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ENVIRONMENTAL IMPACT MITIGATION DURING THE SOLID WASTE MANAGEMENT IN AN INDUSTRIALIZED CITY IN MEXICO: AN APPROACH OF LIFE CYCLE ASSESSMENT

MITIGACIÓN DEL IMPACTO AMBIENTAL DURANTE EL MANEJO DE RESIDUOS SÓLIDOS EN UNA CIUDAD INDUSTRIALIZADA EN MÉXICO: UN ENFOQUE DEL ANÁLISIS DEL CICLO DE VIDA

N.C. Aldana-Espitia[1], J.E. Botello-Álvarez[2], P. Rivas-García[3], F.J. Cerino-Córdova[3], M.G. Bravo-Sánchez[2], J.E. Abel-Seabra[4], A. Estrada-Baltazar[1]*

[1]*Departamento de Ingenieria Quimica, Instituto Tecnologico de Celaya, Av. Tecnologico y A. Garcia Cubas, zip 38010, Celaya, Guanajuato, Mexico.*

[2] *Departamento de Ingenieria Bioquimica, Instituto Tecnologico de Celaya, Av. Tecnologico y A. Garcia Cubas, zip 38010, Celaya, Guanajuato, Mexico.*

[3]*Departamento de Ingenieria Quimica, Facultad de Ciencias Quimicas, Universidad Autonoma de Nuevo Leon, Av. Universidad S/N, Cd. Universitaria, zip 64451, San Nicolas de los Garza, Nuevo Leon, Mexico.*

[4]*Faculdade de Engenharia Mecanica, UNICAMP, Rua Mendeleyev 200, Cidade Universitaria "Zeferino Vaz", Campinas, SP, 13083-860, Brazil.*

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Abstract

The life cycle assessment and the ReCiPe method were used to evaluate the environmental impact of the Municipal Solid Waste Management (MSWM) in a Mexican city. As Functional Unit (FU) was used 1 ton of waste. Two scenarios were considered: MSWM with conventional landfill (A) and MSWM that use the landfill gas to generate electricity (EG). The hotspot of the A scenario was the landfill, the severest midpoint indicator was the climate change, quantified at 2914 kg of CO_2 eq/FU, which contributes significantly to the endpoint indicator damage to human health, evaluated at 90 Pt/FU in terms of single score. For the EG scenario the results showed that the environmental impact was reduced to 298 kg of CO_2 eq/FU and 5 Pt/FU for climate change and damage to human health, respectively. In the overall analysis, the environmental damage for A and EG scenarios was estimated at 90.5 and -20.8 Pt/FU, respectively. This work shows that the EG scenario represents an alternative potential for environmental improvement. However, due to the emissions from landfill will continue for 50 years, causing damage to human health and ecosystems is considered a persistent environmental passive.

Keywords: municipal solid waste management, life cycle assessment, landfill, biogas, recycling.

Resumen

Se empleó el análisis de ciclo de vida y el método ReCiPe para evaluar el impacto ambiental de la Gestión de Residuos Sólidos Urbanos (GRSU) en una ciudad mexicana, empleando una tonelada de residuos como Unidad Funcional (UF). Se evaluaron dos escenarios: GRSU con relleno sanitario convencional (A) y GRSU con aprovechamiento del biogás del relleno para generar electricidad (GE). La etapa crítica del escenario A es el relleno sanitario, su indicador de punto medio más severo es el cambio climático, estimado en 2914 kg de CO_2 eq/UF, que contribuye significativamente al indicador de punto final daño a la salud humana, evaluado en 90 Pt/UF en términos del single score. En el escenario GE el impacto ambiental se reduce hasta 298 kg de CO_2 eq/UF y 5 Pt/UF para el cambio climático y el daño a la salud humana, respectivamente. De manera total, el daño ambiental para los escenarios A y GE fue estimado en 90.5 y -20.8 Pt/UF. El escenario EG muestra una alternativa potencial de mejora ambiental, no obstante, las emisiones del relleno continúan durante 50 años, causando daños a la salud humana y a los ecosistemas, considerado por esto un pasivo ambiental persistente.

Palabras clave: manejo de residuos sólidos municipales, análisis del ciclo de vida, relleno sanitario, biogás, reciclado.

* *Corresponding author. E-mail*: alest@iqcelaya.itc.mx
Phone number: 01 461 61 17575; Fax: 01 461 61 17744

1 Introduction

Municipal Solid Waste Management (MSWM) in different countries is addressed using different strategies, technologies and regulations (Avedoy, 2006; Beylot *et al*., 2013). The amount and types of Municipal Solid Waste (MSW) depend on the particular factors such as urban urbanization and economic development (Dyson and Chang, 2005; Hoornweg and Bhada-Tata, 2012). Worldwide, the average *per capita* generation during the last 10 years has increased from 0.64 to 1.2 kg of MSW per day, and developed countries are responsible for the generation of most of these residues. Members of the OECD (Organization for Economic Co-operation and Development) generate 44% of the waste in the world, with a daily *per capita* generation of 2.2 kg. This is in stark contrast with Africa, which generates only 5% of the waste (Hoornweg and Bhada-Tata, 2012). Economic development and demographic phenomena such as urbanization produce great changes in MSWM, as observed, for example, in China-one of the largest producers of waste in the world, and currently one of the countries with the fastest rate of economic growth (Chen *et al*., 2010).

In Mexico, the daily *per capita* generation of MSW grew from 0.89 to 0.99 kg between 2003 and 2012. In the latter year, the MSW generation reached 42.1 millions of tons. Mexico is a demographically diverse and dynamic country; in the last two decades, it has become an urban nation with 77.8% of its population living in cities. Metropolitan areas and medium-sized cities generate 75% of MSW, constituted mainly by organic waste (52.42%). The presence of plastics has virtually doubled during the last decade, growing from 6.11 to 10.89% (SNIA, 2013; INEGI, 2010).

In Mexico, landfills are the final destination for 74.39% of MSW collected, and 260 currently existing facilities are in line with government regulations (SEMARNAT, 2004; SEMARNAT, 2013a). Landfills are mainly administered by municipal agencies, with a small number being operated by private companies. In 2011, there were only 6 landfills featuring facilities for electric power generation based on biogas (ICMA, 2011).

Europe is currently seeking to reduce the number of landfills by means of restrictive legislation and prohibitions (da Cruz *et al*., 2014; Scharff, 2014). In Latin America, landfills and open dumps are the main form of MSW disposal (Bolan *et al*., 2013; Calvo *et al*., 2007). Landfills, including those that have been closed down, are high-impact environmental liabilities; nonetheless, in countries such as Mexico, this form of disposal still has a long future. The implementation of other means for disposal with lower environmental impact, as well as cultural change toward recycling societies, will require a considerable amount of time. In existing and soon-to-be-created landfills, biogas capture for its combustion and transformation into electric power are more sustainable alternatives (Bolan *et al*., 2013).

The study and analysis of MSWM in Mexico is a complex task due to the great number of factors and actors involved in its implementation. Currently, these systems depend mainly on government agencies; however, the number of formal private enterprises participating in this economic sector has recently increased. Other important actors in MSWM are informal collectors, locally known as *pepenadores* (scavengers). However, their number, organization and coverage are only partially known (Cevantes-Niño and Palacios-Hernández, 2012).

