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Life cycle assessment for municipal solid waste management: a case study from Ahvaz, Iran

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Abstract This study assessed the available status of waste management system in Ahvaz and its impact on the environment, as well as seven other scenarios in order to quantitatively calculate potential environmental impacts by utilizing the life cycle assessment (LCA) method. These scenarios were as follows: scenario 1: landfilling without biogas collection; scenario 2: landfilling with biogas collection; scenario 3: composting and landfilling without biogas collection; scenario 4: recycling and composting; scenario 5: composting and incineration; scenario 6: anaerobic digestion, recycling, and landfilling; scenario 7: anaerobic digestion and incineration. Emissions were calculated by the integrated waste management (IWM) model and classified into five impact categories: resource consumption, global warming, acidification potential, photochemical oxidation, and eco-toxicity. In terms of resource consumption and the depletion of non-renewable resources, the third scenario showed the worst performance due to its lack of any recycling, energy recovery, and conversion to energy. In terms of greenhouse gas emissions and the effect on global warming, scenario 1 and scenario 2 showed that disposing the whole amount of waste resulted in the most amount of greenhouse gases produced. Moreover, 50% gas and energy recovery from landfills, in comparison with the non-recovery method, reduced the index of global warming by 12%. Finally, scenarios which were based on producing energy from waste showed a reasonably positive performance in terms of greenhouse gases emissions and the influence on global warming.

Keywords Life cycle assessment · Municipal solid waste · Waste management · Ahvaz city

Introduction

In recent decades, urbanization and world population growth, especially in developing countries, have created some problems for the environment and public health (Barton et al. 1996; Guerrero et al. 2013; Haupt et al. 2018). Consequently, to improve urban management in metropolises, environmental and economic

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management approaches are required. In developing countries, improved solid waste management system is a costly budgetary item. Poor solid waste management system causes undesirable impacts on the quality of human life (Brunner and Rechberger 2015; Marshall and Farahbakhsh 2013). It is widely accepted that the municipal solid waste management is one of the major environmental challenges of sustainable development. At present, uncontrolled landfills are the dominant option for waste disposal in developing countries (Bosmans et al. 2013; Zhou et al. 2019). Landfill sites that emit gas have a significant impact on global warming. The methane gas produced from landfills has a direct impact on the increase of greenhouse gases (Tian et al. 2013). The infrastructure of municipal solid waste management system should have the potential to develop with population growth and economic development. Poor waste management systems require improvements in their facilities for collection, transportation, and disposal. Although the high cost of constructing new facilities and introducing new technologies are the major stumbling block for changes to be made in old waste management systems (Das and Bhattacharyya 2015; Mavrotas et al. 2015). In fact, municipal solid waste as a renewable source has the potential for recovery of materials and energy. Waste-to-energy technologies are like a renewable energy source and an advanced waste treatment technique (Astrup et al. 2015). Electricity, heat, and transport fuels are the useful forms of energy that are recovered from waste (Pan et al. 2015). The disposal technologies such as composting, anaerobic digestion, and incineration would be deployed for reduction of the environmentally adverse impacts of existing landfill operations (Amin and Moazzam 2016; Dong et al. 2014). From a municipal solid waste management perspective, waste-to-energy technologies are considered as green technologies in comparison with landfill disposal in terms of lower pollutant emissions like mercury and dioxins, reducing the volume of and destroying harmful substances, leading to material and energy recovery and land use (Tan et al. 2014; Tozlu et al. 2016). Among these techniques, anaerobic digestion of organic waste is a well-established technology (Jain et al. 2015). Today, thermal conversion of waste by incineration is also one of the most prevalent waste-to-energy technologies, although the comparatively high costs of alternative disposal technologies are a major reason for the reliance on landfills (Cucchiella et al. 2017).

In recent years, LCA method has been recognized as an indispensable tool to support systematic and accurate decisions taken on waste management systems (Obersteiner et al. 2007; Memon et al. 2007; Thanh and Matsui 2013). LCA methods can make a comparison between different scenarios of waste management systems performance from top to bottom to assess the environmental impacts and consumption of resources (Arena et al. 2003; Laurent et al. 2014). LCA methods have abundant suggestions for making a suitable decision on MSW management technologies that will meet the waste management purposes and goals. Thus, several researches in the literature have been found to be useful methodological examples of the LCA method as a tool for assessment of exiting municipal solid waste management (Fernández-Nava et al. 2014; Abduli et al. 2011), food waste management (Ahamed et al. 2016), and hazardous waste management (Fikri et al. 2016).

In this study, the LCA methodology was used to assess the environmental impacts as well as resource consumption, global warming, acidification potential, photochemical oxidation, and eco-toxicity impact of applying alternative technologies in Ahvaz (a megacity of around 1,200,000 inhabitants, located in the southwest of Iran). For this purpose, seven alternative scenarios of municipal solid waste management system with different processing and disposal methods (such as recycling of useful material, composting, anaerobic digestion, and incineration) were developed and compared with current status of the waste management system regarding their quantitative environmental analysis.

