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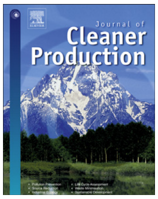

Application of life cycle assessment (LCA) for municipal solid waste management: a case study of Sakarya

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A R T I C L E I N F O

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A B S T R A C T

This paper aims to determine the environmental aspects of a less impactful municipal solid waste management system through life cycle assessment (LCA) methodology. In order to achieve this goal, first, the composition study was conducted in Sakarya, Turkey for one year. The results of first step are to be utilized as a reliable data source in establishing a complete picture of the environmental performances of municipal solid waste management systems with a life cycle perspective. The functional unit of the study was selected as one ton of municipal solid waste generated in Sakarya. System boundaries included collection and transportation of municipal solid waste and its treatment and disposal by MRF, incineration, composting and landfilling methods. Data on the process was gathered from a field study conducted in Sakarya, and from SimaPro 8.0.2 literature and libraries. The data was evaluated with CML-IA methodology by the means of abiotic depletion, abiotic depletion (fossil fuels), acidification, global warming, ozone depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity and photochemical oxidation. According to the results, while landfilling and incineration have been confirmed as the worst waste final disposal alternatives, composting and material recovery showed better performance. An integrated system (MRF, composting, incineration and landfilling) is considered as a solution towards improved sustainability to overcome the existing waste management problem. The paper showed LCA to be a valuable tool which can help governors and managers plan an integrated waste management strategy that provides more preferable environmental outcomes than the strategy suggested.

1. Introduction

Sustainable management of increasing amounts of municipal solid waste has become a major social and environmental concern because improper municipal solid waste management leads to substantial negative environmental impacts (pollution of air, soil and water) and health and safety problems (diseases spread by insects and rodents attracted to garbage heaps and diseases associated with different forms of pollution). Integrated solid waste management (ISWM) that goes beyond the safe disposal of waste is one of the greatest challenges to sustainable management and suggests a solution to the waste problem by emphasizing "from the Cradle to the Grave" responsibility. ISWM combines a wide variety of appropriate and applicable methods, technologies and management approaches in relation to the achievement of specific goals (McDougall et al., 2001). This approach can practically be integrated into the MSW decision-making process through Life Cycle Thinking (LCT) and environmental systems analysis tools such as life cycle assessment (LCA). LCA in many studies has been used as a tool for effective municipal waste management because it helps for the purpose of environmental assessments of alternative waste management systems and/or for the identification of those main areas needing potential improvements (Koci and Trecakova, 2011). For example, LCA was used to compare the environmental impacts of different waste treatment technologies (Kaplan et al., 2009; Finnveden et al., 2005), develop and determine the most environmentally friendly technology (Damgaard et al., 2010), use the modeled output for strategic decisions (Rigamonti et al., 2009) and describe real cases (Chaya and Gheewala, 2007; Blengini, 2008, 2012). Therefore, in this study, LCA was used to compare the environmental impacts of various waste treatment alternatives in order to establish a less impactful waste management system.

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The global practices of MSWM vary from region to region, country to country, and from one municipality to another depending upon the prevailing specific conditions (natural, social, economic, etc.) (Kollikkathara et al., 2009). Table 1 provides an overview of some waste management practices from several countries in the world. As can be seen in Table 1, there are many methods to reduce the volume of the municipal solid waste, such as incineration, waste minimization, waste recovery and recycling; however, landfilling has been the most widely adopted practice for municipal solid waste management worldwide since it is a comparatively simple and economic way for municipal solid waste disposal. Moreover, landfilling is the ultimate disposal method for waste that cannot be recovered. Until recently, Turkey's traditional method of disposing of municipal solid waste was to dump it at open sites—of which there are over 2000—or at sea. In 1993, the accident at the Umraniye-Hekimbasi open dumpsite, which took place in İstanbul as a result of an explosion of the gases compressed within the dumping area, resulting in the death of 39 people (Kocasoy and Curi, 1995), became a starting point in the handling of the municipal solid waste problem. Fig. 1 represents today's disposal methods applied to collected waste in the country. Only 60% of the waste generated by Turkey's population is stored in sanitary landfills and the other 40% of the population receives waste removal services that are not within the regulations (TUIK, 2014). When disposal strategy in Turkey is compared to other countries (Table 1), it is revealed that the application of appropriate methods like landfilling, incineration or composting is crucially insufficient in Turkey. Municipal solid waste management systems are progressing but further development is required in Turkey.

Knowledge on the composition of waste is essential for implementing the most appropriate waste reduction policies and for choosing the adequate waste treatment and disposal processes because MSW composition varies substantially with location, season, socio-economic conditions, waste collection and disposal methods, sampling and sorting procedures and many other factors (Hanc et al., 2011). However, the absence of reliable data on waste composition makes a regional and national evaluation of MSW management difficult. In Turkey, as in many developing countries, there is also a lack of organization and planning in MSW management due to the lack of a reliable database on waste composition even though the majority of the municipal solid waste is organic (Fig. 1).

The study aims to identify a less impactful waste management system for developing countries, e.g. Turkey, by characterizing municipal solid waste composition in the field. The main focus of this study is to investigate the utilization of LCA as a tool in waste management planning by developing different treatment scenarios as an alternative to the current waste management system. At the end of this study, the proper disposal method will be determined according to municipal solid waste content and amount by using life cycle assessment model that is developed by SimaPro 8.0.2 software with the CML-IA method.

2. Materials and methods

2.1. Study area: Sakarya province

Sakarya province of Turkey is also known as Adapazari, located in the northwest of Turkey at an altitude of 31 m above sea level. It has an area of 4817 km^2 and a population of 902,267; 75.4% of whom live in city centers and 24.6% of whom live in villages (SG, 2014). The average MSW generation rate was found to be 1.24 kg/day per capita. In Sakarya, municipal solid waste was disposed by open dumping method until 2008. The metropolitan municipality sanitary landfill site started to be used in 2009. The capacity of sanitary landfill area is 2,895,770 m^3 and total surface area is 17.6 ha. The sanitary landfill site which is 19 km away from city center consists of 3 lots. Landfill gas from this sanitary landfill is collected by 11 vertical gas collection pipes. There are some deficiencies in the new MSW management system such as no leachate treatment and poor source separation collection (Erses Yay et al., 2011).

