Life cycle assessment of municipal solid waste management methods: Ankara case study

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Abstract

Different solid waste management system scenarios were developed and compared for the Municipal Solid Waste Management System of Ankara by using the life cycle assessment (LCA) methodology. The solid waste management methods considered in the scenarios were collection and transportation of wastes, source reduction, Material Recovery Facility (MRF)/Transfer Stations (TS), incineration, anaerobic digestion and landfilling. The goal of the study was to determine the most environmentally friendly option of MSWM system for Ankara. The functional unit of the study was the amount of solid waste generated in the system area of concern, which are the districts of Ankara. The life cycle inventory analysis was carried out by IWM Model-1. The inputs and outputs of each management stage were defined and the inventory emissions calculated by the model were classified into impact categories; non-renewable energy sources exhausting potential, final solid waste as hazardous and non-hazardous, global warming, acidification, eutrophication and human toxicity. The impacts were quantified with the weighing factors of each category to develop the environmental profiles of each scenario. In most of the categories, Source Reduction Scenario was found to be the most feasible management method, except the global warming category. The lowest contribution to GWP was calculated for the anaerobic digestion process. In the interpretation and improvement assessment stage, the results were further evaluated and recommendations were made to improve the current solid waste management system of Ankara.

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1. Introduction

Life Cycle Assessment (LCA) has been defined by Society of Environmental Toxicology and Chemistry (SETAC) “as an objective process to evaluate the environmental burdens associated with a product, process or activity, by identifying and quantifying energy and materials used and waste released to the environment, and to evaluate and implement opportunities to effect environmental improvements” (Barton et al., 1996). LCA is a methodology for examining environmental impacts associated with a product, process or service “from cradle to grave” – from production of the raw materials to ultimate disposal of wastes. LCA was developed in order to take into account issues that are not addressed by other environmental management tools such as statutory environmental impact assessment. It has proved itself particularly useful as a technique for comparing two or more alternative options in terms of their combined potential environmental impacts and ecological sustainability.

The methodology of LCA can be described by four interrelated phases, as shown in Fig. 1, namely goal and scope definition, Inventory analysis, impact assessment, and interpretation. The arrows in Fig. 1 imply that the phases are continuously interrelated. If there are some unsatisfactory and missing parts in one phase, which will affect the intended application of the whole study, then the other phases must be revised and improved.

LCA has been used as an effective environmental management tool in many studies. For example, LCA was used to compare the environmental impacts of different automobiles (Graedel et al., 1995), to compare the environmental impacts of the use of key detergent builder systems (Morse et al., 1995), to lower the VOC content of paint in
the paint industry (Dobson, 1996), to reduce the environmental burdens of the used automotive batteries (Robertson et al., 1997), to compare two groundwater treatment schemes for removing hardness and colour (Sombekke et al., 1997), to compare different forestry operations of clear cutting and shelterwood cutting in forest management systems (Berg, 1997), to compare three degreasing processes in the metal-processing industry and to optimise each process, both environmentally and economically (Finkbeiner et al., 1997), to compare three degreasing processes in the metal-processing industry and to optimise each process, both environmentally and economically (Finkbeiner et al., 1997), to assess different scenarios of treatment of municipal wastewater (Roeleveld et al., 1997), to examine the potential environmental and human health implications of different contaminated site remediation options (Page et al., 1996), etc.

Regulation on Control of Solid Wastes, Official Gazette No.20814, was prepared by the Ministry of Environment (MoE) and came into force in 14.03.1991 to improve the solid waste management in Turkey. However, municipal solid waste management is still an unsolved problem in Turkey. The State Institute of Statistics (SIS) has been gathering information on municipal SWM since 1994. The information on the current solid waste management practices of the municipalities, the solid waste composition, generation quantities from household and commercial institutions, etc., are collected. According to the latest study conducted in 2002, the annual solid waste collection is 25.37 million tons/year offering municipalities with solid waste collection service in Turkey. When the disposal method of this waste is considered, it will be seen that only 27.8% of these values was disposed to landfills, while most of the rest was disposed in dump sites of the municipalities (http://www.die.gov.tr/TURKISH/SONIST/CEVRE/28122004.html, 27 June 2005). As it is well known any uncontrolled disposal of SW without any precaution possesses a great potential for water pollution, public health problems, explosion and landslide. An unfortunate example of such explosion event has occurred in Ümraniye, İstanbul in 28th of April 1993 leading to death of more than 30 citizens (EFT, 1999). Similar explosions also happened in Mamak dumping area in Ankara.

