Life Cycle Assessment of the Management of Municipal Solid Waste: A Case Study

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Abstract

This study compares, from an environmental point of view, different alternative scenaria for the management of municipal solid waste generated in a city of 1.000.000 citizens. Three integrated solid waste management scenaria are developed. Each of these alternatives includes the recycling of part of the recyclable MSW at the source, the collection of MSW in bins, the gathering of MSW from bins, their transportation by trucks to the process - disposal location, the mechanical separation of MSW, the main treatment and the disposal of the residues of the mechanical separation and the main process in a landfill. The main treatment method differs in each scenario. The anaerobic digestion of the biodegradable solid waste, the composting of the biodegradable solid waste and the incineration of volatile solids are accordingly examined. The purpose of this study is the selection out of the three scenaria the most environmentally friendly. To this aim, the Life Cycle Analysis (LCA) method is used as a tool. According to the results the most environmentally friendly scenario is the one where anaerobic digestion and simultaneous exploitation/utilisation of the generated biogas for energy production is used as main treatment method. The scenaria that examine the anaerobic digestion without exploitation of the produced biogas and incineration as main treatment methods are the most undesirable from an environmental point of view.

Keywords

Life cycle analysis; management of municipal solid waste; anaerobic digestion; composting; incineration

1. Introduction

Waste management has become a key issue in environmental protection and urban management and an issue of priority in modern municipalities. Municipal expansion and the changing lifestyles and trends result in an increase in municipal solid waste (MSW) and a growing realization of the negative impacts on the environment, human health and climate change. This problem scourges cities worldwide, especially the highly populated regions where the opportunities for waste minimization through mere treatment (e.g. recycling, home composting of the organic fraction etc.) are limited. Additionally the lack of free space restricts significantly the waste management infrastructure and leads to a continuing increase in the volume of MSW streams. Moreover MSW generation varies in quantity and quality as changes occur in the standard of living and it is expected to double (EEA, 2005). Thus there is a need to develop a comprehensive assessment method, which enables identification of the optimum MSW management option for a specific situation. On the other hand the selection of a better MSW management scenario requires for the environmental aspects to be considered.

According to the legislation, Landfill Directive (1999/31/EC) and Waste Framework Directive (2008/98/EC), the European Union (EU) member states are required to reduce the amount of biodegradable MSW sent to landfills and recycle organic fractions using more environmental options. This strategy stems from the need to protect the environment through the development of sustainable MSW management systems, based on the "waste hierarchy" reduce, reuse, recycling/compost and energy recovery from waste thereby promoting waste prevention. Accordingly, the European members are gradually adopting waste-to-energy and mechanical-biological treatments, methodologies leading to recovery of energy and materials from MSW streams.

Integrated solid waste management reflects an approach to sustainable management of MSW and covers all sources and aspects such as generation, collection, transfer, sorting, treatment, recovery and disposal of waste in an integrated manner. An integrated management would include an optimized waste collection system and an efficient sorting, followed by one or more options such as materials recycling, biological treatment of organic fraction with reduction of disposal volumes and compost production, thermal treatment (e.g. incineration, burning of RDF (refuse-derived fuel) and PPDF (paper and plastic-derived fuel)) with energy recovery, residues inert and energy recovery and landfilling (McDougall, 2001). In addition, a sustainable MSW management system must be environmentally effective (reduction of environmental burdens and emissions to land, air and water, such as CO_2, CH_4, SO_x, NO_x, BOD, COD and heavy metals), economically affordable (acceptable operation cost to the community) and socially acceptable (McDougall, 2001).

Life Cycle Assessment (LCA) is a suitable tool for the sustainability assessment giving the quantitative and overall information on resource consumption and environmental emissions of the systems investigated (Rebitzer, G. et al., 2004 and Pennington, D.W. et al., 2004) and it is standardized under ISO 14041 (1998), ISO 14042 (2000), ISO 14043 (2000), ISO 14040 (2006) and ISO 14044 (2006). Moreover it is a tool for the analysis of the environmental burdens of products or services at all stages of production, consumption, and end use (from "cradle to grave"). Environmental burden includes all types of impacts on the environment including depletion of natural resources, energy consumption, and emissions to air, land and water. The use of LCA ensures that all environmental impacts are assessed within a consistent framework as well. As such, the possibility of "problem shifting" is minimized (Guinèe, J.B., et al., 2000, 2001). LCA, according to the ISO standards, is carried out in four steps: the goal and scope definition, the inventory analysis, the life cycle impact assessment and the interpretation.

The LCA methodology provides an excellent framework and a systematic tool for evaluating MSW management strategies and it is an ideal tool for application in management (Mendes, M.R., et al., 2004; McDougall, 2001; Sonesson U., et al., 2000; Turkulainen T., et al., 2000; Bjorklund A., et al., 1999; Finnveden G.,et al., 1999 and 1995; and Barlaz M.A., et al., 1995). It has been utilized for sustainable MSW management (Guereca et al. 2006) and reduction of local pressures of MSW management with consideration to broader effects across the society (Koneczny K. and Pennington, D.W., 2007). In a wide range of countries such as Italy (Buttol P. et al., 2007; Brambilla Pisoni, E., et al., 2009; Scipioni A., et al., 2009; Cherubini, F., et al., 2009; De Feo, G. and Malvano, C., 2009), Spain (Bovea, M.D. and Powell, J.C., 2006; Guereca L.P. et al., 2006), Sweden (Eriksson, O., et al., 2005), Germany (Wittmaier, M., 2009), United Kingdom (Emery, A., et al., 2007), Turkey (Ozeler et al., 2006; Banar, M., et al., 2009), USA (Contreras, F., et al., 2008), Singapore (Khoo, H.H., 2009) and China (Zhao, Y., et al., 2009), many applications of MSW management are focused on the use of the LCA methodology as a decision support tool in the selection of the best MSW management system from an environmental point of view.

