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Application of Life Cycle Assessment for Techno-Economic Evaluation of Rural Solid Waste Management Strategies: Significance of CO_2 Emission Control from Waste Management Sector in Abyaneh Village, Isfahan Province

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Abstract
Waste disposal in the current situation, which quantity and variety of waste are increasing, needs not only effective management principles but also depends on environmentally-friendly methods to put as less environmental footprint as possible. This study aims to assess the energy consumption, emission of greenhouse gases and air pollutants which normally produce during various waste management scenarios in Abyaneh. The next objective of this research is to choose the best management method and practice which is completely compatible with the environment. In order to reach these goals, after sampling and waste analysis in terms of quantity and quality, results analysis for nine scenarios was conducted. These scenarios, considered for life cycle assessment, are combination of four waste disposal methods including landfill, recycling, composting and incineration. Life cycle inventory was done by IWM-1 model. The potential of economic saving and greenhouse gases and air pollutants emission reduction in various waste management approaches in Abyaneh were evaluated. It was shown that scenarios number 6, 5 and 2 with combination of landfill, recycling and composting methods have the least negative impacts on the environment. Also, the mentioned scenarios were found to be cost effective as they are not accompanied by greenhouse gas and acid gas emission. As produced waste in Abyaneh is consisted of 38.8% and 59% recyclable and compostable waste respectively, the mentioned scenarios can be viable options for effective waste management and can play an important role in reduction of environmental problems in this village.

Keywords: Rural waste, Life cycle assessment, IWM-model, Abyaneh village, Economic saving

Introduction

Globally, waste production trend is on the rise. Rapid urbanization, higher income and welfare levels in communities, rapid economic and social growth and changes in consumption patterns not only increase the quantity of produced waste, but also lead to a change in the quality of wastes (Fiorentino et al. 2015; Nabavi-Pelesaraei et al. 2017). These changes will result in the

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emergence of new pollutants and the possibility of creating many health and environmental hazards (Stamou and Antizar-Ladislao, 2016). Generation of waste seems to be an inevitable phenomenon in societies and its optimal management is one of the main necessities for all societies (Worrell and Vesilind, 2002). Based on the quantity of produced waste, there are various options for waste management in the solid waste management system. These options not only have economic costs, but also include a variety of environmental impacts (Elwan et al. 2015). Selecting the right options requires reliable decision-making tools. Life cycle assessment is a valuable tool that has been introduced and used in the last decade in order to help decision makers for comprehensive waste management planning from environmental perspectives (Fernandez-Nava et al. 2014; Ripa et al. 2017; Kulczycka et al. 2015). Life cycle assessment covers the potential environmental impacts during the life cycle of a product including raw materials, the way the raw materials used, end of life, recycling and final disposal (Hong et al. 2017; Ning et al. 2013).

In the recent years, life cycle assessment has been used in various studies in order to compare different solid waste management methods in numerous countries such as London (Parkes et al. 2015; Al-Salem et al. 2014), Brazil (Coelho and Langea, 2016; Oliverira et al. 2016), China (Hong et al., 2017; Chi et al., 2015), Turkey (Ozeler et al., 2006; Suna-Erses-Yay, 2015) and Iran (Nabavi-Pelesaraei et al. 2017; Rajaeifar et al. 2015). For instance, a comparison between different solid waste management scenarios in the London Olympic Park was shown that advanced heat treatment and burning scenarios along with energy recovery are the most environmentally friendly strategies among other scenarios and compared to direct landfill (Parkes et al. 2015). Energy production from renewable energy sources such as biogas has been paid considerable attention in both developed and developing countries in recent years (Komendantova and Yazdanpanah, 2017; Vahidi et al., 2017; Sadat Majidi and Kamalan, 2017). However, the study in Sao Paulo state in Brazil showed the same result for domestic composting scenario (Oliveira et al. 2016). Also, in Hangzhou,China and Ankara,Turkey scenarios for source reduction and the use of biodegradation methods and anaerobic digestion processes were shown to play an important role in reducing environmental impacts (Chi et al. 2015; Ozeler et al. 2006). In studies conducted in Iran, anaerobic digestion methods, burning and combination of burning and composting have shown the least adverse environmental impacts (Rajaeifar et al. 2015).