The municipalities are authorised and responsible from the solid waste collection, transport and disposal, according to the Public Hygiene Law of Number 1593, the Municipality Law of Number 1580, Greater City Municipality Law of Number 3030 and also Solid Waste Control Regulation published in 1991. The municipalities reserve 40% of their budget for cleaning expenditures and also ‘environmental cleaning tax’ is gathered from the household and commercial institutions. Within the solid waste management system the collection and transportation stages are conducted by the municipalities; however, the solid waste recovery, storage and disposal requirements could not be conducted at the desired level. For example according to the Ministry of Environmental and Forestry, there are only 11 landfiliding sites out of 3215 municipalities in Turkey (http://www.cevreorman.gov.tr/atik_01.htm, 27 June 2005).

LCA has a lot to offer in terms of selection and application of suitable MSW management techniques, technologies, and programs to achieve specific waste management objectives and goals. Thus, several studies in the literature used the LCA as a tool for municipal solid waste management (Barton et al., 1996; Rieradevall et al., 1997; Barlaz et al., 1999; Aprili et al., 1999; Koller et al., 1999; Schwing and Jager, 1999; Valentini et al., 1999; Fuertes and Pedraza, 1999).

The objective of this study was to use the LCA as a tool to compare different solid waste management system options and determine the most feasible system for Ankara, Turkey. To this purpose, five different scenarios of municipal solid waste management systems (MSWMS) that include different municipal solid waste processing and/or disposal methods (MSW-PDMs) were developed and, then, compared with respect to their environmental impacts and costs by using the Integrated Waste Management (IWM) Model developed by White et al. (1995).
2. Methodology

2.1. Integrated waste management (IWM) model

IWM Model which was developed by White et al. (1995) is an Excel TM model with a Visual Basic graphical interface. The goal of the IWM Model is to give municipalities a broad indication of the environmental effects and economic implications of waste management decisions, and to point to strategies that can potentially improve the environmental performance of their waste management system (http://www.iwm-model.uwaterloo.ca/english.html).

The solid waste stream through its life cycle is followed in the model. Each of the stages in the life cycle of solid waste is represented by a box containing input questions, the answers of which define the solid waste management system considered. Even though the waste materials may be physically commingled, the different waste materials were kept separate in the model, which will be needed in characterizing the material composition of the waste, its calorific value and the effectiveness of any treatment process, at any point in the life cycle.

The boxes in the model structure represent pre-sorting and collection, central sorting, materials recycling, biological treatment, thermal treatment and landfilling. Within each stage, as materials are recovered, they are subtracted from the waste stream and entered into a reclaimed materials stream. Other outputs from processes are entered into the relevant columns for emissions and energy, where they accumulate. Total costs for the system accumulate through the life cycle to produce the economic LCI. By the end of the life cycle, all of the materials will have left the waste stream columns and have been entered into either the products or emissions columns. The model then totals the energy consumption, energy production, recovered materials, compost, emissions to air, emissions to water and final solid waste to produce the life cycle inventory for the waste of the chosen region.

2.2. Scope definition

Five different scenarios of MSWMSs that include different municipal solid waste processing and/or disposal methods (MSW-PDMs) were developed and, then, compared with respect to their environmental impacts. Environmental impacts of MSW-PDMs were evaluated by considering their water emissions, air emissions, final solid waste produced, energy consumption and economics. The MSWMS scenarios were developed based on the current MSWMS of Ankara, widely applied MSW-PDMs in Turkey, and the standard MSWMSs applied in the world. The assessment of these scenarios will provide to compare different possibilities for the waste management system of Ankara, so that environmental sustainability could be achieved. The management system components or MSW-PDMs considered in the scenarios were: collection and transportation of MSWs, source reduction, material recovery facility (MRF)/transfer stations (TS), incineration, anaerobic digestion (Biogasification), and landfilling.

2.3. The functional unit and system boundaries

The functional unit used in the scenarios has been defined as the amount of municipal solid waste generated in the districts of Ankara. The system boundaries selected for the life cycle of solid waste was defined as the moment when material ceases to have value, becoming waste and when waste becomes inert landfill material or is converted to air and/or water emissions or regains some value.