Methods

The study area

The city of Ahvaz (center of Khuzestan Province, Iran) is located in 48° 40′ E and 31° 20′ N. Ahvaz population was about 1,149,496 in 2013, and with the possible growth of 2.44%, it will be increased to 1,773,683 by the year 2031. Ahvaz has been well recognized for its environmental issues such as air pollution (dust storm). Its average annual rainfall is 210 mm, and its average annual temperature has been recorded about 25.6 °C during 1976–2011. In Ahvaz, more than 292,000 tons of solid wastes is produced every year. Waste generation exceeds 800 t/day. Municipal solid waste is characterized by a high percentage of organic material or mostly food wastes (around 68.91%). The presence of high percentages of recyclable materials such as paper (10%), plastic (10%), and glass (3%) shows a good recycling feedstock of the waste. There is only one landfill in the region that receives municipal waste, the Sofeireh Landfill, located about 35 km outside of Ahvaz (48° 49′ E and 31° 17′ N). More than 166,000 tons of generated waste (57% of total generated waste) is sent directly to this landfill site. At the Sofeireh Landfill, there is no collection system for landfill gas, and 3% of the total material is transported for recycling. The compost facility receives the remaining 40% of organic waste.

LCA method

The LCA method was utilized to make an environmental comparison between the eight scenarios of waste management systems. Figure 1 shows the LCA steps used in the study. This assessment was conducted in accordance with the LCA methodology of ISO14040 (1996) which consists of four steps: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation of results.

Goal and scope definition

The goal of this LCA method is to compare the environmental burdens of the existing municipal solid waste strategies and other scenarios with each other in order to improve solid waste management system in Ahvaz. The waste management scenarios consist of the following parts: collection and transportation of wastes, materials recovery facility (MRF), composting, incineration, and landfill with/without biogas collection. The LCA for the commonly disposal scenarios was conducted separately to determine overall environmental impact.

System boundaries

The system boundaries in a waste management study are defined as the materials do not have their before value and are like a waste. Therefore, they should be sent to

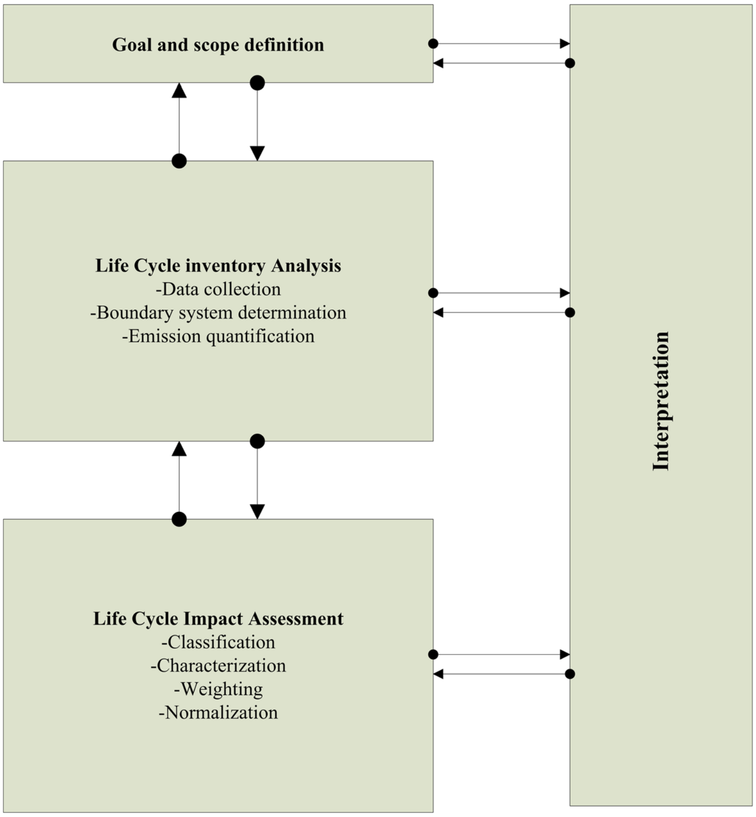


Fig. 1 Life cycle assessment framework phases of this study

landfill sites, or recycled through recycling, composting, or retrieval of energy. In this study, the system boundaries start with the waste collection from the side of the houses, and will end by waste recycling, landfilling (with or without recovery of gas and energy), composting, or converting to energy (with thermal or biological methods). Figure 2 shows the system boundaries.

Functional unit

The functional unit of the scenarios has been defined as the amount of waste produced in a year, by the city of Ahvaz, which must dispose 292,000 tons of municipal wastes.

