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Environmental Performance of Solid Waste Disposal Sites with Different Levels of Control: A Life Cycle Assessment in Mexico

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Abstract

In developing countries, final disposal sites exhibit different levels of operational control, which influence their environmental performance. This study evaluated the environmental performance of four types of final disposal sites in Mexico: sanitary landfill with energy recovery (SLF+ER) and sanitary landfill with gas flaring (SLFGF), controlled site (CS), and open dump (OD), using life cycle assessment for 1 t of municipal solid waste. Biogas generation was estimated using the Mexican Biogas Model 2.0, and Ecoinvent processes were adapted to local conditions; six impact categories were assessed, and a sensitivity analysis was conducted. The SLF+ER scenario showed the lowest impact in global warming, followed by SLFGF and CS, while OD recorded the highest impact, mainly associated with biogas management. In contrast, scenarios with gas capture and treatment showed higher contributions in categories related to combustion processes. Normalized results indicated that freshwater eutrophication and human carcinogenic toxicity are the dominant impact categories. The sensitivity analysis confirmed the influence of the organic fraction on CH_4 generation without altering the relative ranking among scenarios. Overall, increasing the level of environmental control reduces impacts from fugitive emissions but introduces trade-offs across other impact categories, highlighting the need for comprehensive assessments to support decision-making.

Keywords: environmental control; environmental performance; biogas management; life cycle assessment; final disposal sites; municipal solid waste

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Academic Editors: Eduardo Castillo-González, Lorena De Medina-Salas, Mario Rafael Giraldi-Diaz, Manuel Soto and Gerardo Bernache Perez

Received: 26 March 2026
Revised: 18 April 2026
Accepted: 23 April 2026
Published: 27 April 2026

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1. Introduction

Over recent decades, the generation of municipal solid waste (MSW) has steadily increased as a result of population growth, rapid urbanization, and changes in consumption patterns [1,2]. Globally, it is estimated that more than 2.6 billion tonnes of MSW are generated per year, and this figure is expected to reach 3.9 billion tonnes by 2050 [2,3]. This increase poses significant environmental and governance challenges, particularly in developing countries, where waste management faces technical, financial, and institutional limitations, as well as constraints related to reliable information [4].

Although, in recent decades, strategies have been promoted for waste prevention, reuse, recovery, and valorization (recycling or energy generation), a significant proportion of waste continues to be disposed of in final disposal sites (FDS) with varying levels of technical and environmental control. Sanitary landfills with biogas flaring (SLFGF) remain the most widely used option, particularly in developing countries, where treatment alternatives are often limited [2,5]. However, FDS can constitute significant sources of environmental impacts due to greenhouse gas emissions, particulate dispersion, leachate generation, and the risk of soil and water contamination [6–8]. The magnitude of these impacts depends on the level of control over operational conditions and the design of the containment infrastructure, ranging from uncontrolled sites (open dumps, OD) to sanitary landfills with electricity generation from biogas (SLF+ER) [9,10].

In the field of waste management, life cycle assessment (LCA) has been used since 1993 as a tool to evaluate the environmental performance of different collection, treatment, and final disposal systems. LCA enables the systematic quantification of material and energy flows, as well as the associated emissions throughout the life cycle, providing a methodological framework to identify dominant environmental impact processes and support decision-making in waste management [11–13]. In particular, LCA has been applied to evaluate different MSW treatment and disposal strategies, including sanitary landfills with biogas capture, composting, anaerobic digestion, and incineration with energy recovery [14–17]. However, studies comparing the environmental performance among different types of FDS remain limited.

In addition, recent studies have emphasized the importance of integrating sustainability indicators, such as efficiency, productivity, and resource recovery, into MSW management systems [18]. These aspects are increasingly recognized as key components for improving the environmental and operational performance of waste management systems and supporting more sustainable decision-making.

Moreover, processes associated with final disposal are often represented using generic inventories from LCA databases, which may limit the representation of the actual operational conditions of each site. In this context, it is important to develop assessments that integrate emission generation models with environmental inventory databases. This approach allows for a comparative analysis of the environmental performance of different types of FDS under conditions representative of regions in developing countries [19–23].

In the case of Mexico, MSW management presents additional challenges associated with the heterogeneity of operating conditions across FDS. In the country, more than 100,000 tonnes of MSW are generated per day, and a considerable fraction of this waste continues to be disposed of in sites with varying levels of environmental control [24]. The regulation of these sites is established in the Official Mexican Standard NOM-083-SEMARNAT-2003 [25], which defines the environmental criteria for the selection, design, construction, operation, monitoring, and closure of FDS. According to this regulation, it is possible to distinguish between SLFGF with full infrastructure, controlled sites (CS), and open dumps (OD). However, LCA studies that incorporate representative local inventories for these types of sites remain limited, particularly in the Latin American context [21,22,26]. The comparative evaluation of these FDS is particularly relevant in regions where different levels of technical and environmental control coexist.

Despite these advances, comparative LCA studies that explicitly evaluate disposal systems across different levels of operational control using locally adapted emission models appear to be limited, particularly in developing countries [21–23,26].

In light of the above, and given the need for inventories that reflect real conditions in Mexico in order to provide reliable information to decision-makers, this study aims

to evaluate and compare the environmental performance of four types of MSW FDS representative of Mexico: SLFGF, SLF+ER, CS, and OD.

To achieve this, an LCA was conducted. Methane generation was estimated using the Mexican Biogas Model 2.0 (MBM 2.0) [27], and key emissions associated with biogas combustion and fugitive releases were quantified and integrated with background processes from the Ecoinvent database. This approach enables the identification of dominant impact processes and the analysis of how different levels of operational control influence environmental performance under conditions representative of the Mexican context.

This study contributes to the existing literature by integrating a locally adapted methane generation model (MBM 2.0) with a LCA framework, enabling a more context-specific estimation of emissions from MSW disposal sites. Unlike previous studies that rely primarily on generic inventories or focus on single disposal technologies, this work applies a hybrid modeling approach that combines site-specific emission estimates with standardized LCA databases. Furthermore, it provides a comparative assessment of systems representing different levels of operational and environmental control commonly found in developing countries, an aspect that remains underexplored in current LCA studies. This approach allows for a more realistic representation of emission dynamics and facilitates the identification of environmental trade-offs across impact categories, thereby supporting more informed and context-specific decision-making.

The paper is organized as follows: Section 2 describes the materials and methods, including the goal and scope definition, system boundaries, life cycle inventory development, and impact assessment. Section 3 presents the results and discussion, including the evaluation of impact categories and sensitivity analysis. Finally, the conclusions summarize the main findings and their implications for waste management decision-making.

2. Materials and Methods

2.1. Goal and Scope Definition

The objective of this study was to evaluate and compare, through the application of the LCA methodology [28,29], the environmental performance of four MSW FDS representative of Mexico: SLFGF, SLF+ER, CS, and OD. Additionally, the study aimed to identify the main sources of environmental and health impacts associated with each system, as well as to analyze the influence of the level of operational control on their environmental performance.

The study was conducted in accordance with ISO 14040 and ISO 14044 standards [11,12]. The functional unit (FU) was defined as the final disposal of 1 tonne (t) of MSW. The system boundaries include processes associated with final disposal, from the entry of waste into the FDS to the emissions generated during its degradation (Figure 1). The anaerobic degradation of the organic fraction of the waste and the resulting biogas generation were considered, along with its management depending on the type of site evaluated, including direct release to the atmosphere, capture, flaring, or energy recovery, as well as associated fugitive emissions.

In the energy recovery scenario, the system was expanded to include the substitution of grid electricity through energy generation from biogas, applying a system expansion approach [30]. Electricity generated from biogas was assumed to substitute electricity from the Mexican grid, using the corresponding Ecoinvent dataset (version 3.12, Ecoinvent Association, Switzerland). This approach allows avoided impacts to be accounted for based on the displaced electricity mix.

