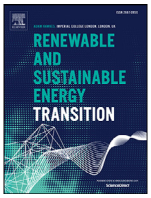
Renewable and Sustainable Energy Transition 1 (2021) 100007

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Transition

journal homepage: www.elsevier.com/locate/rset



Full-length article

Current and prospective situation of municipal solid waste final disposal in Mexico: A spatio-temporal evaluation

Juan Felipe Rueda-Avellaneda[a], Pasiano Rivas-García[a,b,*], Ricardo Gomez-Gonzalez[a,*], Reyes Benitez-Bravo[a], José Enrique Botello-Álvarez[c], Salvador Tututi-Avila[a]

[a] *Facultad de Ciencias Químicas, Universidad Autónoma de Nuevo León, Av. Universidad s/n Cd. Universitaria, San Nicolás de los Garza, Nuevo León 66455, México*
[b] *Centro de Investigación en Biotecnología y Nanotecnología, Facultad de Ciencias Químicas, Universidad Autónoma de Nuevo León, Parque de Investigación e Innovación Tecnológica, km. 10 Highway to the International Airport Mariano Escobedo, Apodaca, Nuevo León 66629, México*
[c] *Doctorado en Ciencias de la Ingeniería, Departamento de Ingeniería Bioquímica, Instituto Tecnológico de Celaya, Av. Tecnológico y A. García Cubas, Celaya, Guanajuato 38010, México*

ARTICLE INFO

Keywords:
Municipal solid waste
Landfill gas
Waste-to-energy
Greenhouse gases mitigation
Geographic information systems

ABSTRACT

Mexico, similarly to other developing countries, has planned landfilling as the central technology to manage municipal solid waste (MSW). In this research, the current and future situation of final disposal of MSW in Mexico was studied, focusing on the spatial and temporal evaluation of final disposal sites (FDS), landfill gas (LFG) emissions, and potential power generation in an 80-year horizon. Geographic information systems were applied for spatial evaluation. The Mexico LFG 2.0 model was used to estimate the LFG emissions in 1782 FDS in operation, considering statal MSW characteristics and local FDS features. The transition towards a MSW management system that is less dependent on final disposal was carried out via a sensitivity analysis of the reduction of FDS in LFG emissions, power generation, and greenhouse gases (GHG) emissions. The study estimated that Mexico had an LFG generation of 2298 Mm^3 in 2020, where only 4.6% of FDS were suited for power generation, up to 2534 GWh y^{-1}. This electricity can avoid the emission of 1.45 Mt CO_2 , since fossil fuels are predominant in the Mexican power grid. The sensitivity analysis showed that suppressing MSW landfilling could reduce 1636 Mt CO_2 eq over the period studied compared to the business-as-usual scenario. The power generation potential of LFG has been used scarcely (165 GWh y^{-1}). Public policies may focus on proposing economic incentives and establishing conditions for a biogas market, increasing the number of SL that use LFG for energy purposes.

1. Introduction

Landfilling is the primary method to treat municipal solid waste (MSW) worldwide [1]. Annually, 740 Mt of MSW are disposed of in landfills, representing 37% of the total MSW generated worldwide [1]. The USA and China are the top MSW generators, having more than 3000 landfills in operation [2].

Landfilling presents several environmental issues. Environmental impacts in midpoint indicators per ton of MSW disposed of have been reported, such as climate change -*e.g.*, 2914 [3], 100–700 [4], and 2659 [5] kg CO_2 eq-; terrestrial acidification -*e.g.*176 [6], 192 [7], and 400 [5] g SO_2 eq-; and eutrophication -*e.g.*, 38 [5], 2691 [6], and 79 [7] g PO_4^{3-} eq-. Human health risk assessments have shown landfills are related to non-cancer and cancer adverse health effects due to the presence of chrome [8], lead [9], benzene [10], naphthalene, hydrogen sulfide, and trichloropropane [11] in their surrounding environment, which can affect workers and people who live near to the landfills.

In comparison to other technologies, landfills present lower investment and operating costs. The construction of a landfill facility for servicing a population of 1 million can cost approximately 10 million USD [1]. MSW treatments as incineration or anaerobic digestion can cost three [12] and 14 times higher than landfills [13], respectively. However, when the cost of externalities (*i.e.*, economic cost for climate change) is accounted for, the difference between landfills and these technologies reduces by half [14]. Landfills have also been described as sites that cause public opposition. Al-Khatib et al. [15] found that 42% of the population near a landfill had problems associated with the MSW facility (*e.g.*, visual appearance, presence of noxious fauna, dust, and putrid odors). Owusu et al. [16] reported that the social unrest due to public rejection of the landfill could cause premature closures. Due to the

---

[*] Corresponding authors at: Facultad de Ciencias Químicas, Universidad Autónoma de Nuevo León, Av. Universidad s/n Cd. Universitaria, San Nicolás de los Garza, Nuevo León 66455, México.

E-mail addresses: pasiano.rivasgr@uanl.edu.mx (P. Rivas-García), ricardo.gomezgz@uanl.edu.mx (R. Gomez-Gonzalez).

https://doi.org/10.1016/j.rset.2021.100007
Received 10 June 2021; Received in revised form 17 August 2021; Accepted 24 August 2021

landfills' environmental, economic, and social impacts, they are the least recommended option to manage MSW [17].

The use of landfills has decreased recently in developed countries. European Union member countries, such as Switzerland, Germany, Belgium, Netherlands, and Denmark, have reduced almost entirely the share of landfills in their MSW management (*i.e.*, 0%, 0%, 1%, 1%, and 2%, respectively). The United States has reduced in 91% the quantity of MSW landfilled since the year 2000 [18], and China plans to decrease the landfill treatment ratio by 40% [19]. These reductions have been achieved due to the implementation of policies in the waste management sector that restrict landfill use. The European Union established that by 2020, the proportion of organic fraction of municipal solid waste (OFMSW) could not account for more than 35% of the total MSW [20]; while by 2030, the reduction of MSW landfilled to 10% of the total must be achieved [21]. China has implemented a pilot program of MSW recycling in 46 cities, and it is projected to increase incineration to 50% of MSW [19]. The United States implemented tax incentives and funding to build waste-to-energy facilities (*e.g.*, incineration and anaerobic digestion plants) and plans to construct dozens in the following years [22].

Trends for landfill use in Latin America are the opposite of those of developed countries. The share of MSW landfilled increased from 22.6 [23] to 68.5% [1] between 2002 and 2018. This rise is explained by the waste policies in developing countries centered on reducing open dumping, which in Latin America still represents 26.8%, and the use of landfills appears as the first solution [1].

Confinement of MSW in final disposal sites -*i.e.*, sanitary landfills (SL), controlled landfills (CL), and open dumps (OD)— is the third source of anthropogenic methane emissions in Latin America due to landfill gas (LFG). In 2020, methane emissions from MSW disposal sites accounted for 992 Mt CO_2 eq, and it is estimated that for 2030 landfill emissions will increase by 20% [24]. Methane is the second greenhouse gas (GHG) in the atmosphere by concentration [25].

National estimation of methane from LFG generation is relevant since these studies support policymaking and define base scenarios for GHG emissions abatement goals. Cai et al. [26] evaluated 1955 operating and 495 projected FDS in China, where they found that the total projected emissions were 23% lower than the business-as-usual (BAU) scenario reported by EPA. The study attributed the difference in the results to the fact that they considered operational and climatic conditions for each landfill. Furthermore, the spatial evaluation allowed identifying zones with the most significant methane emissions to help decision-makers prioritize GHG mitigation policies.

LFG is an energy source due to its methane content that can be used as a fuel. LFG has an average low heating value of 5.17 kWh/m^3 [27]. This heating value enables LFG to be used as a fuel in internal combustion engines and turbines to produce electricity [27]. LGF can also be valorized to biomethane to broaden its energy applications by injecting it into the natural gas grid or utilizing it as a vehicular fuel [28]. Energy recovery of the LFG has a transversal effect on the mitigation potential of GHG emissions. This approach reduces the emissions in the waste sector and mitigates emissions in the energy sector due to the replacement of fossil fuels for a renewable and clean energy source [6]

The energy recovery scenarios from LFG have been evaluated for some countries, Choudhary et al. [29] estimated the climate change indicator and the energy production of MSW disposed of in Indian FDS, founding that OD are the highest contributors to methane emissions due to 75–80% of the total MSW are confined in these sites. This situation caused that only 782 GWh of electricity was generated for LFG in 2019 [30]. Fei et al. [19] assessed spatially and temporally the energy potential of MSW in China, estimating that LFG could produce 7.39 TWh of electricity or 1.70 Gm^3 of biomethane in the 2020 year.

There are few studies related to national LFG emissions for Latin American countries. Santalla et al. [31] estimated for Argentina that, in 2030, these emissions will reach 9.6 Mt CO_2 eq, while in an LFG capture scenario, they could be reduced by 50%. Weitz et al. [32] estimated emissions of 41Gg CH_4 for Panama in 2020. National scenarios of abatement potential for energy recovery from LFG in Latin America have been assessed for Brazil [33]. This study determined that the maximum annual production of LFG in Brazil is 1567 Mm^3, and it would have a maximum installed capacity of 533 MW.

