analyse the environmental impacts of different MSW management strategies that may be implemented in Asturias. The results may provide a basis for making decisions about the future management of MSW in Asturias, given the imminent closure of the existing landfill, whose service life is to come to an end in 2015.

2.3.2. System boundaries

The relevant processes are included within the boundary of the MSW management system, as shown in Figure 5.

The following processes fall outside the scope of study:

- Everything relating to the management of the materials found in the MSW (packaging, paper/cardboard and glass) which is collected separately.
- The potential impact of the disposal of unrecovered fly ash and bottom ash from incineration in a hazardous waste landfill after being subjected to a recovery process. The reason for this is that the rejected fraction thus obtained represents

a very small percentage by weight compared to the total amount of managed waste, taken as the reference value in the study.

Hazardous municipal wastes have not been considered because all such waste is collected selectively and independently from non-hazardous waste and treated by means of specific processes due to representing a potential hazard to human health and the environment. Bulky municipal waste, comprising old electrical appliances and furniture, is not included either as it involves a different collection system to that of the study.

2.3.3. Functional unit

The functional unit of this LCA is the management over a period of one year of 480,000 tons of MSW generated in Asturias.

2.3.4. Software and data quality

SimaPro software version 7.1.8 was used to carry out the LCA along with its associated database (Professional). COGERSA provided data on the transportation of waste, amounts of waste collected and distances travelled during collection, as well as data on consumptions (energy, water, oil and reagents) at each treatment plant: sorting, biomethanization, stabilization, bottom ash recovery, air pollution treatments, leachate treatment, incineration and landfill.

The Ecoinvent v2.0 (2007) database was used to obtain the environmental loads associated with the materials, transport and energy employed in the study. The Spanish energetic mix has been updated (Table 2).

Data on emission of pollutants in sorting, biogas production, stabilization and incineration plants were obtained from Reference Documents on Best Available Techniques (BREFs) for Waste Treatment Industries and for Waste Incineration.

2.4. Life cycle inventory (LCI)

A specific inventory was created for each one of the considered scenarios. The inventory data used for each of the processes involved in the different scenarios are described below.

2.4.1. Transportation

To create the inventory corresponding to the transportation step, the total distance travelled by the collection trucks and the tonnes transported were taken into account over a period of one year. These data were used to calculate the average distance travelled per tonne of waste during the transportation step for each of the transport systems considered in the study (Table 3).

2.4.2. Mixed waste sorting plant

The electricity, fuel, water and reagent consumptions for the mixed waste sorting plant, shown in Table 4, were provided by the company in charge of the Waste Treatment Centre (COGERSA).

2.4.3. Plant for producing biogas from organic waste

The biogas plant consumes electricity, gasoil, water and chemicals (Table 4). As regards the consumption of reagents, the following are used: polyelectrolyte for dehydrating the digestate, sulphuric acid as the absorbent in the gas treatment plant, methanol in the treatment of leachate and lime for neutralization.

The pollutant emissions data were obtained from the BREF Document on Waste Treatment Industries (IPPC, 2006a), from which the emissions given in Table 5 were estimated.

Furthermore, a biogas production of 109.5 m^3 was considered (COGERSA), generating an energy recovery of 229.6 kWh per tonne of waste entering the digester (assuming that 60% of the biogas is composed of CH_4 with a PCI of 8600 kcal/m^3 CH_4, and a 35% electricity yield). Energy recovery only in the form of electricity was considered as there are no industries or towns close to the landfill that could use the generated heat.

2.4.4. Stabilization Plant

The aerobic stabilization plant consumes electricity, gasoil, water and chemicals (Table 4). The consumption in gasoil is due to the mobile machinery used to move the waste (loader, forklifts and truck for transporting the rejected fraction), while the reagents are consumed in treating the gases (absorption by sulphuric acid) and leachate (nitrification-denitrification with methanol).

Data on pollutant emissions were obtained from the Reference Document on Best Available Techniques for Waste Treatment Industries (IPPC, 2006a), on the basis of which the subsequent substances and emissions were considered (Table 6).

2.4.5. Incineration Plant

The consumptions at the incineration plant are given in Table 4. A value of 5515.25 Nm^3 of generated combustion gas per tonne of waste is considered, in accordance with the BREF Document on Waste Incineration (IPPC, 2006b). Furthermore, the electricity produced amounts to 550 kWh per tonne of waste, a value obtained by considering a

PCI of 2070 kcal/kg waste sent to incineration. Of this production, 480 kWh are exported to the grid and 70 kWh are used in-house at the incineration plant.

The data on gas emissions (emission limits have been taken into account) and final waste streams were obtained from Annex V of Directive 2000/76/EC on the Incineration of Waste, except in the case of CO and CO_2, for which only anthropogenic emissions from the fossil C contained in the waste plastic were taken into consideration.

As regards bottom ash recovery, the percentage recoveries of materials vary depending on whether the mixed waste fraction is sorted (sorting) or not before being sent to the incineration plant (Table 7).

Finally, the reference values adopted in the BREF Document on Waste Incineration (IPPC, 2006b) are taken into account to calculate the production of fly ash entrained in the flue gas. This document establishes a value of 82.75 kg fly ash/t incinerated waste after applying the chosen dry process gas treatments.

2.4.6. Landfill

Electricity, water and oil consumptions are shown in Table 4. A leachate generation rate of 0.44 m^3 leachate/t waste deposited in landfill and a 100% capture yield was considered when defining this process. Furthermore, the use of 0.25 t covering material/t deposited waste was also considered, 50% of this material being clay and the other 50% bottom ash recovered in the incineration process.

Other data needed to create the LCI for this process are those relating to generated air emissions and energy recovery as a result of biogas capture and recovery. The emissions were obtained from the European Pollutant Release and Transfer Register (E-PRTR) Report presented by COGERSA for the year 2009, which includes emission factors for all the substances produced by combustion engines used to generate electricity or torches. As regards energy recovery, it is assumed that 987 and 259 Nm^3 of biogas can be collected for every tonne of MSW deposited in the current landfill or stabilized waste landfill, respectively. Considering an 82% capture yield (18% is emitted to the atmosphere) and a 35% electricity yield (COGERSA, 2010), it is hence possible to recover about 1.5 kWh/Nm^3 flared biogas.

When considering landfilling in waste management, it is necessary to consider the post-closure phase, as leachate which must be treated and biogas which must be collected will still continue to be produced during this period. This study employs the approach that estimates a biogas emissions and leachate time horizon of 30 years for sanitary landfill during the post-closure phase (Mc Dougall et al., 2001). The values of harnessed biogas and consumptions at the leachate treatment plant will thus increase, given that biogas capture will be 100% for the first 5 years after closure, 50% the following 5 years, and 10% in the last 20 years, while leachate generation is estimated at 100% during the first 10 years after closure, 60% the following 10 years, and 30% in the last 10 years.

Finally, the haulage of treated leachate in 21 tonne payload trucks to a wastewater treatment plant located at an average distance of 20 km has also been taken into account, while internal transportation within the COGERSA facilities of leachate collected at the landfill to the in-house treatment plant, at an average distance of 5 km for the stabilized waste landfill, was likewise taken into consideration.