2.2. Municipal solid waste characterization

According to Organization for Economic Co-operation and Development (OECD), municipal solid waste is waste collected and treated by or for municipalities. It covers waste from households, including bulky waste, similar waste from commerce and trade, office buildings, institutions and small businesses, yard and garden waste, street sweepings, the contents of litter containers, and market cleansing waste. The definition excludes waste from municipal sewage networks and treatment, as well as waste from construction and demolition activities (World Bank, 2012). Because of the heterogeneous nature of municipal solid waste, determination of the composition is not an easy task. Strict statistical procedures are difficult to implement. For this reason, more generalized field procedures, based on common sense and random sampling techniques, have evolved for determining composition (Tchobanoglous et al., 1993). The most prevalent method in determining the content of domestic solid wastes is a material group analysis in solid waste characterization. Municipal solid waste

Table 1
Solid waste management practices in some countries.

Countries	kg generation/person-day	Landfilling %	Incineration %	Composting %	Recycling %	References
Japan[a]	0.96	1	76	0	19	OECD, 2014.
Canada[a]	1.07	72	4	7	18	OECD, 2014.
EU27[b]	1.37	37	23	15	25	Eurostat, 2013.
Greece[b]	1.36	82	0	3	15	Eurostat, 2013.
Germany[b]	1.64	1	37	17	45	Eurostat, 2013.
Italy[b]	1.47	49	17	13	21	Eurostat, 2013.
Bulgaria[b]	1.03	94	0	3	3	Eurostat, 2013.
Spain[b]	1.45	58	9	18	15	Eurostat, 2013.
Switzerland[b]	1.88	0	50	16	35	Eurostat, 2013.
UK[b]	1.42	49	12	14	25	Eurostat, 2013.
USA[b]	2.00	54	12	8	26	USEPA, 2014.
Korea[b]	0.99	17	24	1	58	OECD, 2014.
Mexico[c]	1.04	95	0	0	5	OECD, 2014.

[a] Reported data for 2010.
[b] Reported data for 2011.
[c] Reported data for 2012.

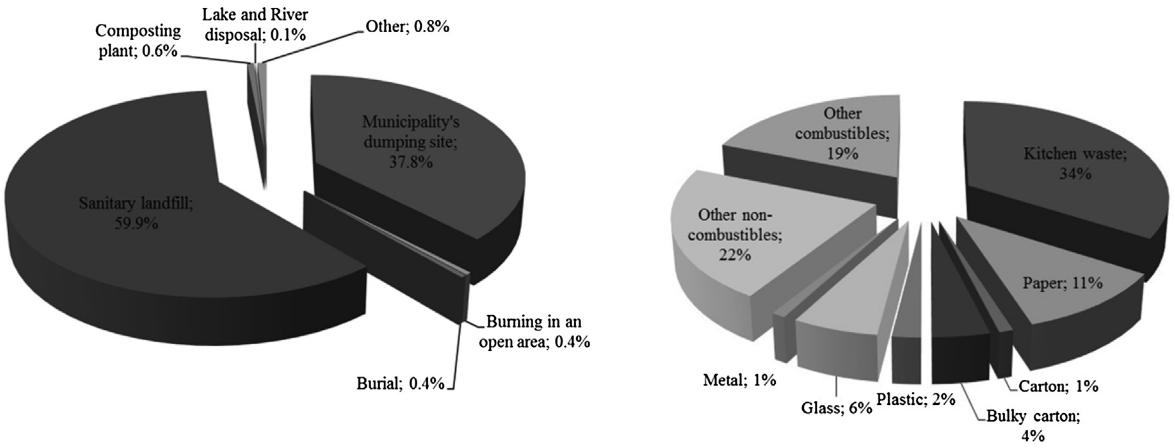

Fig. 1. Municipal solid waste disposal and composition in Turkey.

characterization was carried out according to the standard of ASTM D5231-92 (2003) "Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste". Representative samples for different points of the province (downtown and income levels: low, medium, high) were taken to create a pile of a similar nature like the total municipal solid waste of cities. In order to determine the seasonal change in waste, characterization studies were applied separately in summer and winter. After the representative municipal solid waste collection, hand sorting was applied for the classification of MSW into the seventeen components specified by the Ministry of Environment and Forestry of Turkey (Table 2).

2.3. *Analysis*

After sorting the municipal solid waste, the determination of the moisture content of the waste was made at 75 °C in a drying oven for 24–48 h until a constant weight (TSE, 1992). The calorific value of the dried samples was determined with a bomb calorimeter according to ASTM D 5468-02. 0.9–1 g of each ground waste sample in an LECO AC-500 calorimeter was burned and the temperature change was determined to measure enthalpies of combustion. The heavy metals were also monitored using an ICP-OES (Perkin–Elmer). Prior to analysis, 0.2 g of each sample was digested in a microwave oven with concentrated 6 ml of HCl and 2 ml of HNO_3 and diluted to 50 ml with water (EN 13657, 2002).

Table 2
Solid waste components (material groups).

Solid waste components	
Kitchen waste	Food waste, bread, vegetable, fruit, etc.
Paper	Newspapers, magazines notebooks, etc.
Carton	Milk and fruit juice cartons, Tetra Pak, etc.
Bulky carton	Carton boxes
Plastic	All plastics
Glass	Glass bottles, jars, etc.
Metal	Metal boxes, forks, knives, etc.
Bulky metal	Rack cabinets, desk, etc.
Waste electric and electronic equipment	Phone, radio, etc.
Hazardous waste	Batteries, waste paint, detergent and drug boxes, etc.
Park and yard waste	Brush and tree trimmings, grass, etc.
Other non-combustibles	Stone, sand, dirt, ash, ceramic etc.
Other combustibles	Textile, diapers, shoes, slippers, pillows, carpets, rugs, bags, etc.
Other bulky combustibles	Furniture and furnishings, etc.
Other bulky non-combustibles	
Others	

2.4. *Life cycle assessment (LCA)*

The methodology of LCA can be described by four interrelated phases, namely goal and scope definition, inventory analysis, impact assessment and interpretation.