Table 1
Database characteristics of the final disposal sites in Mexico.

Inputs	Quantity evaluated
Number of FDS	2187 FDS
Composition of the MSW	32 compositions
Waste disposal coefficient per capita	2281 municipalities
Disposal period	1970–2100

FDS: Final disposal sites. MSW: Municipal solid waste.

According to EPA [24], Mexico is the second Latin American country with the largest methane emissions related to landfilling; in 2020, FDS of MSW emitted 24.67 Mt CO_2 eq, and an increase of 21.6% for 2030 is projected based on a BAU scenario.

Mexico has evaluated the emission of LFG at a national scale in the Mexican national inventory of GHG in 2015 [34]. According to this study, the methane emitted in FDS of MSW accounted for 22 Mt CO_2 eq, representing 15.5% of the total methane emissions. However, there is no study of the current scenario and future trends of methane LFG emissions at a national scale and the evaluation of the potential mitigation of GHG through energy recovery from the LFG. Furthermore, the few studies made in Latin America related to national landfill gas emissions do not discuss the final disposal characteristics of the countries nor the effect of the transition toward MSW management system with less participation of FDS in the LFG emissions and the power generation.

The main objective of this study is to characterize the current and future situation of the final MSW disposal in a Latin American country like Mexico, forecasting an 80-year horizon. For this purpose, this article presents a detailed description of the final disposal situation of the country, which, combined with interdisciplinary tools as geographic information systems, allows a national and subnational assessment. The LFG emissions and the technical feasibility of the energy recovery were evaluated for the FDS in Mexico, considering scenarios of reduction of MSW disposed. This study can help policymakers define BAU scenarios for middle and long-term energy planning in the waste sector and identify hotspots of GHG emissions to prioritize mitigation strategies. This methodology could be used in other Latin American countries, whereas it was noted that there are few studies of national emissions of LFG.

2. Methodology

2.1. Current situation of Mexican final disposal sites

In this work, only FDS in operation were studied, and the characteristics evaluated were the number and spatial distribution, operative conditions, infrastructure, and age. For each FDS, the composition and the quantity of MSW disposed of were considered. These data were collected from the National Census of Municipal Government and Delegations [35], except for the MSW compositions obtained from various bibliographic sources (in the Table S1 of the Supplementary Material section, such sources are specified). Table 1 describes the database characteristics of the MSW final disposal in Mexico.

The historical and prospects of the annual MSW disposed on each FDS in Mexico were determined for 1970–2100. This estimation was based on the waste disposal coefficient per capita for the year 2016 from each municipality. The historical and projected population data were evaluated as follows: for the years 1970–2015, the National Census was consulted; for the period 2015–2050, the data were collected from the municipal [36] and state [37] population projections, and for the period 2050–2100 the projections were linearly extrapolated.

The average operational life expectancy of a FDS is ranged between 30 and 50 years [38]. This study used an average life expectancy of 40 years to establish the FDS closure date.

2.2. Generation of landfill gas in final disposal sites in Mexico

The characteristics for each FDS and their respective MSW compositions (described in Section 2.1) were used to assess the LFG emissions over time. The LFG generation was calculated using the Mexico LFG model 2.0 [39], which is described in Eq. (1),

$$Q_{\mathrm{LFG}} = \sum_{i=1}^{n} 2kL_0\left[M_i\right]\left(e^{-kt_i}\right)(MCF)(\mathrm{F}) \tag{1}$$

where Q_{LFG} represents the maximum flow of LFG (m^3 y^{-1}), i indicates the year (y), n is the total time of landfilling of the MSW (y), k represents the methane generation index (y^{-1}), L_0 symbolize the methane generation potential (m^3 t^{-1}), M_i is the mass of MSW in the year i (Mg), t_i is the age of the mass of MSW landfilled (y), *MCF* corresponds to the methane correction factor, and *F* is the fire adjustment factor, which was considered as 1. In this study, the parameters of Eq. (1) were evaluated for each FDS, according to the characteristics considered in Section 2.1.

The rate, *k,* is influenced by the climatic conditions [40], and the composition and physicochemical characteristics OFMSW [41]. Eq. (2) represents the calculation for this parameter, where $\%r_i$ is the percentage of waste i in OFMSW and k_i is the associated rate of waste i. The OFMSW is divided into (i) very fast degradation waste (*i.e.*, food waste), (ii) moderately fast degradation waste (*i.e.*, garden and other organic waste), (iii) moderately low degradation waste (*i.e.*, paper and textiles), and (iv) very low degradation waste (*i.e.* wood and straw).

$$k_{pond} = \sum_{j=1}^{4} (\%r_j \times k_j) \tag{2}$$

The parameter L_0 represents the capacity of methane generation per unit of MSW disposed of [42]. This value can be calculated using Eq. (3),

$$L_0 = MCF \times DOC \times DOC_F \times F \times \frac{16}{12} \tag{3}$$

where *MCF* is the methane correction factor, which considers the reduction of methane generation where landfill management does not ensure total anaerobic conditions; *DOC* is the degradable organic carbon content of MSW and DOC_F is the carbon fraction that can be biodegraded anaerobically, for developing countries DOC_F is often approximated to 0.77 [43]; *F* is the methane fraction in the LFG, which is generally 0.5; and 16/12 is the stoichiometric ratio of C in CH_4.

Eq. (4) describes the estimation of the *DOC* parameter, where *A* is the fraction of MSW that is paper and textiles, *B* corresponds to garden and other organic waste fraction, *C* is the food waste fraction, and *D* is the fraction for straw and wood.

$$DOC = (0.4 \times A) + (0.17 \times B) + (0.15 \times C) + (0.3 \times D) \tag{4}$$

The Mexico LFG model 2.0 was programmed in Python 3.0 [44] to estimate the generation of each FDS in Mexico. From 2187 FDS (Table 1), only 1782 were assessed for LFG generation. The remaining FDS were OD with no reliable information of its opening year.

2.3. Spatial evaluation of landfill gas generation of final disposal sites in Mexico

A spatial evaluation of the LFG generation was carried out using the software QGIS 3.14.[45] The regional division of Mexico is based on the economic regions proposed by Bassols Batalla [46]. Fig. 1S (in the supplementary material section) shows a map with the economic regions.

2.4. Minimization of final disposal and power generation from landfill gas scenarios

The temporal evaluation of the LFG emissions and the power generation were assessed via sensitivity analysis for different scenarios.

The temporal evaluation studied the LFG generation of FDS from 1970 to 2100. For the power generation, it was considered:

- A minimal flow of 5 Mm^3 y^{-1} of LFG for being suitable to install an internal combustion engine [27].
- An LFG composition of 50% methane and 50% carbon dioxide.
- An LFG capture efficiency of 100%.
- A power generator efficiency of 35%. r
- A methane low heating value of 9.32 kWh/m^3.
- A global warming potential (GWP) of 28 for methane.

A sensitivity analysis was carried out to evaluate the effect of reducing the use of FDS on GHG emissions and the potential power generation from captured LFG. Five scenarios of reduction in the use of FDS were evaluated (*i.e.* BAU, 25%, 50%, 75%, and 100%). For each scenario, the trends of MSW disposed of after the time of closure of the FDS (*i.e.* 40 years) were reduced, with the exception of the BAU scenario, where the trend remains the same. The 100% scenario is the most optimistic since it considers that Mexico will change the MSW management to other technologies alternative to FDS. Table 2 describes each scenario and their considerations.

This analysis makes the following assumptions: MSW technological alternatives are available to manage those amounts of MSW that are not confined in FDS, and the environmental burden by these alternatives is not considered.

3. Results and discussion

3.1. Characteristics of final disposal sites in Mexico

3.1.1. Number and spatial distribution

According to INEGI [35], the operating FDS by 2016 were 2197 (Table S2). These sites were located all over Mexico, except for Mexico City, which disposes of its MSW in Mexico State and Morelos. Fig. 1 shows the number of FDS per state, where Oaxaca (385), Veracruz (149), and Chihuahua (131) have the most. The lowest number of FDS were found in Aguascalientes (1), Colima (3) and Tlaxcala (4). The difference between the numbers of FDS is related to the heterogeneity in the amount of municipalities between the states. Oaxaca is the state with more municipalities (569), while Colima (9) and Aguascalientes (11) are two of the states with fewer municipalities.

The implementation of inter-municipal or regional FDS is an MSW management strategy that reduces the number of FDS. This strategy reduces the disposal cost of MSW due to FDS having economies of scale (Kojima, 2019). The SL model cost developed by EPA [47] shows that disposing one t of MSW in an SL with a capacity of 10 t MSW d^{-1} can cost 11.3 times higher than disposing of in an SL with a capacity of 1000 t MSW d^{-1} (Fig. S2).

The use of regional FDS is a trend in Latin America [23]. However, this strategy is uncommon in Mexico, as there were just 126 regional FDS in Mexico (6% of the total). This finding may be attributed to the low inter-municipal cooperation in Mexico [48]. For instance, states whose legislation ease inter-municipal cooperation (*e.g.*, Aguascalientes) [49] had more municipal coverage of regional landfills (100%). On the other hand, states whose legislation inhibits inter-municipal association (*e.g.*, Yucatan) [49] had fewer municipalities covered by regional FDS (1%).

