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Estimation and Modeling of Biogas Production in Municipal Landfill

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ABSTRACT

The municipal solid waste in Landfill is transformed into landfill gas during a biochemical conversion process called bio-degradation .Gas release from landfills has potentially different environmental effects; therefore, assessing and forecasting the rate of production and release of gas from landfill sites is important for designing these sites and for the successful exploitation of gases as energy sources. In this study, by using LandGEM model, in the span of 2018-2037, the amount of gases produced from the municipal landfill of Sirjan, Iran has been predicted. According to the results, the largest amount of landfill gas emission will be in 2038, a year following the last year of disposal of the waste to the landfill. The total amount of produced gas, carbon dioxide, methane, and NMOCs will be 1.219E+05, 8.932E+04, 3.255E+04, and 1.399E+03 tons per year in 2038 for Sirjan. In the next step, the LandGEM outputs were imported into OpenLCA software. The health and environmental effects of landfill gas emissions were evaluated by USEtox and traci method, respectively, in this software. According to the USEtox method, the value of total health effects was obtained as 0.032496 CTUh; in addition, by using the traci method, the most environmental burden falls in the impact categories of global warming, photochemical ozone formation, ecotoxicity, acidification, respiratory effects. By making sound and suitable plans as of this 20-year period and implementing tube in this place, greenhouse gas emissions to the atmosphere can probably be prevented. It is also suggested that landfill gases be used to supply energy to the Sirjan recycling plant.

1. INTRODUCTION

The continuation of human life depends on continuous consumption and the production and discovery of new materials; thus, waste remains wherever consumed [1,2]. Human beings have always faced the problem of waste and how to get it off the environment. The population increase, migration to large cities, population density in cities, rising living standards, increased consumption of citizens, and the production of consumer products have led to mass production of waste [3,4,5].

Lack of attention to the collection and disposal of waste materials in today's society due to the quantity and quality of materials, the excessive development of cities, and the limitations imposed on public services in large cities, as well as the lack of appropriate technology, has created new problems that can be addressed. It is possible to solve these problems through the coordination of science and experience within a framework of proper management [6,7].

Different wastes are the inevitable results of widespread use of chemicals and industrial and agricultural products in everyday life. Global experience has shown that if waste is not managed properly and these materials are not converted to less risky materials, or not repelled in an appropriate manner, they will be a source of great danger and numerous threats[8] Inappropriate waste management problems include soil erosion, air pollution, increased greenhouse gases, production of leachate, contamination of groundwater table, dispersal of wastes, inadequate environment for life, climate change, ozone depletion, human health damage, and damage to the ecosystem; in addition, leachate contains heavy metals such as arsenic, barium, chromium, copper, iron, nickel, and zinc [9,10,11].

Due to the numerous negative effects of urban waste generated, the need for proper management and appropriate strategies to minimize these effects and improve the environment is highly felt. In this regard, the application of environmentally scientific methods can provide sufficient assurance of compliance with the policies and objectives set in the plans and activities of the projects in order to provide the criteria and environmental laws [12].

There are several mathematical models to predict the emissions of waste management plans and options. The most important and most flexible of them is Landgem. This model was developed by the US Environmental Protection Agency that provides a very accurate estimate of the amount of landfill gas produced over the years.

The municipal solid waste in landfill is transformed into landfill gas during a biochemical conversion process called bio-degradation, involving several continuous steps [13]. Landfills gas release has potentially different environmental effects, the most important of which include fire hazards and releases, health hazards, plant degradation, groundwater pollution, an unpleasant odor, and global impact on climate change [14,15].

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Another problem with municipal solid waste in landfill is the organic biodegradation of waste that leads to the release of methane and other gases. Landfill gas is the product of decomposing waste corrosion, containing 40-60 % methane, carbon dioxide and various amounts of nitrogen, oxygen, water vapor, sulfur, etc. [16,17].