2.3.6. Life cycle impact assessment

The life cycle impact assessment based on the results of the inventory was performed using the Impact 2002+ method (Jolliet et al., 2003). This impact assessment method is a combination of four methods: IMPACT 2002 (Pennington et al. 2005), Eco-indicator 99 (Goedkoop and Spriensma. 2001), CML (Guinée et al. 2002) and IPCC. The approach defines 15 mid-point categories (Table 8).

These mid-point categories are structured into four damage categories (Jolliet et al., 2003): Human Health (including mid-point scores for carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, and respiratory organics), Ecosystem Quality (including mid-point scores for aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nitrification, and land occupation), Climate Change (only including the mid-point scores for global warming) and Resource Depletion (including mid-point scores for non-renewable energy and mineral extraction).

3. Results and discussion

Figure 6 shows the results obtained in the damage assessment of the six considered scenarios. The scenarios which include the option of landfill as the final waste treatment are those which present the worse results in all damage categories. Scenario S-0 is the one that contributes most in the Human Health damage category, with a value of 1.04×10^{-3} DALY/t waste. In contrast, S-3 is the one that contributes least to this category, presenting a value of 6.94×10^{-5} DALY/t waste.

All scenarios except for S-0 and S-5 help reduce the impact in the Ecosystem Quality damage category. As regards Climate Change, all scenarios have an impact, S-0 having the most impact (4.63×10^3 kg CO_2 eq/t waste) and S-3 contributing the least to this impact category (31.9 kg CO_2 eq/t waste). Finally, in the Resources damage category, all scenarios that do not include landfill as the final waste treatment are observed to help reduce the impact in this damage category, while the scenarios that do include landfill (S-0 and S-5) are seen to have a substantial impact, presenting values of 30,343.6 and 12,816.5 MJ/t waste, despite involving an energy recovery process.

Figure 7 presents the results of damage normalization. The idea of normalization is to analyse the respective share of each impact to the overall damage by applying normalization factors to damage impact classes in order to facilitate interpretation. To carry out this process, the IMPACT 2002+ method utilizes the emission values of Western Europe as reference values.

In view of the results, it may be concluded that the contribution of the studied scenarios to the Ecosystem Quality damage category is negligible, the most affected categories being Climate Change, Resource Consumption and Human Health. These categories are accordingly analysed below in greater detail.

3.1. Human Health

As already stated, scenario S-0 contributes the most damage in this category, with a value of 1.04×10^{-3} DALY/t waste ($1.45\text{x}10^{-3}$ DALY/t dry waste). This result contrasts with that obtained by Hong et al. (2010). These authors, who also applied the Impact 2002+ method to a similar scenario to that analysed in our study, obtained a value of -1.88×10^{-5} DALY/t dry waste. However, their study did not consider the transport of waste to the treatment centre, the composition of the waste is very different (with 61.4% food waste compared to 38.1% in our study), the energy consumption associated with landfill is lower than in our study (0.17 vs. 3.85 kWh/t waste) and the considered energy recoveries are higher (45.6 versus 9.44 kWh/t waste).

An impact of 1.12×10^{-4} DALY/t waste is obtained for scenario S-1, based on incineration as the only waste management system. Morselli et al. (2008) assess the environmental impact of waste incineration in a region of northern Italy, obtaining an impact on human health of 8.29×10^{-4} DALY/t waste. However, their study did not take into account transportation of waste to the incineration plant or a recovery process for botton ash, although it did consider the construction of the incineration plant. Furthermore, the impact assessment method employed by these authors was Eco-Indicator 99, which includes climate change within the category of damage to human health.

When individually analysing the impact categories that make up this damage category (Figure 8), it can be seen that the impact is mainly due to the effect of respiratory inorganics (RI). According to the Impact 2002+ method, the following substances are taken into consideration to evaluate the impact category of respiratory inorganics: carbon monoxide, ammonia, nitrogen oxides, sulphur oxides, sedimentary particles and particulate matter of below 10 and 2.5 microns in size.

On analysing each of the processes involved in each studied scenario in detail (Figure 9, Table 9), it can be seen that the processes that contribute the most to increasing the impact in the Respiratory Inorganics category and therefore on Human Health are transportation, incineration, stabilization and, to a much greater extent, landfill, whereas sorting and, to a lesser extent, biomethanization contribute to avoiding this impact.

Transportation processes mainly contribute to this damage via emissions of particles and nitrogen oxides, the effect being greater in those scenarios that include selective collection of the organic fraction. The effect of incineration in this impact category is associated not only with direct emissions resulting from the process, but also with indirect emissions, such as those associated with the processes of manufacturing the reagents consumed in the processes used to treat combustion gases. Studies by Morselli et al. (2008) also show that the Respiratory Inorganics category is one of the most affected by the incineration process.

The sorting and stabilization processes are seen to help reduce the effect of incineration in this impact category, as materials which would increase emissions associated with the incineration process in terms of both quantity and hazards (such as plastic and/or organic matter) are separated or removed by means of these processes. For example, scenario S-1, which includes no process prior to incineration, obtains a maximum impact of 0.0785 kg PM2.5 eq/t waste, while scenario S-4, which involves sorting (triage) and waste stabilization prior to incineration, does not exceed a level of impact of 0.0552 kg PM2.5 eq/t waste.

Landfill is one of the most important contributors to this category, although the contributions associated with energy recovery from landfill gas afford substantial benefits. The impact is related to losses in produced biogas which is not collected, these losses generating the most important contributions to the formation of acid-forming compounds (Bovea and Powell, 2006).

As regards the stabilization process, the observed impact is related to direct emissions from the process.

Among the processes that avoid impact, the sorting of mixed waste, via material recovery and the replacement of virgin raw materials that it provides (Morris, 2005; Banar et al. 2009), helps to reduce the impact in this category. Despite the benefits deriving from materials and energy recovery, biogas production has no significant impact compared to the impacts produced in other processes, as the amount of waste being treated in this way is a very small fraction of the total.

3.2. Climate Change

As already stated, S-0 is the worst scenario with an impact of 4.63×10^3 kg CO_2 eq/t treated waste. This value is relatively high compared to similar studies conducted by other authors. For example, Miliūte and Staniškis (2010) analysed the landfill option for the waste generated in the region of Alytus (Lithuania), a total of 45,150 t/year, obtaining a value of 51,230 t of CO_2 eq (1,135 kg CO_2 eq/t waste) for this impact category; Mendes et al. (2004) obtained a value of around 900 kg CO_2 eq/t waste for this impact category when analysing the landfill of waste generated in the city of Sao Paulo in Brazil; while Gunamantha and Sarto (2012) obtained a value of 188 kg CO_2 eq/t waste for a similarly defined scenario for three cities in the region of Yogyakarta in Indonesia. The high value obtained in our study may be due to the fact that the energy recovery considered in our case only refers to electricity generation, without taking into consideration the production of heat, which could also be obtained, given that this possibility is not currently available at the management centre's facilities. Moreover, the landfill under study generates a large amount of leachate, which requires high consumptions in its treatment plant. In contrast, the scenario with the least effect on this impact category is S-3 with only 31.9 kg CO_2 eq/t waste.

A detailed analysis of the contribution of each of the processes involved in each scenario to this impact category (Figure 10, Table 10) shows that transportation, landfill, incineration and stabilization adversely affect this impact category, while the sorting of the mixed waste fraction and biogas production help reduce the impact.

