Life cycle assessment of municipal solid waste management in Samsun, Turkey: different scenarios with emphasis on energy and material recovery

Sevde Üstün Odabaşı[1] · Bertrand Laratte[2]

Abstract

This study presents the first life cycle assessment for the municipal solid waste management system of Samsun, the largest city in the Black Sea region in Turkey (about 1 million people). Its importance is that it proposes to identify the environmental impacts and improvements for the waste management system planned to be implemented by 2023 and the separate collection at source system to be adopted in the future, within the scope of the zero waste policy. Six scenarios were compared using LCA to highlight the potential impacts from transportation. Data were collected from Samsun landfill, Ecoinvent 3 database, regional data collected with the industrial partner and literatures from scientific articles. Life cycle impact analysis was evaluated with the environmental footprint (EF) 3.0 method. In this study, it is reported that environmental impacts are sensitive to transport emissions and the recycling rate of virgin materials. According to the results, the Scenario S3 without the material recovery facility system was approved as the worst final disposal alternative. In contrast, the Scenario S5, which supports the separation of recyclable and organic wastes at the source, showed the most environmentally friendly performance. This research contributes to improving Samsun's current municipal solid waste management (MSWM) system and policies for sustainable development.

Keywords Municipal solid waste · Life cycle assessment · Gas production · Landfilling scenario · Logistic impact · Material recovery

Introduction

Municipal solid waste management (MSWM) has become an increasing problem in developing countries due to rapid urbanization, population, and economic growth [1, 2]. One of the biggest challenges for municipalities in the twenty-first century is collecting, recycling, treating, and disposing of increasing municipal solid waste (MSW) [3–5]. The disposal of MSW, which is 32.3 million tons according to the Turkish Statistical Institute (TUIK) data, is shown in Fig. 1 [6]. Disposal of the remaining solid wastes includes disposal methods such as burning in the open, burying, and dumping into streams and land.

In the European Union policy and Turkish regulations, landfill is at the bottom of the waste disposal hierarchy and it is considered as the least convenient method in terms of treatment [7, 8]. Landfills, especially if not properly designed and managed, can have significant environmental impacts in the different compartments (soil, water, and air), resulting in groundwater and surface water contamination, the occupation of large land areas, and significant greenhouse gas (GHG) emissions may cause its formation [9–11]. The most important of these effects are GHGs [12, 13]. Studies have shown that methane gases formed in landfills constitute the third largest anthropogenic source [14]. Currently, there are 174 landfills in Turkey, and electricity can be generated by collecting landfill gas from only 35 of these facilities [6].

Despite the widespread availability of landfills, a "Zero Waste" policy is currently being adopted in Turkey, and it is aimed to separate the wastes at the source and to recycle

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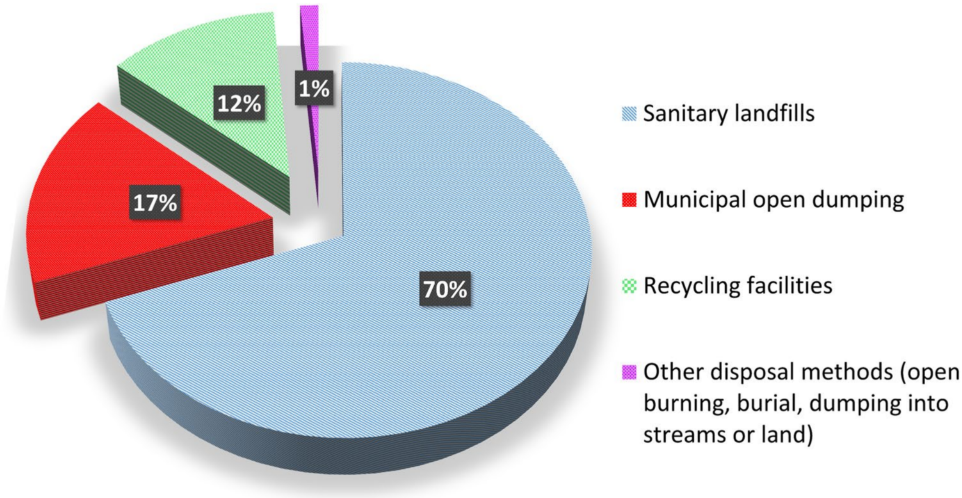
Fig. 1 Distribution of municipal waste collected according to disposal and recovery method [6]



and recover them. According to the EU waste management hierarchy, Turkey aims to develop a sustainable system for its wastes within the "Zero Waste Project" scope until 2023 [15]. Developing a sustainable MSWM system is a complex issue and requires the use of scientific methods to examine the environmental feasibility of such regulations. With the life cycle assessment (LCA) approach, it is possible to measure the potential environmental impacts of the solid waste management system, taking into account both local and site-specific characteristics [16, 17]. It is important to conduct a case-specific LCA study rather than generalized results in this context. In here, LCA can be used to model local conditions and measure the environmental potential impacts of solid waste management systems [18, 19].

A limited number of studies have focused on the LCA of waste management systems in Turkey. Most of the MSWM studies, MSWM was evaluated with life cycle scenarios and environmental impact assessment. Özerler et al. [20] conducted a pioneering LCA study for Ankara, the capital of Turkey. In this study, it is aimed to determine the most environmental friendly option for the MSW system. At the end of the study, it was determined that the most appropriate option was the "reduction at the source". Banar et al. [21], on the other hand, aimed to determine the optimum MSWM strategy for Eskişehir province. In the study, five different scenarios were developed as an alternative to the existing waste management. As a result of the study, they determined the composting scenario as the best scenario (with the lowest environmental impacts). In the study conducted by Erses Yay [22], it was aimed to create a reliable database for the environmental performance of MSWM for Sakarya province. In addition to other studies, a composition study was conducted for 1 year in this study. As a result of the study, it has determined the integrated system (material recovery facility, composting, incineration and storage) as the most suitable solution as an alternative to the existing system. Unlike other studies, Çetinkaya et al. [23], in their study, made the GHG emission calculation to determine the contribution of Aksaray province to global warming, apart from the evaluation of solid waste management strategy. At the end of the study, they determined that 75% landfill and 25% composting scenario as the environmental option for Aksaray province. Methane and carbon dioxide emissions were calculated as 30 and 50 μg/m^3 at ground level and the total radiative stress as 0.021 W/m^2.

This study aims to create local scientific data for MSWM of Samsun within the framework of the ongoing "Zero Waste" study in Turkey and to meet the need for the LCA study, which has not been done before. Unlike previous studies that relied on hypothetical scenarios, this study is based on real and potentially actionable data. Based on Samsun's existing MSWM data, data on the distance traveled by compactor trucks, and waste characterization, different scenarios of waste disposal (incineration, storage, recovery, composting) based on gas production were modeled to identify gaps between different environmental impact indicators. At the end of this study, the best scenario to be followed in decision-making regarding the possible development of MSWM for the city of Samsun was determined.

Materials and methods

Study objective and area

Samsun is one of the largest provinces of Turkey, located in the northern part of the country. The population of Samsun province is 1,356,079, and it has a high inhabitation density in most of the peripheral municipalities. It has a surface area of 1055 km^2, and 17 districts (Alaçam, Asarcık, Atakum, Ayvacık, Bafra, Canik, Çarşamba, Havza, İlkadım, Kavak, Ladik, Ondokuz Mayıs, Salıpazarı, Tekkeköy, Terme, Vezirköprü, and Yakakent) [24]. There are two sanitary landfills that have been serving the entire area for about 14 years (Fig. 2). The biggest problem in Samsun is that the waste is not collected separately from its source. As the waste emission is an important problem, a new system will be introduced in 2023 with a "Zero Waste Project". However, given the population density in this region, it is important to conduct the LCA as case studies and analyze the results and integrate changes in the management plan. In this context, Samsun, which produced approximately 370,000 tons of MSW in 2021, is one of the provinces where the LCA of the MSWM system is needed in order to evaluate the potential environmental impacts and to identify the best scenario to follow to reach the "zero waste" initiative. The study's main purpose is to determine the best scenario with the help of LCA, to reduce the volume of MSW dumped in landfills and encourage separate collection at the source. In addition, when the waste characterization of Samsun is examined, it is seen that half of the MSW is organic waste. Due to the high environmental impact of methane emissions from organic waste fractions buried in the ground, a solution to this problem is also required.