The production of various solid waste materials and concomitant social, economic, and environmental challenges result in many problems in the collection, transport, processing and disposal of waste (Wang et al. 2015; Guereca et al. 2015). Assessing the environmental impacts of waste management cycle plays a significant role in reducing and solving waste management problems (Suna-Erses-Yay, 2015). Therefore, the purpose of this study was to investigate the environmental impacts of different waste management scenarios in Abyaneh in terms of energy consumption, greenhouse gases emissions, acid gases and smog precursors using life cycle assessment approach.

Material and Methods

Case study

The study area in this research is Abyaneh, a village in the central part of Natanz city in Isfahan province. The village is located in the 40 kilometers northwest of Natanz, on the slopes of Karkas mountain, between 51.52923° E longitude and 33.5853° N latitude. Abyaneh is one of the highest residential spots in Iran, reaching 2222 meters above sea level. This village is considered to be one of the renowned villages of Iran due to its traditional architecture and historical places and has moderate climate with a stunning natural landscapes. The tourism industry boom in Abyaneh has generally eliminated agricultural and farming activities in the village. On the other hand it has considerably increased the number of visitors, which inevitably leads to a rise in urban waste production in the village.

Waste sampling

In this study, the selected method for assessing the environmental characteristics of various waste disposal scenarios was life cycle assessment. In order to achieve this goal, it is necessary to determine the quantitative and qualitative characteristics of the produced waste within the study area. Waste quantity was quantified using weight-volume analysis. The sampling was carried out by measuring and weighing the truck load. Referring to the waste disposal site, the garbage truck was discharged and after mixing, the waste was first divided into four equal parts, and then one of the four parts was again divided into four equal parts. This division continued until the sample weight reached to 100 kg (Tchobanoglous et al. 1993). In order to measure the quality of the waste, the sampling container was placed in a flat surface without waste, soil and stone. Following that, separation and weighing was done. In fact, the trash bags were torn and their contents were evacuated. The garbage contents were separated and each part was placed in a specific location. After separation of samples, each part was put into one or more plastic bags and weighed using 0.1 kg accuracy scale.

Integrated waste management (IWM) model

Life cycle assessment was carried out using the IWM-1 model for the considered scenarios. This proposed model by White et al. In 1995 (Chang and Pires, 2015) is one of the life cycle assessment models that can be used to define different waste management scenarios and to compare the environmental impacts of each scenario (Evangelisti et al. 2015; Huang and Chuieh 2015; Allegrini et al. 2015). This model consists of two environmental and economic sub-models, of which only its environmental model was used for the current study. In environmental sub-model of life cycle, the waste stream is investigated from the point of production to the final disposal. Each stage in waste management cycle is presented separately. In order to specify the condition of each management system, the provided questions in the system should be answered. The final results presented by the model are the life cycle inventory (Nabavi-Pelesaraei et al. 2017).

Reducing of greenhouse gases and air pollutants emissions and cost savings from them as a result of various waste disposal scenarios in Abyaneh

Following the life cycle assessment for each considered scenario, the reducing of greenhouse gases and air pollutants emissions and cost savings from them were calculated based on the studies in Environmental Protection Agency of Iran (table 1).

Table 1. Cost savings from reducing of greenhouse gases and air pollutants emission (Deputy for Power & Energy Affairs of Iran, 2015)

Type of gas	Cost (kg/Rial)
NO_X	6000
SO_X	18250
CO	1875
SPM	43000
CO_2	100
CH_4	2100

Result and discussion

Waste composition and quantities

Waste collection with different frequency per week was observed in Abyaneh. Typically, on a monthly basis, the waste collection frequency was three times per week with total weight of three tons. However, on weekends (Thursday and Friday) and on official holidays, due to large number of tourists in the village, the frequency of garbage collection was three times a day with the total weight of three tons. The quantity of produced waste in the studied period (one year) was estimated to be 566.4 tons, which was used as a functional unit at the input of the life cycle assessment system. The composition and quantities of produced wastes in Abyaneh is given in table 2.