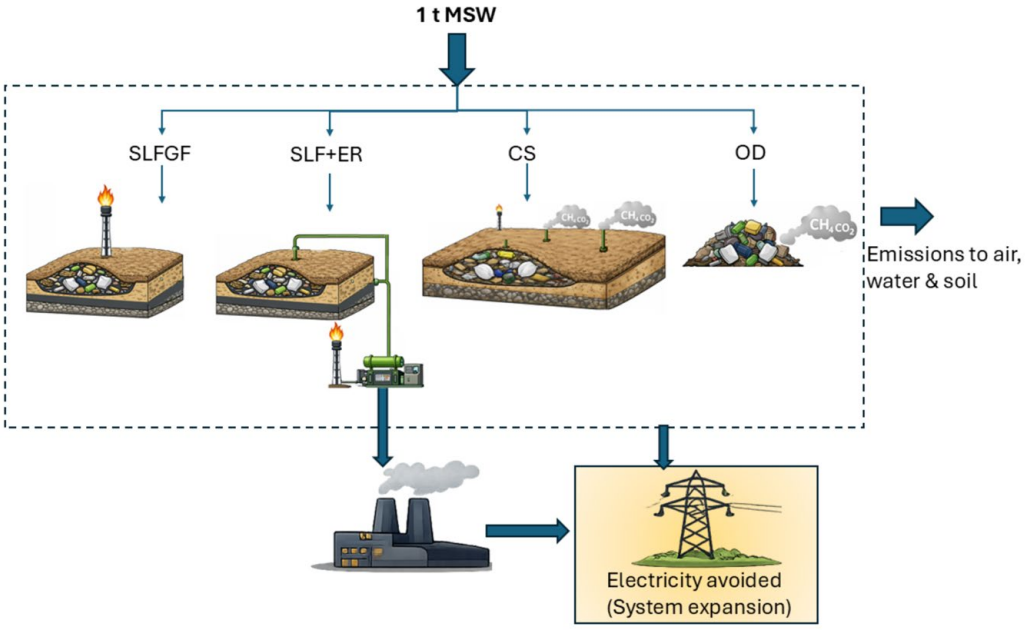

Figure 1. System boundaries of the study, showing the four evaluated FDS scenarios (SLFGF, SLF+ER, CS and OD), including waste input, biogas generation and management, emissions, and electricity substitution in the energy recovery scenario.

Atmospheric emissions associated with biogas management and site operation were included. For the SLFGF, CS, and OD scenarios, biogas and methane generation were estimated using MBM 2.0 [27]. Based on these results, CH_4 emissions, as well as emissions derived from biogas combustion and fugitive emissions, were calculated and incorporated into the inventory of each scenario.

For the sanitary landfill with energy recovery scenario, the corresponding dataset from the Ecoinvent database was used directly, which includes biogas management and utilization. Background and operational processes were modeled using datasets from the Ecoinvent database under the cut-off approach. Emissions to water and soil associated with leachate generation were taken directly from Ecoinvent datasets. These emissions were not further adapted due to the lack of consistent, site-specific data for the evaluated systems. The use of standardized datasets ensures methodological consistency and comparability across scenarios, although it may not fully capture local variability.

2.2. Study Area

The study area corresponds to the operating landfill cell of the Integral Waste Management Center (CIR) in the municipality of Tenango del Valle, located in the central region of Mexico (Figure 2). This CIR operates as an intermunicipal FDS, receiving over 500 t of MSW per day from several municipalities in the region, making its composition representative of the MSW generated in the central region of the country.

Based on this information, four types of FDS (SLFGF, SLF+ER, CS, and OD) were defined, representing different levels of control and operational management, and were considered representative scenarios of typical MSW final disposal conditions in Mexico.



Figure 2. Location of the study area in Tenango del Valle, State of Mexico, Mexico, showing the geographical context of the evaluated final disposal site used as a reference for the analyzed scenarios.

2.3. Characterization of Municipal Solid Waste

Table 1 presents the average composition of MSW characterized in 2024 in the operating cell of the CIR, in accordance with standards NMX-015-SEMARNAT-1985 [31] and NMX-022-SEMARNAT-1985 [32].

Table 1. Composition of MSW characterized in situ in the study area, expressed as percentage by mass.

Components	Composition (%)
Food	20.14
Paper and Cardboard	7.63
Yard Waste (Garden Trimmings)	0.37
Wood	0.88
Rubber, Leather, Bones, and Straw	7.21
Textiles	4.16
Toilet Paper	6.43
Other Organics	11.59
Diapers (assumes 20% organic/80% inorganic)	8.63
Metals	1.13
Construction and Demolition Waste	1.17
Glass and Ceramics	2.78
Plastics	14.84
Other Inorganics	13.04

2.4. Scenario Definition

Four scenarios were defined to represent different levels of technical and environmental control in MSW final disposal, corresponding to the four types of FDS present in Mexico and other developing countries. Table 2 summarizes the main characteristics of each type of FDS.

Table 2. Operational characteristics of the evaluated FDS scenarios (SLFGF, SLF+ER, CS, and OD).

Operational Characteristic	SLFGF/SLF+ER	CS	OD
Liner system	Yes	No	No
Biogas capture	Yes	Partial	No
Waste cover	Yes	Partial	No
Leachate treatment	Yes	Limited	No

2.4.1. Scenario 1: Sanitary Landfill with Biogas Flaring (SLFGF)

The SLFGF includes infrastructure designed for the safe confinement of waste, including liner systems with geomembranes, leachate drainage, and mechanisms for biogas capture (80% collection efficiency) and flaring. These elements aim to reduce pollutant release to soil, water, and the atmosphere through emission control and proper management of the disposed MSW [25].

2.4.2. Scenario 2: Sanitary Landfill with Energy Recovery (SLF+ER)

The SLF+ER maintains the same design and operational conditions as the SLFGF, incorporating a system for energy recovery from captured biogas. The collected gas (80%) is used for electricity generation through internal combustion engines, allowing partial recovery of its energy content and reducing direct CH_4 emissions to the atmosphere [25].

2.4.3. Scenario 3: Controlled Site (CS)

The CS implements basic practices for MSW control, such as compaction and periodic cover. However, the available infrastructure for environmental control is typically limited. These measures improve operational conditions and reduce certain visible impacts compared to OD. Nevertheless, it generally lacks liner systems, geomembranes, and leachate drainage and treatment, and includes only partial biogas capture (50% collection efficiency) [25].

2.4.4. Scenario 4: Uncontrolled Site (Open Dump, OD)

The OD operates without technical or environmental control infrastructure or formal practices. MSW is directly deposited on the ground and remains exposed to environmental conditions. As a result, uncontrolled gaseous emissions and leachate are generated, which may infiltrate the subsurface and eventually reach nearby water bodies [25].

2.5. Life Cycle Inventory

2.5.1. Data Sources

The life cycle inventory was developed based on the MSW composition (Table 1) and the estimation of biogas generation associated with its degradation in each type of FDS, complemented by background processes represented by datasets from the Ecoinvent v3.12 database.

2.5.2. Estimation of Biogas and Methane Generation

The potential generation of biogas in the different types of FDS was estimated using MBM 2.0 from Methane to Markets [27], which applies Equation (1):

$$Q_{LFG} = \sum_{t=1}^{n} \sum_{j=0.1}^{1} 2kL_0 \left[\frac{M_i}{10}\right] \left(e^{-kt_{ij}}\right) (MCF)(F) \quad (1)$$

where

Q_{LFG}: Maximum expected landfill gas flow (m^3/year)
i: 1-year increment
n: calculation year (calculation year) − (initial year of waste disposal)
j: Time increment of 0.1 years
k: Methane generation rate constant (1/year)
L_0: Potential methane generation (m^3/t of MSW)
M_i: Mass of waste disposed in year i (t of MSW)

MCF: Methane correction factor
F: Fire adjustment factor

The model was configured using the MSW composition determined in situ, along with the operational conditions of each type of FDS (Table 2). The simulation to estimate potential biogas generation from the anaerobic degradation of the organic fraction of MSW was conducted over a 100-year time horizon.

For this study, the analyzed area corresponds to Region 3 (Central/Interior Mexico), according to the MBM 2.0 regional classification. The main parameters used in the estimation are presented in Table 3, while additional parameters for each FDS type are provided in the Supplementary Material SA, SE and SH.

Table 3. Methane generation parameters from MBM 2.0 for Region 3 (Central/Interior Mexico), according to waste degradation rate.