In line with the results reported by Morris (2005) and Bovea and Powell (2006), the processes of transportation, landfill and incineration are the main contributors to the emission of greenhouse gases (GHG), mainly CO_2 and CH_4. As regards transportation, this has a lower contribution in scenarios S-0 and S-1 (48.1 kg CO_2 eq/t waste), in which there is no source separation of the organics. The contribution of transportation is slightly higher for the other scenarios (51.4 kg CO_2 eq/t waste).

The savings in GHG in incineration (due to the reduction in the emission of the fossil carbon in the plastic) increase when a sorting process is carried out prior to incineration, obtaining impacts of 3.5 kg CO_2 eq /t waste for scenario S-3 (with prior sorting) versus approximately 81.2 kg CO_2 eq/t waste for S-1, in which there is no kind of sorting is carried out.

Although a significant impact might be expected in the aerobic stabilization of waste process, it is not so large. This is because biogenic CO_2 emissions are not considered as losses, thus reducing the effect of this process with respect to the others. The impact associated with this process is 12.2 kg CO_2 eq/t waste, mainly due to energy consumption during aeration and N_2O and CH_4 emissions during the process.

Landfill in scenarios S-0 and S-5 is the most unfavourably valued waste treatment option due to the significant GHG emissions generated, primarily resulting from landfill gas losses, obtaining maximum damages of 4,586.7 and 1,384.8 kg CO_2 eq/t waste, respectively, in this process alone.
The processes of material recovery and biomethanization of the SSO help reduce the impact in this category, although their repercussions are almost negligible compared to the damage caused by the other processes in the overall behaviour of the scenarios. From the point of view of Climate Change, insufficient energy is recovered in the incineration process to cause more favourable consequences for the environment.

3.3. Resource Depletion

On analysing the contributions of the different processes that make up each scenario to this impact category (Figure 11, Table 11), landfilling, transportation and stabilization are seen to be the processes which adversely affect this category. Transportation is the largest consumer of fossil fuels because of the use of diesel. As in previous cases, those scenarios in which the distance waste is transported is greater (scenarios S-2, S-3, S-4 and S-5) have slightly higher impacts (780.5 MJ/t waste) from the rest (732.0 MJ/t waste). The value obtained by the stabilization process for this impact category is 204.6 MJ/t waste in scenarios S-4 and S-5, basically due to the consumption of reagents used to treat the gases and leachate produced during the process.

Incineration, sorting of the mixed waste and biomethanization help reduce the impact on this category, but not all the processes avoid it to the same extent. As a result of the recovery of energy, metals (ferrous and non-ferrous) and bottom ash (material that can be recovered as an aggregate or filler component), incineration is the most favourable process with respect to this reduction. From this point of view, the separation of materials prior to the incineration process is not conducive to reducing the impact of the process. For example, the savings in scenario S-1, in which no prior sorting is carried out, are -2,801.1 primary MJ/t waste, while in S-4, in which prior sorting is performed, the savings are -1,880.3 primary MJ/t waste.

In the study carried out by Morselli et al. (2008), the authors concluded that the savings in resource consumption that the incineration process presents are due to the energy recovery achieved in the process. However, in their study both fly ash and botton ash are sent to landfill, without considering their possible recycling as a filler.

The materials recovery carried out in the sorting plant (plastic, paper and metal) is also a process which benefits this category. The avoided damage in scenarios S-3, S-4 and S-5, in which a greater amount of materials is recovered (the entire mixed waste fraction passes through the sorting plant), is -816.8 MJ/t waste (S-3) and -830.7 MJ/t waste (S-4 and S-5).

Although materials are recovered and the biogas generated in the biomethanization process is used to produce energy, the consumption of reagents and resources in the process itself means that the damage avoided in this category is somewhat smaller (-30.1 MJ/t waste) in the scenarios that include this process (S-2, S-3, S-4 and S-5).

Finnveden et al. (2005) apply Life Cycle Analysis to assess different solid waste treatment options in Sweden. The treatments considered in the studio are: incineration with heat recovery, landfilling with landfill gas extraction, recycling, anaerobic digestion and composting. The study is applied to the combustible, recyclable and compostable fractions present in municipal waste. The results show that recycling is the treatment that contributes the most to reducing energy consumption, followed by incineration and landfill. When analysing the results obtained with food waste, incineration is slightly more efficient than anaerobic digestion, while composting is found to be the only studied option that requires an energy input.

Hong et al. (2010) also found incineration to be the option that contributes the most to reducing the impact on resource consumption, with savings of -5.73×103 MJ/t dry waste (-2.36103 MJ/t waste), similar values to those obtained in our study. However, when incineration is combined with a composting process, the generated impact on this damage category becomes 657.73 MJ/t dry waste (270.3 MJ/t waste), corroborating the fact that the composting option has a negative impact on this damage category.

4. Conclusions

In line with other studies, our results show that traditional landfill produces the greatest environmental impact in all the analysed categories.

The transportation process produces a significant impact in the analysed damage categories due to the use of fossil fuels.

Biomethanization is a process that contributes to reducing the impact. From the environmental point of view, anaerobic digestion plants are better than other fermentable treatments due to not requiring a major external power supply, mostly from fossil fuels, as they are capable of generating electricity using the biogas that is produced. This represents positive effects in nearly all damage categories as a result of savings and compensation in non-renewable energy.

Incineration adversely affects the categories of Human Health and Climate Change, but helps reduce damage in the Resources category due to the benefits obtained from the electricity generated in the process.

The sorting processes carried out both for the mixed waste fraction and the organic fraction provide savings in the studied categories, given the reduction in emissions due to replacing raw materials, which promotes environmental benefits.

The aerobic stabilization process generates impacts in all the categories, but presents relevant values (compared to the other processes) only in the Climate Change category.

The effect on Ecosystem Quality is considered negligible for all the analysed scenarios. As to the other impact categories (Human Health, Climate Change and Resources), the most favourable scenario is S-3, producing a damage of 6.94×10^{-5} DALY/t waste and emissions of 31.9 kg CO_2 eq/t waste, in addition to supposing savings in resources and energy of -2361.3 MJ/t waste. The management system employed in this scenario includes source separation of the organic fraction followed by biomethanization and incineration of the mixed waste and rejected materials from the organic fraction after the sorting of recyclable materials.

Acknowledgements

This study was made possible thanks to funding received from the Foundation for Applied Research and Technology (FICYT) and from the Consortium for Solid Waste Management in Asturias (COGERSA) (Ref. PC-06-040). The authors are also grateful to Beatriz Garcia for her inestimable help in collecting data.

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Table captions

Table 1 Characteristics and composition of the mixed municipal solid waste in Asturias (Castrillón et al., 2012)

Table 2 Spanish energy mix (Red Eléctrica Española, 2009).

Table 3 Transport process inventory (COGERSA, 2010).

Table 4 Data on consumption, expressed as tonnes of waste, at the treatment plants for the different scenarios (COGERSA, 2010).

Table 5 Air emissions from the biogas production plant (IPPC, 2006a).

Table 6 Air emissions from the stabilization plant (IPPC, 2006a).

Table 7 Percentage recoveries at the bottom ash recovery plant (COGERSA, 2010)

Table 8 Impact categories and units employed in the IMPACT2002+ method (Jolliet *et al.*, 2003).