Management and characterization of MSW

Samsun landfill has started to serve in 2008, and its distance to the city center is approximately 10 km. The other one is Çarşamba landfill, which has been in service since 2010 and is 4 km away from Çarşamba district. Figure 1 shows the districts of Samsun and the locations of the sanitary landfills. Samsun sanitary landfill area is 2,777,000 m^3 and total surface area is 20 ha. Samsun landfill consists of 3 lots in total and landfill gas from sanitary landfill is collected by 220 horizontal gas collection pipes. Carsamba sanitary landfill consists of 2 lots in total and has a surface area of 4.9 ha and landfill gas from sanitary landfill is collected by 46 horizontal gas collection pipes.

According to the Turkish Waste Management Regulation, the collection and disposal of municipal solid waste is the responsibility of the municipalities [25]. According to the Ministry of Environment, Urbanization and Climate Change, most of the municipal solid waste are kitchen waste (49.56%), park and yard waste (2.78%), paper (1.17%), carton (6.50%), bulky carton (0%), plastic (18.84%), glass (4.29%), metal (3.61%), bulky metal (0%), other combustibles (3.56%), other non-combustibles (1.52%), other bulky combustibles (0.74%), other bulky non-combustibles (0.04%), waste electric and electronic equipment (WEEE) (0.03%), ash (1.45%), hazardous waste (0.29%) and others (5.62%) consisting of 17 components. Figure 3 shows the composition of MSW in Samsun. Officially collected recyclable materials amount to 30,150 tons in total. As one does not have any official data and statistic about the recycling rate and collection of the recyclable materials, we are not able to evaluate the flow of this non-official collected waste.

Fig. 2 Location of Samsun's districts and landfills

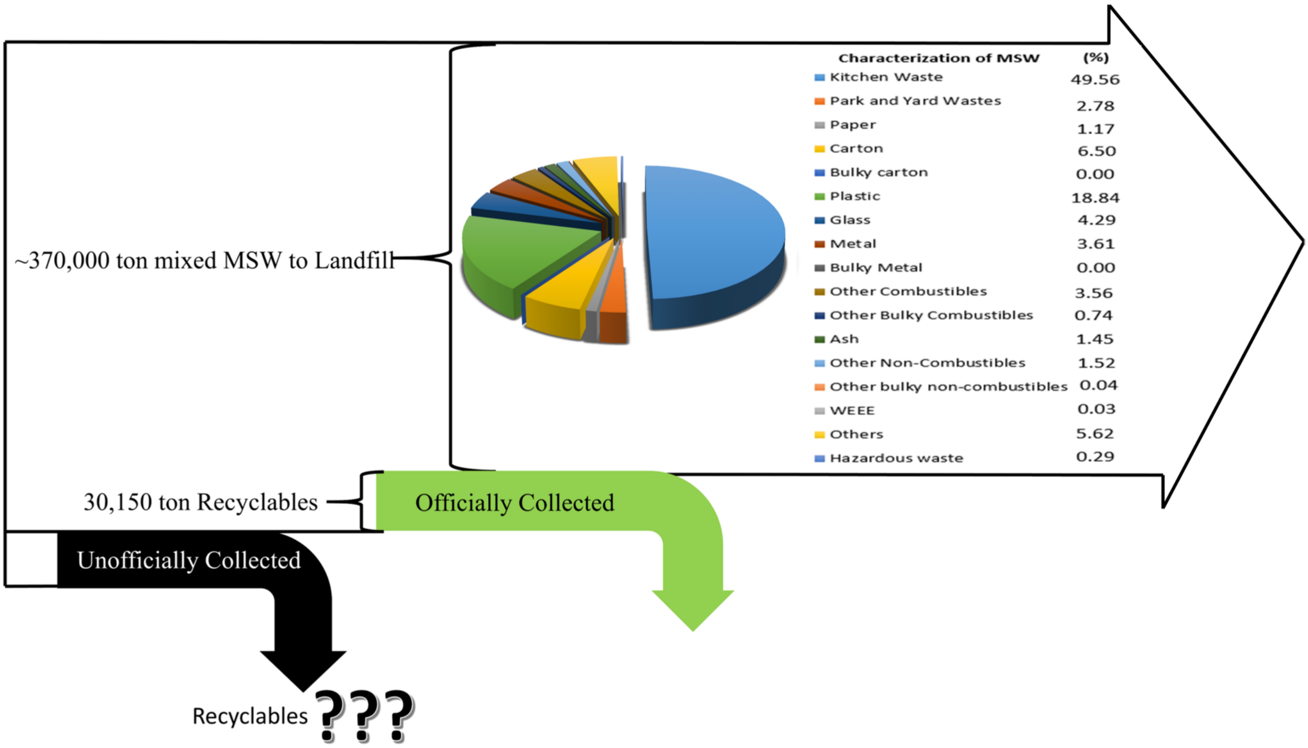


Fig. 3 Stream and composition of municipal solid waste in Samsun

LCA methodology

LCA of the MSWM system in Samsun was conducted in accordance with ISO standards 14040 (2006) and 14044 (2006). The waste management model was created using SimaPro LCA software version 9.1.1.1. The data used in the study were taken from Samsun landfill, municipalities, literature and Ecoinvent v3 databases. The LCA methodology consists of four stages: goal and scope, inventory analysis, impact assessment and interpretation.

Goal and scope

The aim of this study is to examine Samsun's current MSWM system and to determine its environmental impacts, to determine the future scenario with the lowest environmental impact according to the 2023 zero waste policy. It is aimed to evaluate the allocation of environmental impacts (burdens) or benefits (credits) between scenarios. The functional unit (FU) of the study is 369,279.8 tons of MSW produced in the city of Samsun in 2021. The plan for the collection of MSW in Samsun (waste amount and distance to landfills) is given in Fig. 4. There are four transfer stations (Bafra, Vezirköprü, Havza–Ladik, and Kavak transfer stations) in Samsun, and MSW in small districts is stored and collected here and then taken to the Samsun landfill. MSW is transmitted directly from Ilkadım, Canik, Atakum districts to the Samsun landfill, and wastes in other districts are transmitted after they are collected at the transfer station. In the Çarşamba landfill, MSW is transmitted directly in the districts of Ayvacık, Salipazarı, Terme and Çarşamba. Two-thirds of the solid waste in the Tekkeköy district is delivered to the Samsun landfill (14,600 tons), and one-third is delivered to Çarşamba landfill (7300 tons).

Waste collection is calculated for route collection and transport to landfills [26]. Figure 4 shows the route of the collection system that is carried out with rear-loading and diesel trucks with a different ton capacities, depending on the amount of waste they generate depending on the population numbers of the districts. The types of trucks were selected from the SimaPro database depending on the years of manufacture. The engines of trucks and conveyors used in transportation have Euro 6 diesel characteristics [27]. The characteristics and engine capacities of the vehicles used in the transportation network are given in detail in "Transportation and electricity". Transfer stations have been used because some districts have low populations, generate less waste, and are far from landfills. Wastes collected at transfer stations are sent to landfills by trucks with larger capacity. Detailed information about transportation and electrical data is given Table 1.