Waste Category	Rapid Degradation	Moderately Rapid Degradation	Moderately Slow Degradation	Slow Degradation
CH_4 generation index (k)	0.16	0.075	0.032	0.016
CH_4 generation potential (L_0) (m^3/t MSW)	69	138	214	202

Since biogas generated from MSW is mainly composed of CH_4 and CO_2, a CH_4 fraction of 50% in biogas was assumed [33].

Based on the biogas volume generated per t of MSW, as estimated using MBM 2.0 (Supplementary Material SB, SF and SI), the amount of biogas captured and released as fugitive emissions was determined according to the operational conditions of each type of FDS. For SLFGF, an 80% collection efficiency through extraction wells was assumed. The captured biogas is directed either to flaring or energy generation, depending on the evaluated scenario [33,34]. In the case of CS, a partial collection efficiency of 50% was considered to be associated with the limited presence of venting wells or passive gas release and flaring mechanisms. These values fall within reported ranges for biogas recovery in FDS with gas collection infrastructure and are consistent with assumptions used in LCA studies [35–37].

Emissions of CO, VOCs, $PM_{2.5}$, SO_2, NO_x, and residual CH_4 from biogas combustion were estimated using emission factors reported by Olesen et al. [38], expressed in g/m^3 of CH_4. Since these factors were developed for biogas containing 55% CH_4, whereas this study assumes a 50% CH_4 fraction [33], they were adjusted using a correction factor of 50/55 (0.909). Uncaptured biogas was assumed to be released as fugitive emissions through the site cover, applying partial oxidation factors for CH_4 and other compounds. For OD, direct release of generated biogas to the atmosphere was assumed, with no capture or flaring [33] (Supplementary Material SC, SD, SG and SJ).

Estimated emissions were initially expressed in m^3 of CH_4 and subsequently converted to mass (kg CH_4) using the density of CH_4 (0.7168 kg/m^3) under standard conditions [39]. Results were then normalized to the functional unit (1 t of MSW disposed) for incorporation into the LCA inventory. CO_2 generated during biogas combustion was considered of biogenic origin.

Once biogas generation was estimated and CH_4 quantities were determined for each FDS type, CH_4 was incorporated into each scenario inventory as an emission flow. CH_4 emissions originally included in the Ecoinvent datasets were replaced with those estimated from biogas generation using MBM 2.0 and integrated with the processes represented in Ecoinvent to obtain the corresponding inventory for each FDS scenario.

2.5.3. Electricity Generation from Biogas

In the energy recovery scenario (SLF+ER), captured biogas was assumed to be used for electricity generation through internal combustion engines. Based on the captured biogas volume (105.34 m^3/t MSW), corresponding to an 80% collection efficiency, the CH_4 content was estimated assuming a 50% fraction, resulting in 52.67 m^3 of CH_4 per t of MSW. The available thermal energy was calculated using a lower heating value of 35.8 MJ/m^3 of CH_4 [39], yielding 1885.61 MJ/t MSW. Conversion to electricity was estimated assuming an electrical efficiency of 35% [39], resulting in 659.96 MJ, equivalent to 183.32 kWh/t MSW (Supplementary Material SK).

Electricity generation was modeled using the process heat and power co-generation, biogas, gas engine, considering only the electricity fraction. The generated electricity was modeled as a substitution of grid electricity using the dataset Electricity, medium voltage (MX) | market for electricity, corresponding to the Mexican electricity mix in Ecoinvent under the cut-off approach, incorporating an avoided flow of −183.32 kWh/t MSW.

2.5.4. Selection and Adjustment of Ecoinvent Datasets

To represent the different types of FDS, datasets from the Ecoinvent v3.12 database were selected and adapted to local conditions. Biogas generation was consistently estimated across all scenarios using MBM 2.0. Based on these estimates, emissions of CH_4, CO_2, H_2S, VOCs, $PM_{2.5}$, SO_2, NO_x, and NH_3 were calculated (Supplementary Material SC, SD, SG, and SJ).

For the SLFGF and CS scenarios, emissions associated with both fugitive releases and biogas combustion (flaring) were estimated using MBM 2.0 combined with literature-based emission factors. For the SLF+ER scenario, fugitive emissions were estimated using MBM 2.0, while emissions associated with electricity generation from biogas were taken directly from the corresponding Ecoinvent dataset. The OD scenario was modeled using the corresponding Ecoinvent dataset, assuming no biogas capture.

This modeling framework ensures that methane generation and fugitive emissions are treated consistently across all scenarios, while differences in energy recovery and system configuration are represented according to the respective dataset structures. This approach ensures methodological consistency and comparability among scenarios. Table 4 lists the datasets used.

These differences, including infiltration conditions defined in the selected datasets, are inherent to the level of environmental control and operational characteristics of each disposal site type and are intentionally incorporated to represent realistic system configurations, without compromising the comparability of the scenarios.

For the SLF+ER scenario, the Ecoinvent dataset was used as a baseline to represent infrastructure and background processes; however, methane emissions originally included in the dataset were replaced by MBM 2.0 estimates to ensure consistency with locally adapted biogas generation applied across all scenarios. Other emissions (e.g., leachate and soil) were retained due to lack of site-specific data. This hybrid approach enables the integration of site-specific methane estimates with standardized background processes from LCA databases.

Key modeling assumptions and inventory parameters are summarized in Table 5. Additional details on emission calculations and model parameters are provided in the Supplementary Materials (SA–SK), which include all supporting calculations and parameter definitions used in this study.

Table 4. FDS scenarios, corresponding Ecoinvent datasets, and key modeling assumptions.

Site Type (Scenarios)	Dataset	Assumptions
Sanitary landfill with biogas flaring (SLFGF)	Municipal solid waste {RoW} | treatment of municipal solid waste, sanitary landfill | Cut-off, U	80% biogas capture
Sanitary landfill with electricity generation from biogas (SLF+ER)	Municipal solid waste {RoW} | treatment of municipal solid waste, sanitary landfill with energy recovery | Cut-off, U	80% biogas capture
Controlled site (CS)	Municipal solid waste {GLO} | treatment of municipal solid waste, unsanitary landfill, moist infiltration class (300 mm)	50% biogas capture. Moderate rainfall infiltration (300 mm)
Uncontrolled site or open dump (OD)	Municipal solid waste {GLO} | treatment of municipal solid waste, open dump, wet infiltration class (500 mm) | Cut-off, U	No biogas capture. High rainfall infiltration (500 mm)

Note: RoW, Rest of World; GLO, global dataset; Cut-off, U refers to the Ecoinvent cut-off system model with unit processes. Biogas capture efficiencies are based on literature values, while infiltration conditions follow the definitions of the respective Ecoinvent datasets.

Table 5. Key modeling assumptions and life cycle inventory parameters used for the evaluated FDS scenarios.

Parameter	Value	Source	Applied to
Modeling approach	Hybrid (MBM 2.0 + Ecoinvent datasets)	This study	All scenarios
Methane generation model	MBM 2.0	This study; MBM 2.0 [27]	All scenarios
Time horizon	100 years	This study; MBM 2.0	All scenarios
Methane fraction in biogas	50%	[27]	All scenarios
Biogas capture efficiency	80% (SLF), 50% (CS), 0% (OD)	[33–37]	By scenario
Fugitive emissions	Estimated using MBM 2.0 and emission factors from Olesen et al. [38]	This study; literature-based emission factors [38]	All scenarios
Combustion emissions (flaring)	Estimated using MBM 2.0 and emission factors from Olesen et al. [38]	This study; literature-based emission factors [38]	SLFGF, CS
Combustion emissions (energy recovery)	Included in Ecoinvent dataset	Ecoinvent v3.12 dataset	SLF+ER
Leachate emissions	Ecoinvent v3.12	Ecoinvent v3.12 dataset	All scenarios
Electricity generation and substitution	Estimated based on biogas energy content and conversion efficiency; substituted using Mexican grid dataset	This study; Ecoinvent v3.12 (Mexican grid dataset)	SLF+ER
Ecoinvent datasets used	RoW (SLFGF, SLF+ER) and GLO (CS, OD) datasets	Ecoinvent v3.12 datasets	By scenario

Note: MBM 2.0, Mexican Biogas Model version 2.0; SLFGF, sanitary landfill with gas flaring; SLF+ER, sanitary landfill with energy recovery; CS, controlled site; OD, open dump; RoW, Rest of World; GLO, global dataset.