Table 2. Waste components and characteristics in Abyaneh

Waste type	Weight (%)
Food waste	59
Plastic	24
Paper & Cardboard	9
Ferrous & Non-ferrous metals	2.8
Textile	1.2
Glass	3
Wood	1
Total	100

Definition of solid waste management scenarios

Result analysis of collected waste samples was used as raw input data for IWM-1 software in order to compare nine different waste management scenarios. These scenarios include combination of four disposal methods such as landfill, recycling, composting and incineration. In each scenario the energy consumption, emission of greenhouse gases, acid gases and smog precursors were investigated. The considered scenarios are presented in table 3.

Table 3. Nine scenarios of waste management systems used for Abyaneh

Scenario	Composting (%)	Recycling (%)	Incineration (%)	Landfill (%)
1	-	-	-	100
2	-	20	-	80
3	30	-	-	70
4	50	-	-	50
5	30	20	-	50
6	50	20	-	30
7	-	-	20	80
8	30	-	20	50
9	50	-	20	30

In 1st scenario illustrates the current waste management system in Abyaneh. In this method, waste is collected as a mixture and directly transported to the landfill. Landfill site is without liner and gas collection system. 2nd to 6th scenarios were considered to evaluate the impact of recycling and composting processes on solid waste management systems. Paper, iron, aluminum, glass and plastic were selected for the recycling process. In material recycling facilities, the remainder of the waste was buried in landfill. Considering the high level of food waste in the waste composition of Abyaneh (59%), only this part was considered for composting. Windrow method was selected for composting of food waste. 7th to 9th scenarios were considered to investigate the effect of waste incineration on the energy recovery from waste. Energy recovery from waste was considered for electricity generation. Electricity generation methods were considered by nine different scenarios analyzed in the solid waste management system according to the electricity production sources in Iran, as shown in table 4.

Table 4. Sources for the average Iran electricity mix (Tavanir holding company, 2015)

Source	Contribution (%)
Natural Gas	74
Heavy Fuel	11
Diesel & Light fuel oil	9
Hydro	5
Nuclear	1