2.4.1. *Goal and scope definition*

The goal is to compare different MSW management alternatives from the life cycle perspective. The functional unit of the study is 1 ton of generated MSW in Sakarya. Consequential LCA is used for defining system boundary because consequential assessment describes how relevant environmental flows will change in response to possible decisions. As can be seen in Fig. 2, the system boundary of the study that defines what is and is not included in the assessment starts with the collection of MSW and includes waste transport, MSW material recovery facility (MRF), waste treatment alternatives (recycling, incineration and composting) and landfilling of waste. In this study, the following waste treatment alternatives are modeled so that we can compare their environmental impacts:

2.4.1.1. *Alternative 1: baseline scenario-landfilling without any biogas recovery.* Baseline scenario corresponds to the current sanitary landfilling. Municipal solid wastes of Sakarya, since 2009, have been deposited in a certain controlled landfill site (which does not support systems for biogas collection and treatment) almost 19 km northeast of the city center of Sakarya.

2.4.1.2. *Alternative 2: material recovery facility (MRF) and landfilling.* In this alternative, an MRF and a landfill with energy recovery will be added to the system. Metals, paper/cardboard, glass and plastics are separated and recycled at a 40% rate in the MRF to meet the legislative targets for recycling of packaging waste according to the Turkish law responding to the EU Packaging Waste Directive. The rest of the waste will be deposited in Sakarya's landfill which is 19 km northeast of the city.

2.4.1.3. *Alternative 3: material recovery facility (MRF), composting and landfilling.* This alternative explores the potential to reduce the environmental impacts of MSW disposal by recycling and composting. Metals, glass, paper/cardboard and plastics are assumed to be recycled at a 40% rate in the MRF. All the kitchen and yard waste

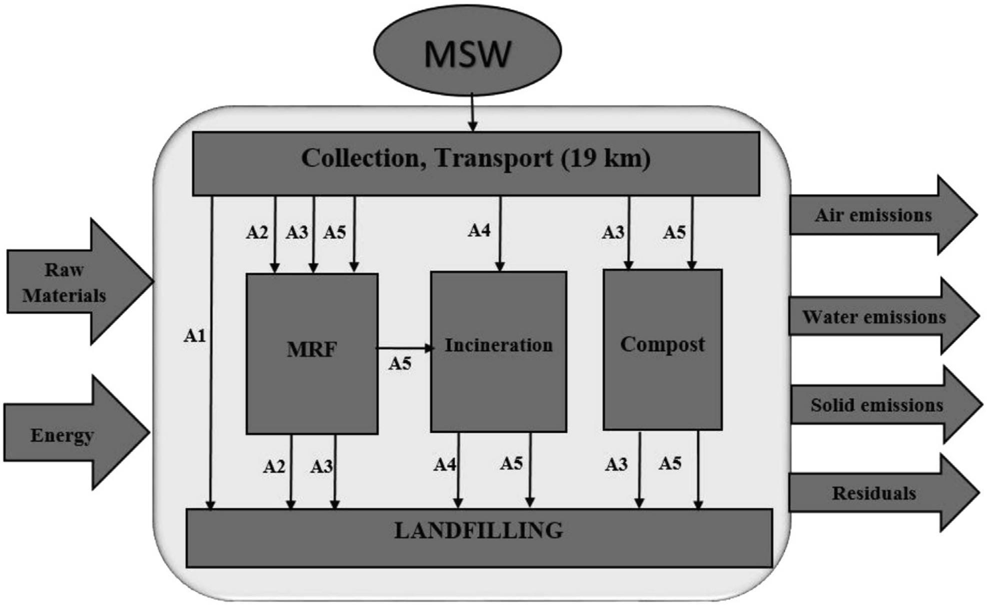

Fig. 2. System boundaries.

will be treated by composting and the rest will be disposed at the landfill.

2.4.1.4. Alternative 4: incineration and landfilling. In this alternative all the waste is transported to the incinerator facility, which represents future aims of Turkey, especially in the metropolitan cities. The residue from the incineration plant is sent to the inert landfill.

2.4.1.5. Alternative 5: material recovery facility (MRF), composting, incineration and landfilling. This alternative investigates the potential to minimize environmental impacts through an integrated MSW management system. Metals, paper/cardboard and plastics are recycled at a 40% rate and kitchen and yard waste is treated by composting; the combustible MSW and the rest of plastic and paper/cardboard is transported to the incineration plant. Finally, the waste generated in the composting, incineration and MRF processes will end up in the landfill as inert waste.

2.4.2. Life cycle inventory

Data for life cycle inventory was gathered from the waste characterization study of Sakarya, reports, literature and SimaPro 8.0.2 database.

2.4.2.1. Transportation and electricity. Road transportation constitutes a part of the environmental impact due to the use of transport means during the collection and transport of waste to the treatment plants (e.g. MRF, recycling, composting and incineration plants) and the landfill. The transportation distance between the waste collection point to Sakarya's landfill is almost 19 km. Therefore, the distance for transporting the waste is assumed to be 19 km in every alternative despite the fact that some waste treatment facilities can be farther away. In this study, it is assumed that the sorting and recycling plant, the compost facility, the incinerator and the landfill are at the same site since the transport emissions for each alternative will not result in any considerable differences in the LCA results. The unit process for the transport is selected from the Ecoinvent Unit Processes in SimaPro 8.0.2 'Transport, municipal waste collection, lorry 21t/CH U'.

All electricity requirements are derived from Turkey's national electricity records and have been created by using medium voltage under the electricity country mix in SimaPro 8.0.2. Based on the data, the electricity mix in Turkey is as follows: coal/lignite 28.3%; liquid fuels 3.7%; natural gas 49.0%; hydro 17.6% and renewable energy and wastes 1.4%. Renewable energy and waste includes geothermal, wind, solid biomass, biogas and waste.