MSW management scenarios

Regarding the goal of the study, eight different alternative waste management scenarios were investigated to assist decision-makers in strategic determinations. These technologies and management approaches were selected because they are able to describe a possible high-quality approach for recycling materials and energy from municipal wastes. It is also useful that these techniques and technologies have already been investigated by other LCA studies aiming to evaluate the best MSW management system. Different approaches and scenario descriptions are shown in Table 1. Scenarios 1 to 7 (S1–S7) are alternative approaches to the current situation of the Ahvaz waste management system (scenario 0 (S0)). Due to the simplicity and cost-effectiveness of landfills, S1 and S2 were selected as landfill-based scenarios. In order to produce valuable products from organic matter and better controlling the leachate, composting was selected in S3. S4 shows the potential for recycling municipal waste. In S5, S6, and S7, different biological and thermal approaches for producing energy from waste were introduced and analyzed.

Life cycle inventory

The life cycle inventory aims to calculate and quantify the environmental burden associated with the waste

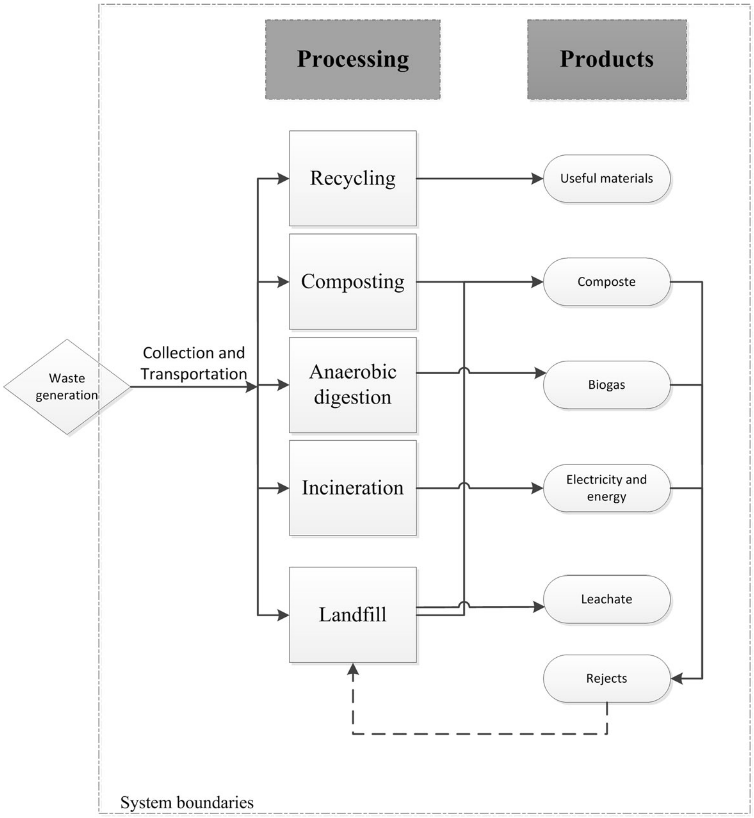


Fig. 2 Options of the developed municipal waste management strategies

Table 1 Different approaches and their descriptions

Scenario number	Disposal approaches	Scenario description
S0	The current state of waste management systems in Ahvaz	Municipal waste is collected and delivered to the processing center. In the center, 40% of the total wastes are separated and converted to compost and 3% of the total wastes are recycled. The remaining wastes which are about 57% are landfilled without recovery of biogas and energy.
S1	Landfilling without biogas collection	Municipal wastes are collected and delivered to landfill without any further treatment and collection of landfill gas.
S2	Landfilling with biogas collection	Municipal wastes are collected and transported to landfill and then 50% of the biogas released by the landfill are collected and used to produce electricity.
S3	Composting and landfilling without biogas collection	The organic and inorganic fractions of municipal waste are separated in a sorting plant at landfill site. The total organic portions of wastes are composted whereas the remaining wastes are landfilled.
S4	Recycling and composting	The useful materials are recycled in a sorting center and the organic portions are composted. The remaining wastes are landfilled.
S5	Composting and incineration	The organic portions of municipal wastes are separated for composting and the remaining wastes are incinerated to produce electricity.
S6	Anaerobic digestion, recycling, and landfilling	The organic portions of municipal wastes are separated for anaerobic digestion to produce biogas. The materials for recycling are separated in sorting plant and the remaining wastes are landfilled.
S7	Anaerobic digestion and incineration	The organic portions of municipal waste are separated for anaerobic digestion to produce biogas and the remaining wastes are incinerated to produce energy.

management system, and results in a list of environmental inputs and outputs. Data were gathered from the current Ahvaz waste management center database and literature (Karamouz et al. 2007). The collected information summary is provided in Table 2. Integrated waste management (IWM) software was utilized as life cycle inventory models to estimate emission in each scenario. In this step, the compost, anaerobic digestion, and incineration plants were located at the edge of the landfill for construction wastes of Ahvaz. The average collection and transport distance to the disposal plant was assumed to be 35 km. There is a distance of 500 m from landfill to waste recycle and compost facility as well.