In Iran, the use of biogas dates back to three centuries ago. Landfill gas control began in the late 1960s and early 1970s in the United States, where huge burial grounds were created. The first device in Europe was used in the mid-1970s with the help of the great experience of the United States in Germany. Then, landfill technology expanded to all of Europe and other countries. In developed countries, landfills are designed in a way that the maximum energy derived from them can be exploited [18].

Omrani et al. (2004) evaluated methane gas released from the Shiraz landfill site. This study utilizes Landgem software package, considers the volume of methane content as 61 %, and calculates the potential coefficient of gas production and the constant production rate of methane as 164 m^3/Mg and 0.06, respectively. In this study, the emission of gas and pollutants from the landfill site of Shiraz are reviewed [19].

Anwar (2012), in a research piece, calculated methane gas from Peninsula Landfill in Malaysia in 2010 and made predictions for 2015 and 2020, concluding that methane emissions in this landfill in 2010 were estimated as 3,10220 tonnes; it is expected that at least 370 thousand metric tons of methane will be produced for the year 2020 [20].

Capellia et al. (2014) conducted landfill emission surveys to measure the gas emission from solid wastes at the landfill site in northern Italy. Before starting the experiments, the Landgem model was used to evaluate the production of methane. based on the results, the landfill gas production in 2014 was estimated at 28530 Mg/year [21].

This paper aims to estimate the amount of generated gases, such as methane, Carbon dioxide, and NMOCs, during the years after waste disposal (waste disposal lasts from 2018 to 2037) in landfill of Sirjan city by predicting future waste production using a LandGEM simulation model and, also, assessing their toxicity impacts on humans and the environment by USEtox and Traci method, respectively.

2. METHODS

2.1. Study area

Sirjan is one of the oldest cities in Kerman province with an area of 17481 square kilometers, equivalent to 7.16 percent of the total area of the province. According to the questionnaire completed by the Sirjan municipality, the population of the city of Sirjan has been declared to be 220000 people. The total number of households in Sirjan has been announced at 73560 households. Sirjan weather is cold in the winter, hot and dry in the summer, and moderate in the spring. The average humidity is 36 % and the average annual rainfall is 142 mm. Sirjan is one of the major agricultural centers in Kerman Province, which plays a major role in agricultural production, especially pistachio production. Sirjan region is rich in minerals including Golgohar iron mines due to the special geological situation, which is more volcanic and filled with igneous rocks. In recent years, the Sirjan city industry has made some progress, including the exploitation of the industrial complex (Gol Gohar) and industrial park, which includes gypsum manufacturing, plastics, ceramic, and bolt industry [22].