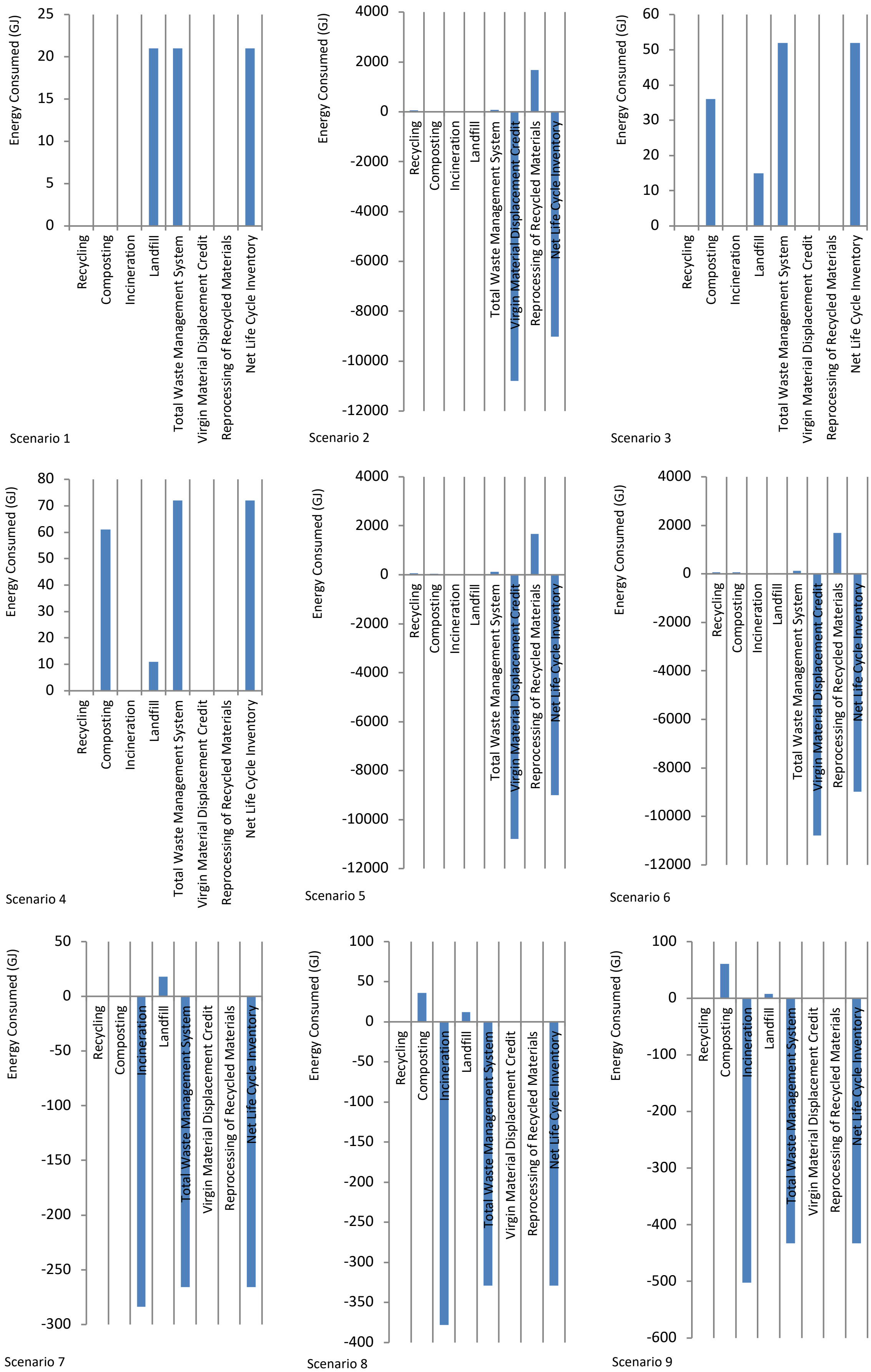
Inventory results

The IWM-1 model was developed for each of the nine scenarios in table 3 and the environmental impacts of each scenario in four impact categories based on energy consumption, greenhouse gas emissions, acid gases and smog precursors was evaluated.

Energy Consumption

The total energy consumption for each waste management scenario in Abyaneh is shown in Figure 2. The total waste management system presented by the IWM-1 model accounts for total amount of consumed energy for collecting, transporting, disposal and reprocessing the wastes. Virgin material displacement credit indicated energy consumption reduced and energy recovery by processing and recycling of materials. The difference between virgin material displacement credit and total waste management system is defined as net emission statistics. Some numbers are indicated as a negative value, indicating a net reduction in the amount of consumed energy.

In 1st scenario all wastes are collected and transported directly to the landfill. Therefore, energy consumption during this scenario accounts for consumed energy to collect and transport waste to landfill. Due to the fact that processing and recycling of wastes was not considered, no excess energy or by-product was produced. Therefore, the consumed energy in this scenario was not recovered and the net life cycle inventory and total waste management system are equal. In 2nd scenario, the quantity of waste transported to landfill reduced since recycling option (20%) was considered in this scenario, which in turn reduces the quantity of energy consumed for landfilling. Energy consumption in the recycling section is associated with consumed energy in the collection and transport of wastes to the material recovery facilities. In this scenario, some amount of energy was consumed in the reprocessing section and more energy conservation was achieved. Energy recovery was achieved as new materials were produced by recycling and replacement of these materials with raw materials consumed in the life cycle. Therefore, net life cycle inventory was reduced and energy was recovered. In 3rd and 4th scenarios, 30% and 50% of compost production was included in the management plan, respectively. Therefore, some quantity of the consumed energy in these scenarios was allocated to the facilities in this section. This amount of energy together with the used energy for waste landfilling are form the total waste management system in these scenarios. Energy saving in these sections can be achieved through the production of compost and other useful by-products.