The goal of this work is the development and application of a suitable methodology for the selection of the most appropriate integrated system for the management of MSW, taking into account environmental considerations. Three integrated MSW management scenaria were developed for the management of MSW generated in a city of 1.000.000 citizens. Each of these alternatives includes the recycling of part of the recyclable MSW at the source, the collection of MSW in bins, the gathering of MSW from bins, their transportation by trucks to the process - disposal location, the mechanical separation of MSW, the main treatment and the disposal of the residues of the mechanical separation and the main process in a landfill. As tools, a spreadsheet model for the design of alternative scenaria and a Life Cycle Assessment (LCA) methodology for assessing the environmental implications were developed. The LCA methodology was used to support decision making in the choice of an integrated system of MSW management through comparison and selection of the most suitable combinations of technology.

In order to select the environmentally friendlier and most viable integrated system for main treatment, different anaerobic and aerobic technologies were considered. The technologies selected are the ones most commonly used in modern waste management systems and are considered state-of-the-art and already broadly verified treatment methods. In particular, processes such as recycling and mechanical separation of MSW followed by different biological treatment technologies or incineration were investigated and the total environmental impact contributions from both construction and operation phases of the whole management system were assessed in each case.

2. Materials and Methods

2.1 Goal and Scope Definition

The goal of this study is the comparison of three alternative scenaria for the management of MSW generated in a city of 1.000.000 citizens, with an average waste generation of 1.000 tons per day (about 1kg/inhabitant/day), from the environmental point of view. In detail, each of these alternatives includes the recycling of part of the recyclable MSW at the source, the collection of MSW in bins, the gathering of MSW from bins, their transportation by trucks to the process - disposal location, the mechanical separation of MSW, the main treatment (anaerobic digestion or composting or incineration) and the disposal of the residues of the mechanical separation and the main process in a landfill.

To identify the best environmental option a spreadsheet model was constructed in order to design the three integrated scenaria considering the quality characteristics and the stoichiometry of MSW. The spreadsheet model has the capability to estimate the quantity of the raw materials and fuels, the energy balance and the emissions in each case as well. The LCA methodology was used in order to assess and evaluate the environmental impacts. Regarding the actual application of LCA, SimaPro 7.1 (PRé Consultants, 2008) was used to evaluate the environmental impacts of inventory aspects for three alternative scenaria for the management of MSW.

2.2 Functional unit

The functional unit is fundamental to the understanding of the results of an LCA, and provides a common basis for the comparison of results (Buttol P. et al., 2007; Ozeler et al., 2006; Consonni et al.

2005b; Mendes et al., 2004; Rebitzer et al. 2004), providing the reference point to which the input and output data are normalized (ISO, 2006). For LCAs of MSW, the functional unit ensures that all of the environmental emissions are based on identical inputs to each waste management system (Cleary J., 2009; Liamsanguan C., 2008). Thus, to compare the three alternative scenaria of MSW management the functional unit is defined as 1.000 tons per day of generated MSW.

2.3 Boundaries of the System

The system is defined as an integrated system for the management of 1.000 tons of MSW its boundary is shown in Figure 1. It consists of recycling of part of the recyclable MSW at the source (household), the collection in bins, the gathering of MSW from bins, their transportation by trucks to the process - disposal location, the mechanical separation, the main treatment and the disposal of the residues of the mechanical separation and the main process in a landfill. As shown in Figure 1, the system boundaries commence at the point where the generated MSW enter, and end where recyclable, reusable and recovery materials and compost, biogas or energy exit. It also includes the potential environmental impacts of the required fuels and energy and materials for both the operation and construction phases.

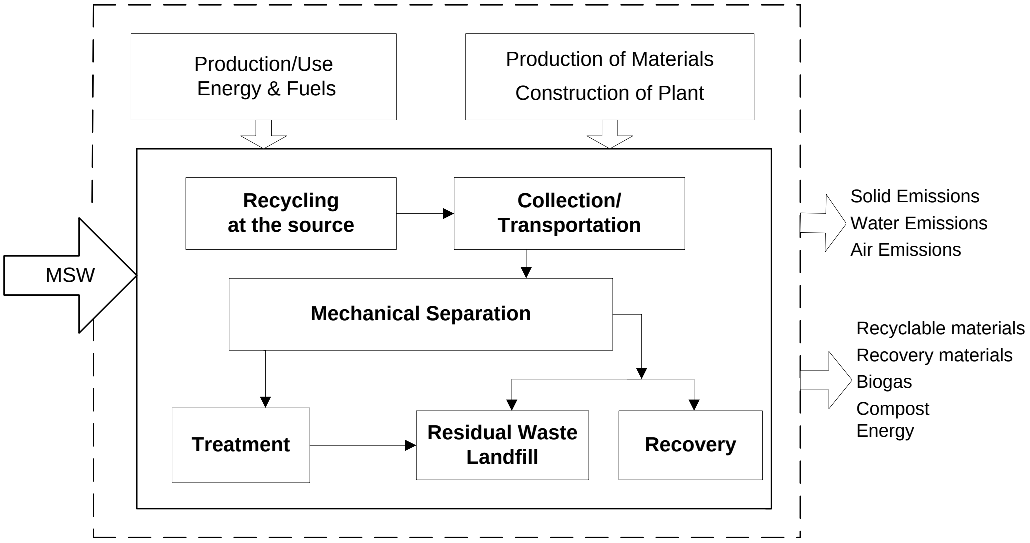

FIGURE 1 - Schematic Flowchart of System - Boundary Analysis.