Table 9 Summary of the contribution of each process to Respiratory Inorganics (kg PM2.5 eq/t waste)

Table 10 Summary of the contribution of each process to Climate Change (kg CO_2 eq/t waste)

Table 11 Summary of the contribution of each process to Resource Depletion (MJ/t waste)

Figure captions

Table 1 Characteristics and composition of mixed municipal waste in Asturias (Castrillón et al., 2012)

Waste composition (%)	Organic matter	38.1
	Paper/Cardboard	20.6
	Textiles	10.9
	Plastics	10.8
	Glass	5.6
	Metals	3.6
	Others	10.5
Waste properties	Density (kg m^{-3})	187
	Moisture (%)	28.5
	Lower Heating Value (kJ kg^{-1})	10,744

Table 2 Spanish energy mix (Red Eléctrica Española, 2009).

Regime	**Type**	**Percentage (%)**
STANDARD	Coal (bituminous coal, anthracite and lignite)	12.0
	Hydraulic	20.1
	Fuel-gas	3.0
	Nuclear	8.0
	Combined cycle	25.0
SPECIAL	Wind	20.0
	Solar	3.7
	Other renewables (biomass)	1.0
	Non-renewables (waste heat, industrial gas)	7.2

Table 3 Transport process inventory (COGERSA, 2010).

Process		Waste load (t/year)	Distance travelled (km/year)	Average distance (km)	Transport vehicle[1]
Direct transport	Home → TS	247,092	1,913,559	162.63	21 tonne payload trucks
	Home → Management centre		486,096	41.28	
Transport via TS		234,857	1,624,853	276.71	40 tonne payload trucks
Transport of SSO		-	-	49.53	21 tonne payload trucks

(1) Ecoinvent v2.0. database

Table 4 Data on consumption, expressed as tonnes of waste, at the treatment plants for the different scenarios (COGERSA, 2010).

Consumption	**Value**					
	(A)	(B)	(C)	(D)	(E)	(F)
Energy (kWh)	22.7	174.25	65.9	73.42	257.4[(1)]	163.6[(1)]
Water (kg)	32	899	521.5	307.5	761.58	479.89
Gasoil (kg)	0.87	0.38	0.45	0.85	0.50	0.50
Reagents (kg)						
Polyelectrolytes	-	0.74	-	-	-	-
Sulphuric acid	-	4.32	4.05	-	-	-
Methanol	-	0.15	0.084	0.062	28.92	18.22
Lime	-	0.041	0.024	14.48	11.56	7.28
Ammonium	-	-	-	2.13	-	-
Activated carbon	-	-	-	0.75	17.34	10.93
Sodium hypochlorite	-	-	-	-	0.077	0.049
Phosphoric acid	-	-	-	-	0.096	0.061

(A) Sorting; (B) Biomethanization; (C) Stabilization; (D) Incineration; (E) Landfill of non-stabilized waste; (F) Landfill of stabilized waste.

[(1)] This energy consumption is the sum corresponding to the operation of the landfill (3.85 kWh/t waste) and the operation of the leachate treatment plant during the post-closure period (30 years).

Table 5 Air emissions from the biogas production plant (IPPC, 2006a).

Substance	**Value**[(1)]
Methane (CH_4)	0.986 g
Sulphuric acid (SH_2)	0.301 mg
Organics	0.021 mg

(1) Per m^3 of generated biogas.

Table 6 Air emissions from the stabilization plant (IPPC, 2006a).

Substance	**Value[(1)]**
Ammonium (NH_3)	102.2 g
N_2O	60.5 g
Nitrogen oxides (NO_x)	100 g
Methane (CH_4)	411 g
Organics	300 g
Particulate matter	174.5 g
Dioxins	508.3 ng
Water (H_20)	303 kg

(1) Per tonne of waste.

Table 7 Percentage recoveries at the bottom ash recovery plant (COGERSA, 2010)

Recovered materials (%)[1]		
Process	**Ferrous**	**Non-ferrous**
WITH sorting	1.5	0.4
WITH sorting + stabilization	2.05	0.55
WITHOUT sorting	3.0	1.3

(1) Percentage recovery with respect to incinerator input

Table 8 Impact categories and units employed in the IMPACT2002+ method (Jolliet *et al.*, 2003)

Impact category (mid-point)	***Units***
Carcinogens	kg $C_2H_3Cl_{eq}$
Non-carcinogens	kg $C_2H_3Cl_{eq}$
Respiratory inorganics	kg $PM2.5_{eq}$
Respiratory organics	kg C_2H_{4eq}
Ionizing radiation	Bq Carbon-14_{eq}
Ozone layer depletion	kg CFC-11_{eq}
Aquatic ecotoxicity	kg TEG water
Terrestrial ecotoxicity	kg TEG soil
Terrestrial acid/nutrient	kg SO_{2eq}
Aquatic acidification	kg SO_{2eq}
Aquatic eutrophication	kg PO4-P limited
Land occupation	m^2 organic arable land
Global warming	kg CO_{2eq}
Non-renewable energy	MJ primary
Mineral extraction	MJ surplus

Table 9 Summary of the contribution of each process to Respiratory Inorganics (kg PM2.5 eq/t waste)

Process	**S-0**	**S-1**	**S-2**	**S-3**	**S-4**	**S-5**
Waste Transport	0.0685	0.0685	0.0734	0.0734	0.0734	0.0734
Sorting of Household Waste	-	-	-	-0.0114	-0.0115	-0.0115
Biomethanization Plant	-	-	-0.0008	-0.0008	-0.0008	-0.0008
Incineration Plant	-	0.0785	0.0702	0.0675	0.0552	
Stabilization Plant	-	-	-	-	0.0368	0.0368
Landfill	1.2540	-	-	-	-	0.3460
TOTAL	1.3224	0.1470	0.1428	0.1287	0.1530	0.4438

Table 10 Summary of the contribution of each process to Climate Change (kg CO_2 eq/t waste)

Process	S-0	S-1	S-2	S-3	S-4	S-5
Waste Transport	48.1	48.1	51.4	51.4	51.4	51.4
Sorting MSW	-	-	-	-21.6	-21.7	-21.7
Biomethanization Plant	-	-	-1.4	-1.4	-1.4	-1.4
Incineration Plant		81.2	71.1	3.5	17.7	-
Stabilization Plant	-	-	-	-	12.2	12.2
Landfill	4,586.7	-	-	-	-	1,384.8
TOTAL	4,634.9	129.3	121.1	31.9	58.1	1,425.2

Table 11 Summary of the contribution of each process to Resources Depletion (MJ/t waste)

Process	S-0	S-1	S-2	S-3	S-4	S-5
Waste Transport	732.0	732.0	780.5	780.5	780.5	780.5
Sorting of MSW	-	-	-	-816.8	-830.7	-830.7
Biomethanization Plant	-	-	-30.1	-30.1	-30.1	-30.1
Incineration Plant	-	-2,801.1	-2,501.8	-2,295.1	-1,880.3	-
Stabilization Plant	-	-	-	-	204.6	204.6
Landfill	29611.5	-	-	-	-	12,692.3
TOTAL	30,343.6	-2,069.1	-1,751.5	-2,361.6	-1,756.1	12,816.5

