## LCA Case Studies

# Managing Municipal Solid Waste

## Energetic and Environmental Comparison Among Different Management Options

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**Abstract**

**Goal.** This research aims to assess the environmental effects of integrated strategies in a municipal waste management system. In particular, analysis is focused on a waste stream in Palermo, where landfill involves the prompt disposal of the most waste after collection. The current local management system is compared with two integrated waste management alternatives. Both the options comply with Italian regulations, but each one predicts adopting the available technologies in different ways.

**Methods and objectives.** Energetic and environmental balances are carried out in each management system referring to local waste composition in order to quantify energy consumption, the recovery of material and energy, and the environmental releases. Impact assessment is carried out to define the environmental profile of each option. Impact categories are defined and inventory data, by means of a suitable aggregation, can be used to evaluate the potential contribution that system inputs and outputs could bring to the relative category.

**Results.** In opposition to the current management, which involves energy balance at a loss, the mass and energy balances outcomes in both of the two hypothetical management systems show the capability to obtain energy and material recovery to a substantial extent. Sorted collection plays a remarkable role in the improvement of environmental performance of management systems. In particular, the thermal treatment of waste associated with energy recovery, and the concomitant material recycling, increase the saving of energy.

**Conclusions.** Environmental pressure factors of the management system are assessed depending on the relevant consumption of raw materials and energy, and on the emission of pollutants. The resulting figures reflect the two different integrated management options as being sustainable solutions for achieving an improvement in environmental performance, which is based on increasing the value of waste, as an alternative to resources, and the reduction of environmental releases. Life Cycle Assessment of municipal waste management systems can be usefully applied to define synthetic indices of environmental impact. These indices could single out possible alternatives in multi-criteria analysis, together with economic and technical parameters.

**Keywords:** Case studies; compost; eco-balance; energy recovery; environmental releases; functional unit; impact categories; integrated management systems; Life Cycle Assessment; material recovery facilities; material recovery rate; municipal waste management; net energy consumption; refuse-derived fuel; synthetic indices; waste valorization

### Introduction

Sustainable waste management means to accomplish the concept of 'more with less', that is the recovery of valuable materials from the waste with less energy and space consumption, and reduced environmental loading. By selecting suitable options for dealing with the various fractions of municipal solid waste, the environmental impacts of the whole waste management system could be reduced. The adoption of sustainable development models in municipal waste management requires the introduction of innovative strategies in order to start environmentally-oriented processes in an urban context. A correct scientific approach to this issue is based on integrated management systems which take the following tasks into account:

- Recovery of secondary materials,
- Biological treatment of organic fraction,
- Incineration with associated energy recovery,
- Landfill of final inert waste.

Life Cycle Assessment is carried out to define energetic and environmental profiles of three different management systems with regards to a waste stream produced in Palermo city.

The main steps of this framework are:

1. Goal definition, Functional unit and Data quality
2. Inventory
3. Impact assessment.
4. The following options are taken into account and compared:

**Option A.** It represents the current municipal waste management system in Palermo. It is essentially characterized by landfill, without remarkable selection or recovery.

**Option B.** Sorted collection is assumed up to 35% of total waste (Italian Legislative Decree 1997, February 5-N.22).

The following treatments are also included:

- Waste selection
- Facilities of material recovery (MRF)
- Production of Refuse-Derived Fuel (RDF)
- Incineration and recovery of energy
- Biological treatment of organic fraction derived from sorted collection and RDF selection
- Landfill of inert waste

**Option C.** Sorted collection is increased up to 50% of total waste. Thermal treatment is not included, but biological treatment is assumed to produce quality compost.

## 1 Goal Definition, Functional Unit and Data Quality

Eco-balance of municipal wastes is carried out in order to assess energetic and environmental profile of the current management in comparison with the integrated alternatives B and C. The functional unit is defined as the amount of household and similar wastes generated in the specified geographical area. All data and inventory outcomes are referred to it. In each option the extent of waste life cycle includes waste from the source to recovery/recycling/landfill and environmental emissions. Data is derived from investigation and/or literature. Local waste characterization is taken into account[1]. European data are used to calculate electricity produced in recovery units. The useful energy value is obtained from the difference between the energy recovered and that consumed (Boustead 1993).