2.6. Life Cycle Impact Assessment

The LCA was performed using SimaPro software (version 10.3, PRé Sustainability, The Netherlands). The impact assessment was conducted using the ReCiPe 2016 Midpoint (H) method [40].

The impact categories evaluated were global warming, terrestrial acidification, freshwater eutrophication, fine particulate matter formation, ozone formation (human health), and human carcinogenic toxicity, selected due to their direct relationship with emissions generated in MSW FDS, including greenhouse gases, acidifying compounds, particulate matter precursors, and contaminants present in leachate [22,41]. This selection is consistent with the goal and scope of the study and focuses on the most relevant environmental impacts associated with the system under analysis, rather than including the full set of categories available in the method.

2.7. Normalization, Sensitivity Analysis, and Interpretation

The characterized results were normalized using the ReCiPe method (Hierarchist perspective), as implemented in SimaPro version 10.3, which includes global (World) normalization factors for the reference year 2010, to compare the relative contribution of each impact category across the four types of FDS analyzed.

A deterministic sensitivity analysis was conducted by varying the organic fraction of the waste by ±10% and ±30% relative to baseline values defined for each scenario based on the initial waste composition for SLFGF, CS, and OD, as these represent the base configurations of the biogas generation model. The organic fraction of MSW was selected as the primary variable due to its direct influence on methane generation and its dominant role in determining global warming impacts.

Variations in biogas collection efficiency were not considered in this analysis, as the objective was to evaluate the influence of waste composition under fixed operational conditions, including constant biogas collection assumptions. Other parameters, such as biogas capture efficiency and electricity substitution, were not included because they are predefined within each scenario and are consistently applied across the modeling framework. Varying these parameters would reduce the comparability among scenarios. Therefore, the selected approach ensures a consistent evaluation of the influence of waste composition within the scope of the study.

The SLF+ER scenario was not included, as it uses the same biogas generation as SLFGF, differing only in energy utilization. Therefore, variations in the organic fraction affect both scenarios equally, and its inclusion does not provide additional insight into the sensitivity analysis.

3. Results and Discussion

This section presents the environmental impact assessment stage, including the selected impact categories, the sensitivity analysis, and the interpretation of results.

3.1. Global Warming

For the global warming category, the SLF+ER showed the lowest impact, followed by the SLFGF, while the CS exhibited intermediate values and the OD recorded the highest impact (Figure 3) (Supplementary Material SL). The impact of the SLFGF was approximately 70.6% lower than that of the OD, reflecting the effect of biogas capture and flaring systems [34]. Similarly, the CS showed an impact approximately 34% lower than that of the OD, although more than twice that estimated for the SLFGF. Compared to the SLFGF, the SLF+ER showed a reduction of about 3%, associated with energy recovery from captured biogas. These differences are mainly due to CH_4 emissions generated during the anaerobic degradation of the organic fraction of MSW [42], as well as variations in biogas capture efficiency and management across the evaluated scenarios.

In the OD, CH_4 is directly released into the atmosphere due to the absence of biogas capture systems, which explains the higher impacts observed in this scenario [43]. In the SLFGF, CH_4 is oxidized to CO_2 through controlled combustion, reducing fugitive CH_4 emissions and the impact in this category [44]. When captured biogas is used for electricity generation, as in the SLF+ER scenario, an additional reduction in global warming impact is achieved through the partial displacement of grid electricity, the benefit of which depends on its carbon intensity [45]. The CS shows intermediate values, indicating a partial reduction in CH_4 emissions associated with lower control in biogas capture and management compared to the SLFGF, without reaching the mitigation levels observed in the latter [43].

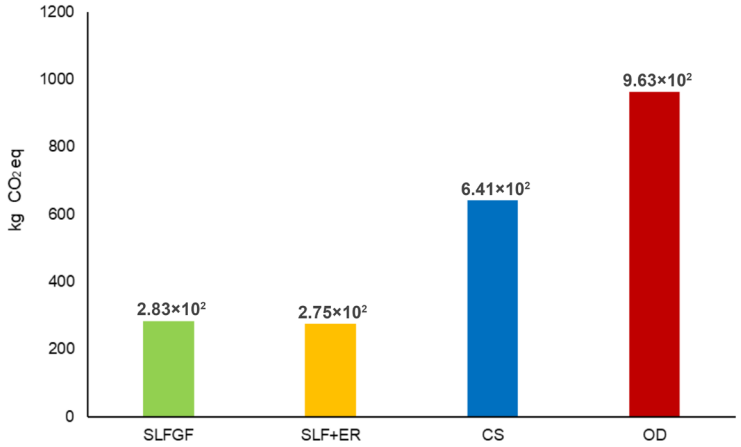

Figure 3. Global warming impacts for the evaluated scenarios (SLFGF, SLF+ER, CS, and OD), expressed per t of MSW.

This behavior is consistent with LCA studies of municipal landfills, which show that global warming impacts are dominated by biogas emissions and mainly depend on CH_4 capture and management efficiency [23,46]. Wang et al. [47] indicate that biogas emissions can account for more than 80% of the total impact in this category when CH_4 capture is limited. Caicedo-Concha et al. [30] and Cheniti et al. [48] reported similar results, confirming that scenarios without biogas capture present higher global warming impacts, whereas capture, combustion, or energy use contributes to reducing greenhouse gas (GHG) emissions. In the present study, the same trend was observed, with sites exhibiting higher levels of biogas control showing lower impacts in this category.

The small reduction between the SLFGF and SLF+ER scenarios (~3%) is explained by the fact that both assume a biogas capture efficiency of 80%, meaning that most global warming mitigation already occurs in the SLFGF. In this sense, the difference between scenarios does not lie in an additional reduction in direct emissions, but rather in the utilization of biogas. Although electricity generation from biogas allows for impact reduction through grid electricity substitution, this effect is limited relative to the total impact of the scenario, particularly due to biogas conversion efficiency and the carbon intensity of the displaced electricity, which is reflected in the marginal reduction observed.

3.2. Ozone Formation (Human Health)

For the ozone formation (human health) category, the SLFGF showed the highest impact, followed by the CS and the SLF+ER, while the OD recorded the lowest value (Figure 4) (Supplementary Material SL). In relative terms, the estimated impact for the SLFGF is approximately 1.8 times higher than that of the CS and nearly twice that of the SLF+ER. The SLF+ER scenario showed slightly lower impacts than the CS (≈11%). In contrast, the OD exhibits the lowest impacts, which is attributed to the absence of combustion processes associated with biogas management. In addition, the dominance of diffuse VOC emissions under low NO_x availability limits the photochemical formation of ozone in this scenario. Although fugitive VOC emissions may be generated from uncontrolled waste degradation [49], their contribution remains low under these conditions.

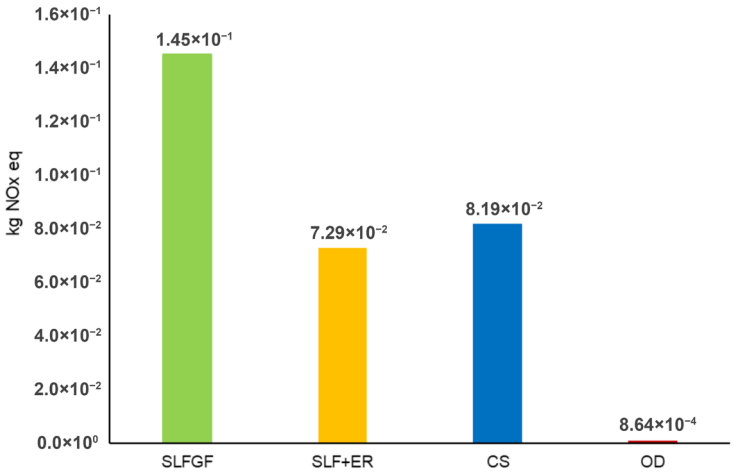

Figure 4. Ozone formation (human health) impacts for the evaluated scenarios (SLFGF, SLF+ER, CS, and OD), expressed per t of MSW.