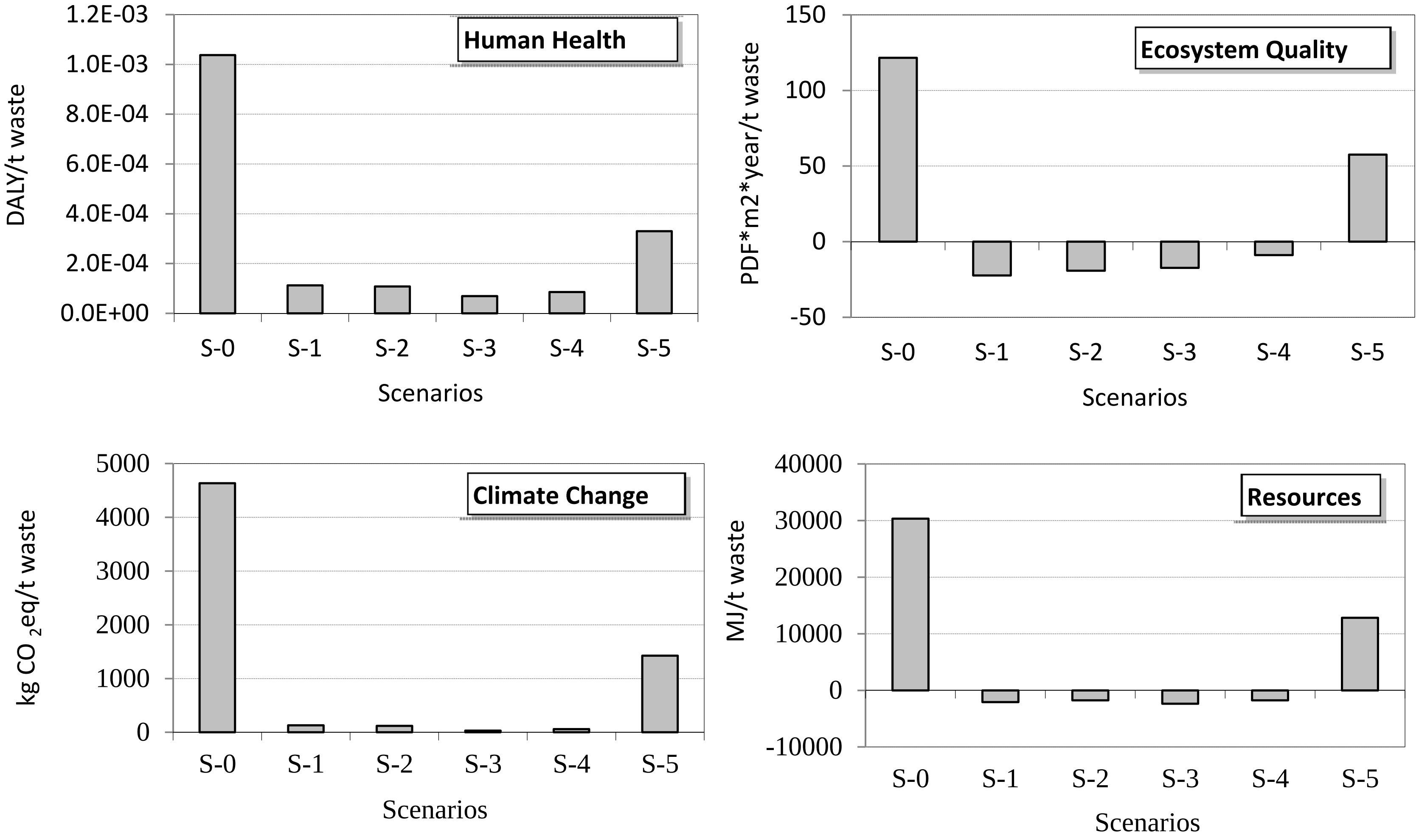

Figure 6. Contribution of each scenario to the damage categories

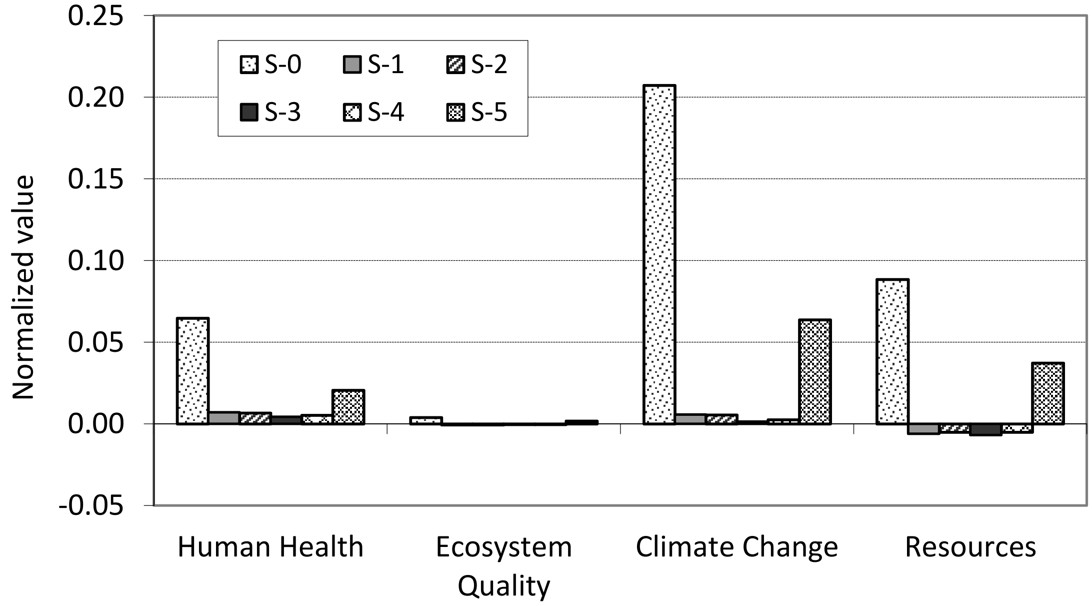

Figure 7. Normalized damage categories in each scenario

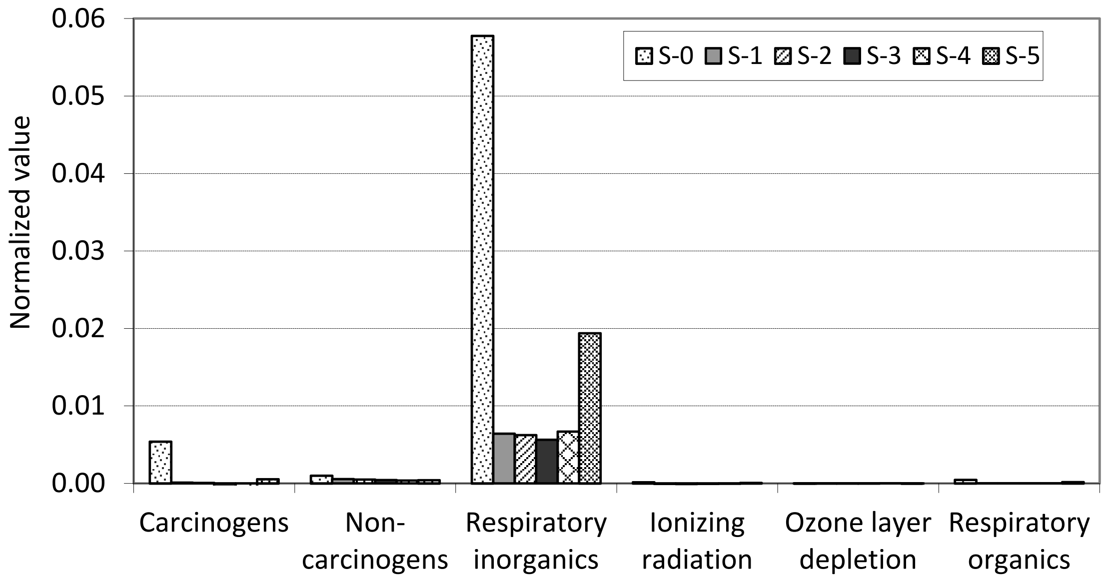

Figure 8. Normalized mid-point scores included in the Human Health damage category