The main treatment is comprised of three different technologies, namely anaerobic digestion, composting aiming at the treatment of biodegradable MSW and incineration. More specifically:

- The anaerobic digestion process is carried out by microorganisms in the absence of oxygen. During the process the decomposition of biowaste occurs in four stages (hydrolysis, acidogenesis, acetogenesis and methanogenesis). The benefits of the process are the production of biogas, a mixture of methane (CH_4) and carbon dioxide (CO_2), a high energy fuel which may be used to produce environmentally-friendly energy and the recycling of biodegradable fraction of MSW into stable soil additives, which are valuable fertilizers. Biogas production depends on the quality of biowaste and the system design. It is typically composed of 55 to 75 percent pure methane. Although state-of-the-art systems report producing biogas that is more than 95 percent pure methane. In particular 1 ton of organic MSW produces a range of 100 - 200 m^3 of biogas (Braber K. 1995). Another factor that contributes to the establishment of anaerobic digestion as a mainstream technology for the organic fraction of MSW is the fact that the digested residue can be considered a quite stable organic matter (Mata-Alvarez J., 2000). Furthermore, the removal of CO_2 constitutes an extra advantage because the CO_2 can be adjusted by restoring or creating organic rich soil (Verstraete et al., 1999). Anaerobic digestion of biowaste has been studied in recent decades, trying to develop a technology that offers waste stabilization with resources recovery (Nguyen P.H.L., et al., 2007). Thus, anaerobic digestion is a suitable technology to treat MSW, it has been considered as a waste to energy technology and it offers an opportunity to deal with some of the problems regarding the reduction of the amount of biowaste, while diminishing environmental impacts and facilitating a sustainable development of the energy supply (Yadvika S. et. al., 2004).
- Composting is an aerobic biological decomposition that relies on different types of microorganisms. It converts biowaste of MSW into a biologically stable product (compost) which improves the physical properties of soils by increasing nutrient and water. Through composting, readily available nutrient and energy sources are transformed into carbon dioxide, water, and a complex form of organic matter compost. Process management can be optimized for a number of criteria, including the rate of decomposition, pathogen control, and odor management. The key parameters are the available carbon to nitrogen (C:N) ratio, the moisture, oxygen availability and temperature.
- Incineration is a thermal treatment which enables the recovery of energy and an efficient way to reduce the MSW volume and demand for landfill space. It is the oxidation of the combustible organic substances contained in the waste materials that converts the organic matter into ash, flue gas, and heat. The ash is mostly formed by the inorganic constituents of the waste, and may take the form of solid lumps or particulates carried by the flue gas. The heat generated by incineration can be used to generate electric power. Moreover the flue gases must be cleaned of gaseous and

particulate pollutants before they are dispersed into the atmosphere. Thus incineration provides the best way to eliminate methane gas emissions from waste management processes, but it is only applicable if certain requirements are met. For example, the supply of combustible waste remains stable and facilities must operate under strict emission limits for the release of pollutants such as SO_2, NO and NO_2, HCl, HF, gaseous and vaporous organic substances expressed as total organic carbon (TOC), CO, dust, heavy metals, dioxins and furans into the atmosphere and the resulting bottom ashes and slag produced must have a total organic carbon content of less than 3% (EU Directive 2001/80/EC and EU Directive 2010/75/EU). Numerous studies propose the incineration of MSW, but this process generally produces significant amounts of polluting flue gases, and gives rise to toxic solid residues as well (Min Li et al., 2004; Moldes A. et al., 2007).

2.4 Alternative Scenaria of management of municipal solid waste

Regarding the scope of the assessment, three basic alternative scenaria for the management of 1.000 tons MSW per day were investigated. Each scenario presents an integrated solid waste management system for the treatment of MSW and consists of the recycling of part of the recyclable MSW at the source, the collection of MSW in bins, the gathering of MSW from bins, their transportation by trucks to the process - disposal location, the mechanical separation of MSW, the main treatment and the disposal of the residues of the mechanical separation and the main treatment in a landfill in that order. The three scenaria are similar but different main treatment is implemented to each scenario. Particularly:

- Scenario I: The main treatment of this scenario is the anaerobic digestion of the fermentable fraction of MSW. This scenario consists of two subsystems. The difference between them is the production energy of produced biogas. According to the design in the first subsystem the treatment finishes off with production of biogas, while the produced biogas produces energy in the second subsystem.
- Scenario II: The main treatment of this scenario is the composting of the biodegradable solid wastes.
- Scenario III: The main treatment of this scenario is the incineration of MSW.