This article studies MSWM in the City of Celaya, Guanajuato, Mexico: a medium-sized city undergoing accelerated urban and economic growth. Celaya covers a territory of 553.18 km^2 and is located at 20° 31' 24" North latitude and 100° 48' 55" West longitude. According to the 2010 census, its population was 468,469 inhabitants, of which 72.65% comprised the urban population, with the rest consisting of the rural population. Its gross domestic product in 2009 was 3,748.8 million USD, coming predominantly from manufacturing (52.30%), services (26.09%), commerce (16.60%), and others (5.01%). The manufacturing sector is mainly composed of metal-mechanic industries, with the automotive industry standing out among them (DGDEM, 2013). Between the years of 2010 and 2014, the municipality of Celaya had undergone industrial growth in the automotive sector with the arrival of providers and companies specializing in assembly (Covarrubias-Valdenebro, 2014)

The economic growth and transformation in this municipality and its surroundings have a direct effect on MSW generation. Worldwide, the search for sustainable strategies for waste management is a preoccupation for society and government entities. Choosing among these strategies must be a result of a systematic methodology that considers the greatest possible number of factors that affect MSWM in an objective and quantitative fashion. The Life Cycle Assessment (LCA) method meets these requirements. In this work, an analysis of MSWM is performed in the municipality of Celaya during the year 2013 using the LCA method, with environmental impact indicators from the ReCiPe methodology, considering two scenarios: Scenario A, corresponding to the current situation of MSWM, and Scenario EG, corresponding to MSWM factoring in the installation of a system for the capture, purification and transformation of biogas into electric power.

2 Methodology

2.1 Description of the system of analysis

In 1996, a waste confinement site denominated "Tinajitas" was built in the Municipality of Celaya. This site was subsequently closed in 2010. In the same year, the Center for Integral Waste Management-*Centro de Manejo Integral de Residuos*, CEMIR-was installed, with three confinement sites (landfills) denominated CEMIR I, II and III, which meet the Official Mexican Norm (Norma Oficial Mexicana) (SEMARNAT, 2004). Table 1 shows some of the characteristics of these MSW confinement sites from 1996 to late 2014.

In this work, the MSWM process of the municipality of Celaya was analyzed during the filling of the CEMIR II landfill in 2013. The walls and floors of this landfill are coated with geomembranes and geotextiles; it features a drainage system for leachate management. The residues entering the site are distributed and compacted into layers to be subsequently covered by a layer of dirt. The site features a system of wells for biogas collection. For leachate containment, there is a cell with surface dimensions 31 m by 10.8 m, a 6.4 m depth, and an approximate capacity of 2,000 m^3. The CEMIR II cell operated for a period of 17 months, from opening to closing.

The MSWM is represented by the black-bordered square in Figure 1, in which the route followed by the MSW can be seen from its origin to final disposal in the landfill (CEMIR II). All MSW flows are expressed in terms of the Functional Unit (FU), defined as 1 ton of waste generated by the city, discussed in greater detail in Section 2.3. The modules constituting the MSWM in Celaya are described below.

2.2 Description of the analysis modules

2.2.1 Collection modules

Waste collection is carried out by means of two systems, Municipal and Private, and the total service coverage is close to 96% of the urban zone and rural communities. The most recent characterization of the garbage collected from households without undergoing a separation process (Table 2) was carried out in 2010 by the Municipal Institute of Ecology (*Instituto Municipal de Ecología*, IMEC) (IMEC, 2014).

Waste collection takes place on sidewalks and at specific points addressing households, commerce and service centers, as well as private and public institutions. Figure 1 shows the proportions of MSW collected through the municipal and private systems: 0.8227 tons/FU and 0.1765 tons/FU, respectively.

The data required to characterize the MSW collection system in terms of the amount of waste generated by the city, of the amount collected by each subsystem (municipal or private), their corresponding use of resources, the capacity and model of the collection vehicles, and the type of collection in each subsystem (sidewalk or specific point) were gathered through a series of interviews and field visits during the waste collection process, as well as technical reports, statistics and personal communications of the

Table 1. Geometry, capacity and filling time of landfills in the MSWM in Celaya over a period of 18 years

Landfill	Dimensions in meters	MSW Confined	Date of opening	Date of closing
Tinajitas	Section 1: 205 W·160 L·Unknown D Section 2: 176 W·170 L·Unknown D Section 3: 187 W·50 L·8D Section 4: 390 W·196 L·Superficial D	1,500,000 t (estimated)	1996	2010
CEMIR I	200 W·75 L·19-20 D	201,839 t	2011	2012
CEMIR II	130 W·90 L·19-20 D	154,784 t	2012	2014
CEMIR III	50 W·200 L·200 L·100 W·20-22 D	81,884 t	Apr-2014	Dec-2014

W: Width, L: Length, D: Depth

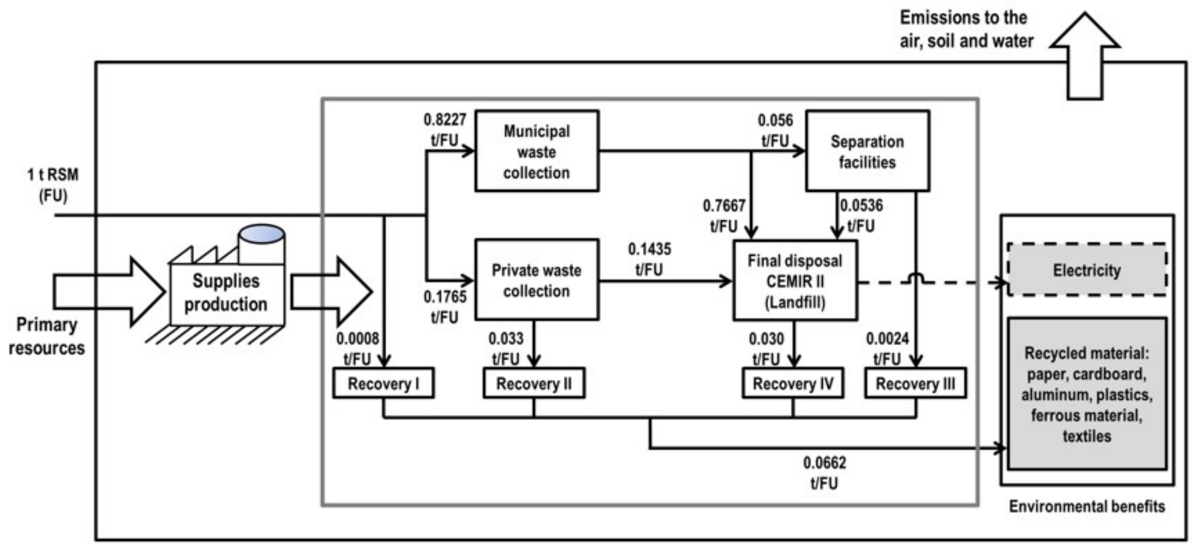

Fig. 1. The system boundaries of the life cycle model for the municipal solid waste management. The flows and solid-line squares represent Scenario A, and the Scenario EG is represented adding the dashed lines.