## 2 Inventory

A model is used to assess more relevant materials and energy inputs/outputs of the system under each option (White et al. 1995). The model is characterized by the following main steps:

**Waste generation.** Municipal waste represents the most relevant stream entering the system. Therefore, it firstly requires the determination of the amount and the composition of municipal waste generated in the given urban area and collected by local analyses. Assessment of waste characterization must be necessary to manage sorted collection and to plan innovative technical strategies. There is not any uniformity in waste composition and the municipal waste category includes waste from different sources, each of which is heterogeneous[2].

**Sorted collection.** The waste collection method determines the subsequent management options and, in particular, if material recycling, biological treatment or fuel burning are feasible in an environmentally sustainable way.

The characteristics and effectiveness of collection strategies will influence the quality of waste valorization (recycling, energy recovery, production of compost).

**MRF and RDF production.** Material recovery facilities are required wherever recyclable materials are collected in a commingled fraction. Energy consumption does remarkably vary according to the amount of fractions to be selected and the technical levels of the process. In this study, residues are estimated as being 30% of lost input (ERRA 1993). Landfill as a treatment method for the residue and the average distance to it has been defined. The model calculates the fuel consumption by transport, which is added to total fuel consumption. RDF is produced by mechanically separating combustible fraction from the waste stream (ETSU 1992). For the purposes of this study, RDF is supposed to be as fuel to burn directly in an incinerator.

**Recycling.** Reprocessing the recovered materials into recyclable materials may result in the saving of virgin materials, and energy consumption, and in the avoidance of environmental releases. In fact, referring to recycling processes for each material, energy use and emissions are calculated. For this purpose, outcomes are compared with the energy consumption and emissions associated with the production of an equivalent amount of virgin material, so that overall savings can be estimated (Habersatter 1991). Energy consumption and environmental releases associated with transport from the sorting or collection facility to reprocessing plants depend on distances; therefore, locating such plants is a strategic stage from an environmental point of view.

**Thermal treatment.** Thermal treatment can be regarded either as a pre-treatment to reduce the volume for final disposal or as a method of waste valorization by recovering energy. It includes both the burning of mixed municipal waste and the burning of selected parts of the waste stream, that is RDF and separated materials from household collections such as paper and plastic which have been recovered but not recycled. In this inventory, RDF has been assumed as the only input, with a heat content value of 16 GJ/ton. Mass and energy balance lead to an estimated energy consumption, energy recovery, air and water emissions and solid residues (ETSU 1992).

**Biological treatment.** It treats both the organic and paper fractions. This process will result in biogasification, with the production of gases (mainly $CO_2$, $CH_4$, water vapor) and a mineralized residue (anaerobic process), or composting, with the production of compost (aerobic process). Either option can be regarded as a pre-treatment to reduce volume and stabilize waste for disposal in landfills or as a method of waste valorization by means of compost and biogas production. In this study, three input sources have been considered:

- Unsorted municipal waste
- Selected biowaste
- Mechanically separated residues from RDF processes.

Mass and energy balances have been carried out by assuming an energy consumption of 30 kWh per ton of waste input to the composting plant and a production of compost of 50% of waste input (ORCA 1992). The remaining 50% is lost by evaporation and emissions.

**Landfill.** According to European regulations, only inert residues can be intended to as landfill for final disposal. Landfill does essentially involve long-term storage for inert materials along with uncontrolled decomposition of biodegradable waste. Environmental outputs consist of biogas and leachate production, the amount of which depends on waste input composition. Biogas and leachate production are estimated. For each previous treatment steps the model inputs are as follows:

- Waste
- Energy
- Raw materials.

[1] It is reported local composition, which was determined in 1995, according to daily waste production for every citizen (1,2 kg) and to different social and economic connotations of city neighbourhood.

[2] The waste sources can be defined as:
- Household waste, generated by individual households.
- Commercial and institutional waste generated by land properties.