Figures 2. Energy consumption for nine waste management scenarios in Abyaneh

However, the energy recovery in these scenarios are not effective enough to be able to reduce the total energy consumption, indicating the net life cycle inventory in these two scenarios is positive. In 5th and 6th scenarios, 20% recycling was added to the previous management plans (3rd and 4th scenarios) and some parts of consumed energy was defined for recycling facilities in this section. This amount of energy together with the energy used in landfill and composting site accounts for total waste management system. Energy recovery in these two scenarios can be achieved by the composting and new materials by recycling. 20 % incineration with energy recovery was considered in management plans of 7th scenario. The same as previous plans, some amount of energy was allocated for required energy recovery facilities in this scenario. Due to the energy production in this scenario, an increase in energy compensation and consequently a negative value for net life cycle inventory was observed. In 8th and 9th scenarios, in addition to 20% incineration, 30% and 50% composting was included in the management plan. The total waste management system in these scenarios consisted for the amount of energy consumed required by composting, landfilling and energy recovery. Energy recovery in these scenarios was accomplished by composting and energy production.

Greenhouse gases emission

Waste disposal is accompanied by gas emission, which accounts for about 50% CH_4 and 50% CO_2. The production of these gases is mainly accompanied by waste collection, transportation and energy consumption in material recovery facilities. Incineration and aerobic composting of wastes can also produce CO_2 (Wang et al. 2015; Liu et al. 2017). Both of these gases are considered as important greenhouse gases and are known as indicators of climate change. However, CH_4 is considered to be a stronger greenhouse gas due to its global warming potential of 24.5 times greater than CO_2 (Fisken et al. 2000; Lee et al. 2016). The greenhouse gas emission in the nine waste management scenarios in Abyaneh is shown in Figure 3.

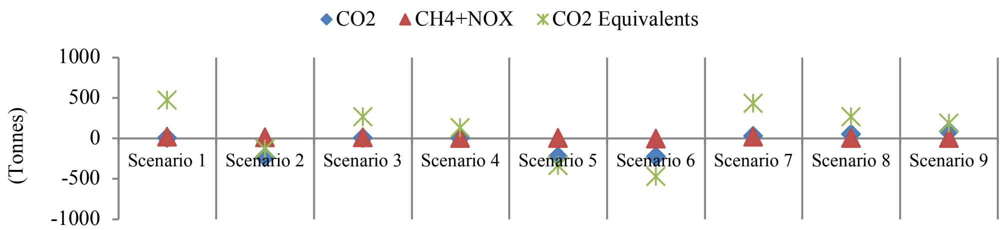


Figure 3. Greenhouse gas emissions in nine different waste management scenarios in Abyaneh

According to Fig.3, the highest emission level of CH_4+NO_X was associated with 1st scenario where landfill is the only waste disposal method. In other scenarios when less amount of waste was transported to landfill, the emission of these gases reduced. Accordingly, scenarios number 7,2,3,8,4 and 5 were ranked second to seventh in terms of CH_4+NO_X emission, respectively. The most CH_4+NO_X emission saving is in 6th scenario as a result of combined composting, recycling and landfilling methods. Also this scenario has the highest amount of CO_2 emission saving. Subsequently, scenarios 5 and 2 were ranked second and third in terms of CO_2 production, respectively. According to the figure, the increased amount of composting was associated with a reduction in greenhouse gas emission. Therefore, emission of greenhouse gases in each of the two 3rd and 4th scenarios (including a combination of composting and landfill method), 5th and 6th scenarios (including a combination of composting, recycling and landfill method) and 8th and 9th scenarios (including the combination of incineration, composting and landfill methods) significantly decreased. This is because composting was increased from 30% in 1st scenario to 50% in the 2nd scenario.

Acid gases emission

The acid gases emitted from solid waste management processes are mainly the result of transport, energy consumption, incineration and landfill gases. The emission of acid gases is considered as an indicator of acid rain. These gases also have the potential to negatively affect the human health (Fisken et al. 2000). The amount of acid gases in nine waste management scenarios in Abyaneh is shown in Fig.4.