General Directorate of Municipal Services (*Dirección General de Servicios Municipales*, DGSM), IMEC, and the Celaya Municipal Government.

2.2.2 Recovery modules

As can be observed in Figure 1, throughout the entire management process, the MSW undergoes four types of selection processes and recovery of recyclable materials. These are briefly described below.

- *Recovery I*: It takes place at the facilities of education and government institutions. This is a selective collection process.
- *Recovery II*: It takes place during private collection, on collection vehicles.
- *Recovery III*: It consists of a set of facilities called "separating plant," located in the vicinity of CEMIR II.
- *Recovery IV*: It is performed at the facilities of CEMIR II by scavengers. Approximately 180 scavengers work at this site, each of which has a collection of approximately 66 kg/day.

During the four recovery stages, the fossil fuel and electricity requirements were evaluated following the data provided by the office of Municipal Services of Celaya.

2.2.3 Recycled material modules

Similar to the information collected in Section 2.1, data on the amount and type of waste classified and separated at each stage were obtained through interviews, field visits during the waste recovery operations, technical reports, statistics and personal communications of DGSM, IMEC and the Municipal Government of Celaya, as well as private organizations.

At this stage, the use of resources or emissions during the processes undergone by the recovered materials to be sold as raw materials or directly reused is not considered. These activities are outside the scope of the LCA, as discussed in Section 2.4

2.2.4 Final waste disposal module (Landfill)

a) Current scenario (A)

Once the MSW goes through all four material recovery processes, its final disposal takes place at the CEMIR II landfill. Given that it does not possess a system for burning the gas produced by the anaerobic decomposition of waste, this landfill continuously emits an environmental load of GHG into the atmosphere. Another effluent of the landfill is the current of leachates that are discarded into an open pond. This installation is not equipped with an environmental load reduction process, in addition to lacking a geomembrane to prevent pollutants from leaking into the subsoil.

A stabilization period of 50 years was considered for the waste in this landfill. Predictions for biogas production and composition for this period were estimated using the Mexican Biogas Model Version 2.0 (MBM 2.0) developed by the United States Environmental Protection Agency, Version 2.0 (SCS Engineers, 2009) and Mexican government agencies. Information on the amounts of fuel utilized in the filling operations was obtained through the DGSM.

The modules and characteristics described in Sections 2.1 and 2.2, as well as the current description of the landfill correspond to the actual situation of MSWM in the City of Celaya, Scenario A, are schematized by the flow diagram (solid lines) of Figure 1.

b) Electric power generation scenario (EG)

This scenario differs from Scenario A in terms of the existence of a system for biogas capture and its transformation into electric power, from the time the site is covered until its depletion after a period of 50 years. Similar to Scenario A, the amount of biogas was estimated using the MBM 2.0. The emissions and use of resources for the manufacture of the electric production equipment as well as the construction of power distribution lines toward the national power grid fall outside the scope of the analysis, for reasons discussed at the end of Section 2.4.

Electric power generation from biogas captured at the landfill was estimated considering the fact that the energy per m^3 is 21 MJ. Fed into an electric station with 35% efficiency, this biogas can produce 2.04 kWh of electricity (Murphy *et al*., 2004).

2.3 Functional unit

In this work, the FU is 1 ton of generated MSW that has not undergone any separation process, with a composition corresponding to the waste generated in Celaya during 2010, indicated in Table 2.

2.4 System boundaries

Figure 1 shows a schematic of the system boundary. The grey square at the center of the figure encloses the limits of MSWM in the Municipality of Celaya. In both scenarios, A and EG, the recovered material (0.0095 tons/FU) represents environmental credits that substitute products of similar type and quality. These emissions and resource expenditures were measured through the expansion of the boundaries, as seen in the square towards the right of Figure 1. In addition, electricity is generated in Scenario EG, which, when used in some subsequent process (outside the boundaries of the analysis), partially substitutes energy from the Mexican national electric network. The emissions and resource expenditures prevented by the recycling operations were evaluated using Ecoinvent 3.1 (Ecoinvent Center, 2014) database. The generation of electric power was also evaluated using this database, which, in its Ecoinvent 3.1 update, considers the Mexican mixed electric generation process.

The MSWM supply production process is considered within the LCA boundaries. This mainly includes fossil fuels such as diesel, gasoline and natural gas; electric power from the national distribution network; and potable water. These data, denominated as the *background*, were taken from the Ecoinvent 3.1 database.

Table 2. Characterization of MSW in 2010.

Type of waste	kg/FU	Type of waste	kg/FU
Food	321.2	Waxed cardboard	9.9
Yard waste	240	Cans	56
Wood	14	Ferrous materials	7.2
Cotton	1.9	Clear glass	22.8
Cloth	3.2	Colored glass	9.5
Leather	1.3	Synthetic fibers	1.2
PET	75.8	Diapers	51.5
Hard plastics	7.3	Construction waste	23.9
Rubber	4.	5 Slab and ceramic	2
Paperboard	77.3	Other inorganic	7
Paper	62.5		

FU: Functional Unit

Both the environmental loads emitted by the system in question and those representing environmental credits, denominated as the *foreground*, were evaluated by means of various methodologies and following the bibliography discussed in Section 2.6. The emissions and resource expenditures related to the construction of machinery and buildings are not considered in the analysis because these activities represent small quantities when compared to the total usage of materials and energy, and their inclusion would only add unnecessary complications (Mendes *et al*., 2004; Gentil *et al*., 2010; Chi *et al*., 2015).

2.5 LCA model

The LCA was performed following a consequential approach. The evaluation model was implemented using the SimaPro 7.3.3® software (PReConsultants, Amersfoort, the Netherlands). The Life Cycle Impact Assessment (LCIA) was developed following the ReCiPe method. The main goal of the ReCiPe method is to transform the extensive list of results of the life cycle inventory into a limited number of environmental impact indicators. These indicators express the relative damage of an environmental impact category. The ReCiPe method is based on two levels of indicators: 18 *midpoint* indicators and 3 *endpoint* indicators. It also generates a *single score* indicator that assigns a specific environmental damage score (Goedkoop *et al*., 2009).

2.6 Inventory of emissions

Emissions originating from collection vehicles, operated with gasoline, diesel and natural gas, were estimated by means of the emission factors of the GREET life cycle model (GREET, 2014).

The biogas production of the CEMIR II landfill was evaluated using the MBM 2.0. This model was implemented on an Excel® spread sheet, which requires the confined MSW amount and characterization (presented in Table 1S of the Supplementary Materials), operations characteristics and strategies of the landfill, and the typical weather conditions of the region in Mexico for its implementation.

The gases generated by the combustion of captured landfill biogas for electric generation (Scenario EG) were estimated following Chapter 2 of Stationary Combustion by IPCC (IPCC, 2006).

The amount of leachates produced during the confined MSW degradation in the landfill was estimated according to the methodology and characteristic parameters reported by Bovea and Powell (2006). An estimated 248.96 L of leachate per ton of confined waste is produced. This work considered that the chemical species present in the leachates periodically deposited in the pond are an environmental load, given that, as mentioned above, this pond does not possess a pollutant reduction process or a cover to prevent pollutants leaching.