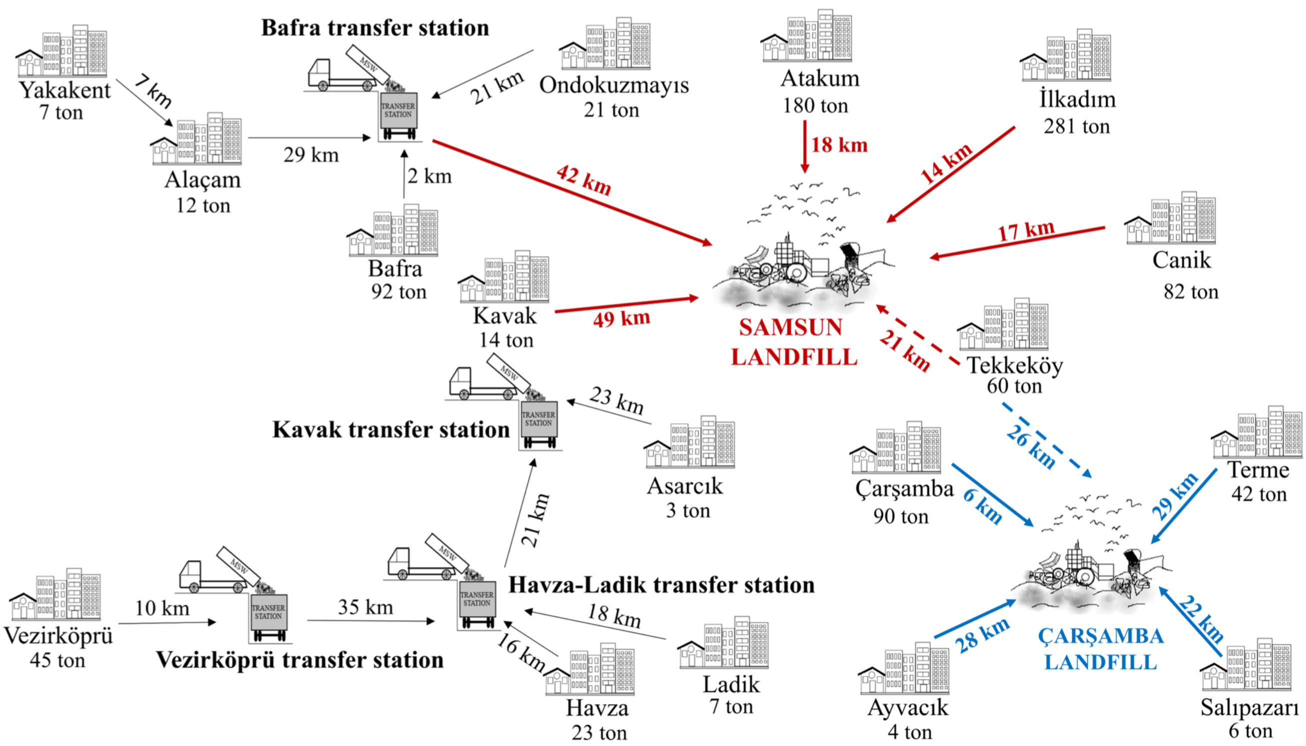


Fig. 4 Daily municipal solid waste amounts and transfer distances in Samsun

System boundaries

The study's system boundaries (see Fig. 5) include direct emissions from the transport and processing of MSW (including electricity and diesel consumption) and avoided emissions from material and energy substitution. Samsun's current MSWM is mixed collection and transportation of waste, separating recyclable waste in the material recovery facility (MRF), and disposal in the final landfill. The transmission line shown with the black arrow in Fig. 4 represents the baseline MSWM. Different materials in the MRF facility: the process of sorting metals, plastics, paper, cardboard, and glass is done manually by workers within the facility on site. The images of the MRF system are shown in the supplementary material "Appendix 2: Waste Sorting (Material Recovery Facility—MRF)". There is a facility within the system where landfill gas formed in the landfill area is collected, electricity is produced, and biogas is managed to obtain heat. The electricity produced is transmitted to the Samsun power line. The waste heat released from electric power-generating motors is used to dry sewage sludge formed in the facility, and a part is used in greenhouse operations. In addition, the leachate generated in the sanitary landfill is collected and transferred to the Samsun advanced biological wastewater treatment plant by tankers. Detailed information about the sanitary landfill is given in the supplementary material.

Waste management in Turkey is still in progress, but it will take time to reach the Turkish regulations. In this context, programs for segregating waste at the source are gradually becoming widespread in Turkey. Within the scope of the "zero waste" policy, which will come into effect in 2023, it is aimed to expand the collection of wastes separately, primarily in educational institutions, official institutions, and factories. Although some municipalities carry out pilot-scale studies on the separation of domestic solid wastes at the source, the effect is negligible at the moment. There is no plan to separate the different wastes at homes for now, that why one has a heterogeneous waste in landfill. However, it will be added in this step after the 2023 target. Therefore, the primary purpose of this study is to combine the existing system with an integrated solid waste system and determine the scenario with the lowest environmental load. According to the Ministry of Environment, Urbanization and Climate Change of the Republic of Turkey plan, separation at source scenarios is intended to be reworked later.

Scenario S0: Baseline scenario: MRF and landfilling. This scenario corresponds to the existing MSWM. This system includes MRF and the energy recovery landfill consisting of a biogas collection system. Metal, paper/cardboard, glass, and plastic are separated and recycled in MRF by Turkish law following packaging waste control and solid waste control regulations. The recycling rates are 1.97% for steel, 8.75% for aluminum, 1.17% for paper, 6.5% for core

Table 1 Distances of transportation and electricity data

Route	Distance (km)	Weight of waste (t)	Type of transport	Fuel/energy supply process
Havza–Ladik transfer station				
Ladik	18	4380	Transport, freight, lorry 16–32 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Havza	16	8395	Transport, freight, lorry > 32 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Vezirköprü transfer station	45	16,425	Transport, freight, lorry > 32 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Kavak transfer station				
Kavak	1	5110	Transport, freight, lorry > 32 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Asarcık	23	1095	Transport, freight, lorry 7.5–16 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Bafra transfer station				
Yakakent	36	2550	Transport, freight, lorry 16–32 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Alaçam	29	4380	Transport, freight, lorry 16–32 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Bafra	2	33,850	Transport, freight, lorry > 32 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Ondokuzmayıs	21	10,220	Transport, freight, lorry 16–32 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Transfer to Samsun landfill				
Havza–Ladik transfer station	70	29,200	Transport, freight, lorry > 32 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Kavak transfer station	49	6250	Transport, freight, lorry > 32 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Bafra transfer station	63	50,730	Transport, freight, lorry > 32 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Canik	17	29,930	Transport, freight, lorry > 32 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Atakum	18	65,700	Transport, freight, lorry > 32 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Ilkadım	21	102,565	Transport, freight, lorry > 32 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Tekkeköy-1	14	14,600	Transport, freight, lorry 16–32 metric tons	Diesel mix at filling station (100% fossil)
Transfer to Çarşamba landfill				
Tekkeköy-2	26	7300	Transport, freight, lorry 16–32 metric tons	Diesel mix at filling station (100% fossil)
Ayvacık	28	1460	Transport, freight, lorry 3.5–7.5 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Salıpazarı	22	2190	Transport, freight, lorry 3.5–7.5 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Çarşamba	6	32,850	Transport, freight, lorry > 32 metric tons, EURO 6	Diesel mix at filling station (100% fossil)
Terme	29	15,530	Transport, freight, lorry 16–32 metric tons	Diesel mix at filling station (100% fossil)
Total landfills' vehicles	1.76E07 MJ		Diesel, burned building in machine	Diesel mix at filling station (100% fossil)
Electricity data				
Inputs from technosphere electricity		Amount	Unit	Supply
Electricity, medium voltage (TR)/electricity voltage transformation from high to medium voltage		1,102,603	kWh	Landfill's data, Ecoinvent, 2019