In scenarios where biogas combustion occurs (SLFGF, CS, and SLF+ER), either through flaring or in internal combustion engines coupled with combined heat and power (CHP) systems, the oxidation of CH_4 leads to NO_x emissions, which act as precursors in the photochemical formation of ozone [50,51]. This behavior has been reported in LCA studies of waste management, where emissions associated with biogas significantly contribute to atmospheric impact categories such as smog or ozone formation (human health) [23,50]. Biogas combustion, both in flares and energy recovery systems, can also generate VOCs that participate in these photochemical processes [50,52].

Consistent with the above, the results show that scenarios involving biogas combustion present higher impacts in this category compared to those where the gas is not burned. However, the magnitude of these differences depends on the type of biogas management and the specific operating conditions of each FDS.

3.3. Fine Particulate Matter Formation

In the fine particulate matter formation category, the SLFGF showed the highest impact, followed by the SLF+ER and the CS, while the OD recorded the lowest value (Figure 5) (Supplementary Material SL). In relative terms, the impact of the SLFGF is approximately 2.4 times higher than that of the CS and about 13% higher than that of the SLF+ER. The CS shows intermediate values, while the OD exhibits the lowest impacts in this category.

The formation of fine particulate matter in FDS is mainly associated with emissions of precursors such as NO_x and SO_2, which undergo atmospheric transformation to form secondary particles (nitrates and sulfates). These emissions originate from combustion processes associated with diesel machinery use and biogas management [52]. In the SLF+ER, biogas combustion in internal combustion engines coupled with CHP systems also generates NO_x and other compounds that contribute to $PM_{2.5}$ formation [53,54]. Such emissions have been widely reported in landfill LCA studies, including NO_x, SO_2, and other pollutants associated with site operation and gas treatment, contributing to air quality impacts [55–58].

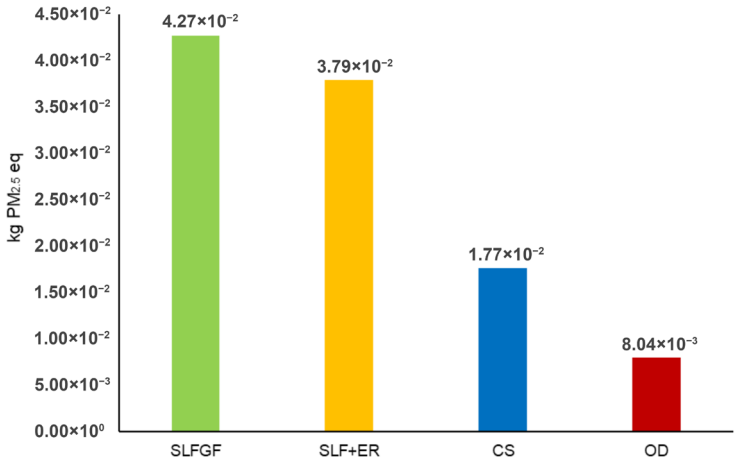

Figure 5. Fine particulate matter formation impacts for the evaluated scenarios (SLFGF, SLF+ER, CS, and OD), expressed per t of MSW.

Consistent with the above, the higher impacts observed in SLFGF and SLF+ER reflect the contribution of these combustion processes. However, the difference between the two scenarios is limited, indicating that energy recovery from biogas does not significantly reduce particulate precursor emissions compared to flaring. In contrast, the OD shows lower impacts due to the absence of combustion processes, while the CS presents intermediate values associated with partial biogas management and lower capture efficiency, which reduces the amount of gas subjected to combustion and, consequently, precursor emissions compared to scenarios with higher capture efficiency [23].

3.4. Terrestrial Acidification

In the terrestrial acidification category, the SLF+ER showed the highest impact, followed by the SLFGF, CS, and OD (Figure 6) (Supplementary Material SL). In relative terms, the impact of the SLFGF is approximately 2.7 times higher than that of the CS, while the energy recovery scenario is about 7% higher than the SLFGF. The CS shows intermediate values, while the OD records the lowest impacts in this category.

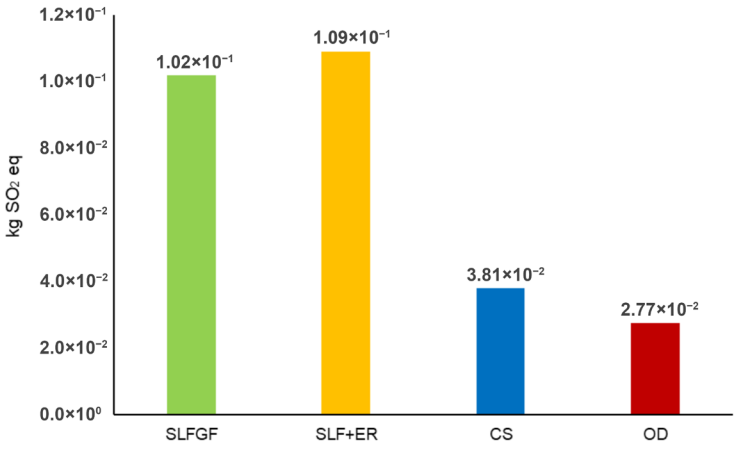

Figure 6. Terrestrial acidification impacts for the evaluated scenarios (SLFGF, SLF+ER, CS, and OD), expressed per t of MSW.

This behavior is mainly associated with combustion processes related to heavy machinery use and biogas management, both in flaring and energy generation systems. Emissions of NO_x and SO_2 are the main precursors of terrestrial acidification, as they oxidize in

the atmosphere to form secondary acidic compounds (nitrates and sulfates), which are subsequently deposited on soils and vegetation [23,50].

Previous LCA studies in waste management have reported similar trends. Caicedo-Concha et al. [30] analyzed different MSW disposal alternatives with various biogas management strategies and found that atmospheric emissions associated with landfill operation and gas management contribute to categories such as acidification. Similarly, Cheela et al. [29] evaluated different waste treatment scenarios, including landfills with and without biogas recovery, and identified that emissions associated with FDS operation influence atmospheric categories such as acidification.

Consistent with these findings, the results show that the highest impacts are concentrated in scenarios with biogas capture and treatment, where emissions from combustion processes significantly increase contributions to terrestrial acidification.

3.5. Freshwater Eutrophication

In this category, results show minimal differences among the evaluated FDS types (Figure 7) (Supplementary Material SL). The SLFGF presents the highest value, followed by the SLF+ER, while the CS and OD record nearly identical values. Differences between scenarios are below 0.2%, despite technological differences. This behavior is associated with the inclusion of long-term emissions in the inventory particularly those related to nutrient release into water bodies, whose contributions are similar across scenarios, limiting the influence of biogas management on this impact category.

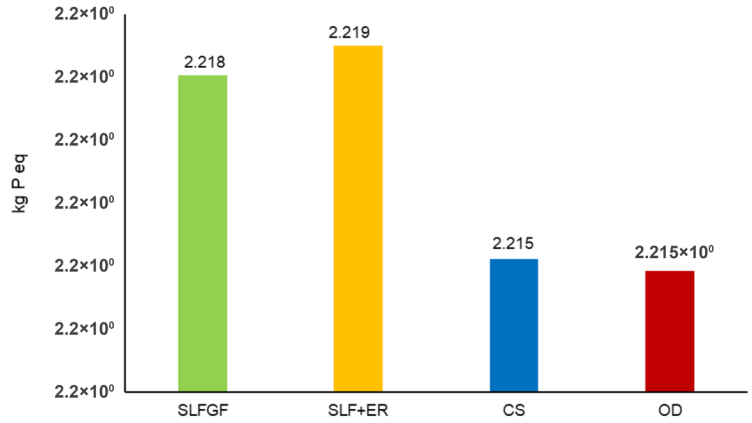

Figure 7. Freshwater eutrophication impacts for the evaluated scenarios (SLFGF, SLF+ER, CS, and OD), expressed per t of MSW.

In FDS, freshwater eutrophication is mainly associated with the release of nutrients present in leachate, particularly nitrogen and phosphorus compounds generated during the degradation of organic waste, which constitute one of the main sources contributing to this category [28,59]. Among these, phosphorus stands out as one of the primary contributors in freshwater ecosystems [7,60]. The slight reduction observed in the SLF+ER compared to the SLFGF is associated with the substitution of grid electricity through biogas energy recovery, which marginally reduces the impact of the scenario by avoiding emissions associated with conventional electricity generation [23,61], without affecting nutrient emissions to water bodies resulting from the generation and release of leachate.