Life cycle impact assessment

This section includes classification, characterization, and weighting steps. Environmental impact categories are defined and used to classify the results of the inventory analysis by IWM in a classification step. A characterization factor which describes the involvement of a given inventory parameter in the allocated impact category provides useful means for quantification. Tables 3, 4, 5, and 6 show the detailed information on the characterization factors for each impact category (greenhouse gas, acidification potential, photochemical oxidation, and eco-toxicity) (Yi and Jang 2016).

Characterization impact (CI_i) can be quantified by the Eq. (1) mentioned below (Yi and Jang 2016):

$$\mathrm{CI}_i = \sum \mathrm{CI}_{ij} = \sum \mathrm{Load}_j \times \mathrm{eqv}_{i,j} \qquad (1)$$

where $\mathrm{CI}_{i,j}$ is the quantity of characterized impact by the jth inventory parameter in the ith impact category (g x-eq/fu, fu = functional unit), Load_j is the value of the jth inventory parameter (g/fu), and $\mathrm{eqv}_{i,j}$ is characterization factor of the jth inventory parameter in the ith impact

Table 2 Summary of the IWM assessment tool inputs

Population	1,200,000
Area	194.94 km^2
Waste generation	292,000 t/year
Organic wastes	201,217 t/year (68.91 wt%)
Paper and cardboard	28,382 t/year (9.72 wt%)
Plastic and PET	28,645 t/year (9.81 wt%)
Metals	7300 t/year (2.5 wt%)
Glass	9431 t/year (3.23 wt%)
Others	25,958 t/year (8.89 wt%)

Table 3 Characterization factors for greenhouse gas in a characterization step

Materials	Conversion factors (unit: kg CO_2 eq/kg)
Carbon dioxide (CO_2)	1.00E=00
Methane	2.10E=01
Nitrous oxide (N_2O)	3.10E=02
CFC-11	4.00E=03
CO	2.00E=00
Tetra chloromethane (TCA)	1.10E=01

category (g x-eq/g). Weighted impact analysis as a way of integration was accomplished by the MET (materials, energy, and toxics) method for five impact categories, as shown in Table 7. Finally, these category scores are summed to produce a single-indicator value (ecological index). Weighted impact (WI) can be calculated using Eq. (2):

$$\mathrm{WI} = \mathrm{W}_i \times \mathrm{CI}_i \tag{2}$$

where W_i is weighting factor of the *i*th impact category in MET model and CI_i is characterized impact of the *i*th impact category obtained from characterization step.

Results and discussion

The normalized results of inventory analysis by IWM per functional unit for eight scenarios are shown in Fig. 3. The considered emissions are greenhouse gases (CO_2 and CH_4), acid gases (NO_x, SO_x, and HCl), smog precursors (NO_x, particulate matter (PM), and volatile organic compounds (VOCs)), heavy metals, and organic substances (Pb, Hg, Cd, dioxins, and biochemical oxygen demand (BOD)) in water and air. Here is the report that can be used to make a comparison between the eight scenarios in each selected impact category. There is an immediate need to implement the new approaches in recycling/recovery processes to achieve a lower energy consumption and emission control (Coelho and Lange 2018). Anaerobic decomposition of landfill waste leads to the release of high amount of by-products such as methane, NO_x, CO_x, and phosphorus and nitrogen compounds (Rana et al. 2019). These pollutants are associated with a series of serious issues including the greenhouse gas (GHG) increase, acidification potential, photochemical oxidation, and eco-toxicity. The effects of emitted pollutants on energy consumption, greenhouse gases, acidification potential, photochemical oxidation potential, and eco-toxicity have been explored and the results are presented in the following sections.

Table 4 Characterization factors for acidification in a characterization step

Materials	Conversion factors (unit: kg SO_2 eq/kg)
NO_X	1.07E=00
SO_X	1.00E=00
Hydrogen chloride (HCl)	8.80E−01

Table 5 Characterization factors for photochemical oxidation in a characterization step

Materials	Conversion factors (unit: kg CH_2 eq/kg)
VOC	6.00E−01
CO	3.00E−01
Methane	3.00E−03
NO_X	2.80E−02
PM	7.00E−02

Energy consumption

In Iran, due to the availability of vast petroleum resources, policy makers have generally ignored energy consumption parameter in their decisions (Abduli et al.

Table 6 Characterization factors for eco-toxicity in a characterization step

Materials	Conversion factors (unit: kg 1,4-DCB eq/kg)
Pb_{Air}	4.70E=02
Hg_{Air}	6.00E=02
Cd_{Air}	1.50E=05
$Dioxin_{Air}$	1.50E=02
Pb_{Water}	1.20E=01
Hg_{Water}	1.40E=03
Cd_{Water}	2.30E=01
BOD_{Water}	1.08E=01
$Dioxin_{Water}$	1.60E=02

Table 7 Weighting factors in MET model (Bosmans et al. 2013)

Category	Weighting factors
Resource depletion	8.80E−01
Greenhouse effects	8.90E−01
Acidification potential	4.00E−01
Photochemical oxidation	2.90E−01
Eco-toxicity	3.00E−01