3.1.2. Classification of the FDS in Mexico

The Secretary of Environment and Natural Resources (SEMARNAT, for its initials in Spanish) classifies FDS according to the available infras-

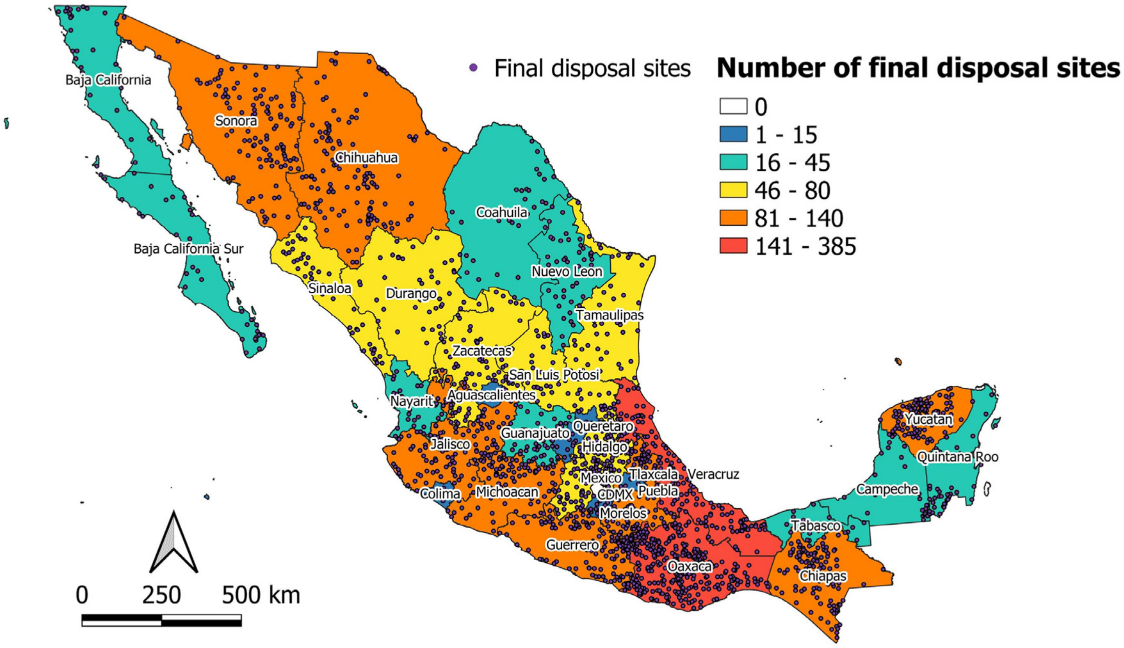


Fig. 1. Number of final disposal sites per state.

Table 2
Description and considerations for FDS reduction scenarios.

Scenarios of reduction in the use of FDS	Consideration of the trends of MSW disposed of after the time of closure of each FDS
BAU	The trend of MSW disposed of remains equal
25%	The trend of MSW disposed of is reduced to 25%
50%	The trend of MSW disposed of is reduced to 50%
75%	The trend of MSW disposed of is reduced to 75%
100%	The trend of MSW disposed of is reduced to 100%

tructure and operating practices: (i) SL are the sites which fulfill all the requirements issued in the landfill Mexican normative, NOM-083 [50], (ii) CS are similar to SL with the difference that CS lacks a system to prevent leachate filtration into groundwater, and (iii) OD which neither has the impermeable system nor any of the other characteristics stated in NOM 083 (*e.g.*, management and leachate treatment, management and flare of the LFG, compaction, and daily coverage of the MSW).

The distribution of Mexican FDS was: 163 SL (7.4%) and 2034 OD (92.6%), none FDS had the characteristics to be considered as CS (Table S2). These results differ from the findings presented by the report of INECC [34], that reported 2637 FDS, 12% corresponds to SL, 60% OD, 7% CS, and 21% not accounted. The difference corresponding to the number in FDS is due to the INECC study considering closed and projected FDS. The discrepancy between the shares of SL, OD, and CS can be attributed to INECC using state normative to define the FDS classification, while this study considers the national normative NOM-083 [50].

The MSW disposed of in SL represented 65% of the total MSW disposed of in Mexico in 2016, while open dumping accounted for 35%. The percentage of SL agree with Espinoza-Tello et al. [23], but the authors reported an OD participation of 12.4%. The difference between both studies is due to the CS denomination. Espinoza-Tello et al. considered CS as the facilities with some infrastructure to manage MSW but without any specifications. In contrast, this study considered CS according to the NOM-083.

The high use of OD in Mexico may be attributed to small-size cities. Cities with a population between 2500 and 100000 inhabitants represent 76% of the municipalities in Mexico and concentrate 29% of the total population. These small-size cities generally manage their MSW inadequately due to budget limitations for building and operating an SF or CS [51].

Table 3 shows the share of the different types of FDS by region and state in Mexico. The South Central and North East regions had SL as the primary method to manage MSW, while the Gulf of Mexico region had the highest share of OD, which is the strategy with the lowest technology. The relation between the disposal infrastructure and the economic indicators is noteworthy, due to regions with the highest share of gross domestic product (GDP) had SL as the main disposal strategy, as shown in Fig. S3B. These results accord with Kaza et al. [1], who reported that territories with higher income have better MSW disposal practices.

3.1.3. Age of the FDS in Mexico

The average age of the FDS was 15.5 years, without a significant difference between SL and OD (Table S2). These results suggest that the promulgation in 2003 of normative to enhance the MSW disposal in Mexico, as the General Law for the Prevention and Integral Waste Management [52] and NOM-083, has fostered SL's construction. However, these efforts have not prevented the emergence of new OD; some of them opened less than five years ago.

Fig. 2 shows the average age of SL and OD age in Mexico. The lowest age of SL in regions as the Yucatan Peninsula (8.7 y) and South Pacific (13.3 y) can be explained as a transition of OD to SL. These zones have longer times for planning the energy use of LFG as they will have delayed production peaks. On the other hand, the highest age of SL in regions as the North West (21.4 y) and North East (18.9 y) can be attributed to earlier waste management planning. These areas could implement different strategies for MSW treatment in the short term since they will have to face the closure of several SL in the following years. For instance, Nuevo Leon, a state in the North East region, has planned to construct an integral MSW management center that includes sorting, recovery, transformation, thermal valorization, and anaerobic digestion

Table 3

Share of the types of final disposal sites in the management of municipal solid waste per state and economic region in Mexico.

Region and state	Share of the MSW disposed of (%)		Region and state	Share of the MSW disposed of (%)	
	SL	OD		SL	OD
North West	57.2	42.8	South Central	81.6	18.4
Baja California	66.9	33.1	Hidalgo	50.4	49.6
Baja California Sur	54.8	45.2	Mexico City*	-	-
Nayarit	66.0	34.0	Mexico State*	85.9	14.1
Sinaloa	63.1	36.9	Morelos	69.2	30.8
Sonora	31.5	68.5	Puebla	74.7	25.3
North	64.8	35.2	Queretaro	89.8	10.2
Coahuila	73.7	26.3	Tlaxcala	78.4	21.6
Chihuahua	80.0	20.0	South Pacific	44.1	55.9
Durango	70.5	29.5	Chiapas	42.9	57.1
San Luis Potosi	46.9	53.1	Guerrero	50.8	49.2
Zacatecas	22.0%	78.0%	Oaxaca	36.8	63.2
North East	80.3	19.7	Gulf of Mexico	21.5	78.4
Nuevo Leon	82.6	17.4	Tabasco	28.4	71.6
Tamaulipas	77.1	22.9	Veracruz	19.5	80.5
West Central	60.1	39.9	Peninsula of Yucatan	72.1	27.9
Aguascalientes	100.0	0.0	Campeche	71.5	28.5
Colima	74.7	25.3	Quintana Roo	82.3	17.7
Guanajuato	47.5	52.5	Yucatan	52.8	47.2
Jalisco	69.7	30.3			
Michoacan	45.3	54.3			

MSW: Municipal solid waste, SL: Sanitary landfill, OD: Open dumps

*The MSW disposed of by Mexico City were accounted to Mexico State and Morelos

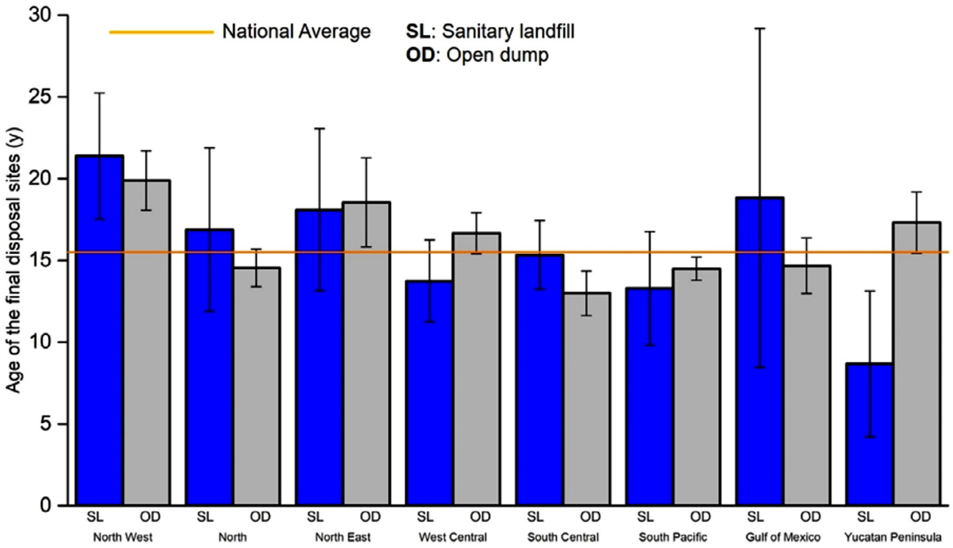


Fig. 2. Average age of the final disposal sites per economic region.

of the MSW [53]. In contrast, the North West region may keep the SL as the primary method as Baja California Sur projects the construction of nine SL [54].