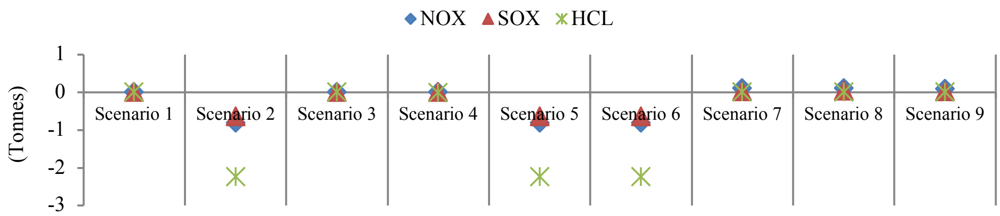


Figure 4. Acid gas emissions in nine different waste management scenarios in Abyaneh

According to Fig.4, the highest NO_X, SO_X and HCL emission in 7th, 8th and 9th scenarios (including combination of incineration, composting and landfilling methods) was observed. This is because these scenarios involved transportation requirements and incineration, which are the main source of acid gas production. In 3rd and 4th scenarios (including combination of composting and landfill methods) and 5th and 6th scenarios (including combination of composting, recycling and landfill methods), emissions of these gases insignificantly changed since transportation requirements in these scenarios were similar. Acid gas emissions saving was observed in 2nd, 5th and 6th scenarios. Recycling facilities and composting in these scenarios mainly contributed to the reduction of acid gas emission.

Smog precursors emission

Smog consists of ground level ozone and inhalable particulates (or PM-10). Ground level ozone is produced when NO_X and VOC_S react in the air in the presence of light. The biodegradation of waste in landfills is an important source of VOC_S within the waste management system. Landfill operations also produce PM-10. The combustion of waste in energy recovery facilities produces PM-10, VOC_S and NO_X (Fisken et al. 2000). The emission of smog precursors in the nine waste management scenarios in Abyaneh is shown in Fig.5. According to this figure, a sharp decrease in emission of NO_X, PM and VOC_S can be seen in 2nd, 5th and 6th scenarios. This suggests that deployment of material recovery and composting facilities can play a significant role in reducing the release of these gases to the environment.

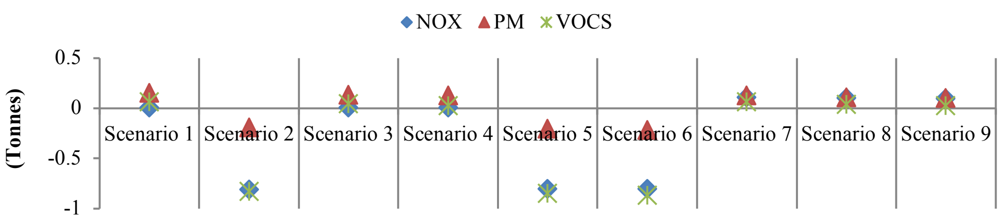


Figure 5. Smog precursors emissions in nine waste management scenarios in Abyaneh

Evaluation of potential economic saving and emission reduction in various waste management approaches

Waste is collected as a mixture and directly transported to the landfill in the current waste management system in Abyaneh. The greenhouse gas and air pollution emissions resulting from this method of waste disposal (1st scenario) is shown in Table 5.

Table 5. Greenhouse gases and air pollutants emissions from 1st scenario

Scenario	Type of gas	Gas emission (tonnes)
1	CH_4	21.993
	CO_2 Equivalents	470
	NO_X	0.007
	SO_X	0.004

The reduction of greenhouse gas and air pollution emissions in 2nd to 9th scenarios (including the combination of landfill, recycling, composting and incineration methods) and cost saving from them were relatively calculated to 1st scenario (100% landfill) and shown in table 6.

Table 6. Variation of cost saving and emission of greenhouse gases and air pollutants in alternative disposal scenarios

Scenario	Type of gas	Emissions reduction (tonnes)	Cost saving (Rial)
2	CH_4	5.186	10890600
	CO_2 Equivalents	601	60100000
	NO_X	0.814	4884000
	SO_X	0.645	11771250
3	CH_4	10.003	21006300
	CO_2 Equivalents	204	20400000
	NO_X	- *	-
	SO_X	-	-
4	CH_4	16.006	33612600
	CO_2 Equivalents	340	34000000
	NO_X	-	-
	SO_X	-	-
5	CH_4	15.19	31899000
	CO_2 Equivalents	805	80500000
	NO_X	0.810	4860000
	SO_X	0.639	11661750
6	CH_4	20.192	42403200
	CO_2 Equivalents	941	94100000
	NO_X	0.808	4848000
	SO_X	0.635	11588750
7	CH_4	4.103	8616300
	CO_2 Equivalents	33	3300000
	NO_X	-	-
	SO_X	-	-
8	CH_4	13.1	27510000
	CO_2 Equivalents	201	20100000
	NO_X	-	-
	SO_X	-	-
9	CH_4	18.094	37997400
	CO_2 Equivalents	282	28200000
	NO_X	-	-
	SO_X	-	-