2011). The energy input which depends on scenarios usually belongs to human labor, electricity, fuels, and transportation. Figure 4 shows the results of energy consumption for each scenario which is directly affected by the quantity of landfilled waste. As seen in Fig. 4, the energy consumption for S3 is more than that for other scenarios due to the lack of energy recovery in landfill and compost processes. Moreover, it is obvious that incineration-based scenarios produce high amount of recoverable energy which is more than other waste-to-energy scenarios. The scenario with incineration and anaerobic digestion (S7) showed the highest energy efficiency and demonstrated the minimal impact on the reduction of non-renewable resources. The highest energy waste in incineration section is related to fuel and electricity consumption (Astrup et al. 2015). In this scenario, organic municipal wastes are converted to energy by anaerobic digestion, and the remaining wastes are used to generate energy by incineration. If the energy consumption was the decision factor and our only concern, then the best available option would have been S7. Previous research indicated that recovery of material and energy in waste disposal had better efficiency in the term of energy saving than other disposal scenarios (Eriksson et al. 2005; Khoo et al. 2012).

Greenhouse gases (CO_2 and CH_4)

The contributions of the scenarios in the greenhouse gas category can also be observed from Fig. 5. In the case of greenhouse gas impact category, the fewest burden was observed in S4, due to reduction of greenhouse gas emissions by recovery of materials as a result of recycling and composting programs. In addition, the waste-to-energy scenarios (S5, S6, and S7) reduced greenhouse gas emissions from energy generation as a result of incineration and anaerobic digestion; therefore, these scenarios can be useful as green technologies. Despite the high contributions from landfill in S2, it was observed to be a less effective option for greenhouse gas control. Moreover, it can be concluded that 50% recovery of landfill gas, compared with the non-recovery of landfill gas, reduced almost 12% of the greenhouse gas production index. The current status of the Ahvaz waste management system (scenario 0) showed poor performance in this case. Consequently, using a new waste management system is essential to reduce the greenhouse gas effect in Ahvaz.

As shown in Fig. 5, landfilling scenario produces more amount of GHG than the incineration scenario. In incineration process, the primary sources of GHG are the burning of materials such as textiles, plastics, woods, or leathers emitting a higher concentration of carbon monoxide and a lower amount of CH_4. Indeed, landfill sites produce higher amount of methane gas compared

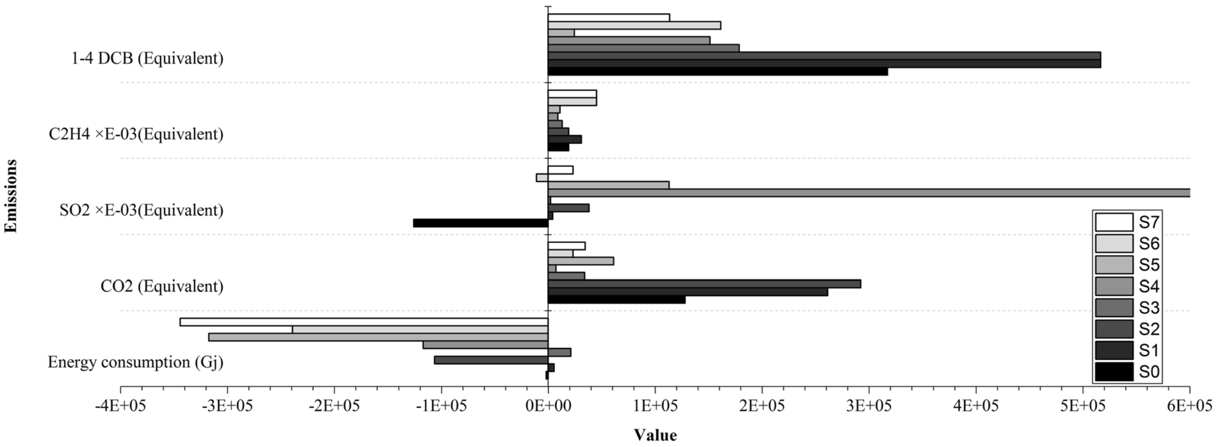
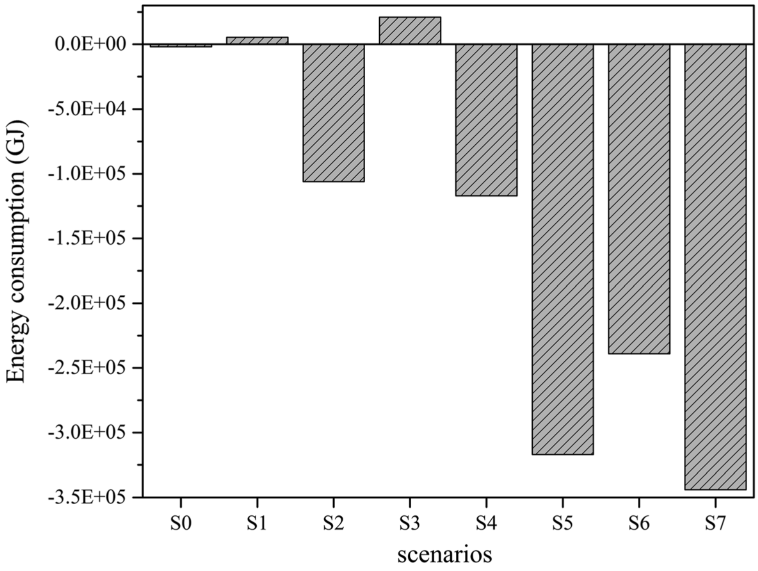