2.4.2.2. Material recovery facility (MRF). The collected municipal solid waste will be separated in a sorting plant and recyclable materials such as metal, glass, paper and plastics will be recycled at a 40% rate based on the relevant regulations. According to Banar (2009), electricity consumption for waste separation and bale compression is 0.059 kWh/ton. Material recovery of the waste is assumed in the recycling alternative but it is also valid for incineration in alternative 5. After losses, one ton of waste material will not replace exactly one ton of virgin material. Paper, plastic and metal is recycled with a rate of 17%, 28% and 5% loss, respectively. Glass will be recovered without loss of material.

2.4.2.3. Composting. The high moisture content of bio-waste results in a lower heat value in MSW, which reduces its combustion efficiency. Therefore, aerobic static pile composting of biowaste, thought as a mix of kitchen and yard waste, will be considered in alternatives 3 and 5. The composting process is based on the inventory data in the literature and the waste composition in this study. Process time for aerated static pile is almost 58 days and the production of compost is 0.38 kg compost/kg bio-waste (Öztürk, 2010). The N, P and K contents of the compost product are calculated by using mass percentages of N, P and K nutrients at 0.83%, 0.2% and 0.99%, respectively (Song et al., 2013). Air emission from the composting is estimated by looking at the chemical composition of the bio-waste which is calculated by using the fractional mass composition of Sakarya's waste and the elemental analysis of kitchen and yard wastes in the literature (Tchobanoglous et al., 1993): $C_{325}H_{519}O_{191}N_{15}S$. The chemical formula helps to calculate CO_2 and NH_3 products at 1.82 and 0.033 ton/ton bio-waste, respectively. However, while 20%–40% of organic carbon is converted to biomass, only 60% of it is CO_2. The nitrogen leakage to air is an estimated 7.5% of nitrogen content in the compost. Of this leakage, 89% is NH_3, 9% N_2O and 2% N_2. 60% of emissions is assumed to be removed in the biological air filter (Finnveden et al., 2000). Among them, there is 437 kg of biogenic carbon dioxide and 0.88 kg of NH_3 and 0.089 kg N_2O per ton bio-waste. Emissions to water are taken from Song et al. (2013). Electricity consumed in the composting process is (61 kWh) 219 MJ/ton bio-waste. The consumption of water and diesel are 89 l and 2.06 l/ton bio-waste, respectively (Blengini, 2008).

2.4.2.4. Incineration. Incineration process will be used for alternatives 4 and 5. In alternative 4, incineration will be considered as the use of a mass burning facility with energy recovery for mixed waste composition. In alternative 5, combustible waste fraction is incinerated in the mass burning facility with energy recovery. The LCI of incineration involves energy recovery, incineration and air pollution control (APC) equipment. The efficiency of energy recovery in alternative 4 is calculated with the heat value of the mixed MSW in Sakarya. In alternative 5, combustible waste fraction has an LHV of 8.52 MJ/wet kg (Harrison et al., 2000) and can generate 1.39E+9 MJ of energy. This energy is converted to 6.59E+7 kWh of electricity at 17% efficiency (Thanh and Matsui, 2013). According to Khoo (2010), a typical incinerator requires the energy input of 70 kWh/ton waste and generates around 20% ash. Fly ash typically amounts to 10–20% by weight of the total ash. The rest of the MSW combustion ash is called bottom ash (80–90% by weight). After combustion, the off-gases pass through a boiler to generate electricity and then are cleaned in the air pollution control (APC) treatment technology. The LCI of stack emissions can depend on either field data or mass emission limits based on regulatory requirements as upper bound constraints (Kaplan et al., 2009). In this study, air emission for the municipal waste incineration is estimated with APC 7. Technical configuration of APC 7 includes particle removal, semi-dry scrubbing, dioxin filter, flue gas condensation and deNOx-technology (SCR) (Damgaard, 2010). Finally, solid residues that come from filter dust, sludge residues (gas-scrubbing system) and burning residues (ash) are delivered to the inert landfill without any energy recovery selected from SimaPro 8.0.2.

2.4.2.5. Landfilling. Unlike the recycling, composting and incineration alternatives, the landfilling process will be used in all scenarios for it is the ultimate disposal method. Alternative 1 is based on data from Sakarya's landfill site. Biogas generated by the landfill is emitted directly into the atmosphere without an emission control system. The highest methane content is measured at 53% in one of the 11 vertical gas collection wells. Landfill gas composition of the well is 53% CH_4, 38% CO_2, 1.4% O_2, 7.3% N_2, 2 ppm CO, and 425 ppm H_2S. Emissions into the air from the decomposing landfilled waste are calculated using LandGEM with a first-order decomposition rate for a given time horizon (Table 3). In theory, the biological decomposition of one ton of MSW produces 442 m^3 of landfill gas containing 55% methane (CH_4) and a heat value of 19,730 kJ/m^3. Since only a part of the waste converts to CH_4 due to moisture limitation, inaccessible waste and non-biodegradable fractions, the actual average methane yield is closer to 100 m^3/tonne of MSW (Vesilind, 2002). In this study, the methane generation was set at 100 m^3 CH_4 per tonne of wet waste, corresponding approximately to 190 m^3 landfill gas (LFG) per tonne of wet waste. Default concentration for the Non-Methane Organic Compounds inventory is 600 ppmv [USEPA, AP 42] where co-disposal of hazardous waste has either not occurred or is unknown. Emissions to soil are considered from the measurement of heavy metal concentrations in this study. Emission to water from the landfill (Table 3) is taken into account with leachate characteristic of Sakarya landfill in mind. Leachate production is estimated to account for around 10% of precipitation at the landfill site (Cabaraban et al., 2008). It was assumed that 80% of leachate from the landfill is collected and transported for off-site treatment and the remaining 20% leaks to aquatic recipients (Finnveden et al., 2000).

Table 3
Main input flows to landfilling; amounts normalized per ton of waste.