2.5 Assumptions

The goal of this study is to provide a transparent and comprehensive environmental evaluation of a range of waste management strategies for dealing with mixed waste fractions of a city of 1.000.000 citizens. As the integrated management of MSW system is complex, several assumptions are required for a proper comparison between the three alternative scenaria. According to the design, the developed alternative scenaria are able to minimize the amount of waste for landfilling, while maximizing material and energy recovery.

First of all the term “generated MSW” includes residential (household) and commercial solid wastes such as food waste, paper, cardboard, plastic, textiles, rubber, leather, wood and yard waste, glass, tin cans, aluminum, ferrous metals, other metals etc. Based on the data of MSW in the Attica region of Greece, generated MSW consists of 55.3% organic waste, 15.7% paper and cardboard, 8.5% textiles, 2.8% metals, 2.8% glass, 2.0% plastics, 7.7% inorganic waste and 5.2% other wastes (rubber, leather, wood etc). Furthermore, all considered alternative scenaria should meet the current nationally (Greek) posed legislation limits regarding waste handling and air emissions (European Commission, BREF, 2006).

According to the design, the percentage in composition of each type of the recyclable (paper and cardboard, textiles, metals, glass, plastics, inorganic wastes and other wastes) at the source waste is about 15%, which amounts to 68 tons. Furthermore, it is assumed that 37.5% of the given city’s population recycles their domestic waste. Out of the total amount of waste produced in each household, the estimated recycled amount is 40% approximately. The source-separated recyclable materials are collected separately from the other waste. Thus, the environmental impacts of the treatment of the above mentioned amount are not taken into consideration.

After the source separation, recycling of part of the recyclable MSW at the source, the quantity of MSW is 932 tons and it consists of 553 tons organic waste, 133 tons paper and cardboard, 24 tons textiles, 24 tons metals, 17 tons glass, 72 tons plastics, 65 tons inorganic waste and 44 tons other streams of waste (rubber, leather, wood etc).

The collection type is assumed curb collection and includes the collection of MSW in stainless steel bins with HDPE cover and the gathering or picking up of MSW from various locations in the city. Excluded from the study is the collection of bulky waste, furniture and special waste such as electric and electronic appliances. The excluded fractions are collected by other collection systems, such as enclosed municipal facilities where people can bring waste. Furthermore, closed-body vehicles are also considered part of the collection system. The sizing of vehicles depends on the amount of waste to be collected as well as the variations in the quantities delivered hourly and daily. In this study, it is assumed that 5.500 bins with capacity 1.3 m^3 per bin and 45 vehicles with load capacity 28 ton are used daily for the collection of the waste. The potential environmental impacts of both raw materials (stainless steel about 5tons and HDPE about 24kg) and manufacturing of bins and the potential environmental impacts of vehicles are taken into consideration.

The required total distance for daily collection is comprised of the local distances (locations of bins) in the city and the distance between the city and the final management point. Specifically, in order for a vehicle to perform door-to-door collection of the neighborhood bins it needs to travel a distance of about

40 km from the city to the treatment / disposal location. So it is estimated that the total distance (distance for gathering and distance travel empty) that vehicles cover daily is about 5.650 km. The diesel consumption for trucks involved in urban and inter-city waste transport is determined. It is mentioned that a system with a lot of collection points consumes a higher quantity of fuel during the waste collection, than a system with only a few collection points. Under the study 65 collection points are arranged.

In addition the potential impacts on the environment of the fuels (fuels of collection truck) and energy (electricity consumes during the operation phase for mechanical separation, biological treatment and incineration) are taken into consideration. It is estimated that daily demands for fuels for both the collection and operation phase are about 0.7 tons.

Separation is a necessary treatment in the recovery of reusable and recyclable materials from the MSW. It also achieves the separation of heterogenous waste and the spin-off of process is a more homogenous waste. The separation process includes manual separation of bulky items and mechanical separation. Manual separation is more practical to segregate recyclables materials and contaminants as MSW move along conveyor lines. The mechanical separation of MSW depends on the treatment method used by each scenario. In other words, on the choice of techniques for the mechanical separation of MSW based on the composition such as organic and inorganic fraction and the physical differences between the particles such as size, shape or density. Under the design of mechanical separation, each scenario depends on the applicable main treatment of MSW. This means that according to the specification of treatment of each alternative scenario different techniques for mechanical separation have been assumed and this provides an appropriate input into the main treatment. In particular, mechanical separation in scenaria I and II (biological technologies for main treatment) includes shredding and screening, cyclone separator, eddy current separator and magnetic separation. Accordingly, mechanical separation in scenario III includes heavy-light separation (separation of light combustible materials), magnetic separation and cyclone separator, eddy current separator, since incineration depends on the calorific value of waste materials. The recovered materials, such as Fe, Al and other metals, from the mechanical separation lead to recovery.

The choice of main treatment (anaerobic digestion, composting or incineration) was based on both the biodegradable fraction and the calorific value of the MSW. For instance, the MSW consists largely of a biodegradable fraction and combustible components such as plastics, thus the biological treatments and the incineration are proper technologies for treatment. It is noted that both waste composition and carbon intensity of energy sources are very important factors to the outcome of the environmental impact of an MSW management system (Mendes et al., 2004). In addition, according to the design, the organic fraction of MSW is transformed by biological processes, such as anaerobic digestion (scenario I) and composting (scenario II). Anaerobic digestion is based on the biodegradable fraction of MSW and coverts it to biogas, while composting is an aerobic process which converts the degradable organic carbon of MSW to CO_2. The study (scenario I) takes into account both the usage and non-usage of biogas for production of energy. Thus, the potential environmental impacts from production of energy from biogas are investigated. In scenario II, for the purpose of the study, composting in static piles was adopted. According to the results the production of compost during anaerobic digestion (scenario I) and composting (scenario II) is 338 ton and 232 tons respectively. Similarly, the choice of incineration for treatment of MSW (scenario III) was based on both the calorific value and the biodegradable fraction of MSW and it is assumed that they have low volatile heavy metal concentration as well.