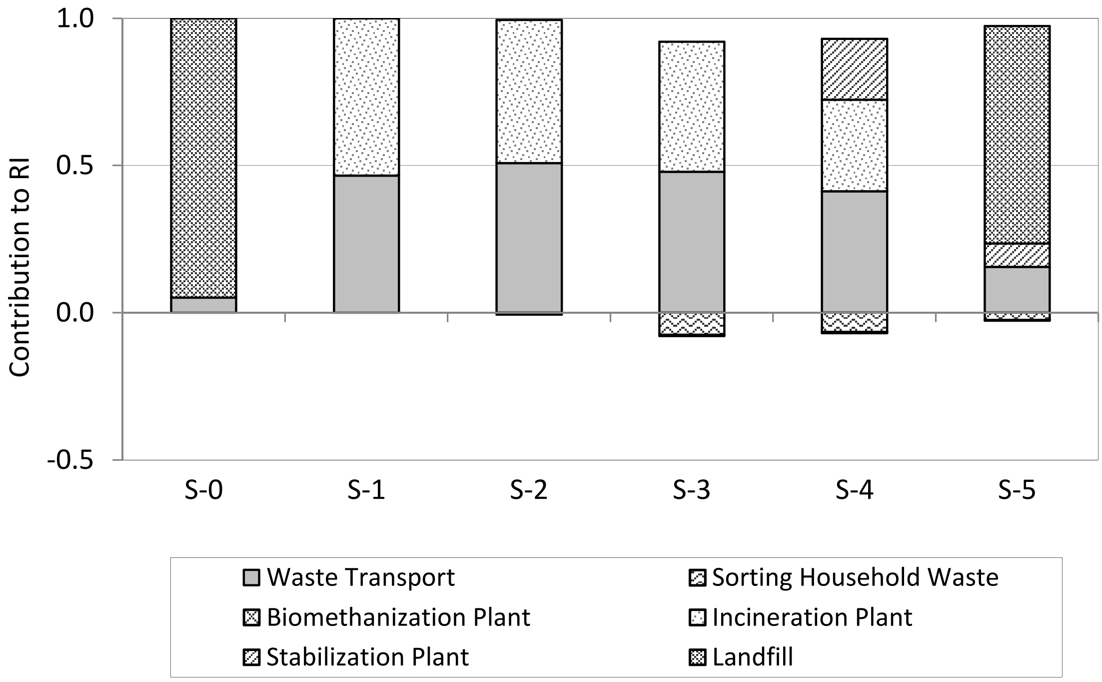

Figure 9. Contribution of each process from each scenario to Respiratory Inorganics