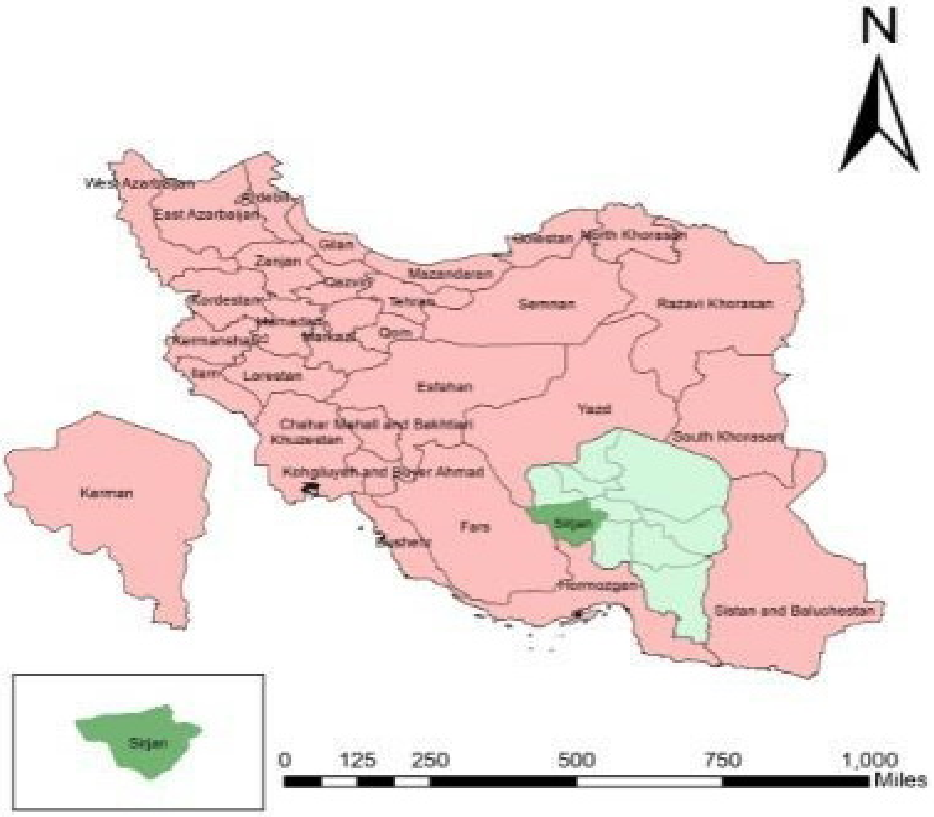

Figure 1. location of Sirjan city in Kerman Province.

2.2. Waste composition

The physical quality of the waste from the city of Sirjan is shown in Table 1. As is clear, organic materials with 68.4 percent are the largest amount of urban waste from Sirjan. The amount of waste produced in Sirjan is on average 150.511 tons per day and the waste generated per person is 685 grams per day.

Table 1. MSW components and characteristics in Sirjan city.

Type of waste	Mass of waste(kg/day)	Waste weight percent
Metals	3656	204
Glasses	3056	2
Other	13545	9
Textiles	2040	1.4
Plastic and PET	12708	8.4
Paper and cardboard	12616	8.4
Organic materials	102890	68.4
Total	150511	100

2.3. LandGEM model

LandGem model is provided by the US Environmental Protection Agency. This model follows the first-order relationship of the monod. LandGem estimates the methane gas mass per tonne/year or mega gram per year using intrinsic power and the mass of waste deposited [23]. The general corresponding formula is as follows (1):

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} K L_0 \left(\frac{M_i}{10} \right) e^{-kt_{ij}} \qquad (1)$$

Q_{CH_4}= Predicted annual production of methane, i= Annual intervals , n= difference between the predicted and first years of waste disposal, j= 0.1 (increase within the studied years), k= methane production constant (1/year), L_0= methane production potential (m^3/Mg), M_i= weight of waste accepted in the i^{th} year (Mg or ton), and t_{ij}= the j^{th} section's age of M_i waste mass in the i^{th} year.

The LandGEM package is provided by the US Environmental Protection Agency's Technology Control Center and can be used as an automatic estimation tool for modeling the emissions from municipal solid waste landfills. The cases that are considered as inputs of the model are: (1) Landfill site history, (2) Waste rate acceptance, (3) Methane production constant and (4) Methane gas Production potential.

In this software, the default values for the production constant and the inherent power of gas production are considered to be 0.02 (1/year) and 170 (m^3/Mg), respectively. These values are the recommended values of clean air act (CAA) for arid and semi-arid areas. The intrinsic power of methane production is equal to the amount of methane gas, where each ton of the waste emits during its lifetime in anaerobic fermentation. The production constant as specified in the above is a coefficient for determining the methane gas production rate. To better understand these relationships, it is enough to note that the area under the curve of the methane gas production rate is equal to the intrinsic power of production [24,25].

2.4. OpenLCA software

In the next step, the values obtained from Landgem outputs are inserted into the OpenLCA software. This software has been developed by Greendelta since 2006 and has valid databases and various methods for assessing life cycle, sustainability assessment, social life cycle assessment, life cycle cost, environmental impact assessment, water and carbon footprints, etc. [26,27]. To assess the toxicity impacts of landfill gases on humans and the environment, the USEtox and Traci method are used in OpenLCA software, respectively.