The model calculates the following outputs:

- Net energy consumption (management energy consumed minus energy production and amount saved through recycling).
- Water and air emissions (primary pollutants released to the environment by a system).
- Material recovery rate (waste flow recovered as secondary materials) and total recovery rate, which includes not only the dry recyclable fraction, but also compost produced by biological treatment.

Fig. 1 shows inputs and outputs of the mass balance for the municipal waste in an integrated management system. Particularly, figures are referred to life cycle inventory carried out for option B.

## 3 Impact Assessment

Inventory results lead to a defined energetic and environmental profile of each management option, but they are not aggregated data and, consequently, not easily explainable. Therefore, they should be processed, aggregated and classified in impact categories related to more relevant environmental issues (Heijungs 1996).

Classification factors lead to assess the extent of contribution that input and output data bring to potential environmental impacts. In particular, primary pollutant flows are calculated for each unit plant, identifying their environmental destination, air, water or soil.

### 3.1 Impact Categories

Impact assessment is carried out, referring to raw materials and energy consumption and environmental releases associated with each step in the waste life cycle. The following categories are defined:

A) **Resources**

1) Net energy consumption
   Energy consumption is due to transport from a treatment site to another and plants management. The production of energy in the recovery section (option B) and the energy saved via recycling are also assessed.
2) Material recovery
   Material recovery and compost rate as the percentage of total waste is assessed.
3) Volume requirement in landfill

It depends on the final amount of solid waste to be intended for landfill and the degree of selected compaction.

B) **Emissions**

a) Global warming
b) Acidification
c) Nutrification
d) Human toxicity
e) Terrestrial and aquatic eco-toxicity.

Fig. 2 shows contributions to each impact category by system, in the three management options.