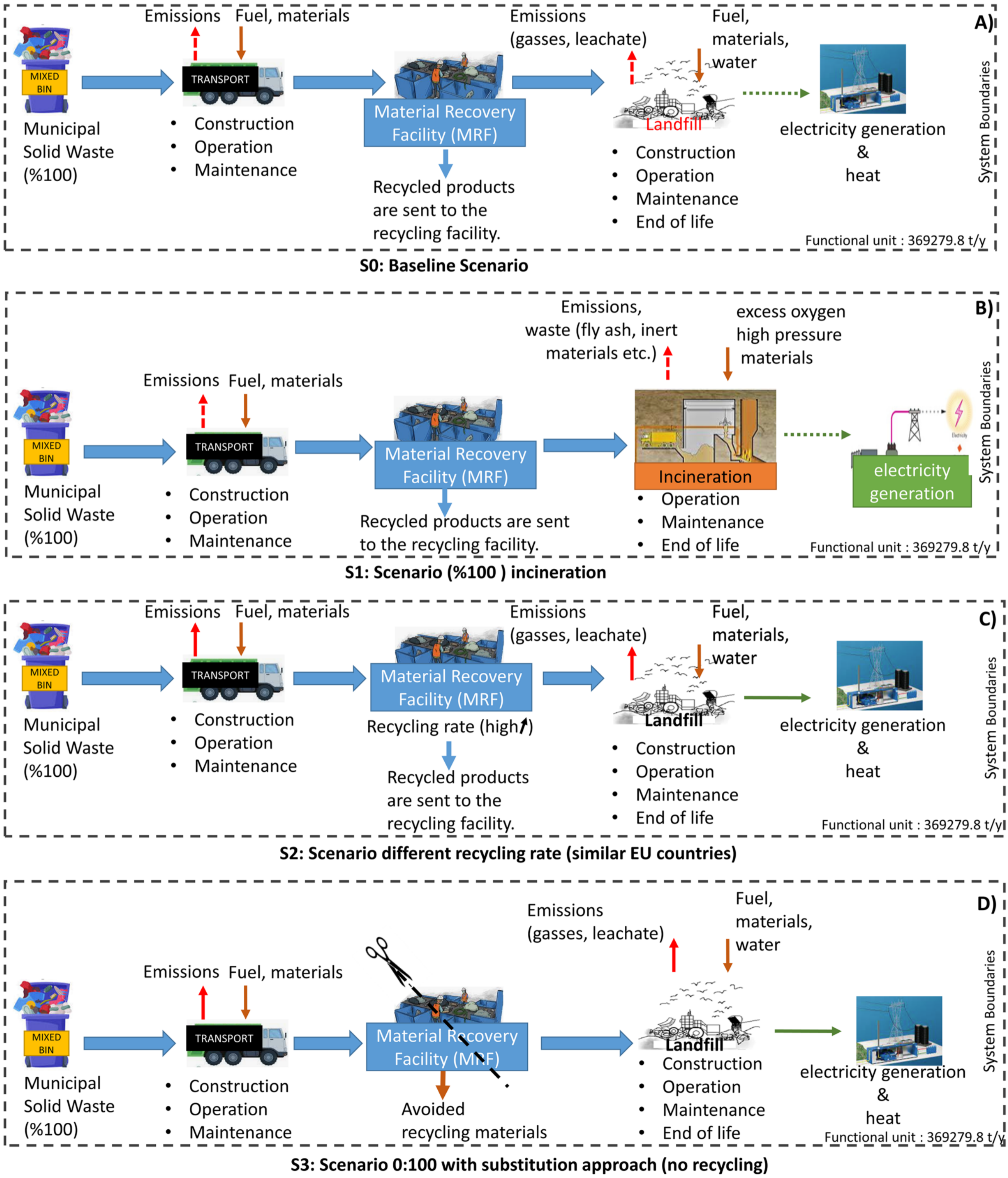


Fig. 5 System boundaries of the study: **A** S0: baseline scenario, **B** S1: scenario (%100) incineration, **C** S2: scenario different recycling rate (similar European Union countries), **D** S3: scenario 0:100 with substitution approach (no recycling), **E** S4: scenario separate collection at source (recyclable waste 25%, MSW 75%), **F** S5: scenario separate collection at source (recyclable waste 25%, organic waste 5%, MSW 70%)

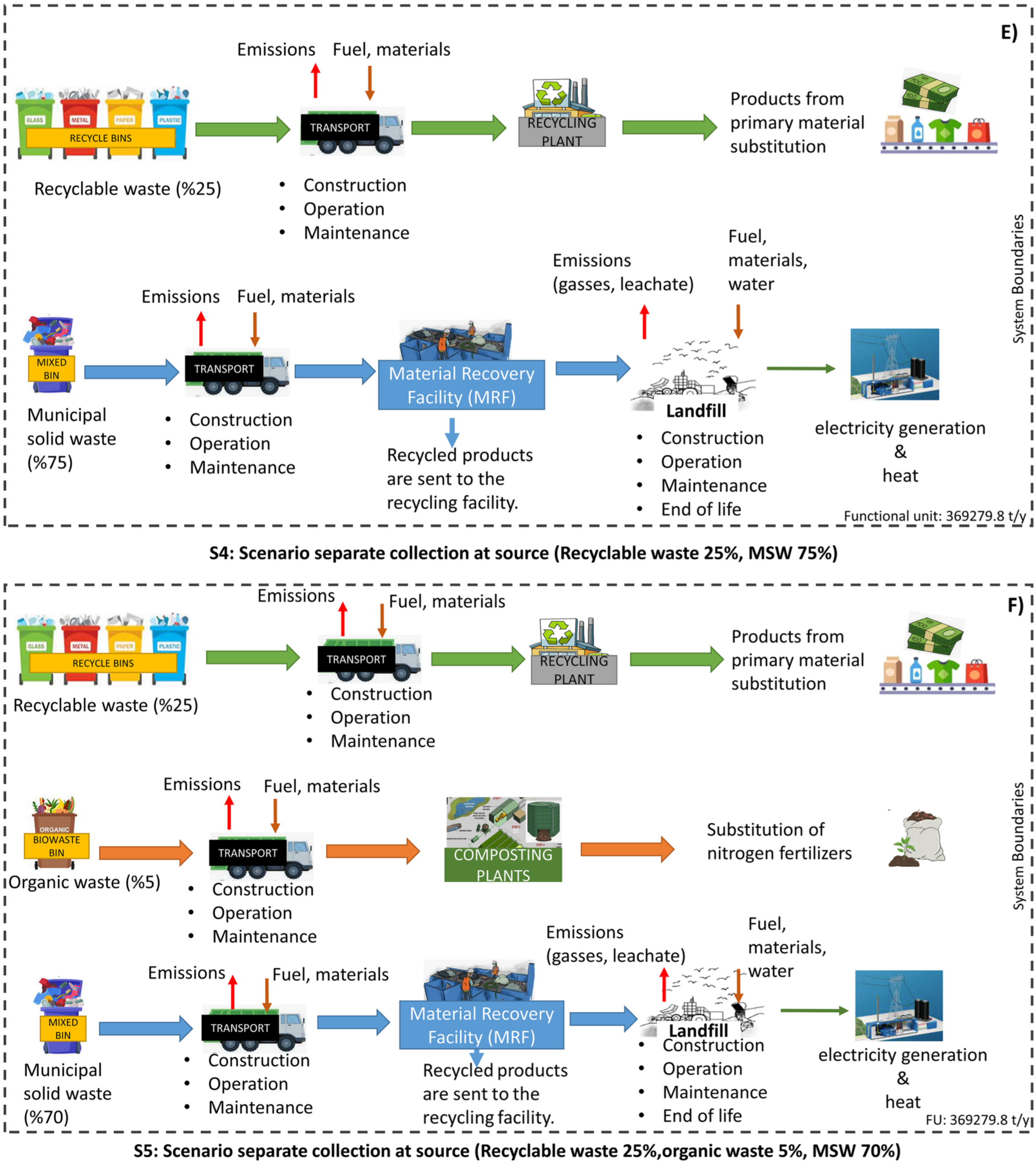


Fig. 5 (continued)

board, 55.05% for mixed plastic, 13.39% for PET, 1.37% for PS and 11.8% for packaging glass. The rest of the waste is deposited in the landfill (Fig. 5a).

Scenario S1: MRF and incineration. In this scenario, after the wastes are separated and recycled in the MRF system according to the regulations in Turkish law, the rest of the wastes are transported to the incineration plant. Building an incineration system is being discussed at Samsun MSWM. However, since the environmental impact of combustion systems is very high, the application is considered risky.

Therefore, this scenario was created based on the disposal by the incineration system. It is aimed to determine the environmental impacts that will occur if Samsun's MSWM combustion unit is added (Fig. 5b).