2.5. USEtox model

For evaluation of effects, complementary methods have been developed in a ready manner. According to the USEtox model, first, it is required to determine those pollutants that affect the impact category. Then, these pollutants become an equal unit for each impact category. In the calculation, conversion factors and characterization factors in each impact category were taken from the OpenLCA software.

The characterization factors represent the impact per emitted unit of the substance; when they are combined with data of the mass emitted, a total impact score (IS) is determined. This makes it possible to recognize the relative importance of separate emissions [28,29].

The characterization factors of human toxicity (human toxicity potential) and aquatic ecotoxicity (ecotoxicity potential) are expressed in comparative toxic units (CTUh) and comparative toxic units (CTUe), respectively [30].

2.6. Traci model

Traci model, developed by the US Environmental Protection Agency, has been designed to assess the environmental impact of various scenarios. In this method, input data are allocated to five impact categories of acidification, ecosystem toxicity, global warming, photochemical ozone formation, and respiratory effects [31,32,33]. Characteristics and parameters of landfill studied are shown in Table 2.

3. RESULTS AND DISCUSSION

Sirjan population growth rate is 1.0024 % according to census results. The period of selection plan for the Sirjan City Landfill is 20 years according to the comprehensive waste management plan of the city of Sirjan. The following formula is used to calculate the population of Sirjan in different years of the project period:

$$P_n = P_0 (1 + r)^n \qquad (2)$$

Therefore, based on the above formula, the population and the amount of waste produced in Sirjan city will be calculated during different years of the project period (Table 3).

Table 2. Landfill properties in LandGEM model.

Beginning year of waste disposal	2018	
Year of landfill closure	2037	
Landfill capacity	Not available	Ton
Methane production rate (k)	0.02	1/year
Methane production potential (L_0)	170	m^3/ton
Concentration of non-methane organic compounds (NMOC)	4000	ppmv
Methane content	50	Volume rate (%)

According to the estimations, the city's population in 2018 is 220000 and, with its current population growth rate in place, the city's population in 2037 will be 555929. The amounts of waste produced in 2018 and 2037 are 54936 and 138821 tons per year, respectively. Total waste produced during these 20 years will be equal to 1816509 tons.

The maximum amount of landfill gas will be in 2038, a year following the last year of waste disposal to the landfill. It should be noted that the present time period provides the best opportunity for exploiting these gases and the production of electricity. Following 2038, landfill gas will gradually decline. Generally, the amount of all gases will reduce over time by increasing the age of landfill. Therefore, any planning for the landfill gas extraction and utilization should be carried out in the first years after the landfill closure. The results of this study show that the amount of landfill gas produced is very high, and the use of energy recovery systems in the form of renewable energy is essential.

Table 3. population growth and estimated urban waste, produced in sirjan from 2018 to 2037.

Year	Population	Waste Production (ton)	Waste in landfill (ton)
2018	220000	54936	54936
2019	231000	57683	112619
2020	242550	60567	173186
2021	254677	63595	236781
2022	267411	66775	303556
2023	280782	70114	373670
2024	294821	73619	447289
2025	309562	77300	524589
2026	325040	81165	605754
2027	341292	85224	690978
2028	358357	89485	780463
2029	376274	93959	874422
2030	395088	98657	973079
2031	414843	103590	1076669
2032	435585	108769	1185438
2033	457364	114208	1299646
2034	480232	119918	1419564
2035	504244	125914	1545478
2036	529456	132210	1677688
2037	555929	138821	1816509

The graph resulting from the implementation of the landgem model in Mg / ton is shown in Fig. 2.