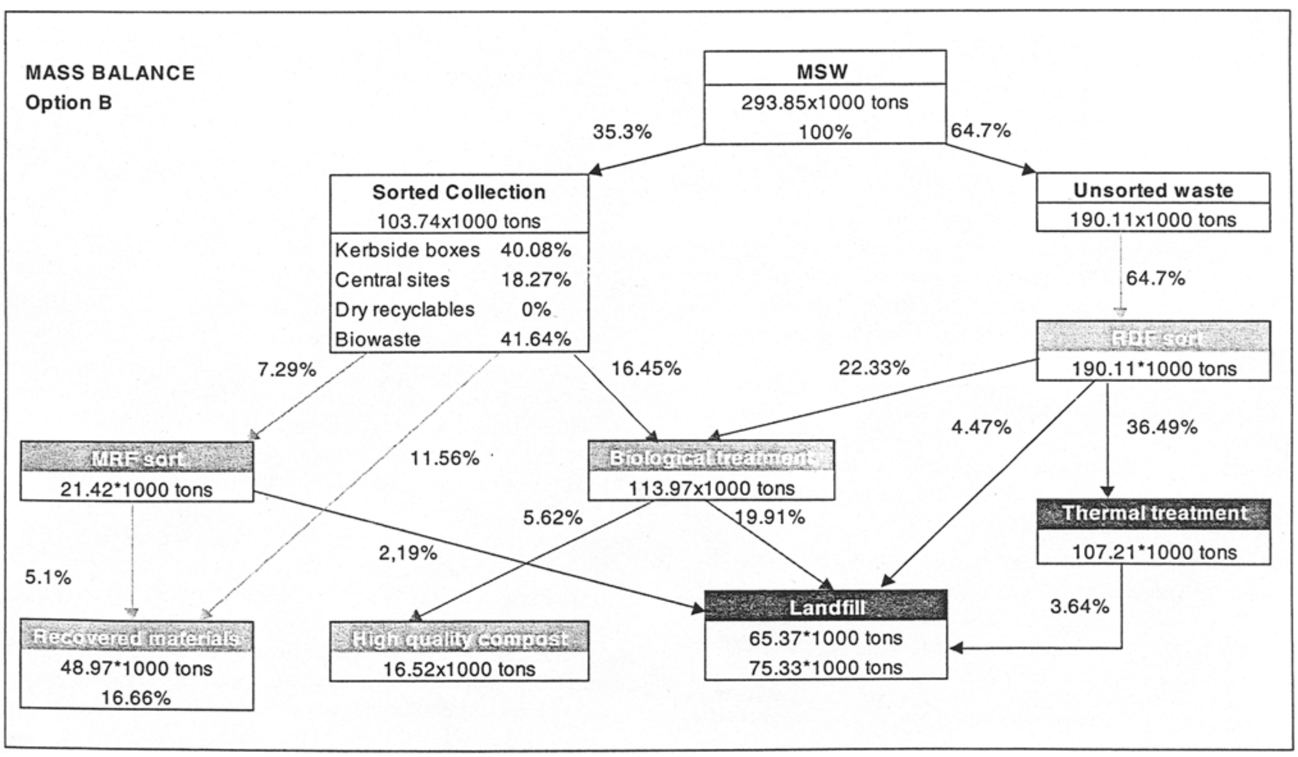


**Fig. 1:** Inputs and outputs in the mass balance for the lifecycle inventory of integrated municipal waste management (Option B)