Scenario S2: MRF (recycling rate similar to EU countries) and landfilling. In this scenario, metal, paper/cardboard, glass, and plastic wastes are separated and recycled in high-recycling MRF systems in EU countries. The recycling rates are 45% for steel, 9% for aluminum, 34% for paper, 34% for core board, 20% for mixed plastic, 20% for PET, 20% for PS, and 65% for packaging glass. The rest of the waste is disposed of in landfills. This scenario was planned to improve Scenario S0 (baseline), taking EU countries as an example. With this scenario, it was examined how recyclable materials mixed with organic waste would be separated in MRF with higher recycling efficiency and how much the environmental burden would decrease accordingly (Fig. 5c).

Scenario S3: MRF (0:100 with substitution approach) and landfilling. In this scenario, the part separated and recycled in the MRF is accepted as 0:100. All wastes are disposed of in the landfill. In the 0:100 approach or the end-of-life (EOL) recycling approach, the recycled product does not receive any credit. Such credits equate to the amount of virgin production avoided due to the use of the recycled product. Specifically for the EOL phase, the idea behind the substitution approach, called 0:100 or cutoff, is that the primary production of materials is not allocated to the primary user. In other words, at this stage, it was taken into account that all wastes had reached the end of their life and could not be recycled, the recycling rate was accepted as zero, and the environmental impact of such a situation was examined. The aim of this scenario is to measure the environmental impact of storing all waste directly in the landfill without recycling in the MRF and producing landfill gas (Fig. 5d).

Scenario S4: This scenario consists of two parts. The first part is the separate collection of recyclable waste (25%) at the source and subsequent transport in the recycling plant. The second part is the collection of mixed waste (75%) and storage in MRF and then in landfills. The purpose of this scenario is to emphasize the source separation and recovery of recyclable waste, which will be implemented in Samsun's MSWM in the future. Since source separation is not currently implemented, it is assumed in the scenario that 25% of the recyclable waste is collected separately at the source (Fig. 5e).

Scenario S5: In this scenario, the recovery of the biodegradable part, apart from the recyclable part, is emphasized. The system's flow is similar to Scenario S4 for recyclable materials, with the organic fraction separated at the source and transported to the composting facility. This scenario consists of three parts. The first part is the separate collection of recyclable waste (25%) at the source and then transportation to the recycling facility. The second part is the separate collection of organic waste (5%) at the source and then transport to the composting facility. Third part is the collection of mixed waste (70%) and storage in MRF and then landfills. The compost percentage of organic waste collected separately from the MSW used in the scenario was determined according to both the actual data in Turkey's National Waste Action Plan and the compost percentages determined by countries experiencing similar problems [28]. The compost percentages of organic waste collected separately from MSW in countries with similar problems are given in Table S3.1 in the supplementary material (Fig. 5f).

Life cycle inventory

Life cycle inventory data were collected from the landfill in Samsun, the literature review and the Ecoinvent database. The landfill input and output flows are given in Table 2.

Transportation and electricity

Road transport constitutes a large part of the environmental impact due to its emissions during the collection of waste and its transportation to treatment/disposal facilities. In Fig. 3, the distances to the waste collection stations and landfills are given. The MRF, incineration, and landfill are assumed at the same site. The unit process for transportation, different capacities lorry according to the amount of waste collected from the districts, were selected from the Ecoinvent database. Electricity data were selected for Turkey Ecoinvent v3 database. In addition, information about the amount of electricity consumption was taken from landfill.

Material recovery facility (MRF)

Mixed recyclables (depending on the scenario) were sent to a MRF [29]. All materials except glass will be recovered as lost at specific rates in recycling. Paper, metal, and plastic will be recycled with losses of 17.5%, 5%, and 28%, respectively [22]. That is, 1 ton of waste material does not replace 1 ton of unprocessed material due to losses. The electricity requirement per metric ton processed for the MRF process is 0.045 kWh [30].

Composting

The composting process was based on inventory data in the literature and the waste composition in this study. Organic waste, considered as a mixture of kitchen and garden waste, was evaluated in Scenario S5 with windrow composting. The processing time was calculated as 58 days, and compost production as 0.38 kg compost/kg biowaste [31]. The electricity consumed during composting is 61 kWh [32].

Table 2 The landfill input and output flows

	Unit	Amount
Outputs to technosphere		
Municipal solid waste	ton	36,927.9
Landfill gas	ton	103,517.3
Electricity	kWh	48,689,964
Heat	MJ	12,850,000
Input from nature		
Occupation, arable land	ha	20
Input from technosphere		
Electricity	kWh	1,102,603
Transport	ton	358,100
Tap water	kg	6485
Diesel, burned in building machine	MJ	1.76E7
Outputs emission to air		
Trichloroethane	µg	100
Toluene	µg	20
Butylbenzenes	µg	1000
Styrene	µg	0.5
Cyclohexane	µg	10
Terpenes	µg	100
Dichlorobenzene	µg	10
Xylene	µg	500
Sulfur dioxide	µg	10
Benzene	µg	1800
Emission to water		
Copper	mg	4.14E4
Cadmium	mg	180
Chemical oxygen demand (COD)	mg	239E9
Chromium	mg	1.36E4
Zinc	mg	9.6E3
Iron	mg	5.72E5
Lead	mg	600
Fluoride	mg	1.99E4
Total phosphorus	mg	7.76E5
Total nitrogen	mg	1.91E8
Cyanide	mg	1.2E3
Emission to waste		
Mixed plastics	ton	1.79E4
Polyethylene terephthalate	ton	2.45E3
Polystyrene	ton	251
Biowaste	ton	1.83E5
Paper	ton	1.42E4
Glass	ton	1.9E4
Aluminum	ton	38.6
Steel and iron	ton	14.8

Incineration

Raw MSW is generally preferred in combustion systems. MSW covers converting chemical energy into heat energy by burning it completely in the presence of sufficient air at high temperatures (980–2000 °C) and generating electricity through the turbine–generator system [2]. A typical incinerator produces 544 kWh of energy per ton of MSW burned [33].

Landfilling

The landfill is often used as final storage. The Scenario S0 is based on data from the landfill of Samsun. Electrical energy is produced with biogas collected in the landfill with horizontal gas collection pipes. Landfill gas composition is 56.4% CH_4, 38.1% CO_2, 0.9% O_2 and 4.6% N_2. Figure 5, obtained according to the future projection of the landfill gas formed in the Samsun landfill, is made with the LandGEM gas emission model (Fig. 6). The leachate flow capacity in the landfill is 60 m^3/day and is collected through drainage pipes and transported to Samsun East Advanced Biological Wastewater Treatment Plant via collectors. Leachate pollution loads chemical oxygen demand is 38,840 mg/L, suspended solids are 1280 mg/L, total Kjeldahl nitrogen is 3190 mg/L, and total phosphorus is 12.94 mg/L.

Life cycle impact assessment

The European platform on life cycle assessment proposes a panel of relevant indicators, even if some of them are still in progress, the EF is now mostly used in Europe [34]. That is why, in our study, the environmental profile of the landfill is expressed by following the EF method 3.0 set—the impact assessment method of the EF initiative, taking into account 11 impact categories [35, 36].

Interpretation

The interpretation step is important to evaluate the results of the study and to identify the processes that contribute the most impact. The requirements specified in the aim and scope should be compatible with the inventory analysis and impact category. Impact assessment should be carried out until these requirements are met. In this study, uncertainty analysis was performed to consolidate the indicators. It is needed to reduce indicators with great uncertainty and to determine data quality. The Monte Carlo method (random sampling) obtained potential environmental impacts with probability distributions [37]. Even if the uncertainty analysis is not an obligation regarding the LCA standard, it should useful when one has a comparison of the different systems, that one decided to conduct such analysis in order to highlight the potential avoided environmental impacts.