Category		Landfilling
Emissions to air (kg)	CH_4	66.60
	CO_2	143
	N_2	0.01735
	CO	0.000437
	H_2S	0.11
	NMVOC	0.405
Emissions to water (g)	COD	1.71
	BOD	0.974
	TKN	0.001299
	AKM	1.031
	Top P	0.00169
	Top Cr	0.000514
	Cr^{+6}	0.000228
	Pb	0.000209
	Fe^{+2}	0.00202
	Fe^{+3}	0.00000121
	Cu	0.000826
	Zn	0.000624

In the second alternative, the biogas naturally released from the landfill is captured with 70% efficiency, and treated and combusted in order to produce energy without emissions. The estimated energy content of the collected biogas is 2624 MJ with a lower heating value of 19.73 MJ/m^3 (Vesilind, 2002). The biogas is burnt in turbines at 30% efficiency to produce 218 kWh of electricity for one ton waste. In alternatives 4 and 5, the rest of the waste and discards derived from all the treatment processes are collected and transported to an inert landfill. The waste material placed in inert landfills generally has low pollutant content and is chemically inert to a large extent. No gas collection occurs and no electricity is needed for gas pumps.

2.4.3. *Life cycle assessment*

In this study, eleven impact categories included in the CML-IA method (It is an update from the CML 2 baseline 2000 method) were investigated: abiotic depletion, abiotic depletion (fossil fuels), acidification, eutrophication, global warming, ozone depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity and photochemical oxidation.

2.4.4. *Interpretation*

The interpretation includes the presentation and evaluation of results and a sensitivity analysis to check the reliability and robustness of the results by making variations in assumptions, methods and data. In this section, two sensitivity analyses are made to check the reliability and sensitivity of results. These analyses are as follows: Sensitivity analysis 1 was performed by changing the impact assessment method to see its effect on results. In the current study, CML-IA is used, but for sensitivity analysis, another method called ReCiPe Midpoint (H) V1. 04 version for European countries (Europe ReCiPe H) is used. Sensitivity analysis 2 was done by changing the assumption regarding recycling rates in the MRF processes, ranging from 40% to 100%, in Alternative 5.

3. Results and discussion

The results of the waste composition analysis are shown in Fig. 3 as an average of one year. As seen in Fig. 3, kitchen waste (food waste, bread, vegetables, fruit, etc.) occupies a large proportion of

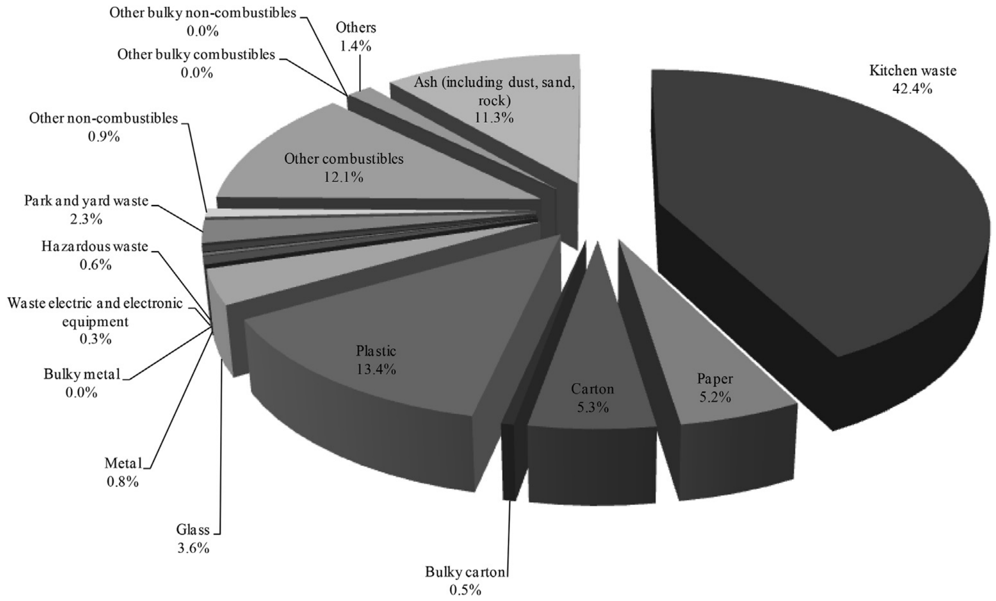

Fig. 3. Waste characterization for Sakarya.

the MSW (42.4%). The other components dominating in the waste composition are plastic (13.4%), other combustibles (12.1%) and the ash (11.3%). All of them cover about 80% of Sakarya's municipal solid waste composition. Paper (5.2%), carton (5.3%) and glass (3.6%) are also significant material types. The remaining 6.7% of municipal solid waste is bulky carton, metals, waste electric and electronic equipment, hazardous waste, park and yard waste, other non-combustibles, other bulky combustibles and non-combustibles and others. Hazardous waste constitutes 0.6% of the municipal solid waste and was mostly composed of the packaging waste of detergents. Despite the fact that there are battery and electronic waste collection systems in Sakarya, a small amount battery and electronic waste was found among the waste. Another important point is other bulky combustible waste (furniture like waste). This kind of waste was not found in any of the districts where characterization studies were performed. This means these kinds of waste are reused by scrap dealers. We can say that a kind of recycling has been developed in Turkey for these kinds of waste. Similarly, the percentage of bulky metal is also 0 in districts where characterization was made. A non-systematical recycling has been developed in these kinds of waste just like combustible bulky waste.

In addition to knowledge of waste composition, the average annual moisture content of municipal solid waste is 59.7% of the wet waste as sampled. In Fig. 4, when we look at the moisture content according to seasons and income level, moisture content was found to be higher than the amount of organic substances found in waste. Considering income level, there is not much difference between organic waste increasing the moisture content but the organic waste amount obtained from downtown was observed to be lower on an annual basis. Considering the seasons, (Fig. 4) moisture content is higher in winter (64% in winter, 56% in summer). Comparison of moisture content with other countries indicates that for developing countries having high organic content such as food waste, the moisture content is significantly higher China: 61% (Zhen-shan et al., 2009), India: 60% (Hazra and Goel, 2009), than the values found for developed countries: USA: 15–40% (Pichtel, 2005).