2.4. The scenarios

The scenarios that are considered in this study and the system boundaries are given in Fig. 2. The first scenario (Fig. 2a) consists of collection, transport and landfilling of MSW and represents the MSWMS in Bursa, İzmir, Gaziantep, Izmit, Foça and Göcek. The second scenario (Fig. 2b), including the source separation before collection, is applied in Bursa at some pilot regions with 20% efficiency and expected to be spread to the whole city. The MSWMS, including MRF before landfilling (the third scenario, Fig. 2c) is applied in Bakırköy and Kadıköy in Istanbul, Bursa, Eskişehir, İzmir, Mersin and was used to be applied in Çankaya District of Ankara (MoE, 2000). The fourth scenario (Fig. 2d), which is WTE-incineration process, has been the most widely applied technology for handling the municipal solid waste streams in many metropolitan regions since 1970, especially in Japan, Switzerland, Denmark, Netherlands, Germany, France, Austria, USA and promoted for a number of years (Chang and Chen, 2000; Childs, 2000; Penfold, 2000; White et al., 1995). The fifth scenario (Fig. 2e), which employs anaerobic digestion before landfilling, is a commonly used application nowadays for the treatment of municipal solid wastes especially in Europe (Dranco process, Six and De Baere, 1992; Valorga process, Coombs, 1990; Komposgas process, Wellinger et al., 1993; SEBAC process, Chynoweth et al., 1993; Biocell process, BTA process, Biowaste process, Tchobanoglous et al., 1993; Wheeler, 2000; Zoethout, 2000).

2.5. Life cycle inventory

The data collection and preparation for Ankara were mainly based on the projects prepared by Sistem PLANlama Müş. Müh. Prj. Ltd. Şti. for the Solid Waste Management System of Ankara (Sistem PLANlama Müş. Müh. Prj. Ltd. Şti., 1992, 1993). These data include the population projections, the waste characteristics and composition, waste management applications, the comparison of the recommended transfer stations and landfill sites, the cost calculations for all the alternatives and operational recommendations for the landfill site. Because of the space limitation, the data used to run the IWM Model could not be presented here but can be seen in Özeler (2001).

In the Ankara Solid Waste Management (SWM) Application Project, the calculated year 2010 waste generation data were used for the assessment of the waste distribution schemes, as these are the average data. The data for the years 1990 or 1995 were the starting years of the design period and the waste
generation rates of these years were low; at the same time, the estimated data for the years 2015–2020 were very high, therefore, the data for these years were not used. In this study, the population and the waste generation data for the year 2010 were used.

In the SWM Application Project Reports as well as in the current application of waste management services in Ankara, it is stated that the districts of Sincan, Etimesgut, Gölbaşı directly dispose of their waste to Sincan–Çağırtepe landfill site. The wastes are dumped into Mamak Open Dumping Site by the other 5 districts. However, in this LCI study, it is assumed that the waste will also be transported to the Sincan–Çağırtepe Landfill Site by the districts Çankaya, Altındağ, Keçiören, Mamak, and Yenimahalle in Scenarios 1 and 2. In case of the existency of TS/MRF (Scenarios 3, 4 and 5) of this study were found to be fitting to the scenarios given in the application project reports only for these districts.

The applied SWM System of Ankara in Scenario 3 was the most feasible management system, recommended by Sistem Planlama Müş. Müh. Prj. Ltd. Şti. (1993), which was preferred over the other alternatives. According to the report of Sistem Planlama, the centers were determined using the populations and the 2010 year estimated waste generation amounts of the regions. The districts of Ankara were separated into several regions and the estimated amount of wastes for each region was indicated on a map. The regions that have high waste densities and relatively lower densities were determined from this map. Using the distribution on the map, the centers were determined and the calculations were done for collecting the waste from these centers and transporting the waste to Sincan–Çağırtepe Landfill Site via the recommended three transfer stations, in the report. The locations of these centers, the transfer stations and

![Diagram](image-url)
The landfill site were shown in Fig. 3. In Fig. 3, the centers and the transfer stations were shown with the letters B and T, respectively. In Scenarios 3, 4 and 5, these transfer stations were assumed to be integrated with material recovery facilities (TS/MRF System). In case of applying Scenarios 1 and 2, the solid waste was directly transported to the landfill site from these centers without transferring the waste to a TS/MRF System.