Fig. 3 Emissions and damages normal index for each scenario

Fig. 4 Energy consumption of the eight waste management strategies



with incineration sites (Rana et al. 2019). Therefore, the control of methane emissions at landfill can significantly affect the extent of GHG emission potential (Bueno et al. 2015; Yay 2015). The material recycling methods lead to increase environmental performance (Nabavi-Pelesaraei et al. 2017). As mentioned, zero emissions from landfills are unstoppable even with utilizing advanced technologies; however, the release of methane into the atmosphere can be reduced to some extent via the collection of methane gas though using modern landfills.

Acidification potential

All of the scenarios except scenario 4 approximately illustrated the same tendency for acidification (Fig. 6). Acidification in composting and landfill scenario (S4) is primarily due to NO_x and NH_3 emissions produced during the composting process and has the highest median of acidifying emissions. Composting had a much more unsought acidification impact than landfill and waste-to-energy technologies. The current status of waste management in Ahvaz (S0) is the most

Fig. 5 GHG emissions of the eight waste management strategies

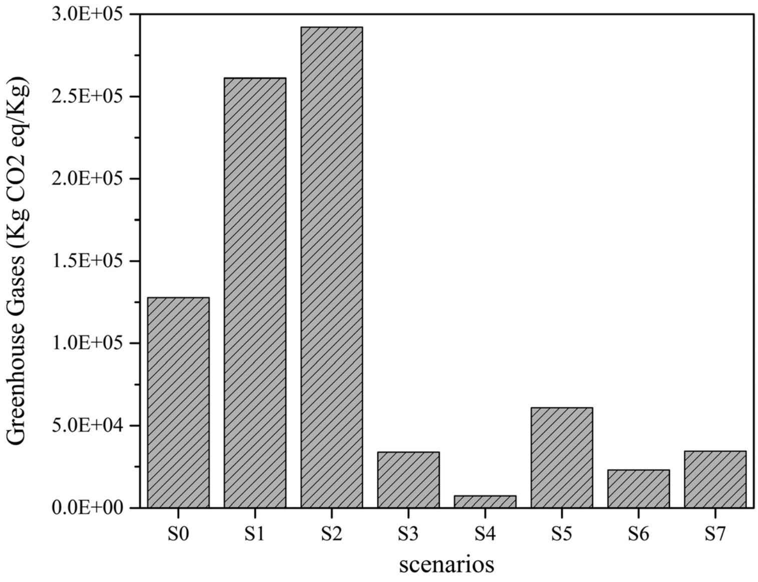
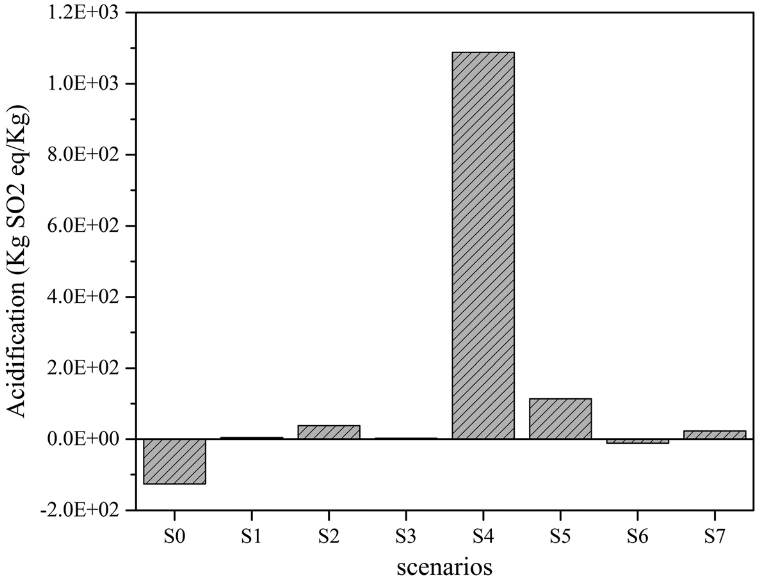


Fig. 6 Acidification potential of the eight waste management strategies



environmentally sound scenario in terms of acidification. The index values for incineration and landfill options obtained in this study are favorably comparable with values reported in previous studies (Nabavi-Pelesaraei et al. 2017; Yay 2015). During incineration process, the content of sulfur and nitrogen in waste get converted to SO_x and NO_x gases, which leads to increase the acidification potential. Indeed, previous studies show the incineration has much higher effect than landfill on the acidification potential (He and Lin 2019; Jeswani and Azapagic 2016). In landfill sites, leachate from landfill sites is big source of hazardous material such as hydrogen sulfide (H_2S) leading to the increase of acidification risk. Therefore, utilizing both recycling and waste recovery can reduce the acidification potential by controlling the oxidation of nitrogen and sulfur (Rana et al. 2019; Coelho and Lange 2018).