3 Results and discussion

3.1 Inventory results

Figure 1 presents the MSW flow distribution during the management process, in terms of the FU. Approximately 93.4% of the generated MSW was disposed of in the CEMIR II landfill; in contrast, in the European Union, only 38% of MSW was placed in landfills, while alternatives such as incineration, composting and recycling had increased coverage (da Cruz *et al*., 2014). In Mexico, while 40% of MSW can be recovered and used as recycled materials, the national recycling average is 4.9% (Góngora-Pérez, 2014). In this case of study, the recovery rate was 6.6% of the total recollected MSW. The selective generation and recollection (Recovery I) does not surpass 1.0%; the average in the country is 10.9% (Góngora-Pérez, 2014). Informal recovery in the streets and waste deposited in uncontrolled sites were not considered in this study. In other Latin-American countries, recovery from the street contributes 30% of the total recovery (Gutberlet, 2015). MSW disposal in uncontrolled sites in Mexico can reach an average of 21% (SEMARNAT, 2013b).

The main features of the MSWM in the city of Celaya in 2013 are presented in Table 3. This table shows that the *per capita* MSW generation in Celaya is 0.73 kg/(d·inhab).

The composition of the material flow in the Recovery processes I-IV is presented in Table 4. The most frequently recovered waste is polyethylene terephthalate (PET) (19.7 kg/FU), cardboard (15.9 kg/FU), paper (12 kg/FU) and aluminum cans (5.5 kg/FU). Together, these four materials make up 80.2% of the total material recovered in all four processes. Material recovery is carried out chiefly by private services (95.16% in Recovery II and IV), mainly due to the demand and appreciation of these materials by the national recycling industry, as well as the international market. In 2010, the cellulose and paper industry collected 3.2 million of tons of paper and cardboard (CNICP, 2012). In the municipality of Celaya, there are 98 registered formal facilities dedicated to the storage of recovered materials. However, it is estimated that large amounts of material are recovered by the informal sector (IMEC, 2014). Informal recollection in the street, dumps and landfills is a source of employment for the marginalized population of the urban areas in Mexico (Cevantes-Niño and Palacios-Hernández, 2012).

During MSWM, a variety of supplies are utilized, particularly fossil fuels. Table 5 shows the amount of resources expended in the total waste management process, in terms of the FU. In Recovery stages I-IV, fossil fuels are used in the transportation of materials to collection centers; in addition, Recovery III uses electric power for processing equipment. Storage centers for recovered materials are private facilities located mainly at the periphery of the urban area; others are located in neighboring municipalities or states. Some centers are exclusively used for storage, while others also process the waste through classification, cleaning, milling and packaging. Processed residues are consumed by local and external recycling industries.

Table 3. Some features of the MSWM in the City of Celaya during the year 2013

MSWM features		
MSW collected	114,093 t	
MSW confined in landfill	106,614 t	
Per capita generation*	0.73 kg/(d·inab)	
Urban collection area	98.8%	
	MWC	PWC
Percentage of MSW collected	82.27%	17.73%
Waste collection transport	46 units: 40 are compactor trucks	61 units
Collection capacity of the transports per day	635 m^3, 387 t	261 m^3, 159 t
Collection waste: One-way Method	96.16%	100%
Collection waste: Exchange Method	3.84%	0%
Recovery I	87.7 t	–
Recovery II	Not estimated	3,770 t
Recovery III	278 t	–
Recovery IV	–	3,431 t

*For the year 2010.

Abbreviations: MSWM, Municipal Solid Waste Management; MSW, Municipal Solid Waste; MWC, Municipal Waste Collection; PWC, Private Waste Collection

Table 4. Waste composition in the recovery stages

Type of waste	Recovery I	Recovery II	Recovery III	Recovery IV
Cans	–	16.8%	0.6%	–
Clear glass	–	6.8%	25.7%	4.1%
Colored glass	–	2.8%	11.4%	–
Ferrous materials	–	2.2%	3.6%	7.2%
Hard plastics	–	2.2%	8.1%	7.8%
Paper	50%	18.7%	7.4%	17.5%
Paperboard	–	23.1%	28.2%	25.3%
PET	50%	22.7%	15%	38.1%
Rubber	–	1.3%	–	–
Synthetic fibers	–	0.4%	–	–
Waxed cardboard	–	3.0%	–	–
Total recovered kg/FU	0.8	33	2.4	30

PET, Polyethylene Terephthalate; FU, Functional Unit

Table 5. Use of resources and energy consumption at every stage of MSWM

Activity	Resource	Quantity/FU	Unit
Municipal waste collection			
	Diesel	8.6350	L
	Gasoline	0.4950	L
	Water	0.1750	L
	Energy cons.	340.5	MJ
Private waste collection			
	Gasoline	0.8480	L
	LPG	0.0760	kg
	Energy cons.	30.4	MJ
Recovery I (Municipal)			
	Diesel	0.0026	L
	Gasoline	0.0002	L
	Energy cons.	0.1	MJ
Recovery II (Private)			
	Diesel	0.1117	L
	Gasoline	0.0098	L
	Energy cons.	4.5	MJ
Recovery III (In separation plant)			
	Diesel	0.2103	L
	Electricity	0.0570	kWh
	Energy cons.	8.1	MJ
Recovery IV (In MSW confinement cell)			
	Diesel	0.1017	L
	Gasoline	0.0089	L
	Energy cons.	4.1	MJ
Landfill			
	Diesel	1.160	L
	Water	23.19	L
	Energy cons.	43.7	MJ

LPG: Liquid Petroleum Gas; MSW: Municipal Solid Waste; FU: Functional Unit.
The energy consumption was calculated from the specific heat values of Mexican fuels reported in Castillo-Hernández et al. (2012) for diesel and gasoline and DOF (2010) for LPG.

The resource consumption per FU is 10.22 L of diesel, 1.36 L of gasoline, 0.076 kg of Liquefied Petroleum Gas (LPG), and 0.057 kWh of electric energy. Together, fossil fuel consumption represents an expenditure of 431.4 MJ/FU. The energy consumption values for municipal and private collection are 413.9 and 172.2 MJ/FU, respectively. Municipal collection presents a high consumption due to the wide coverage in urban areas with heavy traffic, as well as disperse rural communities. In contrast, private companies service strategic routes and zones that generate a high content of recoverable materials and specific collection points.

The emissions produced by fuel consumption that are presented in Table 5, and the amounts of pollutants present in leachates deposited in an open pond are presented in Tables 2S and 3S of the Supplementary Materials.

3.2 Results of the prediction of biogas generated in the landfill

Figure 2 shows the production rate predictions for the CEMIR II landfill using MBM 2.0. This work considered the landfill emissions throughout a period of 50 years, until its closing in 2013. The amount of biogas produced by the landfill estimated by means of MBM 2.0 is a function of the amount of confined waste (Table 1S of the Supplementary Materials) as well as of the characteristic operation parameters of the landfill and regional environmental conditions. Figure 2 shows a rapid increase in biogas production at the beginning of the operation. Approximately 18% of the total biogas produced for the 50-year period is generated during the first three years of operation; the production rate then falls. Similar results were found using other models (Scharff and Jacobs, 2006).