3.1.4. *Composition of the MSW in Mexico*

The average of the OFMSW in Mexico was 50%, similar to the 51.6% reported by SEMARNAT [55]. This fraction is also similar to the average value from developing countries, *i.e.*, 53% [1]. Fig. 3 shows the OFMSW for economic regions in Mexico, where the difference in the MSW composition between the economic regions is notorious. This information is quite helpful for decision-makers selecting MSW treatment strategies alternatives to the final disposal. For instance, cities in the West Central and South Pacific regions may be suitable for methods where OFMSW is used for composting and anaerobic digestion. In contrast, the MSW generated in northern cities and the South Central region can be more appropriate for thermal treatment or refuse-derived fuel. This last technique has been scarcely developed in the SL of Monterrey, Nuevo Leon, where a fraction of MSW is recovered to produce RDF for the cement industry [56].

3.1.5. *Quantity of MSW disposed of in FDS in Mexico*

For 2016, the mass of MSW disposed of in FDS in Mexico was 0.103 Mt d^{-1}. The comparison between MSW disposed of with the estimation of MSW generated (0.122 Mt d^{-1}) showed that the share of MSW confined in FDS is 84.4% [55]. This value is in accord with the rate of MSW collection in Mexico, *i.e.*, 87%. The remained MSW may be disposed of in illegal FDS or within an informal collection and recovery system for recyclable materials. An official report from Mexico City identified 1229 clandestine dumps inside the city [57], while a study by Botello-Álvarez et al. [3] found that informal waste pickers can sort up to 23% of the recyclable fraction of the MSW, which reduce the GHG emissions from MSW management in 8.5%.

Table 4 shows the classification of the FDS in Mexico based on their size, as established in the NOM-083. It is shown that the small-size FDS predominate (*i.e.*, FDS class *B, C*, and *D*) since 87.3% of the FDS received less than 100 t d^{-1} of MSW.

Fig. 4 illustrates the MSW disposal per capita in Mexico. This characteristic maintains a complex relationship between the incomes of the territories (Fig. S3b). In some regions, the large MSW disposal is not

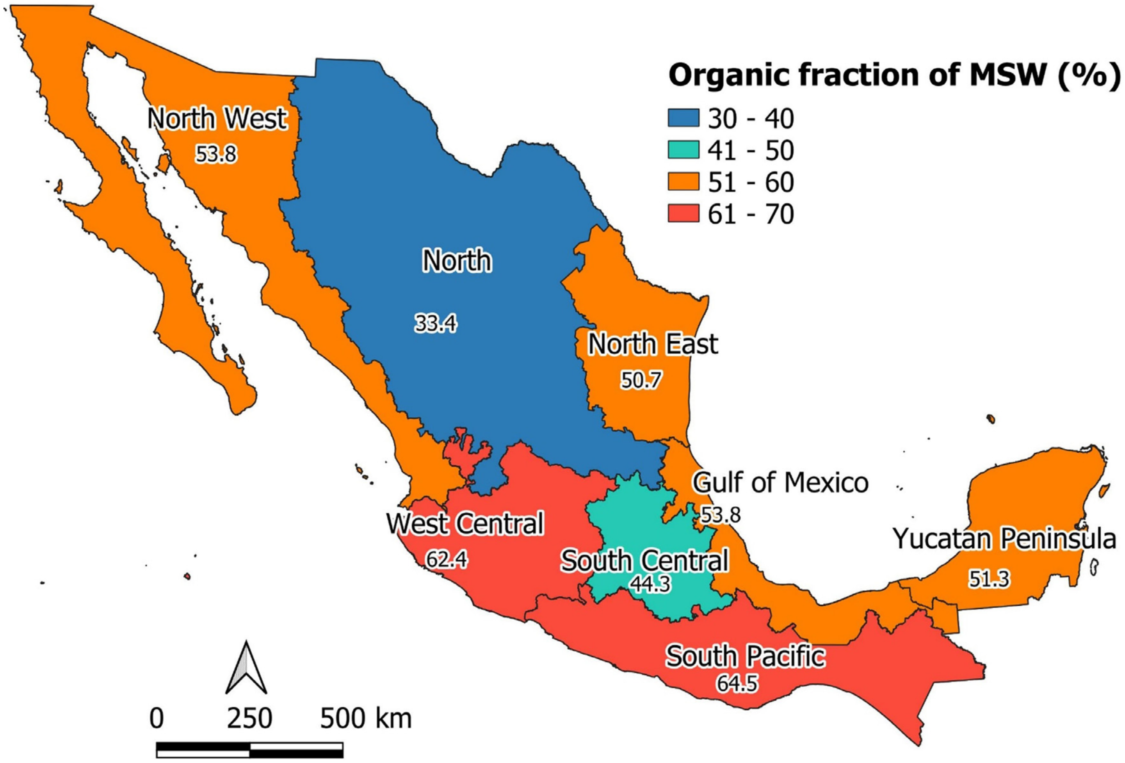


Fig. 3. Percentage of organic fraction in municipal solid waste (MSW) per economic region.

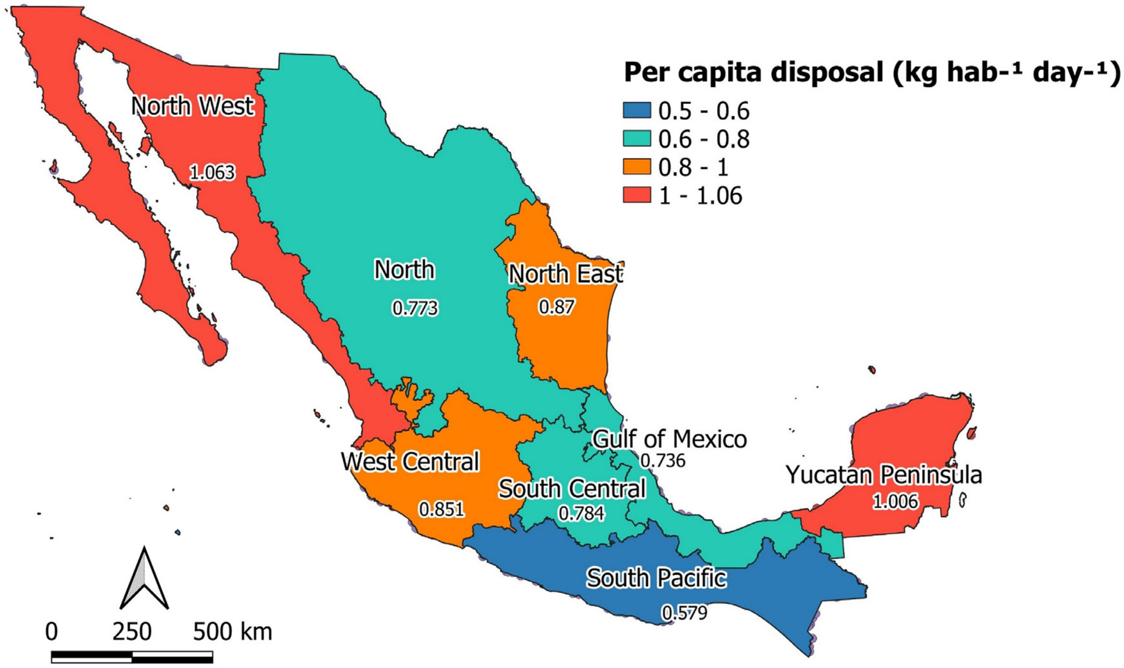


Fig. 4. Per capita municipal solid waste final disposal per economic region in Mexico.

Table 4

Classification of the final disposal sites in Mexico based on the daily capacity to manage municipal solid waste [50].

Classification of FDS	Mass of MSW disposed (t d^{-1})	Number of FDS
A	> 100	166
B	50–100	112
C	10–50	461
D	< 10	1458

related to economic development. For instance, the North West region had the most significant MSW disposal, but it is the third region with the lowest income per capita.

