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MODELING OF BIOGAS GENERATION BY APPLYING CDM METHODOLOGY FOR GREENHOUSE GAS EMISSION REDUCTION: CASE STUDY OF THE MTR SANTA MARIA MADALENA LANDFILL, RJ, BRAZIL

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ABSTRACT

The large amount of greenhouse gases (GHG) emitted by anthropogenic action becomes a challenge that requires initiatives for their mitigation, such as public-private partnerships. In developing countries, this issue is even more problematic, as growing economic development is not accompanied by legislation and initiatives regulating methane released into the atmosphere. This paper aims to measure GHG reduction by applying a United Nations Clean Development Mechanism (CDM) design methodology to a real landfill. The methods used were a case study of a landfill in the state of Rio de Janeiro, Brazil, applying the United States Environmental Protection Agency's LandGem model for the sizing of the produced gases and, finally, the CDM project analysis to define a methodology that applies to the case. The results show that the simple implementation of landfill flares greatly reduces methane emissions, but greater public and private interest in the application of gas mitigation methodologies is still needed. The main limitation of this research is the fact that there are few publications in the area of CDM project methodologies, and that the data used to size the gases in the LandGem model were estimated through population and waste forecasts. Finally, this study can be widely applied in landfills of different locations, not restricted to Brazil.

Keywords: Sanitary Landfill; CDM Projects; LandGem; Waste Management.

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1. INTRODUCTION

In developing countries, the issue of municipal solid waste is considered a social and political issue. In Brazil, in relation to the final disposal of municipal solid waste, 60% of municipalities still dispose of their waste in controlled dumps or landfills, and only 23.7% of municipalities have selective collection (Ministry of the Environment, 2015). Law No. 12,305 / 2010, which establishes the National Policy on Solid Waste, established that the Federal Government, together with the states, should develop targets for the disposal and recovery of dumps, as well as objectives, such as the energy use of gases generated in landfills (Brazil, 2010).

The set of landfill gases, biogas, is produced through anaerobic fermentation of organic matter, and is mainly formed by methane, carbon dioxide and other gases such as hydrogen sulfide. Methane (CH_4), which makes up 50 to 55% of biogas, has a global warming potential up to 32 times higher than carbon dioxide over a 100-year period (Etminan et al., 2016). In this sense, solutions are needed to mitigate their release into the environment.

Worldwide, landfills are responsible for 18% of anthropogenic CH_4 emissions (Bogner et. Al, 2008), which demonstrates the need for solutions that limit the release of methane into the atmosphere. Recent research mentions strategies in the field of biotechnology, such as the development of biofilters capable of oxidizing up to 80% of landfill methane (Gebert; Gröngröft, 2006). In addition, there are studies that show that methane can be used for power generation, heating and even cooling (Gao et al., 2015).

One of the advantages of biogas reuse in developing countries is that the project can meet the standards of the Kyoto Protocol (KP) instrument, the Clean Development Mechanism (CDM) (Barton et al., 2008). The main objective of the CDM is that developed countries, listed in Annex I of the climate agreement - achieve sustainable development while helping developing countries achieve sustainable development at lower costs (UNFCCC, 1998). In 2015, with the Paris Agreement, the climate agreement was reaffirmed with the objective of strengthening the global responsibility for proposing solutions to climate change, as well as promoting sustainable development. One of the main objectives is to limit global temperature rise to approximately 1.5°C above pre-industrial levels (UNFCCC, 2015).

The United Nations Framework Convention on Climate Change (UNFCCC) has developed a series of methodologies for regulating CDM standards projects, thereby reducing greenhouse gas (GHG) emissions. To mitigate emissions, there are methods that apply to various sectors such as industries, transportation, reforestation, and waste management and disposal (UNFCCC, 2018).

Partnerships between countries through the CDM proved beneficial, with economic, social and environmental gains for the project host country (UNFCCC, 2011). In addition, Brazil is one of the countries with the most active CDM projects, most of them in the area of energy and waste (Benites-Lazaro; Mello-Théry, 2019).

To demonstrate the environmental, economic and social advantages of mitigating these emissions, it is necessary to analyze the methodologies applicable to different sectors. Thus, the present work aims to demonstrate some of the environmental advantages of methane mitigation through a case study in a real landfill.

Gas production modeling was done to quantitatively demonstrate the potential for methane mitigation as a factor for sustainable development. The LandGem model, formulated by the United States Environmental Protection Agency (EPA, 2005), was used to estimate the gases produced annually in the landfill. The amount of methane produced annually was converted to carbon equivalent (CO_2e). Finally, a comparison of the landfill CO_2e emissions was made with the implementation of flares, and initial emissions, that is, without any kind of gas reuse. After that, proposals were made based on the results found, so that there is an integration of private and public initiative for project implementation.