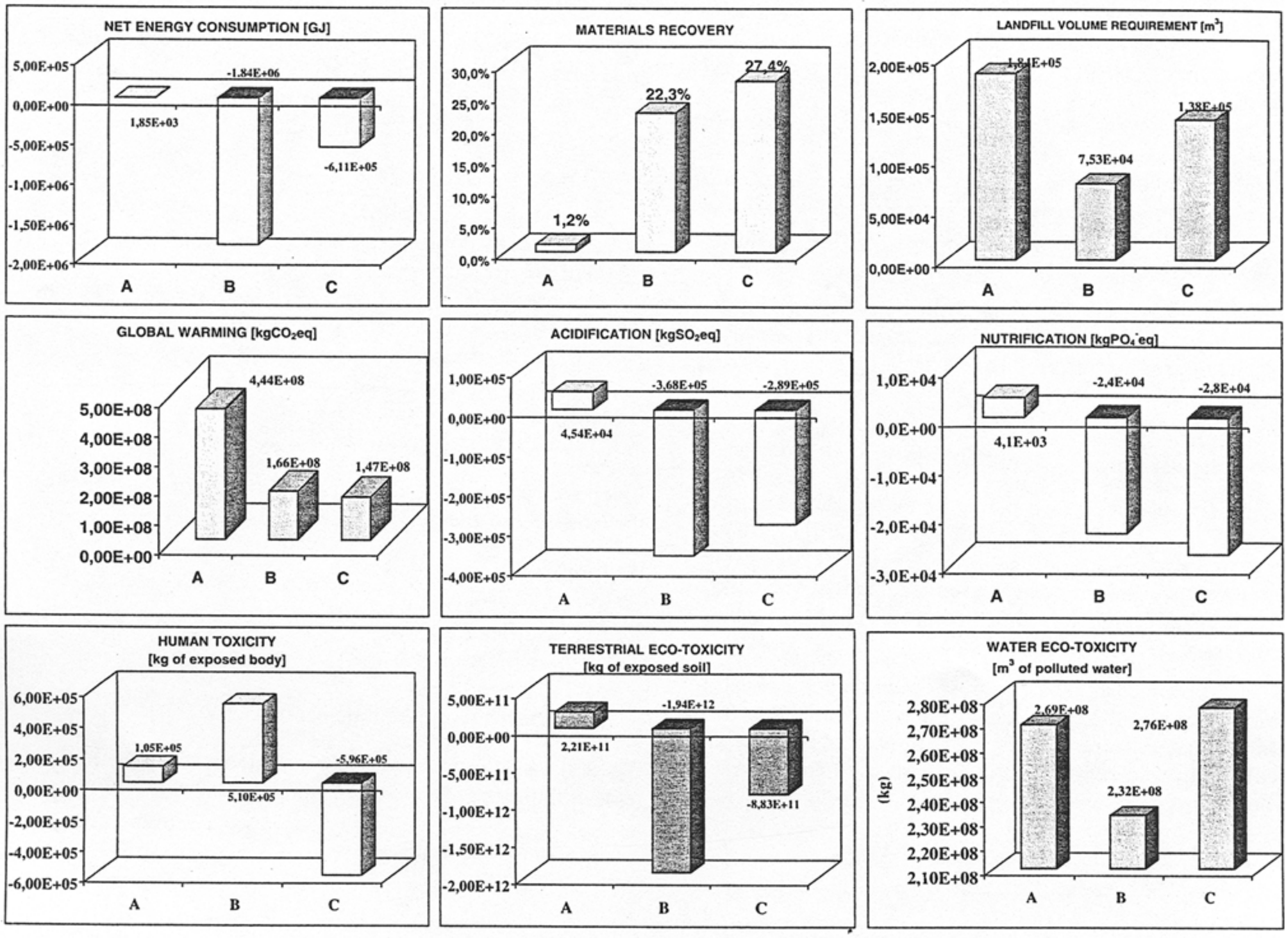


**Fig. 2:** Environmental impacts in each waste management option

## 4 Results

Energy balances are carried out for the three given options. Energy demand in management plants and transport, energy saving by recycling and energy generation in thermal treatment (option B) are estimated. Energy balance inputs and outputs are reported in **Table 1**. The results lead one to make the following remarks:

a) Energy balance is negative in the current management system (option A). The total waste flow is intended for landfill without remarkable selection or another form of treatment, except for a little selection of papers, plastic and glass up to 1.5% of the total waste flow.

b) Integrated management systems – options B and C – involve positive energy balances, depending on recovery of materials and energy. Particularly the introduction of thermal treatment and the concomitant recycling lead to an effective saving of energy.

Therefore, energy recovery with associated cogeneration, could become a worthwhile alternative to natural resources. **Table 2** lists material recovery rates in the three cases study. Its figures show that integrated management strategies should bring a consistent contribution in saving raw materials. Landfill influences land occupation more heavily than the other processes.

## 5 Discussion

The two integrated management alternatives could be effective strategies for reducing environmental releases and using municipal waste as alternative resources. In opposition, current local management is absolutely defaulting, depending on the high environmental pressure in an urban context. Comparison between the two integrated alternatives shows that sorted collection and material recovery lead to lower land requirement for the final waste disposal than the current undifferentiated management. In particular, the thermal treatment in option B determines the reduction of volume requirements in a more relevant way than the other facilities. The increased selection rate in alternative C determines energy saving, but also higher energy costs during collection and biological treatment. The impact assessment evaluates potential environmental impact by system emissions to the relative impact categories. It is remarkable that the thermal treatment would increase the emission levels of carbon oxides, nitrogen oxides, heavy metals, dioxins. However, the introduction of the best available

**Table 1:** Energy balance in the compared municipal waste management options

| | | Collection | Sorting | Biological treatment | Thermal treatment | Landfill | System management | Recycling savings | TOTAL |
|---|---|---|---|---|---|---|---|---|---|
| **Option A** | TOTAL GJ | 26968 | 1182 | 0 | 0 | 7684 | 35834 | | 35834 |
| Recovery: | TOTAL GJ | 0 | 0 | 0 | 0 | 0 | 0 | | 0 |
| Net energy consumption | TOTAL GJ | 26968 | 1182 | 0 | 0 | 7684 | 35834 | 33987 | 1847 |
| **Option B** | TOTAL GJ | 29435 | 49069 | 32648 | 20674 | 2362 | 134187 | | |
| Recovery: | Power MWh | | | 0 | 142952 | 0 | 142952 | | |
| | TOTAL GJ | | | 0 | 1358049 | 0 | 1358049 | | |
| Net energy consumption | TOTAL GJ | 29435 | 49068 | 32648 | -1337375 | 2362 | -1223861 | 618038 | -1841899 |
| **Option C** | TOTAL GJ | 36624 | 19832 | 63994 | 0 | 3921 | 124371 | | |
| Recovery: | Power MWh | | | 0 | 0 | 0 | 0 | | |
| | TOTAL GJ | | | 0 | 0 | 0 | 0 | | |
| Net energy consumption | TOTAL GJ | 36624 | 19832 | 63994 | 0 | 3921 | 124371 | 735374 | -611003 |