For this work, the biogas generation was estimated to be 344 m^3 of biogas per ton of MSW (172 m^3 of CH_4/ton of MSW) in a degradation period spanning 50 years. In a study of a landfill in Granada, Spain, Zamorano *et al*. (2007) found a production of 160 m^3 of biogas per ton of MSW in a period of 40 years. Themelis and Ulloa (2007) reported a production of 100-150 m^3 of CH_4 per ton of MSW; these authors reported an average production of 122 m^3 of biogas per ton of MSW in 26 USA landfills. In Turkey, Melikoglu (2013) reported a production of 94-123 m^3 of CH_4 per ton of MSW. The estimated production in this work is high, mainly due to the high content of degradable organic matter (66%) as well as favorable weather conditions.

3.3 *Results of the environmental impact quantification*

The municipality of Celaya recognizes gas and particulate emissions (PM_{10} and $PM_{2.5}$) originating from brickworks, urban or agricultural solid waste fires at uncontrolled sites, automobile emissions, etc., as anthropogenic environmental hazards (GMC, 2015). It is expected that recent industrial and urban growth will significantly increase the Greenhouse Gases emissions (GHG). In the year 2010 the emissions were estimated at 873,110 tons of CO_2, 725 tons of CH_4, 45 tons of N_2O (902,506 tons of CO_2 eq, IEEG, 2010). According to this study, the total amount of GHG emissions released to the environment during MSWM in 2013 and during the subsequent MSW decomposition in the CEMIR II landfill for 50 years is 333,000 tons CO_2 eq.

This article presents an evaluation of the MSWM environmental impact by means of an LCA, considering indicators commonly used in the literature (Cleary, 2009): Climate Change (CC), Terrestrial Acidification (TA), Freshwater Eutrophication (FWE), and the Fossil Depletion (FD). The evaluation was carried out using the ReCiPe Midpoint (H) method. Figure 3 presents the indicators at each stage of MSWM in Scenarios A and EG; the grey bars correspond to the stages shared by both scenarios, and the black and white bars correspond to the landfills of Scenarios A and EG, respectively. The results from the ReCiPe Endpoint (H) method are presented in Figures 4 and 5. All results are given in terms of the FU. The full values of all indicators of the ReCiPe Midpoint (H) and Endpoint methods are presented in Tables 4S and 5S in the Supplementary Materials.

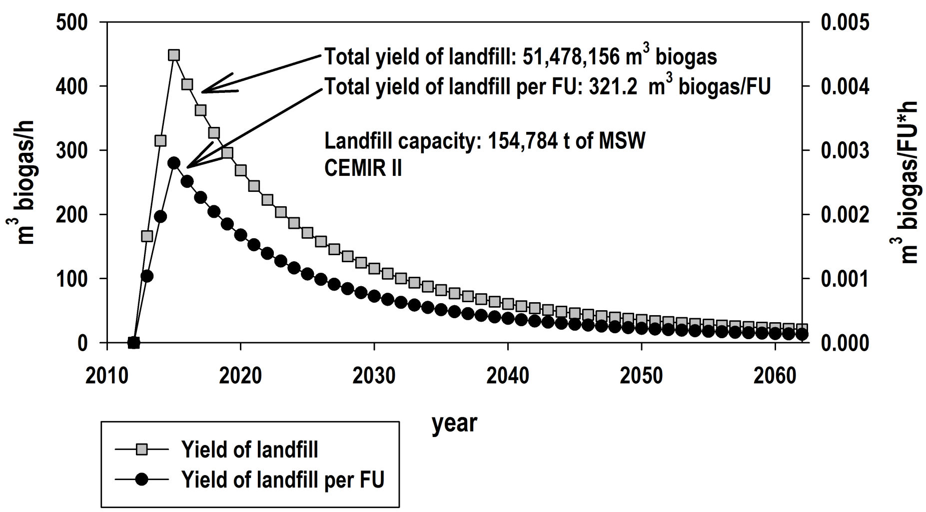

Fig. 2. Biogas productivity from the landfill over a period of 50 years using the Mexico Landfill Gas Model (SCS Engineers, 2009).

3.3.1 Midpoint method results

The installation of an electric power generation plant from landfill biogas directly reduces the GHG emissions between Scenarios A and EG. The CC indicator has values of 2914.4 and 298.4 kg CO_2 eq for Scenarios A and EG, respectively. The main origin of this difference is the combustion of the methane present in the biogas during electric generation. In Figure 3a, it can be seen that the landfills from both scenarios represent great passive environmental hazards whose GHG emissions will last for up to 50 years, as previously estimated (Figure 2). Excluding the landfill from both scenarios, the remaining stages that integrate the MSWM would produce a CC indicator with a negative net value, indicating that the credits gained through material recycling can mitigate the emissions generated by the automotive transport during recollection. This condition can also be observed in the indicators TA, FWE and FD (Figure 3b, c and d). The recollection stage represents an important expenditure of resources by the municipality, with an annual diesel consumption of over one million liters.

For both scenarios and all indicators, the main contribution comes from the landfill. Of the total GHG emissions, the landfill of Scenario A contributes with 2,980 kg CO_2 eq from the release of CH_4 and CO_2. Additionally, emissions originating from the combustion and production of fossil fuels at the municipal and private MSW collection stages at 30.3 kg CO_2 eq are considered. Emissions from the remaining stages are negligible in comparison (1.1 kg CO_2 eq). The recovered material flow, which will subsequently be transformed into recycled materials, represent a saving of 97 kg CO_2 eq. The main constituents of these flows are PET (53.4%), cardboard (18.9%), and aluminum cans (11.8%), and the remaining 15.9% is distributed among hard plastics, ferrous materials, synthetic fabrics, waxed cardboard boxes and rubber. For Scenario EG, the GHG emissions from the landfill is 364 kg CO_2 eq-eight times less than Scenario A. These emissions come from the combustion of biogas during the generation of electricity; their descriptions are presented in Table 2S of the Supplementary Materials. The rest of the emissions are the same as those in Scenario A.

Scenario EG represents savings of 2,616 kg CO_2 eq with respect to Scenario A. This reduction is due to the landfill gas captured for the generation of electric power, as well as the fact that this process can generate 660 kWh of electric energy. This electric energy can substitute energy from the Mexican power grid, representing savings of 266.8 kg CO_2 eq. Similar results have been estimated for other countries (Wanichpongpan and Gheewala, 2007).

Results from the LCAs that evaluate GHG emissions per MSW ton during the utilization of landfill biogas for electric power generation are varied and depend on different factors, such as the definition of boundaries and coverage, methodological assumptions, and particularities of the region (Cleary, 2009). Various authors have reported GHG emissions between 99.4-1,900 kg CO_2 eq/ton MSW (Arena *et al*., 2003; Eriksson *et al*., 2005; Finnveden *et al*., 2005; Mendes *et al*., 2004; Moberg *et al*., 2005; Wanichpongpan and Gheewala, 2007). In this work, we estimated 298.4 kg CO_2 eq/ton MSW. If the biogas generated in Scenario A were burnt in flares, one would theoretically have a total emission of 562.2 kg CO_2 eq, similar to the results of Wanichpongpan and Gheewala (2007), who in a similar study reported 558.71 kg CO_2 eq/ton MSW.