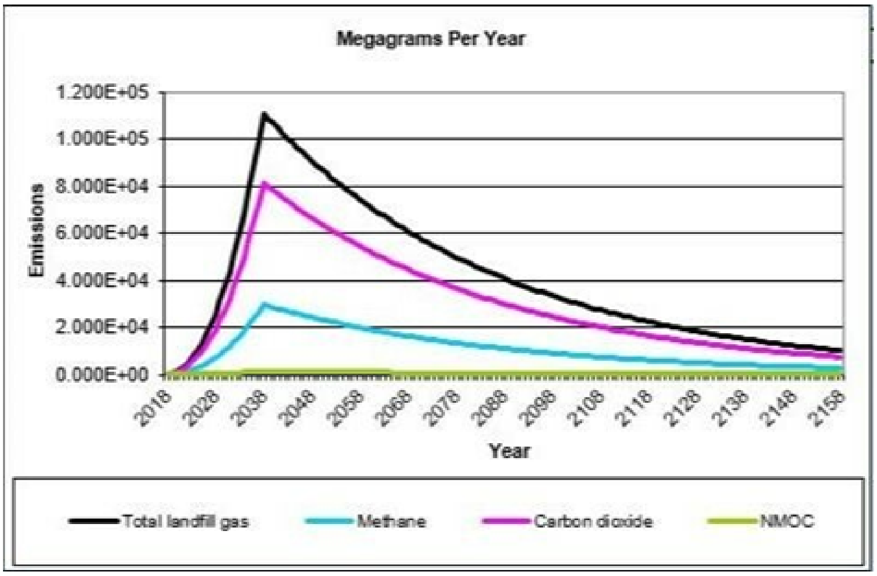

Figure 2. Emission rate curve in Sirjan landfill from 2018 to 2158 using LandGEM simulation (Mg / ton).

The area under the curves shows the total amount of gasses produced. The largest area under the curves belongs to the total landfill gas, carbon dioxide, methane, and NMOC with values of 1.219E+05, 3.255E+04, 8.932E+04, and 1.399E+03 tons per year, respectively, which is an exponential function of time.

The graph resulting from the implementation of the landgem model in m^3 / year is shown in Fig. 3. Figure 3 shows the volumetric production rates for emissions during 140 years. Lifestyle, consumption pattern, culture, and climate of the region are involved in these emissions.

Non-methane organic compounds, also known as NMOC gases, often make up less than 1 % of the landfill gas. NMOC have some adverse effects on human health and the environment. In 1991, the US Environmental Protection Agency identified 94 non-methane organic compounds. Many of these toxic chemical compounds are compounds such as benzene, toluene, chloroform, vinyl chloride, carbon tetrachloride, etc. Finally, 41 of them are halogen compounds, and the rest are non-halogenated. More research on the contaminants in landfill gas has found hundreds of different non-methane organic compounds. About 53 NMOCs, produced in Sirjan landfill and predicted by LandGEM, are shown in Table 4.

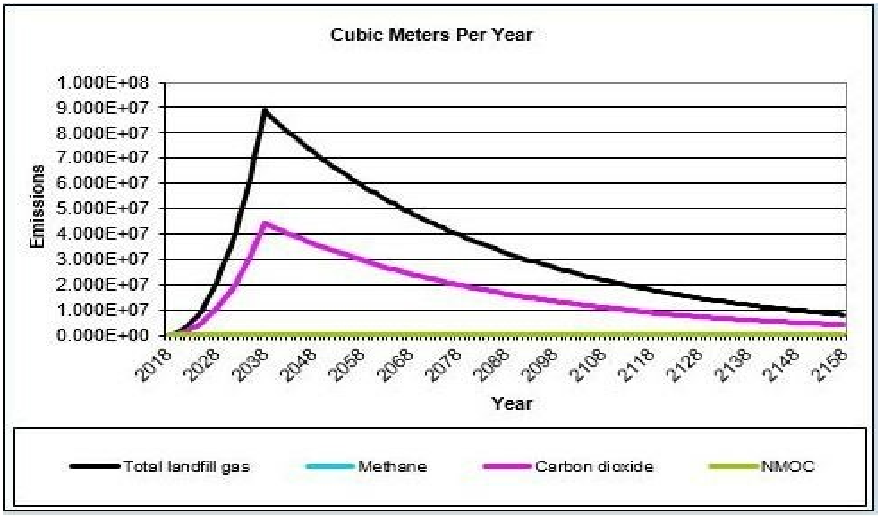

Figure 3. Emission rate curve in Sirjan landfill from 2018 to 2158 using LandGEM simulation (m^3 / year).