* No variation was obtained

According to table 6, in 2nd to 9th scenarios, cost saving was achieved due to the reduction of CH_4 and CO_2 emission. The highest financial value associated with reduction of CH_4 and CO_2 emissions was achieved in 6th scenario with 42403200 and 94100000 Rial, respectively. The associated cost saving of NO_X and SO_X emission was only observed in 2nd, 5th and 6th scenarios. 2nd scenario had the highest associated cost saving with NO_X and SO_X emission, reaching to 4884000 and 11771250 Rials, respectively. 5th and 6th scenarios were ranked as second and third in terms of cost saving, respectively.

Conclusions

All activities involved in solid waste management are not only accompanied by economic burden, but also can bring about serious environmental problems in case relevant technical principles are not considered. Waste disposal in the current situation, which quantity and variety of waste are increasing, needs effective management principles and environmentally-friendly methods to decrease the environmental damages as less as possible. Lifestyle change and energy consumption enhancement necessitate utilization of alternative energy sources in the upcoming years as well as reduction of waste generated from various sectors such as household waste through application of proper management strategies. Effective planning is one of the most important steps in waste management process. In fact, this is a step in which different needs of societies in terms of solid waste management are evaluated and viable options are proposed to decision-makers. Life cycle assessment is one of the previously developed method for management planning. In this study, life cycle assessment was used to gain a valuable insight about different waste management scenarios in Abyaneh village and to choose the most environmentally-friendly plan among different options. In order to achieve this goal, quantity and quality of waste products were characterized in Abyaneh. The results of this analysis was further used for life cycle assessment of nine different waste management scenarios including the combination of landfill, recycling, composting and incineration. The IWM-1 model was considered in this study in four impact categories including energy consumption, greenhouse gases, acid gases and smog precursors. It was found that in six scenarios energy recovery and negative net life cycle inventory can be achieved in energy consumption category. In 2nd, 5th and 6th scenarios this energy compensation was achieved through the production of new materials by recycling and composting, and in 7th, 8th and 9th scenarios this energy compensation was achieved through energy recovery and composting. 2nd, 5th and 6th scenarios were ranked in the first to third place in terms of energy consumption saving, respectively. In the greenhouse gas emission category, saving in CH_4+NO_X emissions in 6th scenario and saving in CO_2 emissions in 6th, 5th and 2nd scenarios were observed, respectively. This was achieved through the recycling of materials, composting and the reduction of waste stream toward disposal site. In acid gas category, saving in NO_X and SO_X emissions in 2nd, 5th and 6th scenarios were observed. Also, HCL emission saved in 6th, 5th and 2nd scenarios. This saving in acid gas emission was mainly achieved through recycling facilities and compost production in mentioned scenarios. In smog precursors category, NO_X emissions were saved in 2nd, 5th and 6th scenarios, respectively, and a fall in release of PM and VOCs was observed in 6th, 5th and 2nd scenarios, respectively. Also the highest cost saving associated with reducing of NOx and CO_2 emission was observed in 6th scenario and the highest cost saving due to the reduction of NO_X and SO_X emission achieved in 2nd, 5th and 6th scenarios, respectively. According to these results, 6^{th}, 5^{th} and 2^{nd} scenarios, with a combination of disposal methods such as recycling, composting and landfill, have the least damage to the environment in all categories. Due to the fact that recyclable materials and compostable materials account for a significant proportion of the waste composition in Abyaneh, i.e. 38.8% and 59%, respectively, applying the considered scenarios can be an appropriate option for the effective solid waste management in this village. It should be noted that the result of the present study is only concerned with the current waste management system in Abyaneh village. In fact, rural waste management in each region needs specific management principles in which quantity and quality of the produced waste in relevant region is taken into account. Based on the obtained results it is also suggested to plan appropriate strategies to practically establish energy production schemes from waste sector in rural areas that needs comprehensive studies and planning in the following years.

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