Touristic activity has been described as a factor that can affect the quantity of MSW managed in a territory. Arbulu et al. [58] estimated that an increase of 1% of the number of tourists in a small-size city could increase 1.25% the MSW generated. Saito [59] found that the tourism sector may represent 10% of the MSW generated. The present study

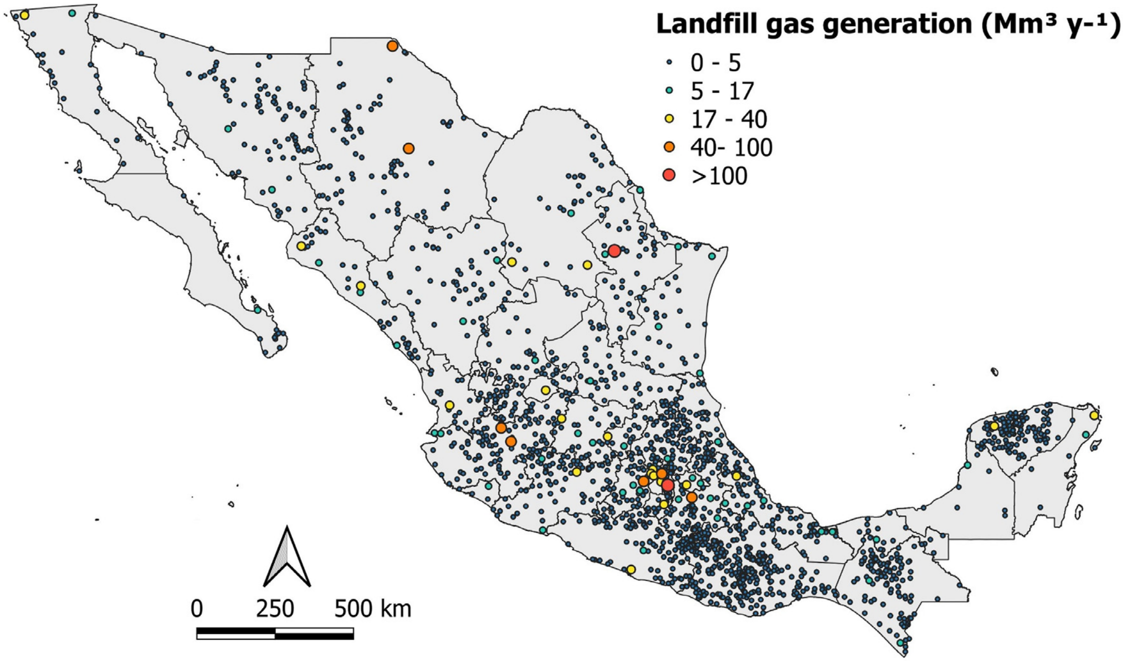


Fig. 5. Spatial distribution of the landfill gas emissions in Mexico.

showed that two of the three regions with the most tourists (*i.e.*, Yucatan Peninsula with 68 million and North West with 37 million annual tourists) are the two regions with the higher per capita MSW disposal rate. This finding suggests that tourism is a driving factor of the MSW generation in Mexico, and policymakers of touristic regions must consider this in the planning of MSW management.

3.2. Spatial evaluation of landfill gas generation in final disposal sites in Mexico

The LFG generation estimated in this work was 2298 Mm^3 for 2020. In other Latin American countries, significant differences have been reported; for Panama 125 Mm^3 [32], for Argentina 902 Mm^3 [31], and Brazil 1567 Mm^3 [33]. These differences can be associated with population size and consumption habits; since in all Latin America, the MSW management strategy continues to be the FDS: 53.5% SL, 15% CS, and 26.8% OD, while the rest of the MSW is recycled [1]. The FDS appears to have a long future in this region.

Fig. 5 presents the spatial distribution of the LFG generation by 2020 of the FDS in Mexico. Just 4.6% of the FDS (equivalent to 82 sites) had an LFG generation higher than 5 Mm^3 y^{-1}, which in Section 2.4 was specified as the minimum flow required for the implementation of technologies for electricity generation. These FDS were classified as large-size (*i.e.*, A), and as shown in Fig. 6, were the primary source of LFG with 86% of the generation. This result implies that few FDS are suitable for power generation from LFG, but these sites have a considerable potential to mitigate GHG emissions because 1788 Mm^3 can be used for electricity generation (Fig. 6). 71 of the 82 FDS with the minimum flow of LFG for power generation were SL. This is an advantage for using LFG because SL requires less infrastructure retrofit for power generation compared to OD [60]. Fig. 6 also shows that OD had a 24%share of LFG generation. These sites could implement other strategies to mitigate GHG, such as flaring the LFG. Dedinec et al. [61] reported that the implementation of flares in FDS in Macedonia could mitigate 25% of the GHG emissions.

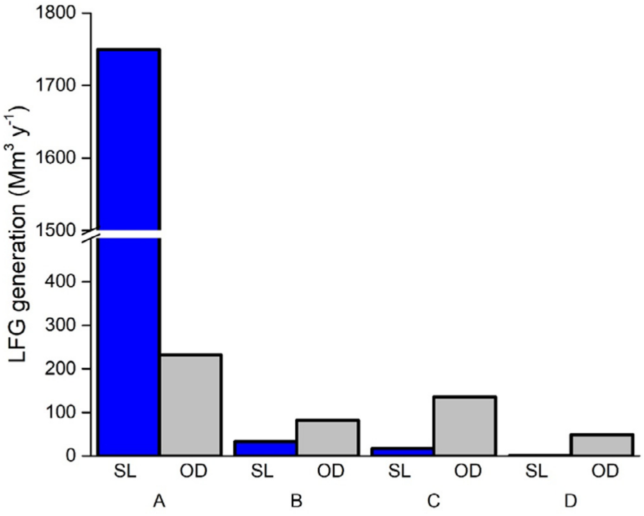


Fig. 6. Generation of landfill gas (LFG) per class and size final disposal sites (FDS).

Fig. 7 describes the LFG generation for the economic regions in Mexico by 2020, where it can be observed a spatial differentiation. The variations in the LFG generation may be attributed to the economic and demographic characteristics of the regions. Fig. S3 describes the population and the share of the GDP in Mexico, showing that central regions had the largest population and GDP, followed by the northern regions. In contrast, the southern regions showed less population and economic development. The economic differences have been related to the North American Free Trade Agreement, which fostered higher economic growth in the states from the Center and North of Mexico [62], attributed to electronic, automotive, chemical, and textile industrial facilities [63].

3.3. Minimization of final disposal and power generation from landfill gas scenarios

Fig. 8 shows the sensitivity analysis of MSW minimization scenarios in the cumulative generation of the LFG in Mexico until 2100. The difference between the BAU scenario and the reduction of the 100% scenario is 177.8 Gm^3 of LFG. The difference suggests the mitigation of

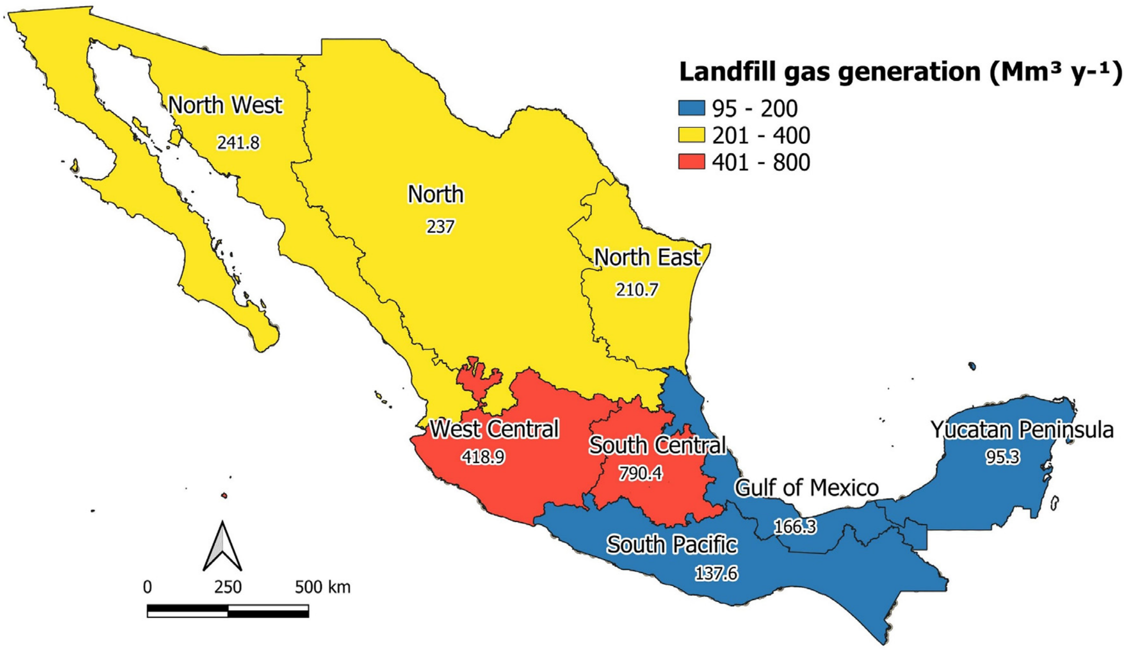


Fig. 7. Landfill gas emissions per economic region in Mexico by 2020.