The magnitude of these impacts largely depends on how emissions to water bodies are modeled and on the assumptions used to represent the interaction between leachate and aquatic ecosystems [22]. Likewise, the results may be influenced by long-term emissions considered in the SLFGF and SLF+ER inventories, which represent the potential release of nutrients following the progressive deterioration of containment barriers [60]. LCA studies

have shown that eutrophication impacts can vary across technological configurations depending on inventory assumptions [20,62].

This behavior is mainly explained by the contribution of emissions to water-related impact categories. Overall, the results suggest that the low variability observed among the analyzed FDS types is mainly associated with how emissions to water are represented in the inventory, rather than operational differences between scenarios.

It is important to note that these impacts are largely influenced by emissions associated with leachate derived from Ecoinvent datasets rather than site-specific modeling. Therefore, these results reflect standardized assumptions for water-related emissions, while methane-related emissions were estimated using locally adapted models. Consequently, these results should be interpreted with caution in terms of absolute values, while remaining valid for comparative analysis among scenarios.

3.6. Human Carcinogenic Toxicity

For the human carcinogenic toxicity category, the OD showed the highest impact, followed by the CS, SLF+ER, and SLFGF, which recorded the lowest impact (Figure 8) (Supplementary Material SL). In relative terms, the impact of the SLFGF is approximately 41% lower than that of the OD, while the CS shows a reduction of about 18%. The SLF+ER shows a reduction of approximately 39% relative to the OD.

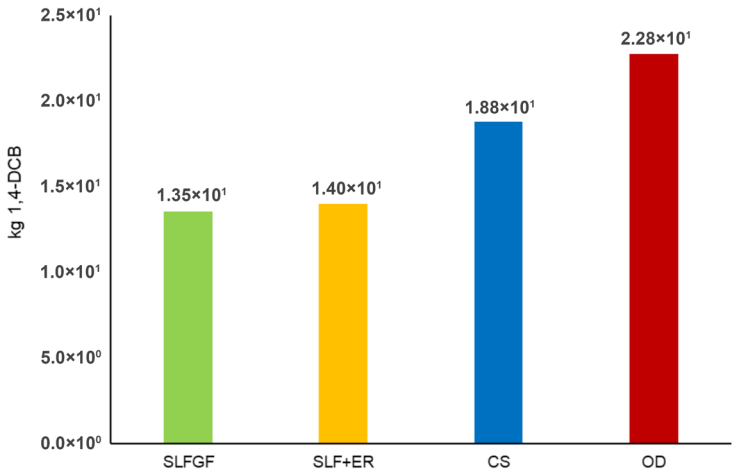

Figure 8. Human carcinogenic toxicity impacts for the evaluated scenarios (SLFGF, SLF+ER, CS, and OD), expressed per t of MSW.

This behavior is associated with the presence of containment and control barriers in FDS with higher levels of management, which limit the release of contaminants into the environment.

This category in FDS is mainly associated with the potential release of heavy metals and persistent organic compounds present in the waste, such as arsenic, cadmium, chromium, or chlorinated organic compounds [63]. These contaminants can be mobilized through leachate, atmospheric emissions, or other flows associated with waste degradation [64]. In the OD, the absence of containment barriers and leachate management promotes the dispersion of contaminants into soil and nearby water bodies, explaining the higher observed impact. In contrast, the SLFGF and SLF+ER incorporate liner systems, leachate collection, and operational control, which limit the migration of contaminants into these media and reduce potential human exposure to carcinogenic substances [20,65].

In the SLF+ER, the reduction observed relative to the OD, although slightly lower than that of the SLFGF, results in a slightly higher impact compared to the latter and is

associated with the substitution of grid electricity through energy generation from biogas, which reduces emissions associated with conventional electricity generation [66].

Similar results have been reported in LCA studies of MSW management, where this category is linked to heavy metal emissions in leachate and solid waste [30,48]. Uncontrolled landfills show higher contributions due to the release of contaminants into water and soil [60], whereas FDS with higher levels of control show reduced impacts [67]. Likewise, landfill leachate may contain heavy metals and organic compounds with the potential to migrate into soils and groundwater [28,68], whereas FDS that incorporate containment infrastructure present lower risks [69].

Overall, the results show that no FDS achieves the best performance across all impact categories [55]. The SLFGF shows the lowest impacts in categories dominated by fugitive emissions and potential contaminant release, such as human carcinogenic toxicity, as well as low values in global warming, due to biogas capture and structural confinement of waste. The SLF+ER shows a comparable performance, presenting the lowest impact in global warming and additional benefits associated with biogas energy recovery.

In contrast, scenarios with biogas capture and combustion (SLFGF and SLF+ER) show higher impacts in categories associated with combustion processes, such as ozone formation (human health), particulate matter formation, and acidification, due to NO_x emissions and other pollutants derived from biogas combustion and machinery use. The OD shows higher impacts in categories related to fugitive emissions and contaminant dispersion, but lower contributions in those associated with the combustion of captured biogas.

It is important to highlight that impacts in the human carcinogenic toxicity category are influenced by emissions associated with leachate, which were derived from Ecoinvent datasets. Similarly, freshwater eutrophication is primarily driven by nutrient releases, particularly nitrogen and phosphorus compounds. These emissions are mainly represented through background processes rather than site-specific modeling, whereas methane-related emissions were estimated using the MBM 2.0 model. As a result, these findings reflect standardized assumptions for contaminant release to water and soil, and the dominance of these impact categories can be considered largely database-driven. Therefore, results should be interpreted with caution in absolute terms, while remaining valid for comparative evaluation among scenarios.

Although background processes were represented using Ecoinvent datasets, key emissions associated with biogas generation and management were specifically estimated for the Mexican context, improving the representativeness of the evaluated FDS. Consequently, comparisons among FDS should consider multiple impact categories, as strategies that reduce certain impacts may increase others [41]. The categories evaluated in this study cover the main environmental impacts associated with waste management, providing a representative basis for comparison among scenarios.

However, differences in dataset structures and assumptions among scenarios may influence absolute impact values, and therefore results are primarily interpreted in comparative terms.

The trade-offs observed among impact categories are primarily driven by the interaction between emission control and secondary emission processes. Increased biogas capture reduces CH_4 emissions and consequently lowers global warming impacts; however, it also results in higher emissions from combustion processes, including NO_x and particulate matter precursors, which contribute to impact categories such as ozone formation, particulate matter formation, and acidification [70]. In contrast, systems with limited control exhibit higher fugitive CH_4 emissions but lower combustion-related impacts [55].

From a decision-making perspective, these results indicate that no single disposal strategy is optimal across all impact categories. SLF+ER may be preferable in contexts where

climate change mitigation is a priority, particularly when high biogas capture efficiencies are achieved. However, in scenarios where air quality and human health-related impacts are prioritized, the additional emissions associated with combustion processes should be carefully considered. Therefore, decision-making should be based on a multi-criteria approach that explicitly accounts for trade-offs among impact categories and aligns with local environmental priorities.

Beyond these decision-making implications, the findings can also be interpreted within the broader context of circular economy strategies. Recent approaches in waste management emphasize the integration of LCA with techno-economic analysis and multi-criteria decision-making frameworks to evaluate not only environmental impacts but also resource recovery potential, energy efficiency, and system-level optimization. In this context, the findings of this study provide a relevant basis for assessing the environmental implications of different disposal configurations, which can support the transition toward more integrated and resource-efficient waste management systems [71].

3.7. Normalized Environmental Impact Results

The characterized results were normalized using normalization factors provided by the ReCiPe method (Hierarchist perspective), as implemented in SimaPro version 10.3, corresponding to global (World) normalization factors for the reference year 2010, to compare the relative contribution of each impact category across the evaluated FDS, identifying eutrophication and human carcinogenic toxicity as the dominant categories (Figure 9a) (Supplementary Material SM).