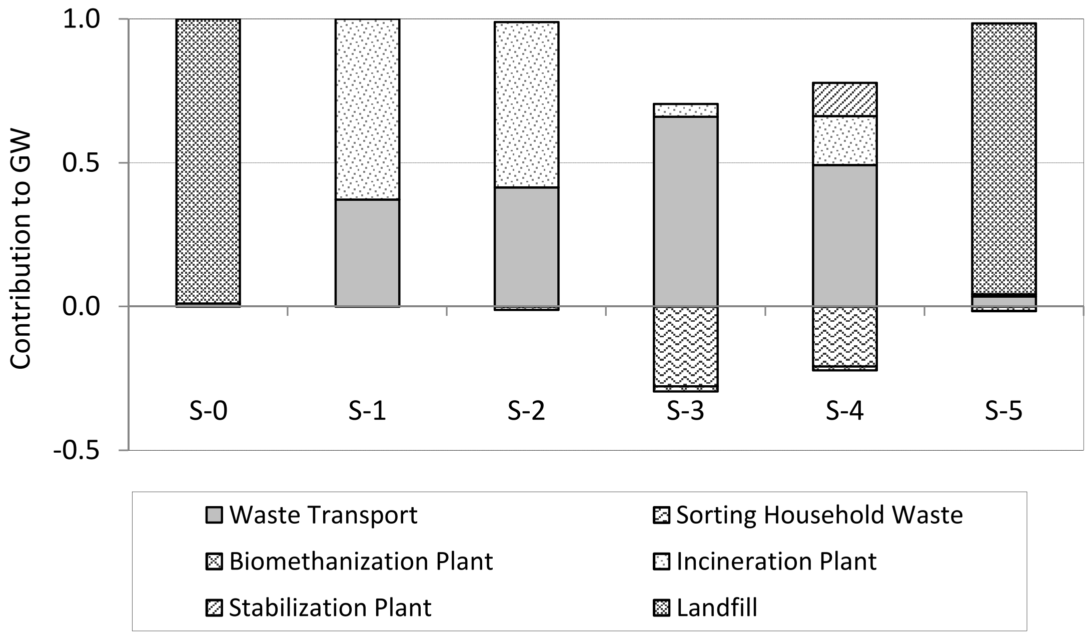

Figure 10. Contribution of each process from each scenario to Climate Change

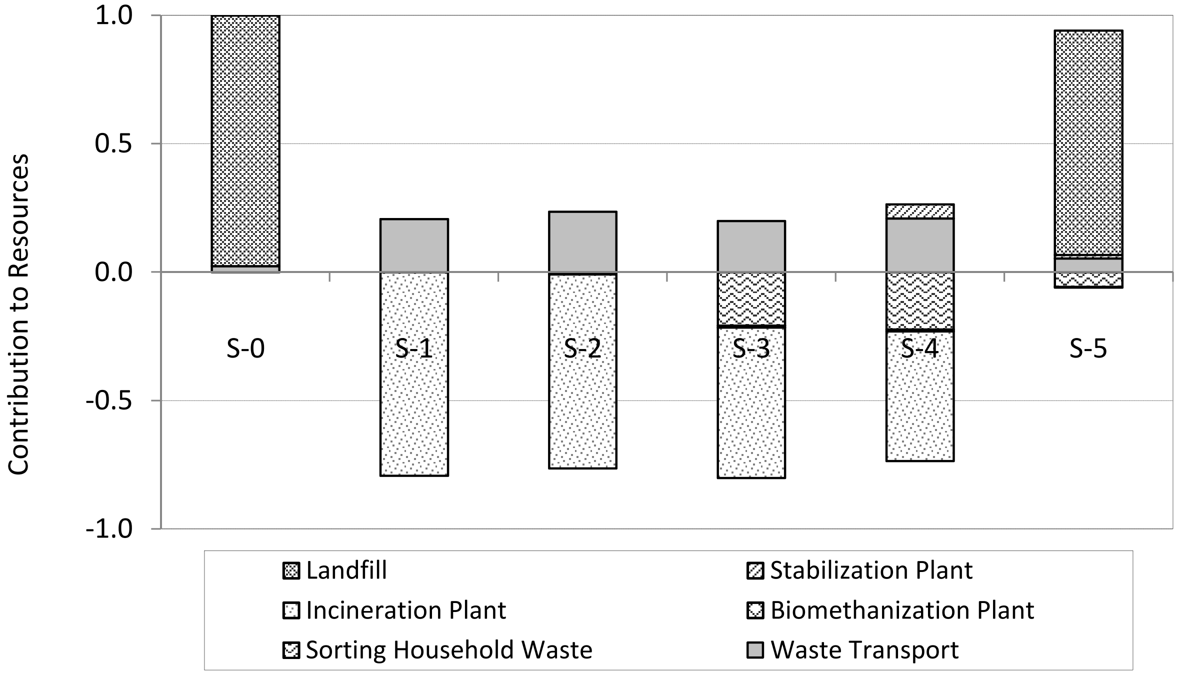

Figure 11. Contribution of each process from each scenario to Resource Depletion

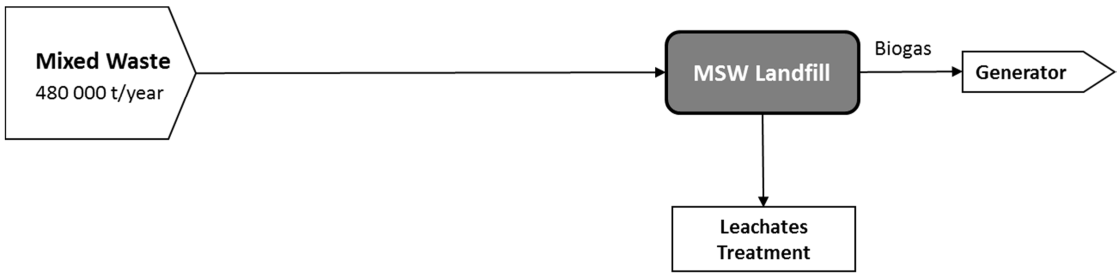

Figure 1. Flowchart of the current scenario (S-0)

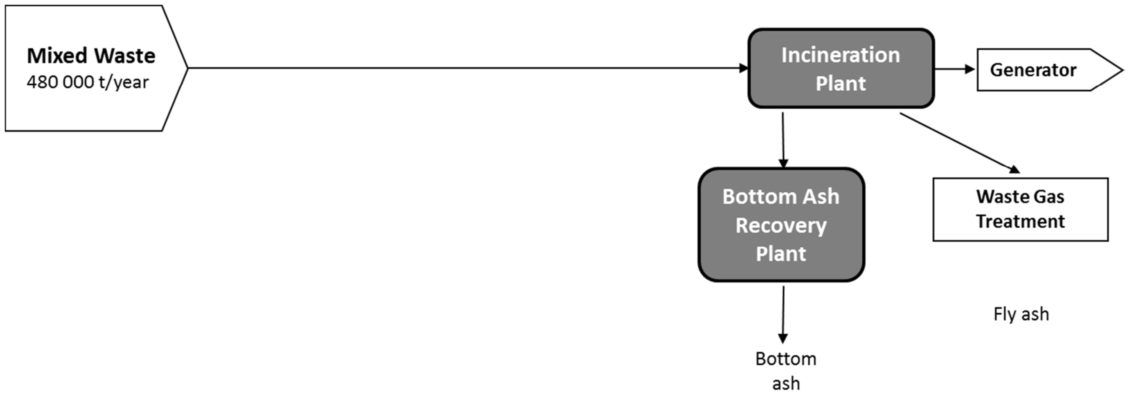

Figure 2. Flowchart of the current scenario (S-1)