Incineration reduces the volume of the combustible fraction of MSW by 85% to 95%. On the other hand, the gaseous products derived from the incineration of MSW include carbon dioxide (CO_2), water (H_2O and flue gas), nitrogen (N_2) and sulfur dioxide (SO_2). Furthermore, during the operation, the production of solid residue such as bottom ash and fly ash is significant.

The residue fraction from the mechanical separation and both biological treatment (resistant organic matter and digested sludge) and incineration (bottom ash and fly ash) of alternative scenaria I, II and III, a quantity of 187 ton, 557 ton and 225 ton respectively, is disposed to landfill without energy recovery. A production of 0.15 m^3 of leachate from each landfilled ton is assumed, but the potential impacts of leachate treatment on the environment are not included as the energy and resource requirements are negligible.

The life cycle impact assessment includes the quality and quantity of raw materials, fuels, and energy inputs during both the operation and construction phase. The manufacturing of bins and the raw materials for the construction of facilities are included as well. However, the production of equipment such as truck and separators, its maintenance and personnel are not accounted for due to the lack of representative data. The extraction and production of fuels, as well as the extraction and production of electricity used during the operation phase, are also included. The energy requirements are calculated based on average electricity consumption.

The construction phase and all activities such as transportation of raw materials and construction of facilities, as well as resources (e.g. concrete, steel, gravel, etc.) consumed are taken into consideration. The production of vehicles and the equipment are excluded, because the impact of these activities is normally small, compared to contributions from the operation phase. The exclusion of these factors does not limit the value of the approach, as these parameters are assumed to be equally important in all scenaria considered.

2.6 Data Inventory

The LCA software SimaPro 7.1 was used to evaluate the environmental impacts of inventory aspects and to the life cycles for three scenaria. The data have been collected from various sources. Inventory data for raw material acquisition for operation and construction, along with electricity production and heat generation were obtained from the SimaPro libraries and databases. The energy demands have been obtained from the data bases BUWAL 250 (1996) and ETH Energy version, incorporated in the SimaPro 7.1 software package (PRé Consultants, 2008).

The fuel demands for transportation have been estimated by taking into account road transportation and a truck capacity of 28 tons (kg/km). Electrical energy in Greece is produced using four different sources, namely lignite, oil, natural gas and hydropower (P.P.C., 2006). The contribution of each source to the average national electricity mix, based on installed power (MW), is 43%, 19%, 13% and 25% respectively. However, hydropower is used only at peak times and in fact contributes only 10% to the total annual average electricity mix.

Figures 2, 3 and 4 depict the flowcharts of Scenaria I, II and III and they include the mass balance of the alternative scenaria.