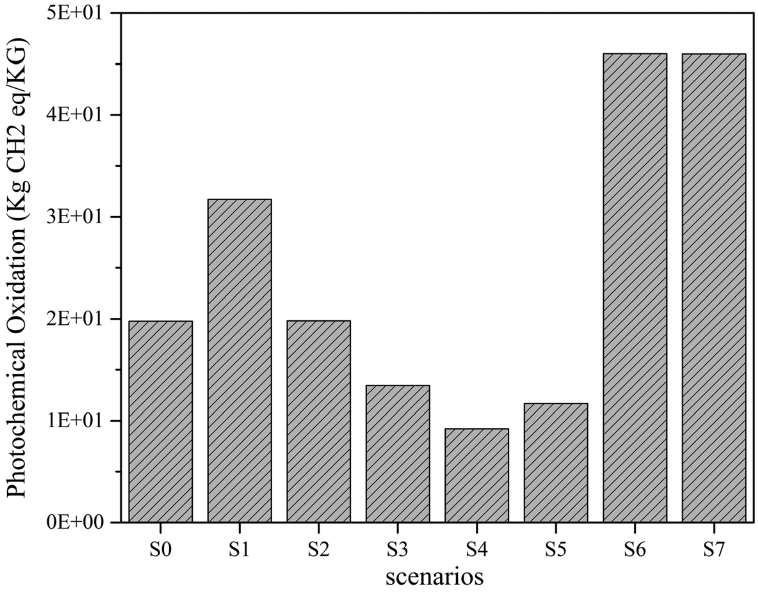
Photochemical oxidation

Increased ozone concentration in the ambient atmosphere is responsible for the photochemical oxidant effect (Banar et al. 2009). The incineration-based and anaerobic digestion–based scenarios (S6 and S7) showed the highest effect. Among the alternative scenarios investigated, S4 had the lowest impact on photochemical oxidant (Fig. 7). Photochemical oxidant effect on landfill-based scenarios was caused by methane production. S6 and S7 showed higher values than other scenarios because of NO_2 emissions and methane production. Although all the scenarios have a negative effect on the photochemical oxidation, the application of alternative approaches for recovery of the organic compounds by recycling or energy production could have a significant effect on the decrease of this index (Ibáñez-Forés et al. 2018).

Eco-toxicity

Eco-toxicity presents negative effect of the chemical elements on ecosystems. The eco-toxicity of the landfill scenarios is several times higher than the alternative ones due to lack of material and energy recycling. This is generally caused by the heavy metals in the landfill leachate. The leachate has a tendency to transport towards ground water, consequently, causing high risk of eco-toxicity (Henriksen et al. 2018; Roumak et al. 2018). Moreover, the recycling process and selective collection of organic waste lead to a lower heavy metal release compared with mixed collection process, resulting in a lower level of eco-toxicity potential (Coelho and Lange 2018). In addition, air pollution, as a result of waste-to-energy technologies, can cause a higher risk of eco-toxicity. The emissions from the stacks such as dust, dioxins, NO_x, CO_x, SO_x, VOCs, and HCl significantly affect the toxicity potential (Beylot et al. 2018; Tong et al. 2018). In all of the investigated scenarios, the results indicate a negative eco-toxicity effect. Also, more potential effects on eco-toxicity of waste-to-energy technologies are caused by air pollution. Scenarios 1 and 2