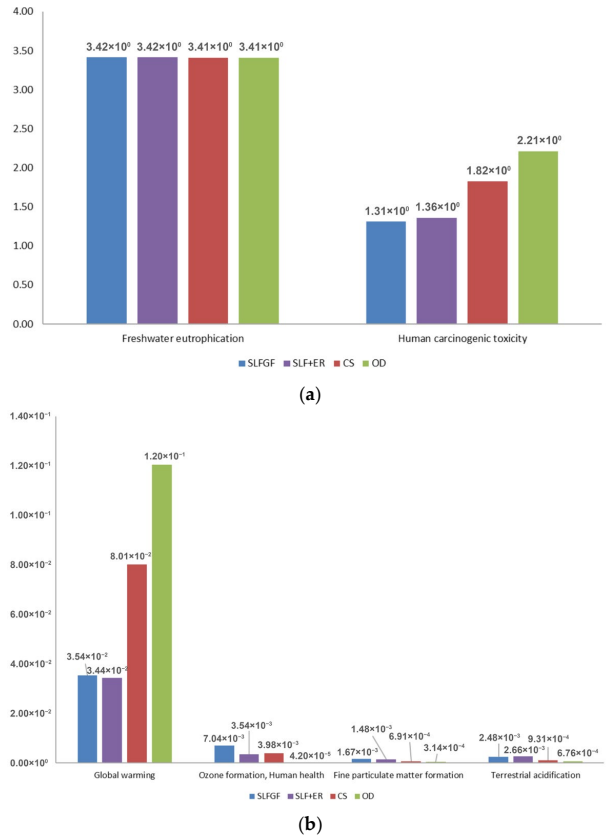

Figure 9. Normalized environmental impact results for the evaluated scenarios (SLFGF, SLF+ER, CS, and OD). (**a**) Impact categories with the highest relative contribution. (**b**) Impact categories with the lowest relative contribution.

The normalized results indicate that freshwater eutrophication is the category with the highest contribution across all evaluated FDS, with minimal variations on the order of 0.01 (Figure 9a). These values are significantly higher than those of the other categories, indicating that impacts associated with nutrient release are predominant. This behavior is consistent with the previously identified dominance of leachate-related flows, particularly those considered long-term emissions, which explains their predominant contribution across all scenarios.

Human carcinogenic toxicity corresponds to the second highest contributing category in normalized terms, with a particularly high contribution in the OD compared to FDS with higher levels of control. Although the SLF+ER incorporates biogas energy recovery, it does not present the lowest impacts, maintaining a relevant contribution in this category relative to the SLFGF [60,72].

Categories associated with atmospheric emissions show considerably lower contributions. Among them, global warming has the highest contribution within this group, with values of 0.035 for the SLFGF, 0.034 for the SLF+ER, 0.080 for the CS, and 0.120 for the OD. Ozone formation (human health), fine particulate matter formation, and terrestrial acidification show even lower values, consistent with the processes described in previous sections.

The results provide clear evidence to support decision-making in MSW management, indicating that increasing the level of control in FDS can significantly reduce impacts associated with CH_4 release and toxic substances. However, they also highlight the need to implement integrated strategies that prioritize leachate management and treatment, given its dominant role in environmental impacts.

Furthermore, the results suggest that biogas energy recovery is an effective alternative for mitigating impacts associated with climate change; however, its implementation can be optimized by increasing collection efficiency (90–95%) and ensuring proper management of combustion systems to avoid increases in categories associated with these processes. Consequently, the selection and improvement of final disposal technologies in the Mexican context should consider these trade-offs, directing investments toward both the control of gaseous emissions and the mitigation of impacts on water resources.

3.8. Sensitivity Analysis

To evaluate the influence of MSW composition on LCA results, a sensitivity analysis was performed by varying the organic fraction by ±10% and ±30% relative to the baseline composition (Supplementary Material SN, SO, SP, SQ). These values represent plausible changes in waste composition associated with regional variability and sampling conditions. The modified compositions were simulated using MBM 2.0 to estimate the corresponding biogas generation for each case. The resulting values were incorporated into the Ecoinvent inventory, and the impact categories were recalculated in SimaPro version 10.3 (Supplementary Material SR).

The results are presented in Figure 10, which shows the percentage variation in global warming impact for the analyzed FDS (SLFGF, CS, and OD), excluding SLF+ER. This category was the most sensitive to variations in the organic fraction of MSW. In the SLFGF, a 30% increase resulted in a 6.8% increase in global warming impact, while a 30% reduction led to a 9.5% decrease. In the OD, the impact decreased by 1.43% with a 30% increase, whereas a 30% reduction resulted in a 17.66% decrease. In the CS, the impact increased by 7.27% in the +30% scenario and decreased by 10.38% in the −30% scenario. These results indicate that the response of climate impact to the organic fraction is not uniform across FDS and depends on how the model represents organic matter degradation and biogas generation.

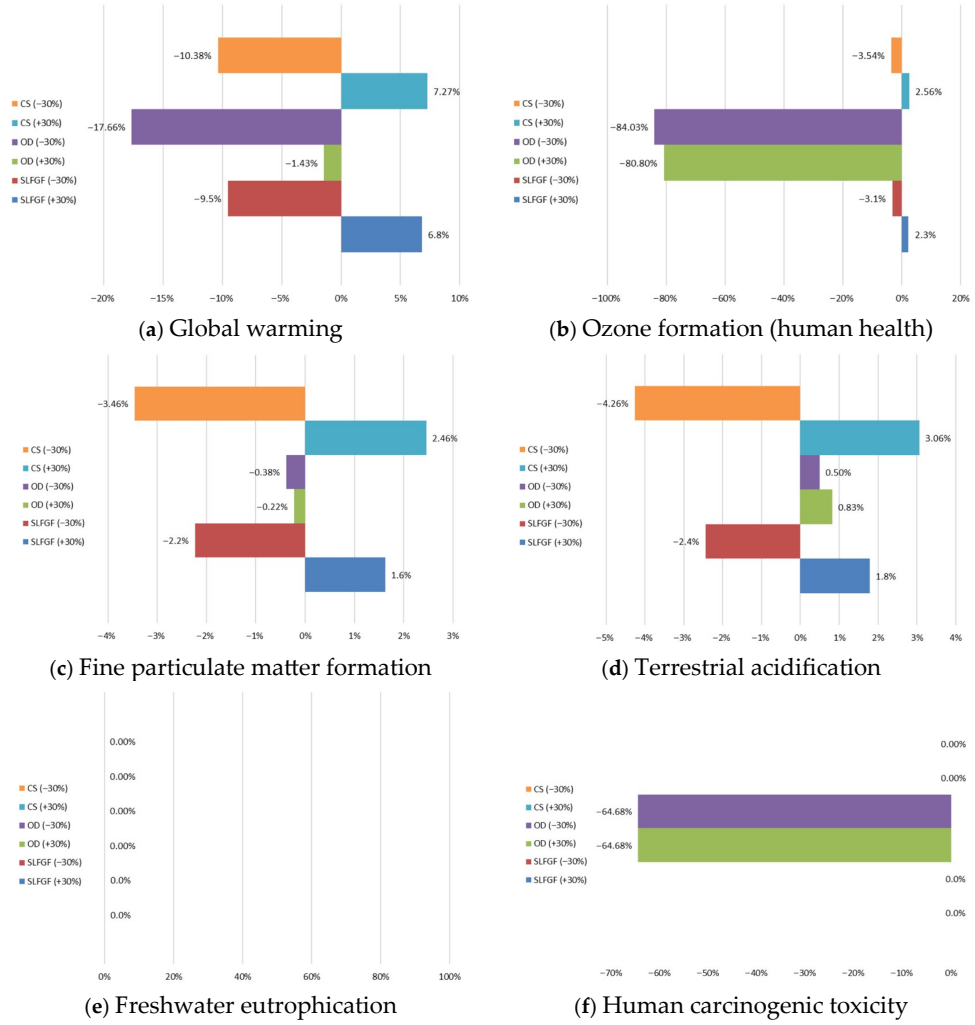

Figure 10. Sensitivity analysis results for variations of ±30% in the organic fraction of MSW, showing the relative change (%) in impact categories for the evaluated scenarios (SLFGF, SLF+ER, CS, and OD) with respect to baseline conditions. Results are based on the FU of 1 t of MSW.