The TA impact category, presented in Figure 3b, was quantified at -0.27 and -2.24 kg SO_2 eq for Scenarios A and EG, respectively. These negative values suggest that the way in which MSWM was carried out in both scenarios has a positive environmental effect. For both scenarios, the activities causing the greatest impact take place during municipal and private collection, at 0.088 kg SO_2 eq, mainly due to NO_X and SO_X emissions from collector trucks, presented in Table 2S of the Supplementary Materials. In addition, the impacts avoided in both scenarios by means of material recycling are -0.427 kg SO_2 eq, chiefly from the recovery of PET (42%), cardboard (25%), aluminum cans (14%), and hard plastics (5%) and the rest from synthetic fibers, waxed cardboard boxes, ferrous materials and rubber.

The TA impacts assigned specifically to Scenario A (black bar in Figure 3b) are 0.068 kg SO_2 eq, due to the activities involved in the deposition of MSW into the landfill, especially NO_X and SO_X emissions from trucks. This TA value is also assigned to Scenario EG, given that both scenarios have the same filling activities; however, in Scenario EG, the generation of electricity represents environmental credits, generating a value of -1.91 kg SO_2 eq (white bar in Figure 3b). The quantitative values of the gases causing terrestrial acidification are found in Table 2S of the Supplementary Materials.

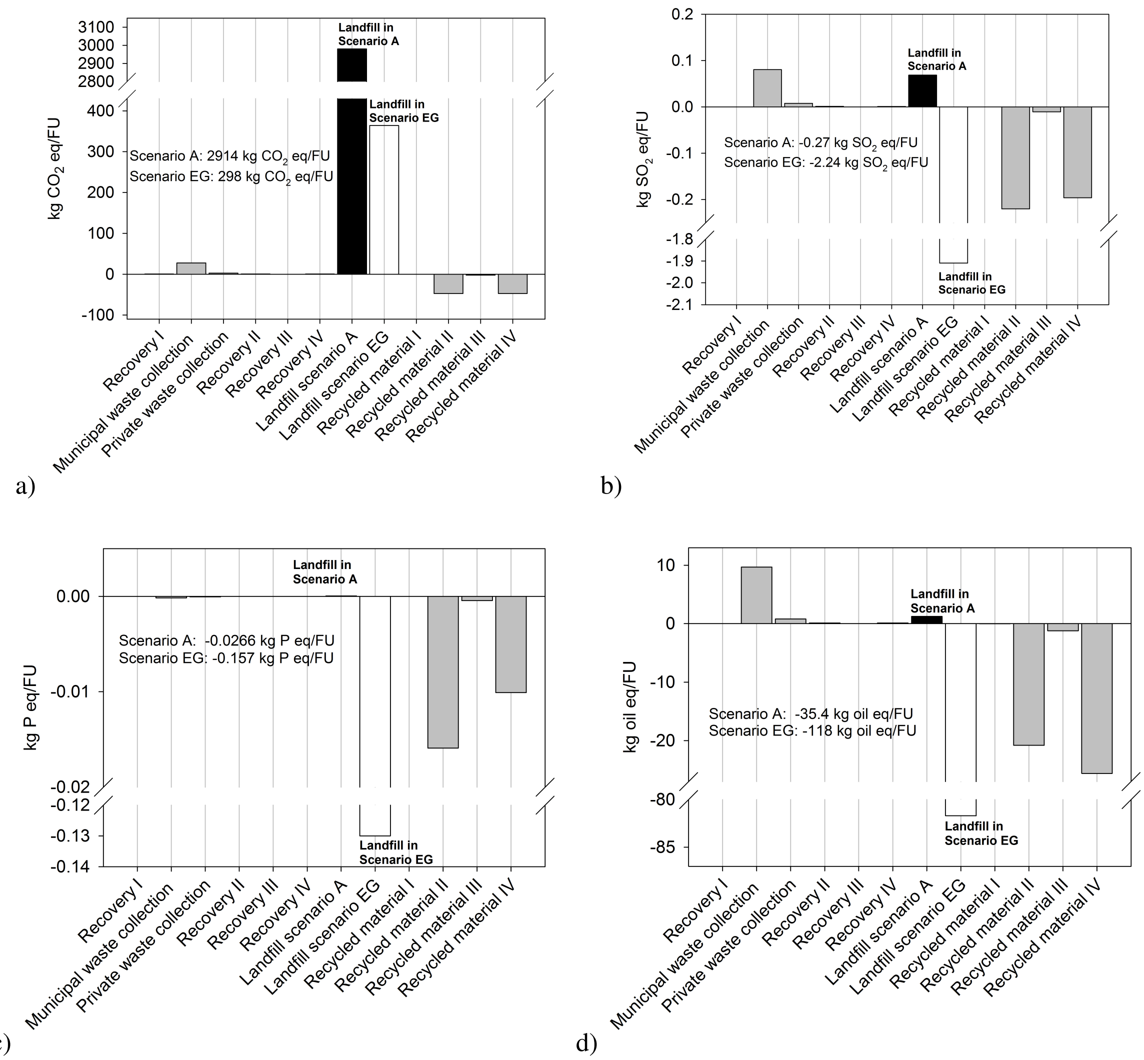

Fig. 3. LCIA results of the two MSWM scenarios, according to the ReCiPe Midpoint (H) method. a) Climate change indicator. b) Terrestrial acidification indicator. c) Freshwater eutrophication. d) Fossil depletion.

In similar LCA studies of MSWM where landfill biogas is captured for electric generation, as in Scenario EG, the TA indicator lies between -0.41 and 0.99 kg SO_2 eq/ton of MSW (Arena *et al*., 2003; Aye and Widjaya, 2006; Eriksson *et al*., 2005; Hong *et al*., 2006; Mendes *et al*., 2004).

Results of the evaluations of the FWE indicator are presented in Figure 3c. Values of -0.0266 and -0.157 kg of P eq were obtained for Scenarios A and EG, respectively. Similar to the TA indicator, management of MSW represents environmental credits. The results for Scenario EG are relatively similar in comparison to those by Bovea *et al*. (2010), who used the CML method characterization factors (Guinee, 2002) to estimate between -0.125 and -0.21 kg of PO_4^{3-} eq/ton of MSW for MSWM systems with landfills that generate electricity from captured biogas, as well as boundaries and stages similar to those discussed in this work.

The FD indicator measures the variation in the fossil fuel availability. The term "fossil fuels" refers to a set of resources that contain hydrocarbons, including volatile materials such as methane and oil and non-volatile materials such as coal (Goedkoop *et al*., 2009).

Contributions to the FD indicator by the stages integrating the MSWM are presented in Figure 3d. The values for Scenarios A and EG are -34.5 and -118 kg oil eq/FU, respectively. For Scenario A, the estimated value depends mainly on the credits obtained through saving hydrocarbons in the fabrication of new products elaborated with recycled raw materials (Recycled material I-IV, -47.6 kg oil eq/FU). The FD indicator in the MSW collection (municipal and private) is 10.5 kg oil eq, due to the use of fossil fuels in collector trucks (Table 5).