The energy value of the waste components depends on its calorific value, which is influenced by the moisture content and hydrogen content of the waste. The World Bank's (1999) guide on 'Incineration of Municipal Waste' recommends that a min. heat value (LCV) of 6000 kJ/kg (1435 kcal/kg) during all the seasons for sustained combustion for adopting the thermal treatment process. Looking at the calorific values, no significant difference could be found according to the seasons. The average higher heat value (HHV) of Sakarya municipal solid waste is determined as 3768 kcal/

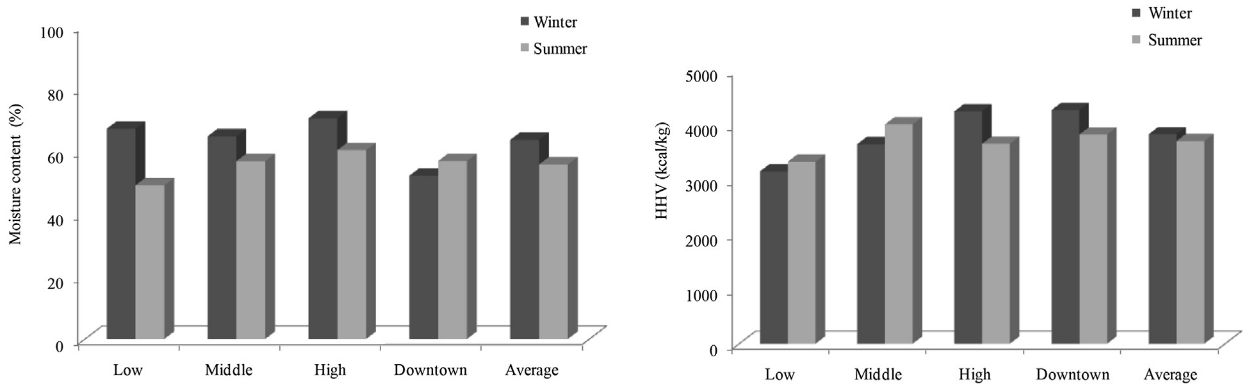

Fig. 4. Moisture content and the higher heating values of the solid waste according to income levels and seasons.

Table 4
The higher heating values of the mixed MSW in Sakarya and some other materials.

Raw materials as a fuel	HHV (kcal/kg)	HHV (MJ/kg)	References
Mixed municipal solid waste of Sakarya (dry basis)	3768	15.776	Present Study
Mixed municipal solid waste of İzmir, Turkey (dry basis)	3182	13.322	Akinci et al., 2012.
Mixed municipal solid waste of Eskisehir, Turkey (wet basis)	3041	12.732	Banar et al., 2008.
Forest residue (dry basis)	3935	16.473	Boundy et al., 2011.
Wheat straw (dry basis)	4060	17.000	Parikh et al., 2005.
Sugar cane leaves (dry basis)	4158	17.410	Parikh et al., 2005.
Herbaceous biomass (dry basis)	4329	18.123	Boundy et al., 2011.
Coal (wet basis)	5725	23.968	Boundy et al., 2011.
Coke (dry basis)	7434	31.124	Parikh et al., 2005.

kg Table 4 indicates the comparison of the higher heating values of the mixed MSW in Sakarya to HHVs of other materials and waste.

Heavy metal analyses of the mixed waste are provided in Table 5. Heavy metal concentrations in Sakarya municipal waste are found in the following order: Al > Fe > Ba > Mn > Cu > Cr > Pb > Ni > Cd. This trend is also confirmed by Nas et al. (2008) who conducted a municipal solid waste characterization study in Gümüşhane, Turkey. Despite Al and Fe concentrations in Sakarya, municipal solid waste was found to have the highest values, while heavy metals such as Cd, Ni generally coming from industrial or household hazardous solid waste were found in negligible amounts. When Cd, Cr, Cu, Ni, and Pb contents in the waste samples are compared to the respective limit values in the Soil Pollution Control Regulation (SPCR), it is seen that the concentrations do not exceed the limits.

The results of the LCA characterization analysis for each impact category of all waste treatment alternatives are reported in Table 6. As shown in the table, the results investigated for each impact category are as follows:

Table 5
Heavy metal concentrations in the mixed solid waste of Sakarya and legal limits in the soils established by the Turkish Soil Pollution Control Regulation (SPRC, 2005).

Parameter	Value (mg/kg oven dry waste)	Turkish legal limits (mg/kg oven dry soil)	
		pH 5-6	pH > 6
Cd	0.5≤	1	3
Cr	32	100	100
Cu	36	50	140
Ni	21	30	75
Pb	25	50	300
Al	5310	–	–
Fe	2850	–	–
Mn	122	–	–
Ba	127	–	–

Table 6
Life cycle characterization results.

Impact	Indicator	A1	A2	A3	A4	A5
Abiotic depletion	kg Sb eq	1.99E-6	1.76E-6	4.74E-6	9.93E-6	6.54E-6
Abiotic depletion (fossil fuels)	MJ	136	121	325	681	448
Global warming (GWP 100a)	kg CO_2 eq	1.84E3	512	−874	346	−1.03E3
Ozone layer depletion (ODP)	kg CFC-11 eq	3.83E-6	3.82E-6	3.71E-6	5.4E-7	2.54E-6
Human toxicity	kg 1,4-DB eq	47.9	42.8	25	20.6	9.79
Freshwater aquatic ecotoxicity	kg 1,4-DB eq	20.8	18.4	20.7	29.8	19.6
Marine aquatic ecotoxicity	kg 1,4-DB eq	7.16E4	6.35E4	6.37E4	8.33E4	5.49E4
Terrestrial ecotoxicity	kg 1,4-DB eq	1.28	1.13	0.568	0.0658	0.0265
Photochemical oxidation	kg C_2H_4 eq	0.405	0.112	−0.0237	0.0143	−0.0748
Acidification	kg SO_2 eq	0.169	0.162	−3.31	0.414	−3.27
Eutrophication	kg PO_4– eq	0.0662	0.057	−1.21	0.181	−1.18