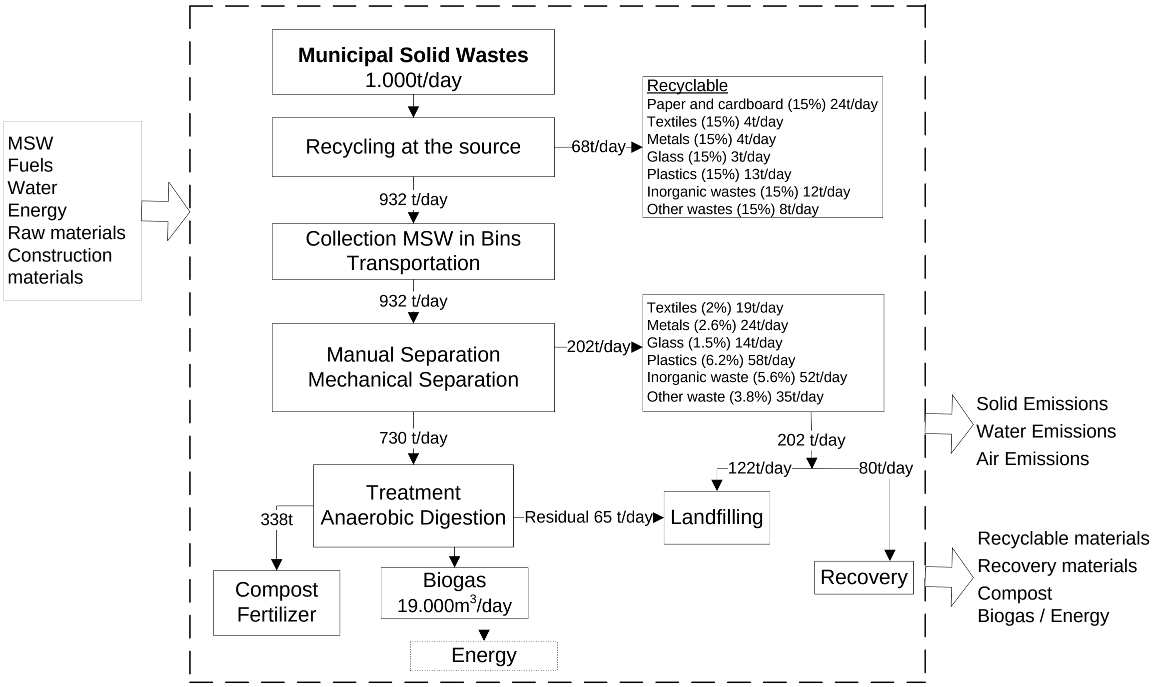

FIGURE 2 - Flowchart of Scenario I

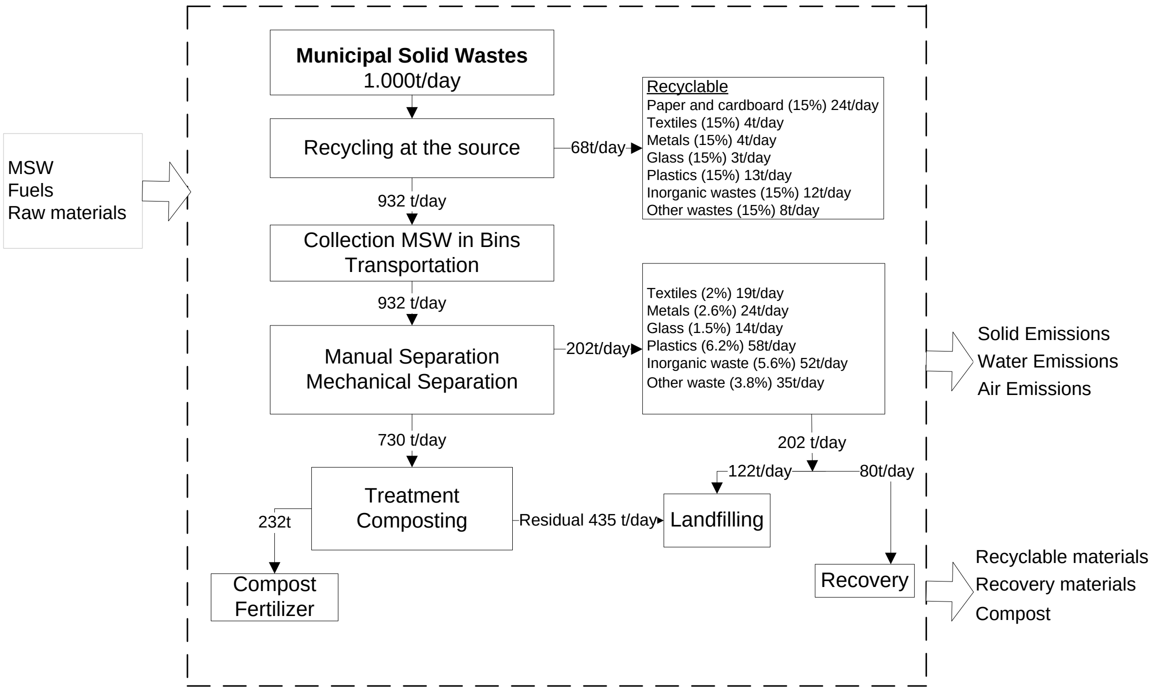

FIGURE 3 - Flowchart of Scenario II

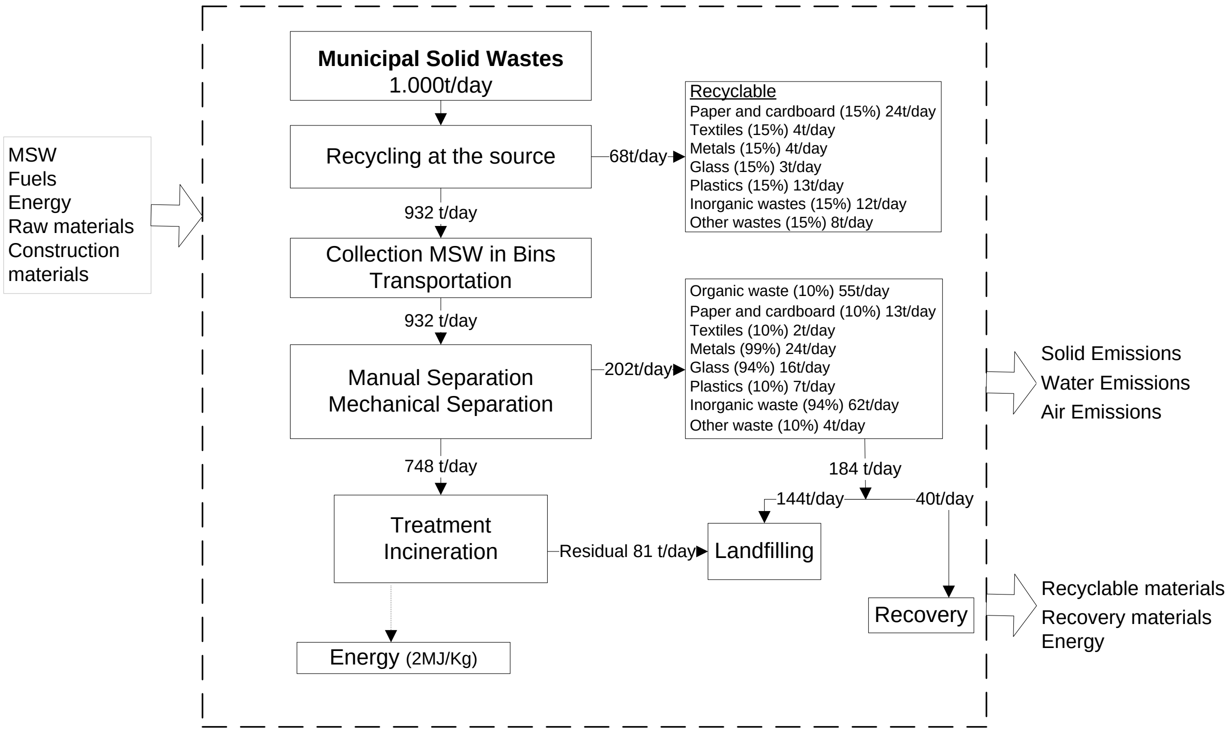

FIGURE 4 - Flowchart of Scenario III

2.7 Environmental impact assessment

The emissions of each alternative integrated scenario were grouped into environmental impacts. For the environmental impact assessment, the CML 2 baseline 2000 methodology, World 1995 normalisation/weighting set, available in SimaPro 7.1, was utilized. The CML method is an internationally accepted approach, which is based on the problem-oriented approach. The impact categories considered in the CML 2 baseline 2000 methodology are the Abiotic Depletion Potential (ADP, kg Sb eq), the Global Warming Potential (GWP, kg CO_2 eq), the Acidification Potential (AP, kg SO_2 eq), the Eutrophication Potential (EP, kg PO_4 eq), the Ozone Layer Depletion Potential (OLD, kg CFC-11 eq), the Human Toxicity Potential (HTP, kg 1,4-DCB eq), the Freshwater Aquatic Ecotoxicity Potential (FWAETP, kg 1,4-DCB eq), the Marine Aquatic Ecotoxicity Potential (MAETP, kg 1,4-DCB eq), the Terrestrial Ecotoxicity Potential (TEP, kg 