Figure 3d shows a small impact of 1.24 kg oil eq/FU for Scenario A due to the use of fossil fuels in filling activities (Table 5). Scenario EG, however, presents savings of -81.7 kg oil eq due to the production of 660 kWh of electric energy that can substitute electric power from the Mexican power grid, which according to the EcoInvent 3.1 database (Ecoinvent Center, 2014) comes from 0.0759 kg oil eq of natural gas, 0.0451 kg oil eq from carbon, and 4.5×10^{-3} kg oil eq from crude oil, per kWh. The fuels contributing to the total FD impact are the following: -22.0 kg oil eq from natural gas, -9.75 kg oil eq from crude oil, and -3.69 kg oil eq from carbon in Scenario A and -72.0 kg oil eq from natural gas, -33.4 kg oil eq from carbon, and -12.6 kg oil eq from crude oil in Scenario EG.

3.3.2 Endpoint method results

Figures 4 and 5 present results of the ReCiPe Endpoint (H) method indicators for 17 category indicators and 3 environmental damage indicators, respectively. All indicators are denoted as points of the single-score indicator (Pt). In this index, all individual environmental impacts are normalized and included into a single indicator with the goal of making quick comparisons. The disadvantage of using a single-score indicator is that the normalization process requires the weighting of different environmental impact indicators, which has a relative degree of subjectivity (Arafat *et al*., 2015). Further explanation can be found in Goedkoop *et al*. (2009).

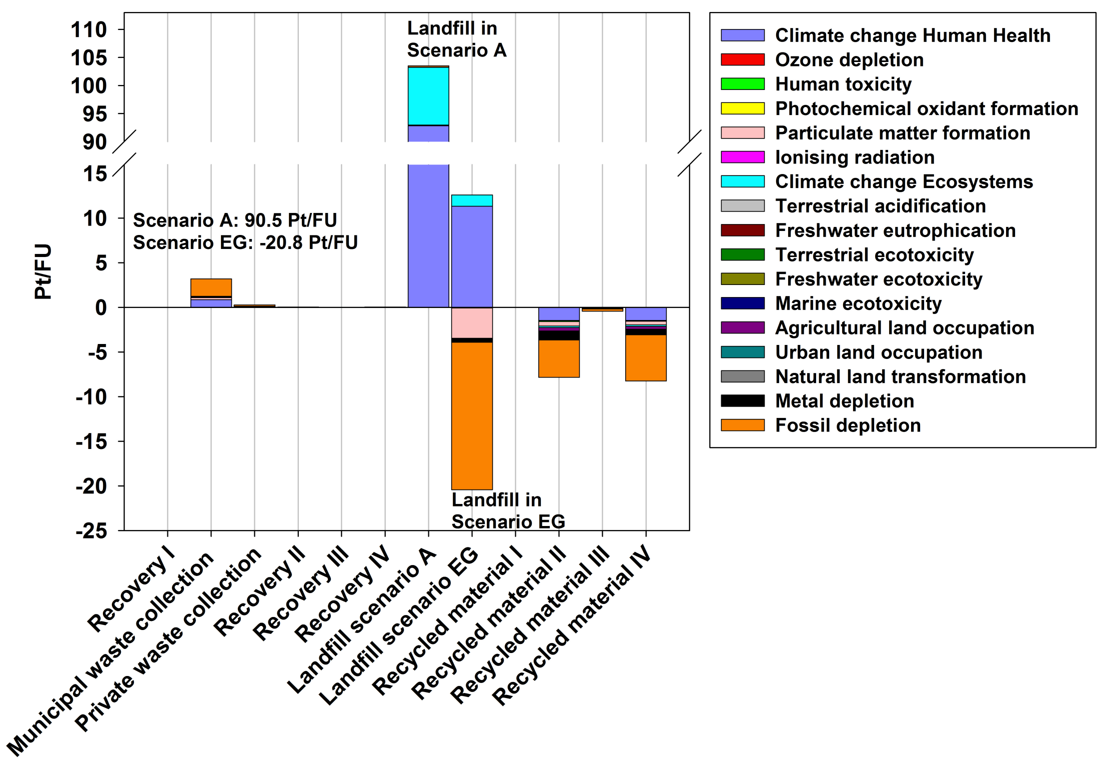

Fig. 4. LCIA results for the two MSWM scenarios according to the ReCiPe Endpoint (H) method: contribution of 17 environmental indicators.

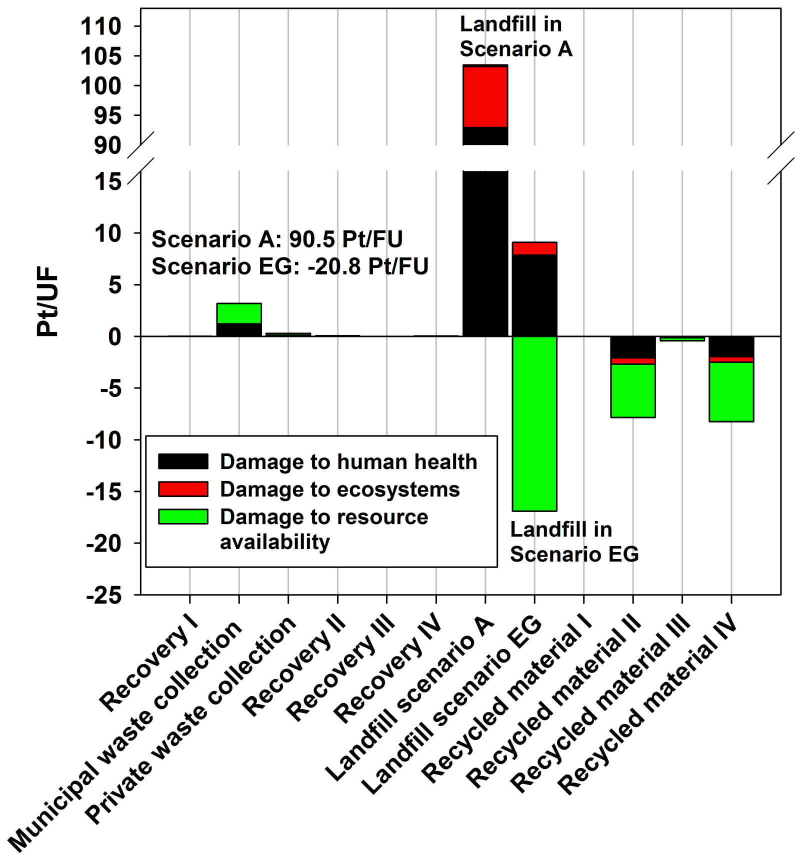

Fig. 5. LCIA results for the two MSWM scenarios, according to the ReCiPe Endpoint (H) method: contribution of three environmental damage indicators.

Figure 4 presents the contribution of the different indicators at each stage of the MSWM. For Scenarios A and EG, the total impacts are 90.5 and -20.8 Pt, respectively. The main impact indicators are the following: effects on human health due to climate change, with 90.8 and 9.3 Pt; fossil depletion, with -7.2 and -24.0 Pt; climate change of ecosystems, with 10.1 and 1.0 Pt; and the particulate matter formation, with -0.5 and -4.0 Pt for Scenarios A and EG, respectively. The fossil depletion indicator, FD (Figures 3d and 4), represents the main source of environmental credits due to the recovery of materials for recycling and the production of electric energy.