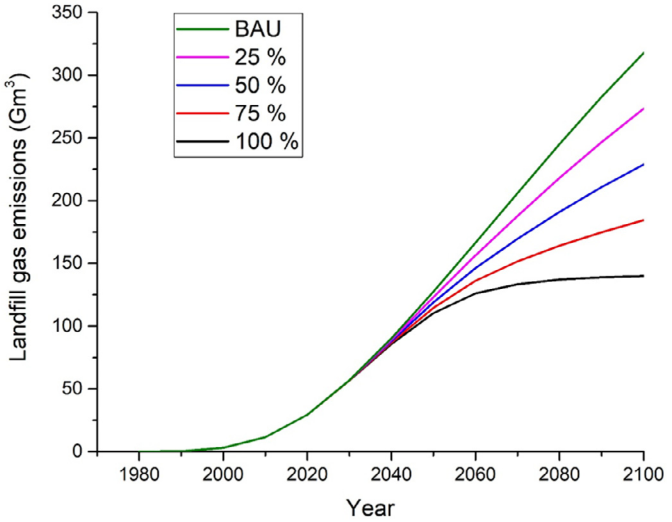


Fig. 8. Sensitivity analysis of landfill gas emissions for BAU, 25, 50, 75, and 100% scenarios of reduction of the use of final disposal sites.

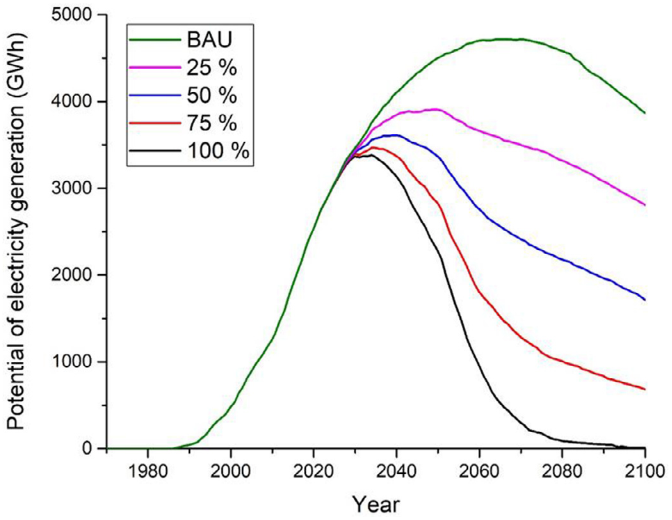


Fig. 9. Sensitivity analysis of power generation potential for BAU, 25, 50, 75, and 100% scenarios of reduction of municipal solid waste (MSW) final disposal.

1636 Mt CO_2 eq in 2020–2100, representing an annual mean emissions mitigation equivalent to 44.5% of the total GHG emission in the Mexican waste sector in 2015 [34]. This account does not consider the marginal emissions of the alternative technologies of MSW management. It is well known that MSW treatments as recycling, waste-to-energy (thermal and no-thermal), and composting have a considerable potential to mitigate the GHG emissions in the waste sector [64].

The South-Central Region, specifically Mexico City, has made efforts to reduce the use of FDS in its MSW management. In 2004, a pioneer waste statute was decreed in Mexico City, which established separation of MSW at the source [65]. After the closure of the SL Bordo Poniente in 2011 -which was the largest Mexican SL with a capacity for MSW management of 12000 t MSW d^{-1} [66]- the capacity of the composting plants increased from 103.75 t d^{-1} to 1388 t d^{-1} in 2015 in the period 2010–2015 [67,68]. Mexico City has also deployed strategies to recover valuable MSW, such as 1587 selective collection routes and two sorting facilities, which recovered 163 t d^{-1} for recycling [57]. Nevertheless, these actions have just reduced the MSW in the FDS by less than 20% [57], and they did not prevent the South-Central region from becoming the most significant contributor to the cumulative LFG generation, even in the more optimistic scenario (*i.e.*, 100% reduction scenario), with a share of up to 34% since the year 2040 (Fig. S4). This result denotes that FDS will be releasing large quantities of LFG in the mid and long term; even drastic changes in the MSW management were made due to the characteristics of the environmental liabilities of these sites [69]

Fig. 9 describes the electricity generation potential for the scenarios. The BAU scenario presented the most significant electricity generation potential, with a peak in 2065 (4717 GWh). This generation may represent 8.7% of the current generation from the North East region [70]. Fig. 9 also shows that for 2020 Mexico has an estimated potential of 2535 (scenario 100%) to 2537 GWh (BAU scenario). This potential represents 0.77% of the total electricity generation of Mexico and may replace the consumption of approximately 211416 households, considering an average monthly consumption of 1000 kWh [70]. The mitigated emissions for the potential replacement of electricity are described in Fig. S5, where the avoided emissions to 2020 are 1.45 Mt CO_2 eq and can go up to a maximum of 2.7 Mt CO_2 eq by the year 2065 for the BAU scenario.

The reduction of final disposal sites increases the use of other methods to manage MSW. As mentioned in section 2.4.1, this study did not account for the environmental impacts of the alternative methods nor the environmental credits for the valuable products obtained from them. Therefore, the low potential of electricity generation for the scenarios of final disposal reduction should not be interpreted as an adverse situation from an environmental assessment approach.

Mexico has used its electricity potential from LFG scarcely, as presented in Fig. S6, where the projected flows of LFG used for power generation due to the current projects are shown. It is observed that by 2020, less than 6 % (137 Mm^3 y^{-1}) of the LFG generated was used for electricity generation since just eight FDS had the technology for power generation [70]. These FDS had the installed capacity to generate 165 GWh y^{-1} [56], approximately 7 % of the potential estimated by that year.

The low potential of LFG used for power generation can explain the higher cost of this technology compared to conventional electricity production (*e.g.*, fossil-fuels-based technology). Francisca et al. [71] reported for Argentina that power generation from LFG can cost 83 USD MWh^{-1}, which is almost six times the price in the energy market. A study for the use of LFG for electricity and steam generation in the South Pacific region of Mexico showed financial profitability with an internal rate of return of 25% [72]. Nevertheless, the payback time of the project was long (*i.e.*, 9.4 years), and heating applications are challenging in Mexico due to the incipient market of renewable heat [73].

The economic feasibility of the LFG energy projects depends mainly on public policies. For instance, most of the Mexican FDS with power generation from LFG were developed under the Clean Development Mechanism [56]. This strategy allows developed countries to purchase emissions reductions (*i.e.*, carbon credits) from developing countries to meet GHG reductions [60]. The effect of carbon credits on power generation from LFG has been evaluated by Maalouf and El-Fadel [64], where they found that the breakeven point for this technology was reached with a carbon credit price of 21 USD/MtCO_2 eq mitigated.

Conclusions

The purpose of this study was to present the situation of the final disposal of the MSW in Mexico, along with a national estimation of current and prospective emissions of LFG from FDS and its potential use for power generation. One of the main findings from this research was that 2034 OD are still operating and contribute with 24% of the national LFG emissions. The OD in operation hinder the achievement of Mexico's commitment to the MSW sector within the nationally determined contributions to the Paris Agreement, which consists of capturing the LFG in every FDS by the year 2030. Other strategies such as reducing MSW disposed of in FDS can reduce the GHG emissions in 1636 Mt CO_2 in a period of 80 years.

The composition and share of the MSW disposed of in SL (65%) in Mexico are advantageous to using LFG to produce electricity. The potential electricity generation of the country by the year 2020 was 2534 GWh y^{-1}. This energy can avoid the emission of 1.45 Mt CO_2 eq since fossil fuels are the primary component of the electricity mix in Mexico. The power generation potential of LFG has been used scarcely (165 GWh y^{-1}) since just eight SL had the technology to use the LFG for electricity generation. Public policies may focus on proposing economic incentives and establishing conditions for a biogas market, increasing the number of SL that use LFG for energy purposes. This study identified the central and northern regions as the zones that could benefit from these policies.

Further work is required to establish the GHG emitted by electricity generation using national inventories to calculate the environmental credits of using the LFG for power generation and quantify other potential environmental impacts. An economic analysis is needed to determine the breakeven points of the waste-to-energy projects based on FDS.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to acknowledge the Faculty of Chemistry UANL for the laboratory space. J.F. Rueda-Avellaneda would like to acknowledge CONACYT for the national scholarship granted.

Funding

This work was supported by the Consejo Nacional de Ciencia y Tecnologia from Mexico [Grant No. 862015]

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rset.2021.100007.

References

[1] S. Kaza, L.C. Yao, P. Bhada-Tata, F. Van Woerden, What a waste 2.0: A Global Snapshot of Solid Waste Management to 2050, The World Bank, Washington, 2018 Washington, D.C..

[2] C. Xiaoli, D.J. Tonjes, D. Mahajan, Methane emissions as energy reservoir : context , scope , causes and mitigation strategies, Prog. Energy Combust. Sci. 56 (2016) 33–70, doi:10.1016/j.pecs.2016.05.001.

[3] J.E. Botello-Álvarez, P. Rivas-García, L. Fausto-Castro, A. Estrada-Baltazar, R. Gomez-Gonzalez, Informal collection, recycling and export of valuable waste as transcendent factor in the municipal solid waste management: a Latin-American reality, J. Clean. Prod. 182 (2018) 485–495, doi:10.1016/j.jclepro.2018.02.065.