**Table 2:** Recovery rate of waste fractions and total material recovery rate for each management option

| | Paper | Glass | Me-Fe | Me-nFe | Plastic film | Plastic rigid | Textiles | Materials recovery rate | Compost rate | Total recovery rate |
|---|---|---|---|---|---|---|---|---|---|---|
| Option A | 1.4% | 7.5% | 0.04% | 0.04% | 1.04% | 1.04% | 2.5% | 1.2% | 0.0% | 1.2% |
| Option B | 39.2% | 61% | 81% | 59% | 11.3% | 11% | 10% | 16.7% | 5.6% | 22.3% |
| Option C | 43% | 69% | 82.5% | 82.5% | 0.3% | 0.1% | 0.3% | 19.6% | 7.8% | 27.4% |

technologies could warrant emission level to remain within a range fixed by regulation.

## 6 Conclusion

By comparing the energetic results of the two examined integrated systems, the hypothesis of thermal treatment (option B) involves a 70% increase in energy recovery, in comparison with the biological treatment of the unsorted waste (option C). Besides, the higher efficiency of sorted collection and material recycling in option C brings an increase in energy saving, due to the avoided consumption of raw materials, but, at the same time, it involves higher energetic loads during collection and biological treatment. Therefore, the overall energy recovery in such a scenario is remarkably lower than in option B. It should mean that waste incineration has the main share in energy saving.

Sorted collection and material recovery/recycling facilities determine the following improvements in comparison with the current local management system:

- An overall materials and compost recovery rate, that is 22.3% in option B and 27.4% in option C, respectively.
- Reduction of volume requirement in landfill for inert waste disposal, that is 25% for option C and 60% in option B, respectively. The higher rate in option B is obviously due to the assumption of waste incineration.

The results of the Life Cycle Assessment lead to define the energetic and environmental performance of each examined alternative, but it is clear that suitable criteria are necessary to select the available options in multi-attribute decisional procedures, taking into account economic, energetic and environmental factors. Therefore, useful synthetic indices should be defined which establish a hierarchical order among alternatives to be comparatively ranked in decision-making processes.

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## Appendix

### 1 Inventory

The inventory stage is carried out with reference to the whole life cycle of wastes in each examined management system. Sequential method is applied. Results of the model used (see references) are:

- System inputs:
  - Net energy consumption
- System outputs:
  - Landfill inert volume requirement
  - Recovered materials
  - Compost
  - Environmental emissions.

Both dry recyclable materials and produced compost give the overall recovery rate in comparison with total amount of waste entering the management system. Data is derived from local field research and/or literature on the subject. Inventory about electricity generation is carried out with reference to an average European scenario, based on the Union for the Connection and Production of Electricity model (UCPTE90), characterized by the following mix of electricity generating sources in 1990:

| | |
|---|---|
| Coal | 29% |
| Fuel oil | 9.60% |
| Gas | 9.50% |
| Hydro | 15.16% |
| Nuclear | 36.20% |

The net consumption of energy is obtained by a balance between the consumed electricity and the recovered electricity. Environmental releases, associated to fuel consumption, are computed according to the average consumption of the vehicle involved. Fuel and electricity consumption determines the impacts due not only to their actual use, but also to the mining, transport and production. Every time that fuel or electricity is used, the consumption of thermal energy, including pre-combustion energy, the environmental emissions, and the solid waste production must be added to the overall inventory results. **Fig. A1** shows local municipal solid waste characterization (Beccali et al. 1999). **Table A1** lists literature data on energy consumption and environmental emissions in electricity and fuel use (Boustead 1992, Habersatter 1991).