1,4-DCB eq) and the Photochemical Oxidation Potential (POP, kg C_2H_4). These impact categories were chosen because they are the most relevant to waste treatment and recycling practice and they cover the categories used in LCA applied to waste management (Bjarnadóttir et al., 2002).

3. Results

According to the life cycle, the results (normalized environmental impacts) of the three alternative scenaria in terms of relative contribution to the main impact categories of CML 2 baseline 2000 methodology, are presented in Figure 5. Furthermore, a comparison of the three alternative scenaria for the management of MSW, in terms of relative contribution to the life cycle for the main impact categories Global Warming Potential (GWP, kg CO_2 eq), Acidification Potential (AP, kg SO_2 eq), Eutrophication Potential (EP, kg PO_4 eq) is shown in Figures 6, 7 and 8.

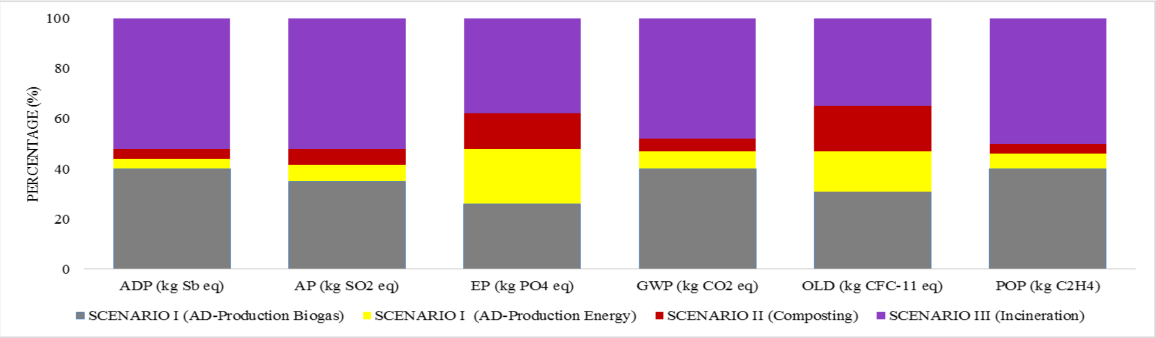

FIGURE 5 - Contribution of all alternative scenaria to the impact categories (CML 2 baseline 2000 methodology methodology)

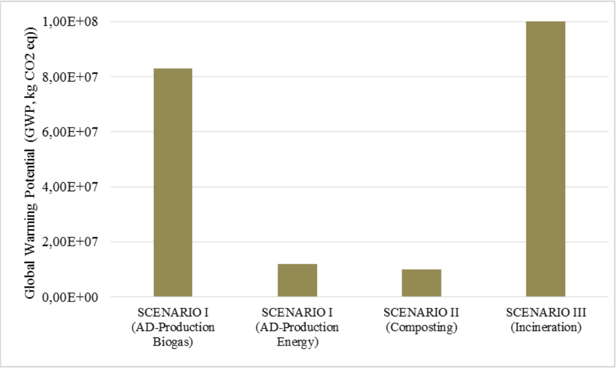

FIGURE 6-Contribution of all alternative scenaria to the impact category GWP (Global Warming Potential, kg CO_2 eq)