The model simulations for Scenarios 1 and 2 were carried out separately for each center (B1, B2, B4, B5, B6), as the amount of waste transported from these centers and the distances between centers–landfill site were different. The model simulations were also carried out separately for each TS/MRF System (T1, T2, T3) in Scenarios 3, 4 and 5, as the amount of waste arriving to these stations and the distances between centers–transfer stations and transfer stations–landfill site were different. In addition, data for more than one TS/MRF system could not be entered to the model.

3. Results and discussion

The IWM Model was run for each scenario based on the data gathered at the inventory analysis stage. The results of the simulations carried out revealed detailed information on the economical and environmental aspects of the scenarios. Due to space constraints, this manuscript will focus on the comparison of the environmental profiles of all the scenarios only.

As it can be observed from Table 1, the lowest energy use was obtained in Scenario 2. In all scenarios, the highest contribution to the net energy use impact category were caused by the collection stage. The net energy use was found to be equal at the collection stage in all scenarios except Scenario 2, because of the lower collection frequency applied in Scenario 2. As excess energy was produced in Scenario 4 from the incineration stage, also less amount of energy was consumed in this scenario. The excess energy production was due to the amount of input to the incineration process in Scenario 4. There

Table 1

<table>
<thead>
<tr>
<th>Scenario</th>
<th>NESEP (GJ Th./tonne waste managed)</th>
<th>SW non-hazardous (t/tonne waste managed)</th>
<th>SW hazardous (t/tonne waste managed)</th>
<th>GWP (kg CO₂–eq/tonne waste managed)</th>
<th>AP (kg SO₂–eq/tonne waste managed)</th>
<th>EP (kg O₂–eq/tonne waste managed)</th>
<th>HTP (kg body weight/tonne waste managed)</th>
</tr>
</thead>
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<tr>
<td>1</td>
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<td>2.7266</td>
<td>0.0041</td>
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<td>0.4585</td>
<td>0.0812</td>
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<tr>
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<td>2.0648</td>
<td>0.0030</td>
<td>3245.0070</td>
<td>33.2759</td>
<td>130.5495</td>
<td>75.1319</td>
</tr>
</tbody>
</table>

NESEP: Non-renewable energy sources exhausting potential; SW non-hazardous: Non-hazardous portion of the solid waste; SW hazardous: Hazardous portion of the solid waste; GWP: Global warming potential; AP: Acidification potential; EP: Eutrophication potential; HTP: Human toxicity potential.

Denotes the minimum contribution.
was also energy production from Scenario 5, but as the total input to this scenario was less than Scenario 4, as seen from Table 1, Scenario 5 contributed more to the net energy use category. In Scenario 5, there was not only the biological process, but also pre-sorting to sort organic wastes that require energy. Therefore, the energy consumption at the biological treatment stage was calculated to be higher than energy production. Here it must be noted that the efficiency of energy (electricity) production from methane was taken as 30%. Scenario 3 used less amount of energy in the overall total than Scenario 1, despite the other contributing stages such as MRF and landfill, due to the savings obtained from the recycling stage of these scenarios.

Within the solid waste category, both the non-hazardous and hazardous solid wastes were compared (Table 1). The lowest contribution arose from Scenario 4 with respect to non-hazardous solid waste amounts, whereas the highest contribution was also obtained from this scenario in case of hazardous waste amounts. The solid waste was arising as waste treatment residues and industrial solid wastes resulting from energy generation, and production of fuel and other raw materials to landfill in Scenario 4. The amount of hazardous waste was arising from the waste treatment residue of thermal treatment as fly ash, as well as from leachate treatment in the landfill stage of Scenario 4. However, in other scenarios hazardous waste was originating only from leachate treatment in the landfill stage. Therefore, the highest value was obtained from Scenario 4 with respect to hazardous waste. As a result of the source reduction in Scenario 2, the secondary materials obtained were higher than the other scenarios leading less solid waste input to landfill.

The contributions of the scenarios to global warming category can also be observed from Table 1. In case of global warming impact category, the least burden was originating from Scenario 5, due to reduction of greenhouse gas emissions by energy generation as a result of the anaerobic digestion. If the only concern was the GW impact category, the best available option would be Scenario 5. Despite the high contributions from collection and landfill stages in Scenario 2, it was observed to be the other less contributing option to GW, which was due to the collection frequency applied in this scenario. The highest effect to GW was originated from Scenario 4, because CO\textsubscript{2} was the only major GHG.