### 2 Impact Analysis

With reference to each management scenario involved, primary pollutants are estimated and their environmental destination is identified for each stage of the waste life cycle.

a) Inventory data are aggregated and classified according to the impact categories, depending on the main environmental issues on the local and global scale.

b) Definition of Classification Factors
They provide the standard model for the classification of environmental interventions as environmental effects. They are defined by applying the linear methodology. For a given substance, each factor is defined as the enhancement of environmental effect, due to the emission of the unit substance (Heijungs 1996). In particular, given a function $f(x)\ x \rightarrow y$, where the independent variable $x$ represents the emission of a substance, $y$ represents the potential effect associated to $x$. If $\Delta x$ is the increase of $x$ due to a given alteration, $\Delta y$ is

the related increase in the environmental effect at a global scale. By applying the linear methodology, if $\Delta x << x$, the following expression can be written:

$$\Delta y = \left[\frac{df}{dx}\right]_x * \Delta x \quad (1A)$$

By assuming that $\left[\frac{df}{dx}\right]_x$ is a constant:

$$\Delta y = I * \Delta x \quad (2A)$$

where $I$ is the classification factor and represents the increase of environmental effect due to a unitary $\Delta x$.

c) Characterization

This step consists of assessing the environmental profile, as a list of all environmental effects in which a waste management system plays a part.

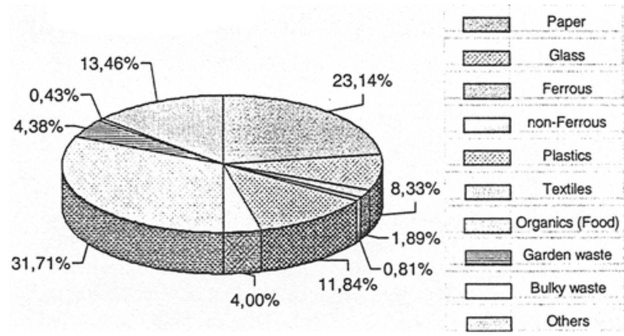

**Fig. A1:** Characterization of municipal solid waste stream in Palermo

**Table A1:** Data on fuel and electricity production and use

| Impact Data on Fuels and Electricity Consumption | | | | |
|---|---|---|---|---|
| | Petrol | Diesel | Electricity | Natural gas |
| Energy (GJ) | 42 | 44.1 | 9.5 | 42.1 |
| Solid Waste (ton) | 0.0053 | 0.0057 | 0.0491 | 0.003 |
| Air Emissions (g) | | | | |
| Particulates | 2446 | 2564 | 197 | 3220 |
| CO | 25323 | 26548 | 349 | 39 |
| $CO_2$ | 2491318 | 3036258 | 441657 | 2061211 |
| $CH_4$ | | | | |
| $NO_x$ | 32301 | 33901 | 1236 | 29604 |
| $N_2O$ | | 41 | 70 | 43 |
| $SO_x$ | 9640 | 10106 | 2502 | 660 |
| HCl | 36 | 38 | | |
| HF | 36 | 38 | 0.01 | |
| $H_2S$ | | | | |
| HC | 10395 | 10898 | 2112 | 53932 |
| Dioxines/Furans (TEQ) | | | | |
| $NH_3$ | | | 0.49 | 0 |
| As | | | | |
| Cd | | | | |
| Cr | | | | |
| Cu | | | | |
| Pb | 144 | | | |
| Hg | | | | |
| Ni | | | | |
| Zn | | | | |
| Water Emissions (g) | | | | |
| BOD | 36 | 38 | 0.15 | 0 |
| COD | 36 | 38 | 0.44 | 0 |
| SS | 36 | 38 | 0.15 | 0 |
| TOC | 396 | 415 | 4.7 | 31 |
| AOX | | | | |
| Dioxines/Furans (TEQ) | | | | |
| Phenols | 36 | 38 | 0 | 0 |
| $NH_4$ | | | 0.62 | 0 |
| Total metals | 36 | 38 | | |
| As | | | | |
| Cd | | | | |
| Cr | | | | |
| Cu | | | | |
| Pb | | | | |
| Hg | | | | |
| Ni | | | | |
| Zn | | | | |
| Fe | | | 0.003 | |
| Cl | 36 | 38 | 0.02 | |
| F | 36 | 38 | 1.335 | |
| $NO_3^-$ | | | 1.32 | |
| $S^-$ | | | | |