The abiotic depletion factor (ADF) and abiotic depletion (fossil fuels) are determined for each extraction of minerals and fossil fuels (kg antimony equivalents/kg extraction) based on concentration of reserves and rate of deaccumulation (Goedkoop et al., 2004). Incineration in alternative 4 has the highest impact of abiotic depletion due to the consumption of fossil fuels such as hard coal, natural gas and lignite for electricity. Landfilling is safer than incineration for mixed waste. Global warming potential for a time horizon of 100 years (GWP100) is expressed in kg carbon dioxide/kg emission (Goedkoop et al., 2004). In landfilling alternatives (A1 and A2), methane is the main contributor to global warming. While the lack of an emission control system in alternative 1 causes the methane to be emitted directly into the atmosphere, in alternative 2, the CH_4 is partially destructed but a 30% is still released directly into the atmosphere as a result of fugitive emissions from the landfill. Global warming effect in incineration is a result of the combustion of fossil carbon in MSW, eg. rubber and plastic. In alternatives 3 and 5, the prevention of carbon dioxide dinitrogen monoxide releases due to production of compost and fertilizer creates a positive impact for the global warming potential. Ozone layer depletion is caused by methane bromotrifluoro-Halon 1301, a consequence of crude oil production, petroleum and natural gas. The best alternative against ozone depletion is alternative 4 which includes incineration. Human Toxicity Potentials (HTP) describe fate, exposure and effects of toxic substances for an infinite time horizon and are expressed as 1,4-dichlorobenzene equivalents/kg emission (Goedkoop et al., 2004). Transport and heavy metals are the main concerns for HTP. Alternatives 1 and 2 have the highest human toxicity effect due to barium, chromium, lead and nickel produced during landfilling and transportation. Alternative 2 is better than alternative 1 as it entails the recycling of metals. In alternative 4, arsenic, PAH (polycyclic aromatic hydrocarbons), cadmium, barium and chromium have an important impact on HTP resulting from the use of incineration and electricity. A5 is the best alternative in this impact category. Nickel, copper and barium are primary pollutants emitted during landfilling processes and cause freshwater, marine and terrestrial ecotoxicity in alternatives 1, 2 and 3. On the other hand, barium, vanadium, aldicarb, hydrogen fluoride, mercury and arsenic are the leading pollutants emitted from natural gas, electricity and incineration in alternatives 4 and 5. Photochemical oxidation impact indicator defines substances with the potential to contribute to photochemical ozone formation as volatile organic compounds (VOCs), which contain hydrogen (not fully substituted) and/or double bond (s) (unsaturated) (Hauschild and Wenzel, 1998). Landfilling causes the most adverse impact on photochemical oxidation due to methane emissions. The best results are achieved in A3 and A5 thanks to the application of composting. Sulfurdioxide emissions caused by the transportation and incineration processes and the using of electricity also create the effect of photochemical oxidation. The acidification potential is defined as the number of H^+ ions produced per kg substance relative to SO_2 (Bauman and Tillman, 2004). The major acidifying pollutants are SO_2, NO_x, HCl and NH_3. A1, A2 and A4 have a bigger impact than in other scenarios; A3 and A5 are lower due to their higher percentage of compost utilization as fertilizer. In alternatives 1 and 2, the impacts stem from the transportation of the compounds with sulfur and nitrogen. In alternative 4, NO_x and SO_2 emissions released during the incineration of waste cause

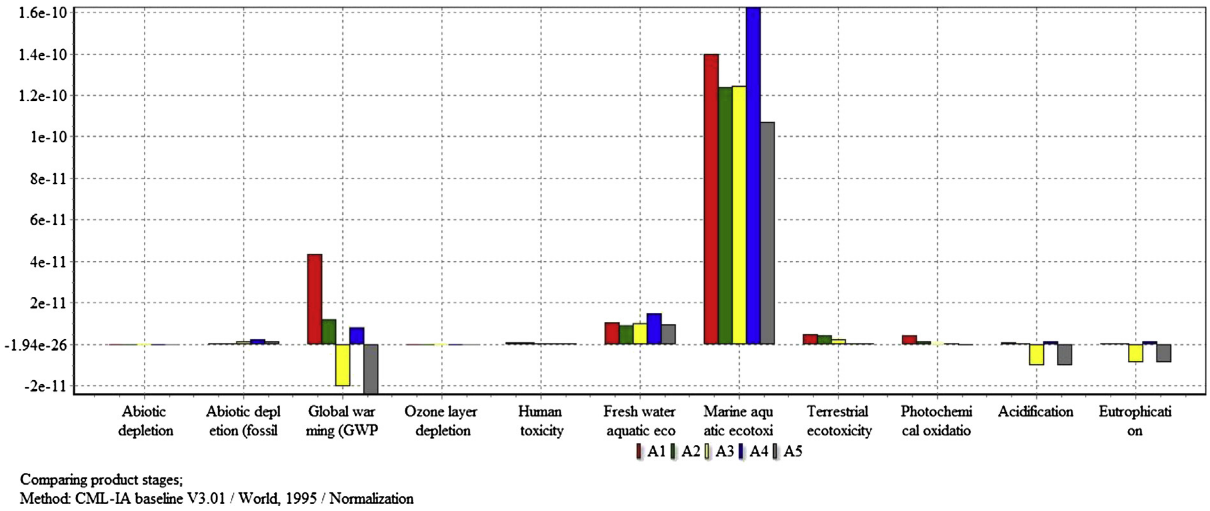

Fig. 5. The results of the LCA normalization analysis.

acidification. Eutrophication is a phenomenon that can affect terrestrial as well as aquatic ecosystems. Nitrogen (N) and phosphorus (P) are the two nutrients most implicated in eutrophication (Bauman and Tillman, 2004). While nitrogen oxides released during the transportation process in alternatives 1 and 2 are dominating contributors, nitrogen oxides and phosphate arising from the transport, incineration and composting procedures in alternatives 3, 4 and 5 are the main causes of eutrophication. On the other hand, alternatives 3 and 5 are the best options for they help to cut out ammonia and nitrogen oxides by producing compost and fertilizer. Generally, it can be said that in the transportation process, the consumption of resources (oil) followed by NOx production gave birth to the largest environmental impact whereas in the landfilling process, the emissions to air and water were of higher environmental importance, especially methane in air emissions and heavy metals such as barium in water emissions. The environmental benefits would be generated by the MRF process for it helps recover resources and the composting process for it produces compost and fertilizer. On the other hand, while incineration has a bigger impact on the environment due to air emissions such as carbon dioxide, sulfurdioxide and nitrogen dioxides, the impact of electricity consumption results from the consumption of resources e.g. oil, coal and natural gas.