The acidification potential of Scenarios 1, 3, 4 and 5 were found to be very near to each other and as the mostly contributing scenarios (Table 1). In all the scenarios, the highest contribution to acidification was caused by the collection stage. However, the least potential was obtained from Scenario 2. The applied collection frequency reduced the energy consumption and the effects resulting from production and use of fuels. Scenario 2 was the best management application with respect to acidification potentials, whereas Scenario 4 was found to be worst case.

The highest burden with respect to the eutrophication impact category was determined to be originating from Scenario 1. Furthermore, the results were found to be very near in all scenarios, except Scenario 2. It was observed to be the lowest contributing scenario to eutrophication with 80.89 kg O\textsubscript{2}-eq/tonne waste managed EP. The collection frequency of Scenario 2 resulted in the reduction of contribution from collection stage, which was the most contributing management stage. If the valuation of each scenario were investigated, it could be seen that the contribution from collection and savings from recycling were calculated to be equal in Scenarios 1, 3, 4, 5 and Scenarios 3, 4, 5, respectively. However, the difference in other stages caused the overall difference.

The last impact category was human toxicity (Table 1). The highest impact of 853.18 kg body weight/tonne waste managed, was caused by Scenario 4 resulting mostly from the incineration process. The highest contributing stage in other scenarios was the collection stage. In Scenario 2, the least environmental impact was found with respect to human toxicity potential of the waste management system, because of the collection frequency applied. The equal amount of savings from recycling stage was obtained from Scenarios 3, 4 and 5. Between these scenarios, the least potential impact was observed in Scenario 3.

The final step of the Impact Assessment phase is the valuation where relative values or weights are assigned to different impacts so that the evaluator can compare the importance of the various impacts. Valuation step is the least developed step of the impact assessment. The major shortcoming is that assigning weights is highly subjective, depending on the values of the assessor and the relative importance of the particular item. There is no formal scientifically based procedure for doing is at present time (Bishop, 2000).

Therefore, valuation was not carried out in this study. For the interested audience, the details of the available valuation methods (ecological scarcity factors, environmental loading factors, environmental acceptability factors, etc.) are described in Graedel and Allenby (1995).

4. Conclusions

This study was conducted to determine the most feasible solid waste management system in terms of its environmental effects for Ankara, Turkey. This was accomplished by using the LCA as a tool to compare different solid waste management system options. Best of our knowledge, this is the first study in Turkey which used the LCA as waste management tool. The results of the study indicated that:

- Scenario 2 (Source Reduction + Collection + Transportation + Landfilling) was the most feasible management train due to the source reduction process and subsequent recycling of the sorted materials.
- In case of energy use, Scenario 2 revealed the least energy consumption due to the lower collection frequencies applied in the collection stage as the recyclables were sorted at the source. It was followed by Scenario 4 (Collection + Transportation + MRF + Incineration + Landfilling). Energy was produced as a result of the process, which decreased the overall total energy use of the scenario.
- The minimum amount of final non-hazardous solid waste was obtained from Scenario 4; however, the highest amount of hazardous solid waste was also arising from this scenario, which caused higher toxicity impacts.
- In terms of GWP Scenario 5 (Collection + Transportation + MRF + Anaerobic Digestion + Landfilling) was found to be the most feasible system. Scenario 2 followed it as compared with the other scenarios.
- In terms of acidification and eutrophication potentials of the scenarios, Scenario 2 was found to be exerting the least impact due to collection frequency and recycling of dry recyclables.
- The highest human toxicity impacts was caused by the thermal treatment case, Scenario 4, due to high hazardous solid waste production that would lead to high heavy metal emissions. The least contribution in terms of human toxicity impacts was observed to be Scenario 2.

According to Table 1, Scenario 2 was found to be the scenario with minimum contribution in all the impact categories, but GW and FSW were the exceptions to this scenario. However, it was the second minimum case for these exceptions. Therefore, Scenario 2 was determined to be the best option with respect to environmental concerns.

Along with the literature search, the results obtained in this study has led to the conclusion that LCA can be successfully applied to ISWM Systems as a decision support tool. In fact, waste management activities also have environmental burdens. Therefore, LCA tool should be implemented for waste management activities to find the optimal solution in addition
to industrial products and processes to develop and/or improve the best practical environmental option.

LCA has been widely used in the world since 1990s to improve the methodology and the required databases. In Turkey, despite the standards about LCA prepared by ISO (14040–14043), only TS-ISO 14040 was published on the subject and the tool has not started to be applied yet. The more LCA studies are conducted, the more detailed and related databases will be obtained, not only for the products but also for the waste management activities.

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