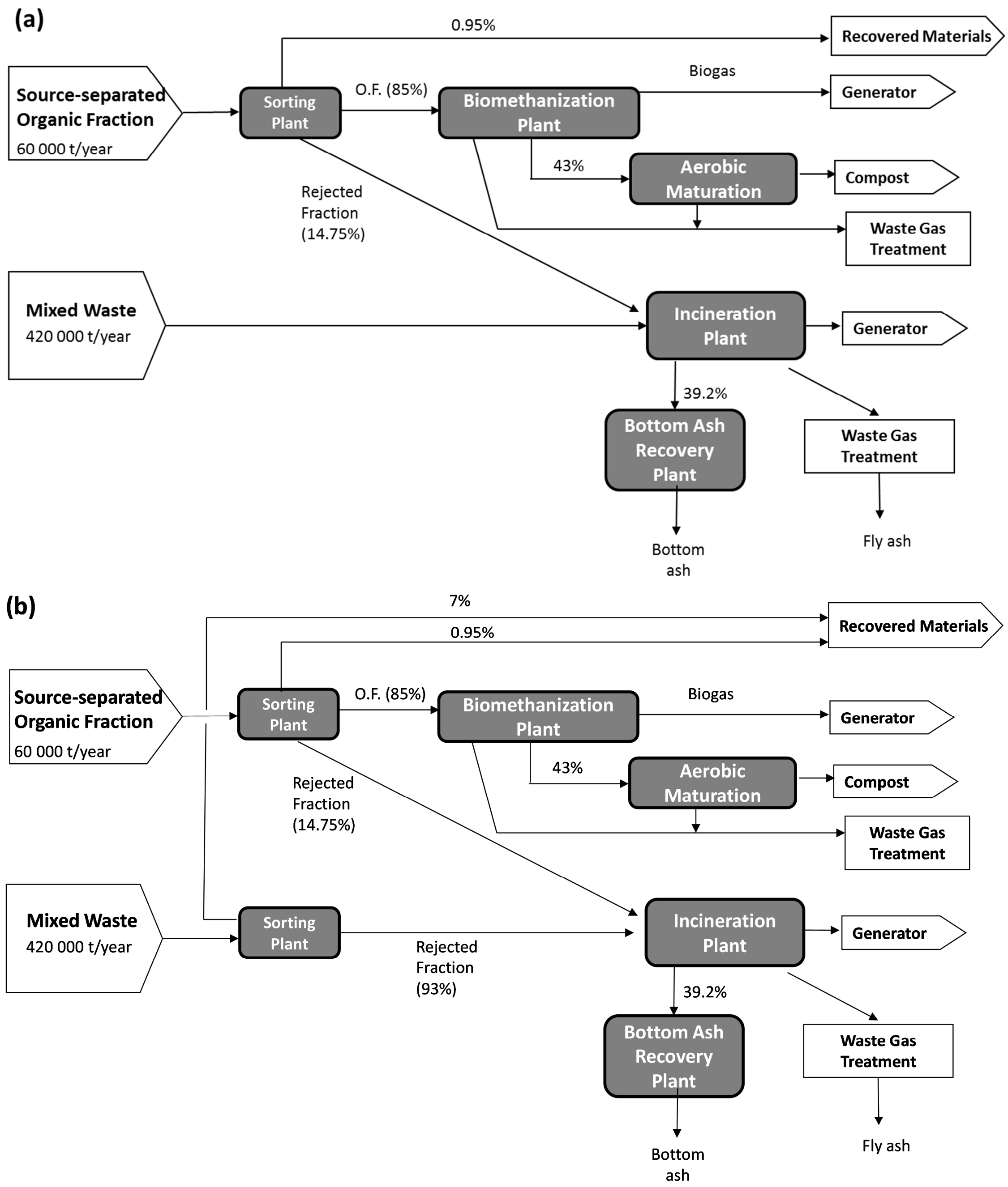

Figure 3. Flowchart of the main steps involved in scenarios S-2 and S-3

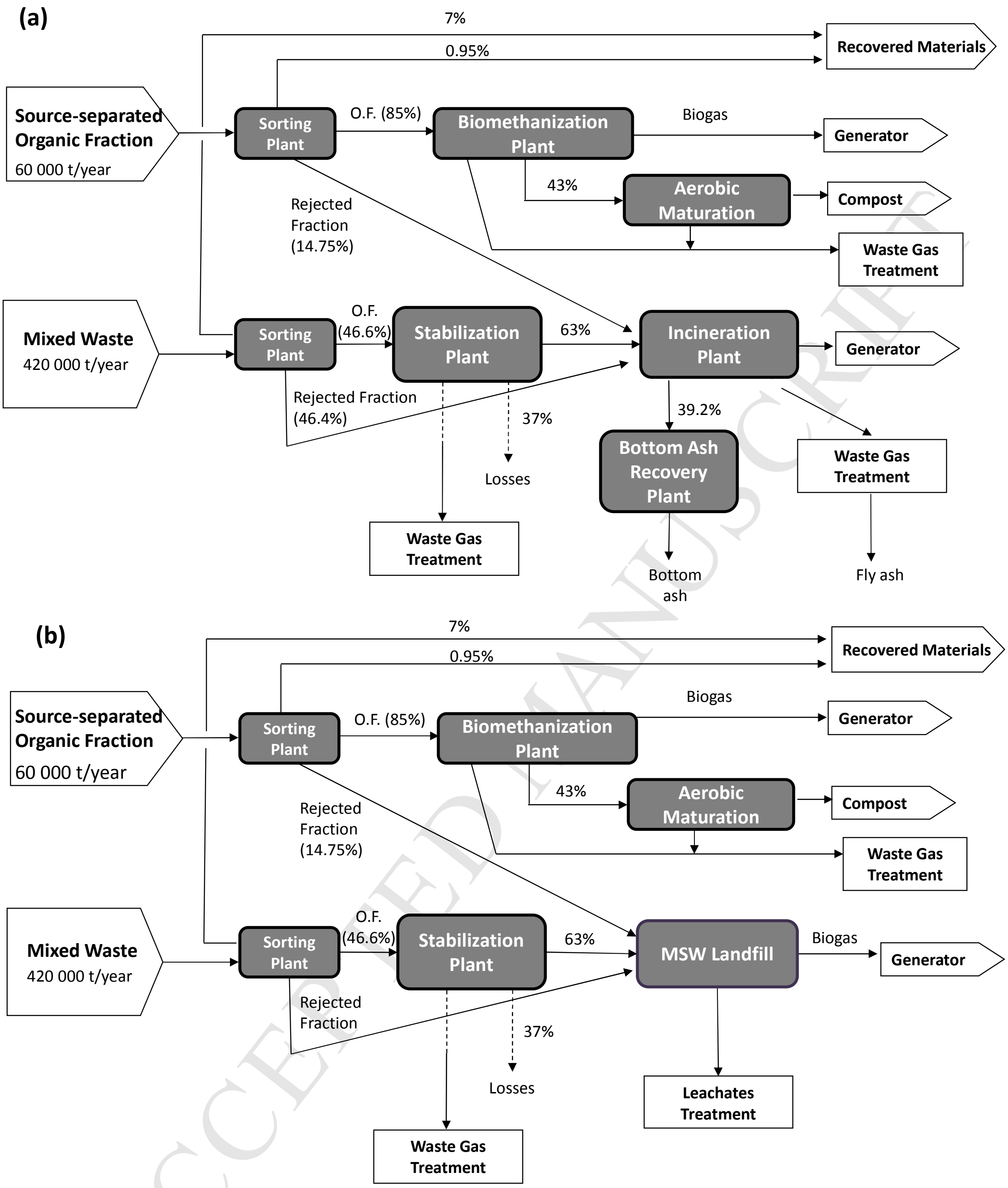

Figure 4. Flowchart of the main steps involved in scenarios S-4 and S-5

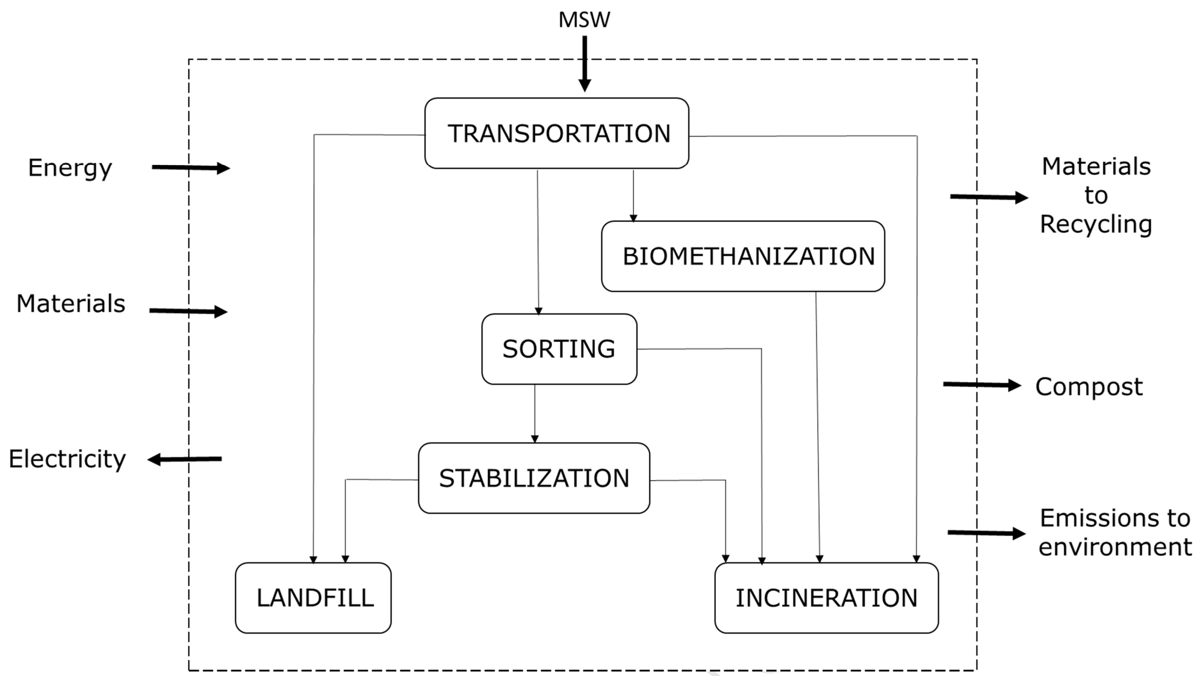

Figure 5. System boundary of the waste management system

Highlights

Six waste management scenarios were assessed by LCA methodology.

Four damage categories were considered, according to the Impact 2002+ method.

Waste landfilling is the option with greater environmental impacts.

Sorting and biomethanization processes provide savings in the studied categories.

Incineration helps to reduce damage in the Resources Depletion category.