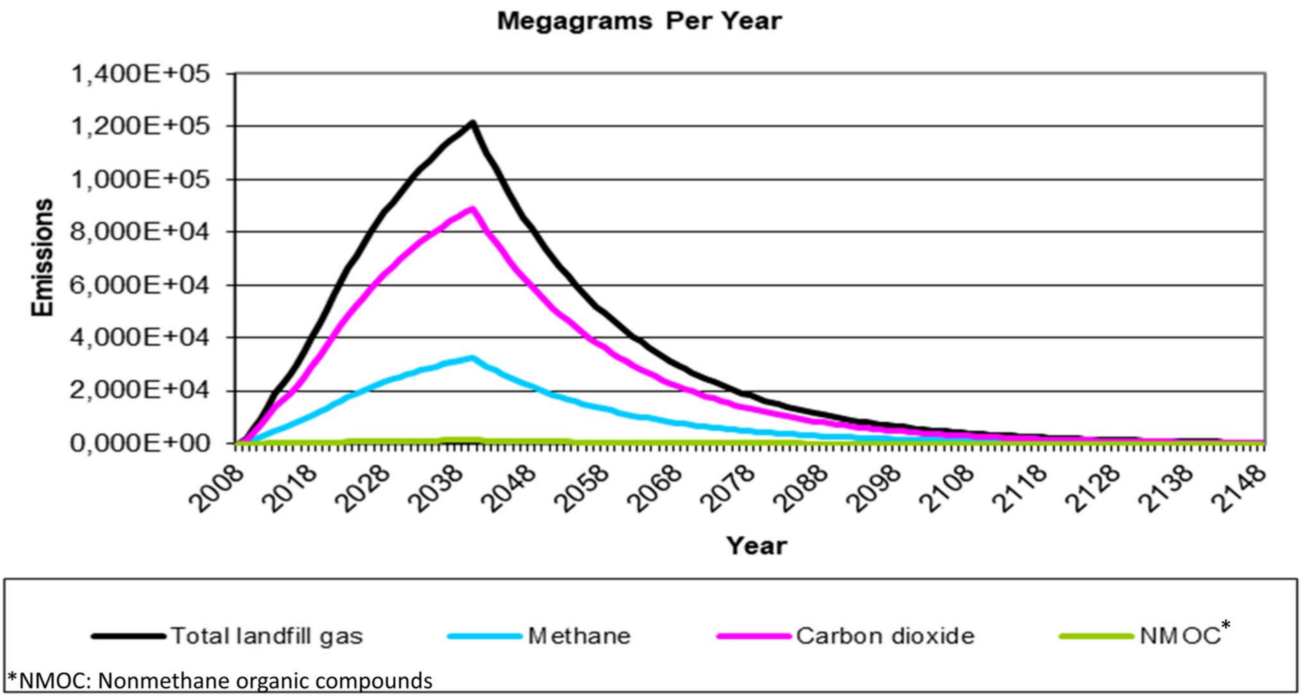


Fig. 6 Distribution projection of gas production by years with the United States Environmental Protection Agency LandGEM model

Results and discussion

In this section, the results related to Samsun MSWM scenarios by converting LCIs to potential environmental terms are shown and discussed. According to the results of the analysis, it is aimed to determine the sensitivity in environmental impacts using different impact assessment methods and recycling rates in the MRF processes in the scenarios. In the S0 and S1 Scenarios, low recycling rates according to the Turkish standards applied in the existing landfill are considered, while in S2, high recycling rates applied in European countries are taken into account, and in the Scenario S3, it is accepted that there is no recycling during the MRF. Finally, Scenarios S4 and S5 include a separate collection of waste at the source in addition to a mixed collection. Samsun's future MSWM plan is to separate waste that can be recycled at the source. For this reason, these scenarios were created assuming certain percentages of waste and organics that can be recycled at the source. Very high rates were not determined when making separate collection assumptions at source. This is because separate collection at source has not yet been implemented in our country. These scenarios show how the environmental impacts will change due to improvements to the default system. According to these results, the scenario that causes the most negative environmental impact is S3. Due to the lack of recycling in the scenario, one has a major environmental impact in all impact categories. In other scenarios, it has been determined that environmental gains are generally achieved due to the recycling. In addition, when Scenarios S4 and S5 were examined, it was determined that the environmental impacts were less than the other scenarios. Accordingly, separation at the source is more effective than MRF. When the environmental effects of Scenarios S4 and S5 were compared, it was determined that Scenarios S5 had less environmental impact. Although the rate of separate collection of organic waste at the source is low, it has contributed to reducing environmental impact. As a result, it has been determined that Scenarios S4 and S5 for Samsun are more advantageous than other scenarios in terms of both energy consumption and environmental aspects.

Particular attention can be made to four indicators; it seems that the impacts are generated mainly by land use, resource use—mineral and metals, climate change-biogenic, and human toxicity noncancer organics (Fig. 7). Among these factors, land use refers to the soil quality index as an indicator. Since land occupation is in all scenarios, its environmental impact is high [38]. The proposed model for midpoint resource depletion is the abiotic resource depletion "ultimate reserves" version. The abiotic depletion potential is measured in kg antimony equivalents (Sb-eq) per kg extraction [38]. Abiotic depletion has a high impact due to the consumption of fossil fuels such as hard coal, natural gas, and lignite for electricity. At the same time, it causes depletion of abiotic resources in the fuel consumed by the vehicles during the transportation of wastes to landfill. In the EF method, IPCC 2013 climate change

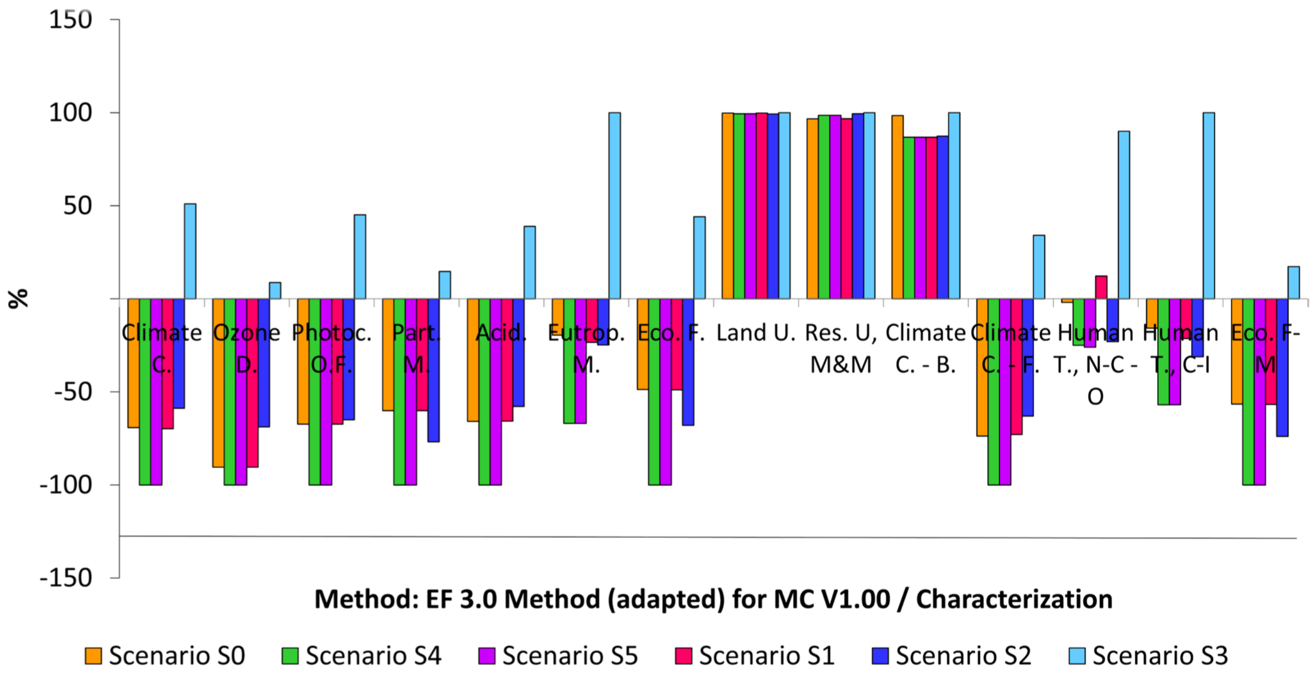


Fig. 7 Characterized results for comparative analysis results of landfill scenarios. Climate C.: climate change, Ozone D.: ozone depletion, Photoc. O.F.: photochemical ozone formation, Part. M.: particulate matter, Acid.: acidification, Eutrop. M.: eutrophication marine, Eco. F.: ecotoxicity, freshwater, Land U.: land use, Res. U, M&M: resource use, minerals and metals, Climate C.-B: climate change—biogenic, HumanT., N-C-O: human toxicity, noncancer—organics, Human T. C-I: human toxicity, cancer—inorganics, Eco., F-M: ecotoxicity, freshwater—metals