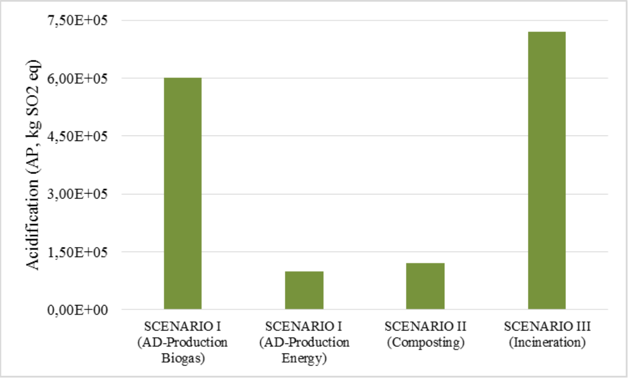

FIGURE 7-Contribution of all alternative scenaria to the impact category AP (Acidification Potential, kg SO_2 eq)

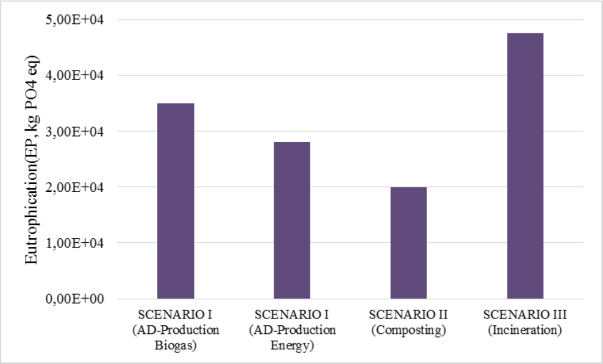

FIGURE 8-Contribution of all alternative scenaria to the impact category EP (Eutrophication Potential, kg PO_4 eq)

The most substantial ratio of all examined under the studied categories of environmental impacts in scenaria I and III, derives only from operation and construction of the main treatment. For example, according to the results of scenario I (subsystem: anaerobic digestion without production energy), the total ratio for the category Global Warming Potential (GWP, kg CO2 eq) allocates 10% from stages collection, transportation and mechanical separation and 90% from the main treatment (anaerobic digestion). Similarly the total ratio for category Global Warming Potential (GWP, kg CO2 eq) allocates to 12% from stages collection, transportation and mechanical separation and 82% from main treatment (incineration) in scenario III. Consequently, the contribution of the main treatment is essential for all impact categories of each of the alternative scenaria.

It is significant to mention that the results of scenaria I and II include both the operation phase and the construction phase of of main treatment, while the composting (scenario II) does not need facilities for the operation phase. This means that potential impacts from the construction phase or raw materials such as concrete, in scenario II, are negligible. Moreover the demands of electricity during the operation phase of scenaria I and II contribute significantly to all impact categories compared with scenario II (composting), since the demands of electricity of scenario II during its operation phase are negligible. In particular, the total contribution of scenario I (subsystem: anaerobic digestion without production energy) is distributed:15% for construction phase (extraction and production of raw materials) and 50% for the demands of energy (extraction raw materials and production of energy) while 35% derives mainly from the process. Furthermore, during the operation of scenario II, the retention time for the process is higher than the retention time of the anaerobic digestion or incineration, the dimension of the composting plan is estimated about 250.000m^2 and the demands for air are about 2.590ton per day. Therefore, scenario II is more harmful than the other two alternative scenaria.

On the other hand, the impacts of scenario III are higher due to the air emissions of the process. Furthermore, the emissions to air from incineration depend on the nature and composition of MSW (the process requires suitable composition of MSW) and consist of a huge volume of flue gases. Nevertheless, the main problems associated with incineration are the large volume of gaseous emissions, which may pose health risks and hazardous solid wastes that remain after incineration as fly ash or air pollution control residues and bottom ash which require safe disposal.

Comparing the results (Figures 6, 7 and 8) of the alternative scenaria I and II with main treatment anaerobic digestion and incineration respectively, it turns out that scenario I achieves the reduction of the environmental impacts of categories Global Warming Potential (GWP, kg CO_2 eq), Acidification Potential (AP, kg SO_2 eq) and Eutrophication Potential (EP, kg PO_4 eq). With regard to energy consumption, the implementation of anaerobic digestion with production of energy results in the reduction of the percentage in all impacts categories.

Based on the overall results of the environmental impact assessment as presented in Figure 5, anaerobic digestion with production of energy (scenario I) has proved to be an ideal integrated scenario for the management of MSW and this process provides a reduction of environment impacts, converts biowaste to valuable items, while simultaneously producing energy leading to a reduction of electricity consumption.

Therefore, the interpretation of the results provides the conclusion that the most environmentally friendly prospect is scenario I, anaerobic digestion with production of energy, while the least preferable scenario is scenario III based on incineration as treatment.

4. Conclusion

A methodology for the evaluation of different management scenaria of municipal solid waste generated in a city of 1.000.000 citizens, taking into account environmental considerations, was developed. Three integrated alternative scenaria were considered. A spreadsheet model was developed and used to estimate the design inventory data from both the construction and the operation phases of all alternative scenaria. The Life Cycle Assessment (LCA) methodology was used to quantify the potential environmental impacts for each scenario.

The interpretation of the results provides the conclusion that the most environmentally friendly prospect is the scenario based on anaerobic digestion with production of energy, while the least preferable is the scenario based on incineration.

The final outcome of this work can be of use to engineers involved in waste management, local authorities (involved in decision-making) and practitioners of LCA.

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