Categories associated with combustion processes, such as ozone formation (human health), fine particulate matter formation, and terrestrial acidification, generally show variations below ±3% in the SLFGF and up to approximately ±4% in the CS. These categories are dominated by emissions of NO_x, SO_2, and $PM_{2.5}$ from biogas combustion and site operation; therefore, variations in the organic fraction have a secondary influence. In the OD, large percentage variations are observed in ozone formation (human health), with reductions of up to 84.03%. This is due to low baseline NO_x emissions, where small absolute changes produce large percentage differences; however, in absolute terms, these differences remain small.

Freshwater eutrophication remains constant across all analyzed cases, indicating that dominant flows are not influenced by the organic fraction or biogas generation. Similarly, human carcinogenic toxicity remains constant for SLFGF and CS, while in the OD a reduction of 64.68% is observed; however, identical values across OD cases indicate that these emissions are not linked to biogas generation.

Consistent with the above, similar trends were observed for ±10% variations, although with smaller magnitudes and without altering the relative ranking among FDS; therefore, they are not discussed in detail. In some cases, non-linear responses were identified; for example, in the OD, a 10% increase in the organic fraction results in a 5.58% decrease in

climate impact. This behavior is associated with how the model represents degradation dynamics and biogas generation over time.

Despite these variations, the relative ranking among FDS remains unchanged, confirming the robustness of the study's conclusions.

The results show that, although biogas control and utilization significantly reduce global warming impacts, their effect on other categories is limited. In particular, freshwater eutrophication and human carcinogenic toxicity are dominated by leachate-related emissions, considered here as long-term emissions resulting from the progressive deterioration of containment barriers and their eventual infiltration into water bodies. This explains the low variability observed among FDS with different levels of control in these categories (Figure 10e).

It is important to note that background processes were represented using Ecoinvent datasets, while key emissions associated with biogas generation and management were specifically estimated for the Mexican context, improving the representativeness of the evaluated FDS. However, incorporating leachate treatment systems could reduce impacts in water-related categories, representing an important area for future research.

4. Conclusions

The environmental performance of four types of MSW FDS in Mexico was evaluated using an LCA approach that integrates CH_4 generation estimated with MBM 2.0, along with fugitive emissions and emissions associated with biogas flaring, together with background processes.

The results confirm that biogas management is a key factor in reducing global warming impacts, with capture scenarios showing lower CH_4 emissions compared to uncontrolled sites. However, energy recovery from biogas does not substantially modify the environmental profile relative to flaring, as both depend on the same capture efficiency, limiting additional benefits from electricity generation.

In contrast, freshwater eutrophication and human carcinogenic toxicity are dominated by leachate-related emissions, particularly long-term emissions, indicating that biogas control alone does not ensure improvements across all impact categories. These findings highlight the importance of leachate design and management as critical elements in reducing environmental impacts. However, it is important to note that these impacts are largely influenced by standardized datasets (Ecoinvent), which may not fully represent site-specific conditions.

The results based on the 100-year time horizon highlight the relevance of long-term emissions associated with final disposal systems, particularly those related to the representation of leachate in life cycle inventories. These emissions are typically associated with long-term processes represented in life cycle inventories, which may lead to potential releases to soil and water bodies over extended periods. Although these processes are represented through standardized datasets, the findings emphasize the importance of long-term monitoring of final disposal sites to generate local and regional data. Such information is essential to improve inventory development, support system supervision and maintenance strategies, and enhance the representativeness of assessments in developing countries.

Additionally, FDS with higher levels of control show increased impacts in categories associated with combustion processes, confirming trade-offs among impact categories. No single FDS type achieves optimal environmental performance across all categories.

The sensitivity analysis confirms that the organic fraction of waste is the most influential parameter in CH_4 generation and climate-related impacts, without altering the relative ranking among FDS, supporting the robustness of the results.

Overall, this study provides a more representative assessment of MSW disposal in developing countries by integrating locally adapted emission modeling with LCA

databases. The results indicate that decision-making should not focus on a single mitigation pathway, but rather on integrated strategies that simultaneously address gaseous emissions and water-related impacts.

From a decision-making perspective, improving environmental performance requires prioritizing both leachate management and biogas control. In particular, strengthening leachate collection and treatment systems remains a key strategy due to their contribution to several impact categories, although these results should be interpreted with caution given the use of generic datasets. At the same time, increasing biogas collection efficiency (e.g., toward 90–95%) is critical to reduce climate change impacts. However, the implementation of biogas utilization strategies, including energy recovery, should be carefully optimized, as combustion processes may increase impacts in categories related to air emissions, such as ozone formation (human health), particulate matter formation, and acidification.

These findings emphasize that effective waste management strategies must explicitly consider trade-offs among impact categories, providing a balanced and context-specific basis for decision-making in municipal solid waste systems, particularly in developing country contexts.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments13050247/s1, as Excel file containing Supplementary SA to Supplementary SR. SA—Supplementary Material A. MBM SLFGF. SB—Supplementary B. Biogas generation SLFGF. SC—Supplementary C. Emissions SLFGF. SD—Supplementary D. Emissions SLF+ER. SE—Supplementary E. MBM CS. SF—Supplementary F. Biogas generation CS. SG—Supplementary G. Emissions CS. SH—Supplementary H. MBM OD. SI—Supplementary I. Biogas generation OD. SJ—Supplementary J. Emissions OD. SK—Supplementary K. Electricity generation from biogas. SL—Supplementary L. Impact Categories. SM—Supplementary M. Normalization. SN—Supplementary N. Waste composition in the +30% sensitivity scenario. SO—Supplementary O. Waste composition in the −30% sensitivity scenario. SP—Supplementary P. Waste composition in the +10% sensitivity scenario. SQ—Supplementary Q. Waste composition in the −10% sensitivity scenario. SR—Supplementary R. Impact categories with sensitivity scenarios.

Author Contributions: Conceptualization, E.M.-Z., M.d.C.H.-B., F.C.-R. and N.F.-Á.; methodology, E.M.-Z., E.R.R.D., F.C.-R. and S.J.T.-M.; validation, E.M.-Z., E.R.R.D., F.C.-R. and N.F.-Á.; formal analysis, E.M.-Z., M.d.C.H.-B. and E.R.R.D.; investigation, E.M.-Z., M.d.C.H.-B. and S.J.T.-M.; resources, M.d.C.H.-B., E.R.R.D. and F.C.-R.; data curation, E.M.-Z., E.R.R.D. and S.J.T.-M.; writing—original draft preparation, E.M.-Z., M.d.C.H.-B., F.C.-R. and N.F.-Á.; writing—E.M.-Z., M.d.C.H.-B., F.C.-R., E.R.R.D. and S.J.T.-M.; supervision, M.d.C.H.-B. and N.F.-Á.; project ad-ministration, M.d.C.H.-B. and N.F.-Á.; funding acquisition, M.d.C.H.-B. and N.F.-Á. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Tecnológico Nacional de México, through the research project "Proposal for the operation of a sanitary landfill from a sustainability perspective" with code 18196.23-P.

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Materials. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors thank the company "Constructora y Operadora de Rellenos Sanitarios, S.A. de C.V." for the facilities provided for the on-site characterization of the disposed MSW. They also thank the Secretariat of Science, Humanities, Technology and Innovation (SECIHTI) for the maintenance scholarships awarded to one PhD student in Environmental Sciences at the Tecnológico Nacional de México/Instituto Tecnológico de Toluca, División de Estudios de Posgrado e Investigación.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FDS	Final Disposal Sites
MSW	Municipal Solid Waste
LCA	Life Cycle Assessment
MBM	Mexican Biogas Model
SLFGF	Sanitary Landfill with Gas Flaring
SLF+ER	Sanitary Landfill with Energy Recovery
CS	Controlled Site
OD	Open Dump
CH_4	Methane
CO_2	Carbon Dioxide
NO_x	Nitrogen Oxides
SO_2	Sulfur Dioxide
VOCs	Volatile Organic Compounds
$PM_{2.5}$	Fine particulate matter
GHG	Greenhouse Gas
FU	Functional Unit
RoW	Rest of World
GLO	Global
CHP	Combined Heat and Power

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