was determined as the reference method. Accepted values for Global Warming Potentials are expressed in kg CO_2 eq per time horizon 100 years (GWP-100) [38]. Landfills are biochemical reactors that produce CH_4 and CO_2 emissions due to anaerobic digestion of solid wastes, and the CO_2/CH_4 molar ratios consisting of landfill gases are in the range of 0.7–1. Global biogenic CO_2 emissions from landfills reach approximately 11.2–16 million tons per year [39]. Although the biogas produced in the storage is collected without being directly released into the atmosphere, the biogas is partially destroyed. Approximately, 30% of fugitive emissions are released into the atmosphere, contributing to global warming [22]. Human toxicity midpoint, noncancer effect category is adapted from USEtox 2.1 model, and its unit is comparative toxic unit for human health (CUTh). Collecting and transporting stages are critical concerns for human toxicity. Since there is no MRF in Scenario S3, it causes the most environmental impact regarding human toxicity due to contact with more waste during transportation and storage.

During the current operation of the Samsun landfill site, the life cycle impact assessment for 1 kg of waste was evaluated according to 11 characterization factors. In Fig. 8, while it is determined that diesel consumption from vehicles and plastic waste, steel and aluminum waste, paperboard waste and organic waste cause negative environmental effects, it is seen that the environmental impact of waste recycling and electricity and heat generation from biogas is positive. Organic waste, paper waste, and diesel consumption are the leading factors affecting global warming. The paper waste recycling rate in MRF in Samsun landfill, which is currently operating, is quite low. For this reason, the high rate of paper waste disposed of in landfill increases global warming. In addition, since there is no composting unit for bio wastes, all organic wastes are disposed of in the landfill system. Gas emissions such as carbon dioxide and nitrous oxide as a result of the breakdown of wastes affect the global warming potential. Although the landfill gas is collected, it is not collected with 100% efficiency, and fugitives have occurred. Another factor affecting global warming is the fuel consumption of the vehicles used in the field and for waste transportation. NO_X and SO_2 emissions from these vehicles increase the global warming potential by dispersing into the atmosphere. The most important factors affecting the ozone layer and photochemical ozone formation parameters are diesel consumption from vehicles and organic waste [22]. Acidification is mainly due to NH_3, NO_2, and SO_X emissions. Characterization factors for acidification are expressed in moles per unit of mass emitted [38, 40]. In the current landfill system, the most significant impact on acidification occurs during the collection of wastes. The sulfur and nitrogen transport of the compounds contribute to acidification. It is also one of the parameters affecting acidification in

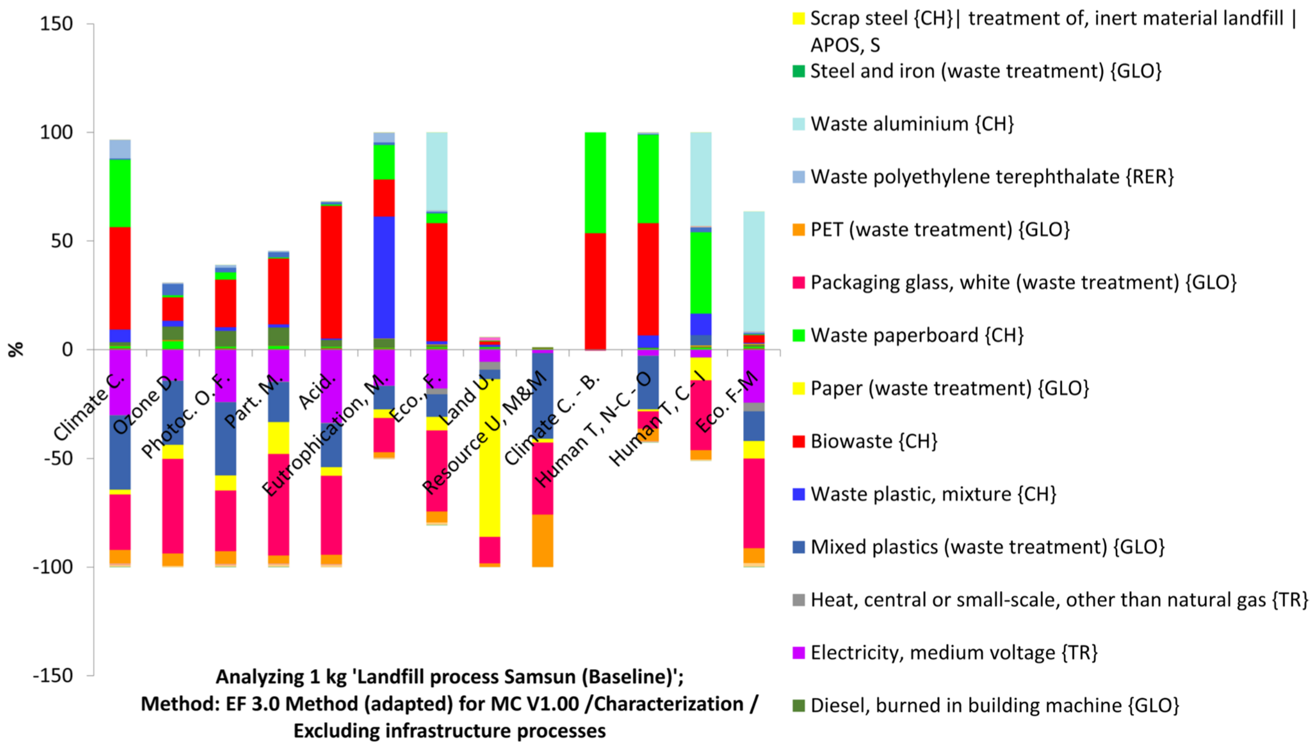


Fig. 8 Characterized life cycle impact assessment results for 1 kg municipal solid waste. Climate C.: climate change, Ozone D.: ozone depletion, Photoc. O.F.: photochemical ozone formation, Part. M.: particulate matter, Acid.: acidification, Eutrop. M.: eutrophication marine, Eco. F.: ecotoxicity, freshwater, Land U.: land use, Res. U, M&M: resource use, minerals and metals, Climate C.-B: climate change—biogenic, HumanT., N-C-O: human toxicity, noncancer—organics, Human T. C-I: human toxicity, cancer—inorganics, Eco., F-M: ecotoxicity, freshwater—metals

ammonia contained in landfill gas [41]. Eutrophication is a phenomenon that can affect terrestrial and aquatic ecosystems. In the current landfill system, NO_X production causes eutrophication after the (diesel) fuel consumption resulting from the transportation of wastes. In addition, emissions that result from the decomposition of wastes such as organic waste, aluminum waste, and paper waste during waste storage affect eutrophication. The low recycling rate in the MRF system and the disposal of wastes in landfill are factors that increase eutrophication. Ammonia formed from the decomposition of wastes causes marine eutrophication, phosphate causes freshwater eutrophication, and nitrogen concentration is the factors affecting terrestrial eutrophication [38].