The LandGEM outputs were imported into the OpenLCA software, and their potential risk was calculated by USEtox and Traci method. According to USEtox method, pollutants are assigned to four impact categories and their impact scores are obtained. Table 5 shows the final results of the impact assessment of pollutants in each impact category. In addition, by applying Traci method, the impact assessment was carried out in five impact categories including acidification, global warming, ecotoxicity, photochemical ozone formation, and respiratory effects. Table 6 shows the final results of the impact assessment of pollutants in each impact category.

Table 4. The amount of gases and pollutants produced in the Sirjan's landfill in 2037.

Gas/emission	Emission rate	
	(m^3/year)	Mg/year
Total amount of gases produced at landfill	7.916E+07	9.885E+04
Methane	3.958E+07	2.640E+04
CO_2	3.958E+07	7.245E+04
NMOC’s	3.166E+05	1.135E+03
1,1,1-Trichloroethane (methyl chloroform)	3.800E+01	2.108E-01
1,1,2,2-Tetrachloroethane	8.707E+01	6.079E-01
1,1-Dichloroethane (ethylidene dichloride)	1.900E+02	7.820E-01
1,1-Dichloroethene (vinylidene chloride)	1.583E+01	6.383E-02
1,2-Dichloroethane (ethylene dichloride)	3.245E+01	1.336E-01
1,2-Dichloropropane (propylene dichloride)	1.425E+01	6.696E-02
2-Propanol (isopropyl alcohol)	3.958E+03	9.895E+00
Acetone	5.541E+02	1.339E+00
Acrylonitrile	4.987E+02	1.101E+00
Benzene - No or Unknown Co-disposal	1.504E+02	4.886E-01
Benzene - Co-disposal	8.707E+02	2.829E+00
Bromodichloromethane	2.454E+02	1.672E+00
Butane	3.958E+02	9.568E-01
Carbon disulfide	4.591E+01	1.454E-01
Carbon monoxide	1.108E+04	1.291E+01
Carbon tetrachloride	3.166E-01	2.026E-03
Carbonyl sulfide	3.879E+01	9.691E-02
Chlorobenzene	1.979E+01	9.265E-02
Chlorodifluoromethane	1.029E+02	3.701E-01
Chloroethane (ethyl chloride)	1.029E+02	2.762E-01
Chloroform	2.375E+00	1.179E-02
Chloromethane	9.499E+01	1.995E-01
Dichlorobenzene	1.662E+01	1.016E-01
Dichlorodifluoromethane	1.267E+03	6.369E+00
Dichlorofluoromethane	2.058E+02	8.810E-01
Dichloromethane (methylene chloride)	1.108E+03	3.915E+00
Dimethyl sulfide (methyl sulfide)	6.174E+02	1.596E+00

Ethane	7.045E+04	8.811E+01
Ethanol	2.137E+03	4.096E+00
Ethyl mercaptan (ethanethiol)	1.821E+02	4.705E-01
Ethylbenzene	3.641E+02	1.608E+00
Ethylene dibromide	7.916E-02	6.186E-04
Fluorotrichloromethane	6.016E+01	3.438E-01
Hexane	5.224E+02	1.873E+00
Hydrogen sulfide	2.850E+03	4.039E+00
Mercury (total)	2.296E-02	1.915E-04
Methyl ethyl ketone	5.620E+02	1.686E+00
Methyl isobutyl ketone	1.504E+02	6.266E-01
Methyl mercaptan	1.979E+02	3.960E-01
Pentane	2.612E+02	7.839E-01
Perchloroethylene (tetrachloroethylene)	2.929E+02	2.020E+00
Propane	8.707E+02	1.597E+00
t-1,2-Dichloroethene	2.216E+02	8.937E-01
Toluene - No or Unknown Co-disposal	3.087E+03	1.183E+01
Toluene - Co-disposal	1.346E+04	5.157E+01
Trichloroethylene (trichloroethene)	2.216E+02	1.211E+00
Vinyl chloride	5.778E+02	1.502E+00
Xylenes	9.499E+02	4.194E+00

Table 5. Results of impact assessment of landfill gases in every impact categories based on USEtox method.