[4] G. Sauve, K. Van Acker, The environmental impacts of municipal solid waste landfills in Europe: a life cycle assessment of proper reference cases to support decision making, J. Environ. Manag. 261 (2020) 110216, doi:10.1016/j.jenvman.2020.110216.

[5] É. Lebon, N. Madushele, L. Adelard, Municipal solid wastes characterisation and waste management strategy evaluation in insular context: a case study in reunion island, Waste Biomass Valorization 11 (2020) 6443–6453, doi:10.1007/s12649-019-00860-1.

[6] H.K. Jeswani, A. Azapagic, Assessing the environmental sustainability of energy recovery from municipal solid waste in the UK, Waste Manag. 50 (2016) 346–363, doi:10.1016/j.wasman.2016.02.010.

[7] H. Khandelwal, A.K. Thalla, S. Kumar, R. Kumar, Life cycle assessment of municipal solid waste management options for India, Bioresour. Technol. 288 (2019) 121515, doi:10.1016/j.biortech.2019.121515.

[8] S. Thongyuan, T. Khantamoon, P. Aendo, A. Binot, P. Tulayakul, Ecological and health risk assessment, carcinogenic and non-carcinogenic effects of heavy metals contamination in the soil from municipal solid waste landfill in Central, Thailand, Hum. Ecol. Risk Assess. (2020) 1–22, doi:10.1080/10807039.2020.1786666.

[9] B.S. Sidhu, D. Sharma, T. Tuteja, S. Gupta, A. Kumar, Human health risk assessment of heavy metals from Bhalaswa Landfill, New Delhi, India, in: NJ Raju, W Gossel, M Sudhakar (Eds.), Manag. Nat. Resour. a Chang. Environ., Springer International Publishing, Cham, 2015, pp. 215–223, doi:10.1007/978-3-319-12559-6_16.

[10] K. Yaghmaien, M. Hadei, P. Hopke, S. Gharibzadeh, M. Kermani, M Yarahmadi, et al., Comparative health risk assessment of BTEX exposures from landfills, composting units, and leachate treatment plants, Air. Qual. Atmos. Heal. 12 (2019) 443–451, doi:10.1007/s11869-019-00669-w.

[11] C. Wu, J. Liu, S. Liu, W. Li, L. Yan, M. Shu, et al., Assessment of the health risks and odor concentration of volatile compounds from a municipal solid waste landfill in China, Chemosphere 202 (2018) 1–8, doi:10.1016/j.chemosphere.2018.03.068.

[12] A. Maghmoumi, F. Marashi, E. Houshfar, Environmental and economic assessment of sustainable municipal solid waste management strategies in Iran, Sustain. Cities Soc. 59 (2020) 102161, doi:10.1016/j.scs.2020.102161.

[13] L.S. dos Muchangos, A. Tokai, A. Hanashima, Greenhouse gas emissions and cost assessments of municipal solid waste treatment and final disposal in Maputo City, Environ. Dev. Sustain. 21 (2019) 145–163, doi:10.1007/s10668-017-0027-5.

[14] M.X. Paes, G.A. de Medeiros, S.D. Mancini, C. Gasol, J.R. Pons, XG. Durany, Transition towards eco-efficiency in municipal solid waste management to reduce GHG emissions: the case of Brazil, J. Clean. Prod. 263 (2020) 121370, doi:10.1016/j.jclepro.2020.121370.

[15] I.A. Al-Khatib, A. Abu Hammad, O.A. Sharkas, C. Sato, Public concerns about and perceptions of solid waste dump sites and selection of sanitary landfill sites in the West Bank, Palestinian territory, Environ. Monit. Assess. 187 (2015) 186, doi:10.1007/s10661-015-4401-1.

[16] G. Owusu, M. Oteng-Ababio, R.L. Afutu-Kotey, Conflicts and governance of landfills in a developing country city, Accra. Landsc. Urban Plan. 104 (2012) 105–113, doi:10.1016/j.landurbplan.2011.10.005.

[17] EPA. Advancing Sustainable Materials Management: 2013 Fact sheet-assessing trends in material generation, recycling and disposal in the United States. 2015.

[18] OECD. Municipal waste 2015. 10.1787/data-00601-en.

[19] F. Fei, Z. Wen, D. De Clercq, Spatio-temporal estimation of landfill gas energy potential: a case study in China, Renew. Sustain. Energy Rev. 103 (2019) 217–226, doi:10.1016/j.rser.2018.12.036.

[20] European Parlament, 1999.

[21] European Parlament, European Union, 2018.

[22] C. Mukherjee, J. Denney, E.G. Mbonimpa, J. Slagley, R. Bhowmik, A review on municipal solid waste-to-energy trends in the USA, Renew. Sustain. Energy Rev. 119 (2020) 109512, doi:10.1016/j.rser.2019.109512.

[23] P. Espinoza-Tello, E. Martinez-Arce, D. Daza, M. Soulier-Faure, H. Terraza Informe de la evaluación regional del manejo de residuos sólidos urbanos en América Latina y el Caribe 2010. 2011.

[24] EPA. Global non-CO_2 greenhouse gas emission projections & mitigation 2015–2050. 2019.

[25] C. Pratt, K. Tate, Mitigating methane: emerging technologies to combat climate change's second leading contributor, Environ. Sci. Technol. 52 (2018) 6084–6097, doi:10.1021/acs.est.7b04711.

[26] B. Cai, Z. Lou, J. Wang, Y. Geng, J. Sarkis, J. Liu, et al., CH_4 mitigation potentials from China landfills and related environmental co-benefits, Sci. Adv. 4 (2018) eaar8400, doi:10.1126/sciadv.aar8400.

[27] EPA, LFG Energy Project Development Handbook, EPA, 2017 https://www.epa.gov/lmop/landfill-gas-energy-project-development-handbook, doi:10.1385/MB:32:3:197.

[28] P.Y. Hoo, H. Hashim, WS. Ho, Opportunities and challenges : landfill gas to biomethane injection into natural gas distribution grid through pipeline, J. Clean. Prod. 175 (2020) 409–419, doi:10.1016/j.jclepro.2017.11.193.

[29] A. Choudhary, A. Kumar, S. Kumar, National municipal solid waste energy and global warming potential inventory: India, J. Hazard. Toxic Radioact. Waste 24 (2020) 6, doi:10.1061/(asce)hz.2153-5515.0000521.

[30] IEA. Data and statistics. Renewables Inf 2020 Ed 2020. https://www.iea.org/data-and-statistics?country=INDIA&fuel=Energy supply&indicator=WasteGenBySource (accessed March 8, 2021).

[31] E. Santalla, V. Córdoba, G. Blanco, Greenhouse gas emissions from the waste sector in Argentina in business-as-usual and mitigation scenarios, J. Air Waste Manag. Assoc. 63 (2013) 909–917, doi:10.1080/10962247.2013.800167.

[32] M. Weitz, J.B. Coburn, E. Salinas, Estimating national landfill methane emissions: an application of the 2006 intergovernmental panel on climate change waste model in Panama, J. Air Waste Manag. Assoc. 58 (2008) 636–640, doi:10.3155/1047-3289.58.5.636.

[33] R.M. Lima, A.H.M. Santos, C.R.S. Pereira, B.K. Flauzino, A. Pereira, F.J.H. Nogueira, et al., Spatially distributed potential of landfill biogas production and electric power generation in Brazil, Waste Manag. 74 (2018) 323–334, doi:10.1016/j.wasman.2017.12.011.

[34] INECC, Residuos, Inventario Nacional de Emisiones de Gases y Compuestos de Efecto Invernadero 1990–2015 en México [National Inventory of Greenhouse Gases and Compounds emissions 1990-2015 in Mexico], INECC, 2018 http://cambioclimatico.gob.mx:8080/xmlui/handle/publicaciones/226.

[35] INEGI, Censo Nacional de Gobiernos Municipales y Delegacionales [National Census of Municipal and Delegational Governments], INEGI, 2017, p. 2017 https://www.inegi.org.mx/programas/cngmd/2017/#Datos_abiertos.

[36] CONAPO, Proyección de las poblaciones de los municipios de México 2015–2030 [Projection of municipal populations of Mexico 2015-2030], CONAPO, 2019 https://www.gob.mx/conapo/documentos/proyecciones-de-la-poblacion-de-los-municipios-de-mexico-2015-2030.

[37] CONAPO, Proyecciones de la población de México y de las entidades federativas, 2016–2050 y conciliación demográfica de México, 1950–2015 [Population projection from Mexico and federative, 2016-2050 and demographic from Mexico, 1950-2015], CONAPO, 2018 https://datos.gob.mx/busca/dataset/proyecciones-de-la-poblacion-de-mexico-y-de-las-entidades-federativas-2016-2050.

[38] G.L. Sivakumar Babu, P. Lakshmikanthan, L.G. Santhosh, Assessment of landfill sustainability, in: International Conference on Sustainable Civil Infrastructures (ICSCI-2014), Springer Singapore, 2017, p. 367.

[39] SCS Engineers. Manual del usuario modelo mexicano del biogás versión 2.0 2009.

[40] M.J. Krause, G.W. Chickering, T.G. Townsend, Translating landfill methane generation parameters among first-order decay models, J. Air Waste Manag. Assoc. 66 (2016) 1084–1097, doi:10.1080/10962247.2016.1200158.