Characterization values have shown that land use, resource use, ecotoxicity, and climate change are important impact categories for MSWM alternatives. When the scenarios are examined, it is seen that waste recovery increases as recyclable and organic wastes are collected separately at the source and the recycling rate in the MRF system increases, and acidification and eutrophication potential and global warming values decrease by controlling nitrogen and sulfur oxidation. As a result, it has been confirmed by other studies that the MRF system is a system that has a positive environmental impact due to acidification, eutrophication, global warming, and recovery of resources [9, 13, 20, 22, 42, 43]. However, in Scenarios S4 and S5, separate collection of waste at the source reduced the impact of climate change more than MRF. For this reason, it is known that collecting waste separately at the source has significant advantages, such as reducing environmental impacts and making recycling more effective, compared to the MRF system [44]. In the study, the best scenario in terms of environment is the S5 scenario, where recyclable and organic wastes are collected separately at the source. In the S4 scenario, only recyclable wastes were collected at the source with the same percentage. However, despite the slight difference, separate organic waste collection caused less environmental impact. In Scenario S2, although the MRF system included the European recycling system, separate waste collection at the source caused less environmental impact. In the study, the worst scenario from an environmental perspective was the S3 Scenario, which does not support the production of products from secondary materials or recycled materials, where the system is always obtained from virgin sources, and there is no MRF system.

In this paragraph, the results obtained by the Monte Carlo method are reported to determine the general uncertainties. Monte Carlo technique was used by performing LCI data set uncertainty analysis for six scenarios based on the EF method. The impact assessment was calculated 5000 times. Uncertainty analysis was performed up to 95% confidence level and showed the mean, median, and standard deviation. Figure 9 is given for a clear understanding of the uncertainty analysis results.

According to the Monte Carlo analysis results, all scenarios have a positive and negative distribution. The negative distributions are due to the source separation, separate collection of waste at the source, waste recycling with the MRF system, and energy recovery from landfill gas. Within six scenarios, the categories of land use, resource use-minerals, and climate change biogenic showed sensitivity. Scenario S3 was determined to have the most harmful environmental impact. Scenario S5 was determined to be the most environmentally friendly scenario.

The results of Scenarios S4 and S5, which are based on assumptions and support the separation of waste at the source, which includes Turkey's future MSWM plan, reveal that recycling is very important in MSWM. This practice, accepted worldwide, is also planned to be implemented in Turkey. However, realistically, even MRF recovery/recycling rates are far behind developed countries. In many cities in Turkey, there are difficulties in separating, collecting, and disposing of waste. Nevertheless, the findings of this study showed the importance of a zero-waste system. Therefore, Scenarios S4 and S5 are examples of developing this awareness.

Conclusion

In this study, the LCA of six different scenarios was carried out to evaluate Samsun's existing MSWM and to develop this system. Within the scope of Turkey's "Zero Waste Policy", it aimed to change the system implemented until 2023 and to reduce the environmental impacts in the examined categories. In this context, in the study, the sensitivity of environmental impacts was determined using different recycling rates of MRF for the economic sustainability of the existing MSWM system. According to the LCA results, the highest environmental impact is in Scenario S3 for using virgin resources where there is no recovery in MRF. The most environmentally friendly waste management option is Scenario S5, where recyclable and organic wastes are collected separately at the source. On the other hand, characterization factors that cause adverse effects in all scenarios are land use, resource use, minerals and metals, climate change—biogenic and human toxicity, and noncancer—organics, and the most significant reduction potential comes from the separate waste collection at the source in Scenario S5. While the climate change-biogenic

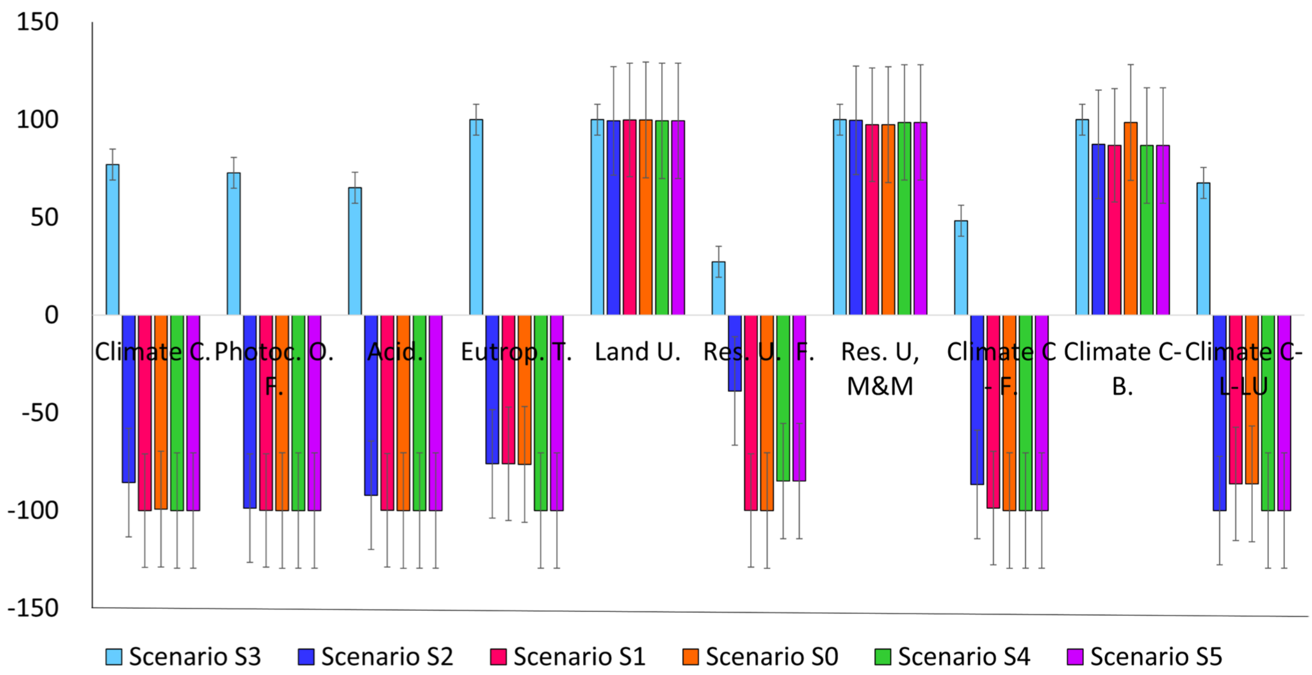


Fig. 9 Characterized life cycle impact assessment results and uncertainty analyses results from the Environmental Footprint method. Climate C.: climate change, Ozone D.: ozone depletion, Photoc. O.F.: photochemical ozone formation, Part. M.: particulate matter, Acid.: acidification, Eutrop. M.: eutrophication marine, Eco. F.: ecotoxicity, freshwater, Land U.: land use, Res. U, M&M: resource use, minerals and metals, Climate C.-B: climate change—biogenic, HumanT., N-C-O: human toxicity, noncancer—organics, Human T. C-I: human toxicity, cancer—inorganics, Eco., F-M: ecotoxicity, freshwater—metals

factor was 385 kg CO_2 eq in Scenario S0, it decreased to 305 kg CO_2 eq in Scenario S5. However, the land use factor also creates a relatively small difference between Scenario S0 and Scenario S5. Waste-to-energy recovery and material recovery rates are two components of different emphasis in this study and generally lead to a reduction in environmental impacts. In addition, the emissions of vehicles used in transportation and on-site are another factor that increases the environmental impact. Using diesel fuel for vehicles causes an increase in greenhouse gases and, indirectly, climate change. Based on the indicators obtained, the overall conclusion is that the environmental gains of MSW are higher than its environmental impacts. Moreover, the results showed that the effects of all characterization factors decreased as the recycling percentage increased in MRF. However, according to European standards, even if recycled waste is collected as in MRF systems, collecting waste separately at the source causes less environmental impact. For this reason, increasing the recycling rate of the MRF system alone is not an effective MSWM approach. Waste must be collected separately at its source. Society needs to be educated to collect waste by separating it at its source, and recycling activities must be developed. Apart from education, to popularize integrated waste management, separate collection bins for all kinds of waste should be placed next to garbage containers in all neighborhoods, and separate waste collection should be encouraged. Otherwise, the system's sustainability will be difficult in countries like Turkey. Study results showed that municipalities and governments can use the LCA system to determine the environmental impacts of different technology and planning options for MSWM. As a result, recycling systems need to be improved due to the environmental effects of the current MSWM system in Samsun.

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Data availability The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval Not applicable.

Consent to participate All the authors provide consent to participate.

Consent for publication Not applicable.

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