Fig. 7 The photochemical oxidant effect of the eight waste management strategies

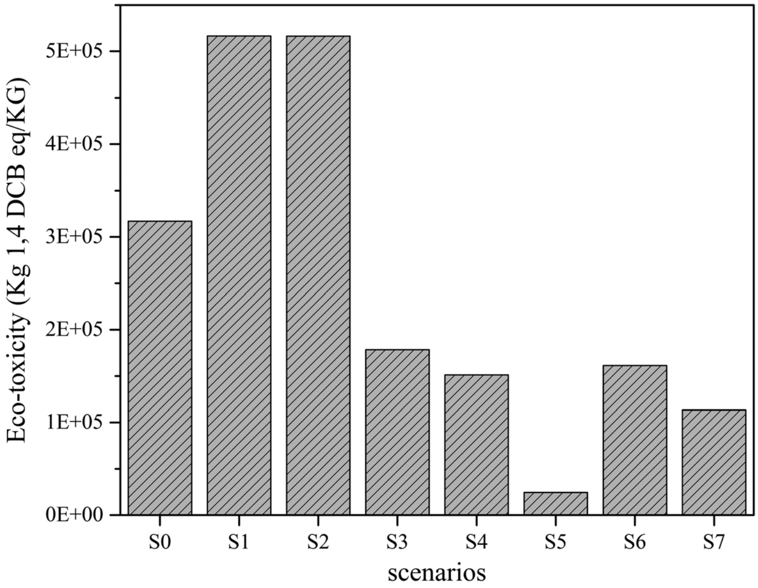


had a more undesirable impact on eco-toxicity damage to the ecosystem (Fig. 8). Scenario 5 (composting and incineration) showed the least significant effect on eco-toxicity damage. In addition, the current status of waste management in Ahvaz requires fundamental alterations for eco-toxicity impact to be controlled.

Ecological index

The ecological index of the environmental burden in waste management scenarios is considered as all the environmental output of the waste life cycle. The results of this index provided comprehensive environmental information helpful for selecting the optimum waste management process in each phase. Figure 9 shows the impact of various scenarios on all the environmental categories and provides a complete picture for informed decision-making. The results showed the waste-to-energy-based scenarios protected non-renewable resources and decreased output emissions. Therefore, based on Fig. 9, combined utilization of incineration and anaerobic digestion technologies (S7) was

Fig. 8 Eco-toxicity potential of the eight waste management strategies



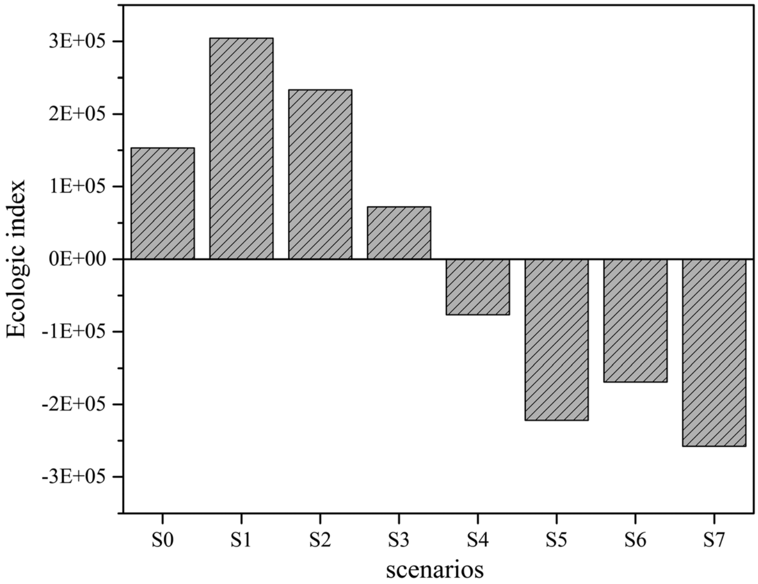


Fig. 9 Ecologic index for the eight waste management strategies

nominated as the appropriate superseded solid waste management system among the other scenarios. Landfill-based scenarios noticeably yield the worst environmental results as seen from the higher ecological index of scenario 1 (landfill with biogas collection) compared with the other scenarios. Therefore, S1 has the highest negative impact from an environmental perspective. In addition, the current waste management program in Ahvaz has higher value in ecological index due to its emphasis on landfilling. This approach has to be improved by introducing alternative waste-to-energy technologies to decrease air pollution emissions.

Conclusion

This study introduced seven different commonly used MSW management scenarios and also analyzed the existing MSW management system in Ahvaz. The results were characterized and compared with each other in order to provide useful and scientific information for policy makers in Ahvaz when and if they face making decisions regarding the construction of MSW treatment plants. The main conclusions from this study are as follows:

- Scenario 7 (incineration and anaerobic digestion) was the most feasible management strategy due to the recovery of energy.
- In the case of energy use, scenario 3 (composting and landfilling without biogas collection) revealed high energy consumption values due to the low energy recovery. Moreover, in this case, waste-to-energy-based scenarios showed appropriate performance.
- The minimum amount of final eco-toxic solid waste was achieved from scenario 7. The highest amount of eco-toxic solid waste was produced in scenario 1, which caused higher toxicity impacts.
- In terms of the greenhouse gas effect, scenario 4 (recycling, composting, and landfilling) was found to be the most feasible system. Waste-to-energy-based scenarios showed better results compared with the other scenarios.
- In terms of acidification potential, scenario 4 was found to be exerting the most impact due to NO_x and NH_3 emissions during the composting process.
- The highest photochemical oxidant impacts were caused by thermal treatment cases and anaerobic digestion, scenarios 6 and 7, due to high pollution emission production. The fewest contributors in terms of photochemical oxidants were detected to be scenario 4.

Overall, scenario 7 was found to be the scenario with a minimum contribution in all the impact categories (except in the category of photochemical oxidant). Therefore, a combination of incineration and anaerobic digestion technology is determined to be the best alternative for the current waste management system in Ahvaz with respect to environmental concerns.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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