[41] Q. Aguilar-Virgen, P. A. Taboada-González, S. Ojeda-Benítez, Modelo mexicano para la estimación de la generación de biogás [Mexican model to estimate landfill gas generation], Ing. Académica La Fac Ing Univ. Autónoma Yucatán 15 (2011) 37–45 https://www.revista.ingenieria.uady.mx/volumen15/modelo.pdf.

[42] IPCCGuidelines for national greenhouse gas inventories, Institute for Gloval Environmental Strategies, Hayama, 2006.

[43] MJ. Krause, Intergovernmental panel on climate change's landfill methane protocol: reviewing 20 years of application, Waste Manag. Res. 36 (2018) 827–840, doi:10.1177/0734242X18793935.

[44] G. Van Rossum, FL. Drake, The Python Language Reference Manual (2011).

[45] QGIS DT. Open source geospatial Foundation project. QGIS geographic information system 2019.

[46] Á. Bassols Batalla México: formación de regiones económicas. 1979. 10.1007/s13398-014-0173-7.2.

[47] EPA, Final background information document for life-cycle inventory landfill process model, EPA, Office of Research and Development Research Triangle Park, NC 27711, 2011.

[48] IMCO, Propuestas transversales [Interdisciplinary proposals], in: Acciones urgentes para las ciudades del futuro [Urgent accions for the cities from the future], IMCO, 2010, pp. 185–202. https://imco.org.mx/indice_de_competitividad_urbana_2010_acciones_urgentes_para_las_ciudades_de/.

[49] L. Santín Del Río, Las intermunicipalidades y los retos estratégicos para el desarrollo sustentable de los municipios [The intermunicipality and the strategic challenges for the sustainable development of the municipalities], RC et Ratio 7 (2013) 11–31 http://contraloriadelpoderlegislativo.gob.mx/Revista_Rc_et_Ratio/Rc_et_Ratio_7/Rc7_1_Leticia_Santin_Del_Rio.pdf.

[50] SEMARNAT. Norma oficial mexicana NOM-083-SEMARNAT-2003. Mexico: 2003.

[51] S.M. Oakley, R. Jimenez, Sustainable sanitary landfills for neglected small cities in developing countries: the semi-mechanized trench method from Villanueva, Honduras, Waste Manag. 32 (2012) 2535–2551, doi:10.1016/j.wasman.2012.07.030.

[52] Congreso de los Estados Unidos Mexicanos, Ley General para la Prevención y Gestión Integral de los Residuos [General Law for the Prevention and Integral Waste Management], Diario Oficial, 2003 Mexicohttps://www.gob.mx/cms/uploads/attachment/file/131748/23._LEY_GENERAL_PARA_LA_PREVENCI_N_Y_GESTI_N_INTEGRAL_DE_LOS_RESIDUOS.pdf.

[53] Gobierno del Estado de Nuevo León, Gestión Integral de Residuos Sólidos Urbanos y de Manejo Especial en la Zona Metropolitana de Monterrey [Integral Management of Municipal Solid and Special Waste in the Metropolitan Zone of Monterrey], Gobierno del Estado de Nuevo León, Monterrey, 2020 Nuevo Leónhttps://www.proyectosmexico.gob.mx/proyecto_inversion/0851-gestion-integral-de-residuos-solidos-urbanos-y-de-manejo-especial-en-la-zona-metropolitana-de-monterrey-nuevo-leon/(accessed June 3, 2021).

[54] A. Flores Ramos Invertirán 40 millones de pesos en nuevos rellenos sanitarios para BCS. D El Indep 2019.

[55] SEMARNAT, Residuos [Waste], in: Informe de la situación del medio ambiente en México 2018 [Report of the environmental situation in Mexico 2018], SEMARNAT, Mexico City, 2019, pp. 450–487. https://apps1.semarnat.gob.mx:8443/dgeia/informe18/tema/pdf/Informe2018GMX_web.pdf.

[56] GIZ Mexico, Proyectos de Aprovechamiento Energético a partir de Residuos Urbanos en México [Energy Use Projects from Municipal Solid Waste in Mexico], GIZ, 2018 https://www.giz.de/de/downloads/giz2019-ES-EnRes-Proyectos-de-Aprovechamiento.pdf.

[57] SEDEMA, Inventario de Residuos Sólidos CDMX 2017 [Solid Waste Inventory Mexico City 2017], SEDEMA, 2017.

[58] I. Arbulu, J. Lozano, J. Rey-Maquieira, Waste generation flows and tourism growth: a stirpat model for Mallorca, J. Ind. Ecol. 21 (2017) 272–281, doi:10.1111/jiec.12420.

[59] O. Saito, Resource use and waste generation by the tourism industry on the big island of Hawaii, J. Ind. Ecol. 17 (2013) 578–589, doi:10.1111/jiec.12007.

[60] E. Lokey, Renewable energy project development under the clean development mecanism, Renewable energy project development under the clean development mecanism, A guide for Latin America, Earthscan, London, 2009.

[61] A. Dedinec, N. Markovska, I. Ristovski, G. Velevski, V.T. Gjorgjievska, T.O. Grncarovska, et al., Economic and environmental evaluation of climate change mitigation measures in the waste sector of developing countries, J. Clean. Prod. 88 (2015) 234–241, doi:10.1016/j.jclepro.2014.05.048.

[62] J. López Arévalo, Ó. Peláez Herreros, B. Sovilla Sogne, Causas del crecimiento económico desigual de las fronteras norte y sur de México en la era del TLCAN, Rev. Econ. Fac. Econ. Univ. Autónoma Yucatán 28 (2011) 39, doi:10.33937/reveco.2011.26.

[63] A.V. Gonzalez, E.A. Mack, M. Flores, Industrial complexes in Mexico: implications for regional industrial policy based on related variety and smart specialization, Reg. Stud. 51 (2017) 537–547, doi:10.1080/00343404.2015.1114174.

[64] A. Maalouf, M. El-fadel, Life cycle assessment for solid waste management in lebanon : economic implications of carbon credit, Waste Manag. Res. 37 (2020) 14–26, doi:10.1177/0734242X18815951.

[65] Gobierno del Distrito Federal, Ley de Residuos Sólidos del Distrito Federal [General Law of Solid Waste from Federal District], Gaceta Oficial del Distrito Federal (2003) http://www.paot.org.mx/centro/leyes/df/pdf/2019/LEY%20_RESIDUOS%20_SOLIDOS_25_06_2019.pdf.

[66] D. Enciso Gómez, P.H. Antonio Cervantes, F. Robles Martínez, E. Durán-Páramo, D.G. Castro-Fontana, Geographic information systems for optimizing waste transportation to landfill sites in the state of Mexico, Mexico Rev. Int. Contam. Ambient. 35 (2019) 55–67, doi:10.20937/RICA.2019.35.esp02.06.

[67] PAOT, Diagnóstico actual del flujo de residuos sólidos urbanos que se genera en el Distrito Federal [Current diagnostic of the municipal solid waste flow generated in the Federal District], PAOT, Mexico City, 2011 http://centro.paot.org.mx/documentos/paot/estudios/flujo_residuos_DF.pdf.

[68] SEDEMA, Inventario de Residuos Sólidos. Ciudad de México 2015 [Inventory of Solid Waste. Mexico City 2015], SEDEMA, Mexico City, 2015 https://www.sedema.cdmx.gob.mx/storage/app/media/IRS-2015-14-dic-2016.compressed.pdf.

[69] N.C. Aldana-Espitia, J.E. Botello-Álvarez, P. Rivas-García, F.J. Cerino-Cordova, M.G. Bravo-Sanchez, J.E. Abel-Seabra, et al., Environmental impact mitigation in an industrialized city in Mexico : an approach of life cycle assessment, Rev. Mex. Ing. Química. 16 (2017) 563–580.

[70] SENER, Programa de desarrollo del sistema eléctrico nacional 2018-2032 [Development program of the national electrical grid 2018-2032], SENER, Mexico City, 2018.

[71] F.M. Francisca, M.A. Montoro, D. Alejandro, Technical and economic evaluation of biogas capture and treatment for the Piedras Blancas landfill in Córdoba, Argentina. J. Air Waste Manag. Assoc. 67 (2017) 537–549, doi:10.1080/10962247.2016.1243594.

[72] P.E. Escamilla-García, M.E. Jiménez-Castañeda, E. Fernández-Rodríguez, S. Galicia-Villanueva, Feasibility of energy generation by methane emissions from a landfill in southern Mexico, J. Mater. Cycles Waste Manag. 22 (2020) 295–303, doi:10.1007/s10163-019-00940-3.

[73] I. Sanchez, R. TorresCámara Nacional de la Industria de Conservas Alimenticias, Calor solar para procesos industriales: Estudio de potencial en la industria de conservas alimenticias en México [Solar heat for industrial processes: Potential study in the preserved food industry in Mexico], Cámara Nacional de la Industria de Conservas Alimenticias, Mexico City, 2018 https://calorsolar.mx/wp-content/uploads/2020/06/GIZ-Estudio-potencial-CANAINCA-2020.pdf.