When we compare all alternatives for the CML-IA method, it can be seen that alternative 1 and 4 have negative environmental impacts while alternatives 3 and 5 create environmental benefits. The MRF process's main benefit is that it helps avoid resource consumption. In the composting process, the main benefit is the production of fertilizer. As expected, alternative 5 (MRF, composting, incineration and landfilling) is the best municipal solid waste management option, but alternative 3 (MRF, composting and landfilling) also performs well. Normalization values (Fig. 5) indicated that marine aquatic, freshwater aquatic, terrestrial ecotoxicity and global warming are the most significant impact categories for MSW alternatives. Landfilling in alternatives 1 and 2 has larger environmental impact on global warming, photochemical oxidation and terrestrial ecotoxicity. Incineration has a significant impact on freshwater aquatic and marine aquatic. Composting and MRF in alternatives 3 and 5 have a positive environmental impact on abiotic depletion, abiotic depletion (fossil fuels), acidification, eutrophication and global warming due to fertilizer and compost production and the recovery of resources. In the end, landfilling which has also been confirmed by other researches (Abeliotis et al., 2012; Koci and Trecakova, 2011; Banar, 2009; Zaman, 2009; Song et al., 2013) is the worst waste final disposal alternative despite energy recovery.

Fig. 6 indicates the sensitivity of the environmental impacts by using different impact assessment methods and by using different recycling rates in the MRF process. At the end of first sensitivity analysis, it can be concluded that no significant changes were seen in results after the sensitivity analysis, which supports the reliability of our results. The second sensitivity analysis indicated that as the recycling rates of paper/cardboard, plastic, glass and metals range from 40% to 100%, environmental benefits from Alternative 5 will increase with an increasing recycling rate.

4. Conclusions

The study is conducted to determine the less impactful municipal solid waste management system by using life cycle assessment (LCA). The municipal solid waste characterization study, which was conducted to highlight the waste management system plans, will be an important basis for regulation, melioration on recycling, biomethanization, composting, incineration, landfilling and other waste management activities and the establishment of new decision mechanisms by LCA.

As seen in the characterization study, majority of the domestic waste of Sakarya consists of kitchen waste (42%). With a detailed investigation on organic waste, it is possible to benefit from the composting process as an ideal disposal method. Within waste composition, kitchen waste is followed by recyclable waste such as paper/cardboard 11%, plastic 13%, glass 4% and metal 1%. Waste recycling activities should be improved by separation at source and also the public should be made conscious of recycling through education. Combustible waste with a 12.1% ratio could be incinerated as it is not suitable for recycling. Hazardous metals (for human health) such as chromium, copper and lead are observed in very small quantities. The most prevalent metal observed in Sakarya's domestic waste is aluminum.

According to the LCA results of this study, the highest environmental impacts arises from landfilling without energy recovery in alternative 1 and mixed waste incineration with energy recovery in alternative 4, and the most environmentally friendly waste management option is alternative 5, which includes MRF, composting and incineration. Alternative 5 is the best option with higher environmental benefits but may not be economically sustainable

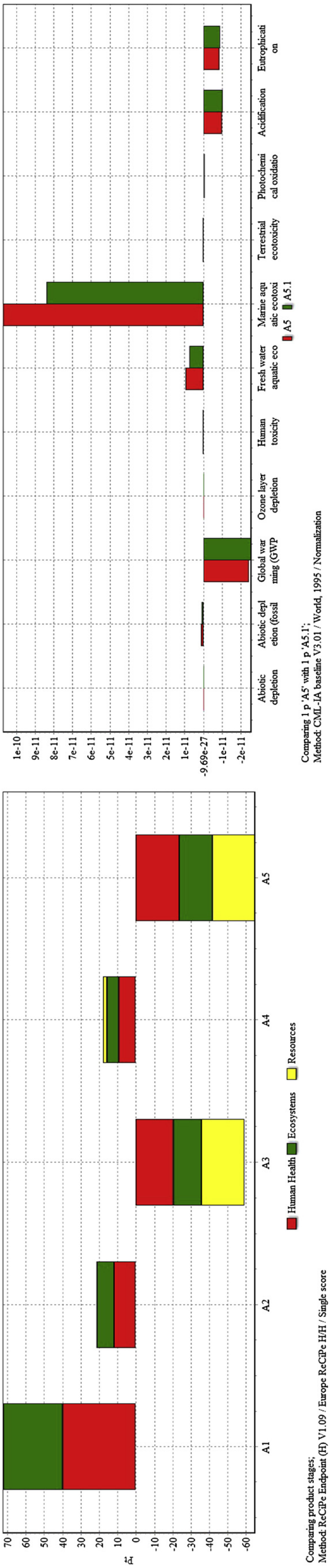

Fig. 6. Sensitivity analysis with different impact assessment methods and recycling rates.

owing to its high investment and operation costs in the short term. Therefore, Alternative 3 can also be a favorable option. The results indicate that LCA can be a useful tool for the planning of municipal waste management as it allows municipalities to directly compare the actual environmental impacts of different technologies and planning options. As a conclusion, the current management system of MSW in Sakarya is not suitable for future use because of its substantial environmental impacts.

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