Figure 5 illustrates the distribution of damages in the management of MSW. For Scenario A, damages to human health represent the greatest impact, with 90.0 Pt, followed by damage to ecosystems, with 9.2 Pt. In contrast, the damage to resource availability has a net beneficial effect of -8.7 Pt. In Scenario EG, the indicators are drastically reduced to 5.0 Pt for damage to human health, 0.2 for damage to ecosystems, and -25.9 for damage to natural resources.

Recycling processes present a contribution of -16.5 Pt. Figure 5 shows that the greatest contribution comes from the indicator of damage to resource availability, at 68%, followed by damage to human health, at 25%, and damage to ecosystems, at 7%. In the Municipality of Celaya, only approximately 24% of the total materials that are apt for recycling are recovered; however, recovery tasks present technical limitations associated mainly with the non-selective collection of MSW, which could be solved by the transformation of the population into a recycling society. One LCA study carried out by Song *et al*. (2013) using the Eco-indicator 99 reports that increasing the recycling rate by 20% contributes to a

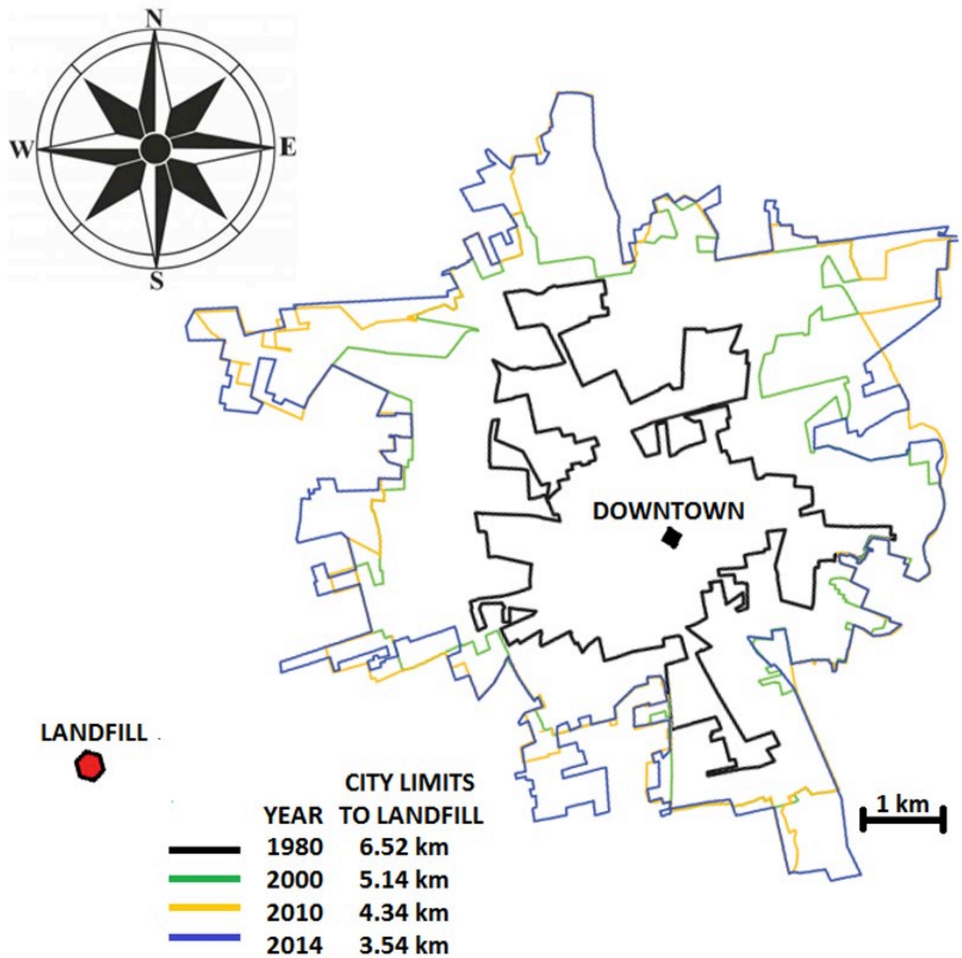

Fig. 6. Contour of the urban area of the city of Celaya in different years, and its proximity to the landfill CEMIR II.

reduction of approximately 80% of the environmental impact.

In Figure 5, the damage to human health indicator of the landfill stands out due to its large contribution in the current MSWM situation in the municipality of Celaya (Scenario A). The installation of an electric generation plant or, alternatively, the burning of the produced gas, significantly reduces the environmental impact, although the potential health effects persist. This impact incites further interest due to the possible harmful effects of the emissions on the health of workers and the population living near the landfill. In a review of the studies carried out in the UK with groups of people living near or working in the management of a landfill, it is noted that no concrete evidence was found for the impact of landfills on health. They attribute this to the strict legislation, as well as the careful construction and operation of landfills in the UK (Macklin *et al*., 2011). However, chemical substances considered toxic have been found in landfill emissions (Capra *et al*., 2014; Li *et al*., 2012; Macklin *et al*., 2011). In the MSWM in Celaya, a series of erroneous practices have been observed, such as the recovery of material inside the landfill by informal collectors, without any observance of safety measures; the absence or insufficiency of classification tasks and waste treatment was present prior to placement in the landfill. Thus, this risk must be appropriately considered, especially given the growth of the urban area toward the landfill, as can be observed in Figure 6.

Conclusions

The disposal of MSW in landfills represents an environmental passive with complex remediation alternatives. For our case of study, the severest midpoint indicator is the climate change, due to landfill emissions calculated at 2980 kg of CO_2 eq/FU. In addition, as a consequence of the landfill emissions, the indicator of damage to human health is increased. These indicators have a global context; nevertheless, the affectation of local vulnerable populations can occur with more intensity by bad operating practices and deficient infrastructure in landfills, as well as disorganized urban sprawl. The capture and use of landfill gas for electricity generation (EG scenario) is a favorable alternative compared to conventional strategy (A scenario), the emissions of greenhouse gases are reduced to 298 kg CO_2 eq/FU which represent the decreasing of about 94% in the damage to human health. The recovery and recycling of materials play an important role on mitigating environmental impacts. However, in this case study the recycling rate is low (only 6.6%) compared to the average rate for other countries, and this activity is practically informal. In a Mexican context, the mitigation of environmental impacts in actual landfills involve extraordinary efforts and resources. An alternative to reduce the need in using landfills, is to increase the recovery and recycling of materials through legislation, infrastructure improvement and changes in the habits of the population

List of abbreviations

MSWM	Municipal Solid Waste Management
MSW	Municipal Solid Waste
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
EG	referring to the Electric Generation scenario
A	referring to the Actual scenario
CEMIR	Center for Integral Waste Management
FU	Functional Unit
GHG	Greenhouse Gases
CC	Climate Change
TA	Terrestrial Acidification
FWE	Freshwater Eutrophication
FD	Fossil Depletion

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