Impact category	Reference unit	Result
Freshwater ecotoxicity	CTUe [PAF m3.day.kg-1_emitted]	11203.51
Human health - carcinogenic	CTUh [cases/kg_emitted]	0.008201
Human health - non-carcinogenic	CTUh [cases/kg_emitted]	0.024295
Human health - total impact	CTUh [cases/kg_emitted]	0.032496

Table 6. Results of impact assessment of landfill gases in every impact categories based on Traci method.

Impact category	Reference unit	Result
Acidification	kg SO_2 eq	7593.32
Ecotoxicity	CTUe	16460.96
Global Warming	kg CO_2 eq	7.32E+08
Photochemical ozone formation	kg O_3 eq	508414.8
Respiratory effects	kg PM2.5 eq	4.59596

The endpoint effects of pollutants with emphasis on health have been achieved by USEtox method. Carcinogenic pollutants include tetrachloroethane, acrylonitrile, benzene, chloroform, ethanol, hexane, toluene, xylene, and bromodichloromethane. In addition, pollutants allocated to the impact category of freshwater ecotoxicity are tetrachloroethane, 2-Propanol, acetone, acrylonitrile, benzene, Carbon disulfide, chloroform, ethanol, hexane, methyl ethyl ketone, dichlorobenzene, pentane, toluene, xylene, and bromodichloromethane. As observed, different impact categories share many of these pollutants. A pollutant may cause contamination and damage to health and the environment in a number of ways.

In the Traci method, the greatest environmental burden is attributed to the global warming impact category, which is due to high levels of carbon dioxide, methane, and chloroform produced in the landfill. The impact category of photochemical smoke after global warming has the highest environmental burden, which is due to the release of pollutants to the environment such as acetone ,2-Propanol, Acrylonitrile, Benzene, Butane, Carbon disulfide, Carbon monoxide, Chloroform, Ethane, Ethanol, Hexane, Methane, Methyl ethyl ketone, o-Dichlorobenzene, Pentane, Propane, Toluene, and Xylene. The impact category of ecotoxicity (due to the release of acrylonitrile), acidification (due to the release of H_2S), and respiratory effects (due to the release of CO) are ranked, respectively.

The results of this study showed that methane production is inevitable due to the anaerobic fermentation carried out at urban waste disposal sites. Methane emissions are among the factors of environmental degradation. While the landfill gas management and use of methane gas, carrying energy, will not only prevent the release of this gas to the atmosphere, but also generate revenue and energy savings. With regard to the energy contained in this gas, management and retrieval will be very important.

4. CONCLUSIONS

The goal of integrated waste management is to pursue sustainable development goals. To assess sustainable development, tools that can predict the environmental burden of each system are needed. Therefore, in this study, the amount of gases produced in Sirjan landfill from 2018 to 2037 was estimated using LandGem model. Further, the environment, health, and toxicity effects of landfill gas emissions were evaluated using Traci and USEtox method in OpenLCA software. According to the results, the maximum amount of landfill gas release will occur in 2038. The total amount of gas production, methane gas, carbon dioxide, and NMOCs will be 1.219E+05, 3.255E+04, 8.932E+04, and 1.399E+03 tons per year in 2038 for Sirjan city. In addition, impact scores of freshwater ecotoxicity, human health (carcinogenic), human health (non-carcinogenic), and human health (total impact) were achieved as 11203.51, 0.008201, 0.024295, 0.032496, respectively, in this year. In the Traci method, the most environmental burden belongs to impact categories of global warming, photochemical ozone formation, ecotoxicity, acidification, and respiratory effects, respectively. It is suggested that landfill gas be used to supply energy to the Sirjan recycling plant.

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