2. LITERATURE REVIEW

Searching the Scopus database with the keywords landfill "AND" CDM did not yield abundant results covering both topics cited. 85 documents were found. Among them, the ones with the highest number of citations related to the keywords, besides the most recent and pertinent to the objective of this work, were selected. About 80% of the articles were published from 2008, which proves to be a recent theme and still needs to be explored by the academy. After this screening, it was possible to observe a limitation that reveals a scarcity of available literature about the CDM projects tool linked to landfills.

With the growth of developing countries' economies, there is greater waste production, which requires partnerships between countries to reduce the world's GHG that affect the planet. Studies such as Bogner (2008) and Barton et al. (2008) demonstrate the potential of the Kyoto Protocol CDM tool to reduce emissions from the waste sector.

In the first study to compare methane generation estimation models, Thompson et al. (2009) demonstrated the effectiveness of the LandGem model in estimating landfill gas. Using only the keyword "LandGem" in Scopus, 96 documents were found, 35% of which were published in 2017, 2018 and 2019. This model is easily accessible, free and highly reliable; thus, it was chosen to be applied in this case study.

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As they are recent themes, only after 2005 the first research of the LandGem model and CDM projects began to be published. Thus, there are materials available for consultation that favor public/private partnerships regarding solid waste management and the advantages of mitigating emissions.

2.1 Climate change and CDM projects

Research indicates that rising temperatures in the last 30 years of the 20th century have affected the phenology of organisms, the rate and distribution of species, and the composition and dynamics of communities (Walther *et al*., 2002). With studies increasingly highlighting the results of anthropogenic activities in ecosystems, discussions and partnerships have been held to mitigate climate change affecting ecosystems worldwide.

The CDM is an instrument of the Kyoto Protocol so that the signatory and non-signatory countries of the climate agreement, signed in 1997, can benefit each other. UNFCCC verifies carbon dioxide emission reduction through GHG emission reduction certificates in projects implemented in developing countries, increasing the expectation of sustainable development (UNFCCC, 1998). With the Paris Agreement, in 2015, this partnership between the countries was ratified, with the proposal of mitigating mechanisms of greenhouse gases - as can be observed in article 6, paragraph 4 of the agreement (UNFCCC, 2015):

A mechanism to contribute to the mitigation of greenhouse gas emissions and support sustainable development is hereby established under the authority and guidance of the Conference of the Parties serving as the meeting of the Parties to this Agreement for use by Parties on a voluntary basis. It shall be supervised by a body designated by the Conference of the Parties serving as the meeting of the Parties to this Agreement, and shall aim: (a) To promote the mitigation of greenhouse gas emissions while fostering sustainable development; (b) To incentivize and facilitate participation in the mitigation of greenhouse gas emissions by public and private entities authorized by a Party; (c) To contribute to the reduction of emission levels in the host Party, which will benefit from mitigation activities resulting in emission reductions that can also be used by another Party to fulfil its nationally determined contribution; and (d) To deliver an overall mitigation in global emissions.

Studies show that reducing methane concentrations directly affects the temperature near the earth's surface (Jones *et al*., 2018). Therefore, methane emissions need to be controlled, especially in the waste area, where landfills and wastewater accounted for approximately 18% of the world's anthropogenic methane emissions in 2004 (Rogner *et al*., 2007).

With the implementation of CDM projects, sustainable development indicators were observed in the economic, environmental and social areas, with increased job creation, technology exchange, pollutant reduction, poverty reduction, etc. (UNFCCC, 2011; Olsen; Fenhand, 2008). In addition, as regards waste management, GHG emission reductions can be achieved through recycling, including informal waste picker cooperatives (King; Gutberlet, 2013).

Brazil was the country that had the first project registered under the CDM mechanism in 2004. It was in the waste area, in Rio de Janeiro, at the Nova Gerar landfill, located in the municipality of Nova Iguaçu. In addition, Brazil is the Latin American country with the most CDM projects registered, most of which is in the energy industry and waste management area (UNFCCC, 2019).

There are 342 projects registered in Brazil; Of these, 214 are from the energy area and 130 from the waste area (Benites-Lazaro; Mello-Théry, 2019) (Figure 1). There are still few indicators to measure the benefits of CDM projects, but there are recent studies that demonstrate benefits in landfill projects in Brazil. They are: a) participation of waste pickers cooperatives and associations in CDM projects; b) reduction of negative impacts related to landfill activities; c) reduction of environmental impacts in the area surrounding the landfill and efficiency in the biogas capture system (Cruz *et al*., 2017).

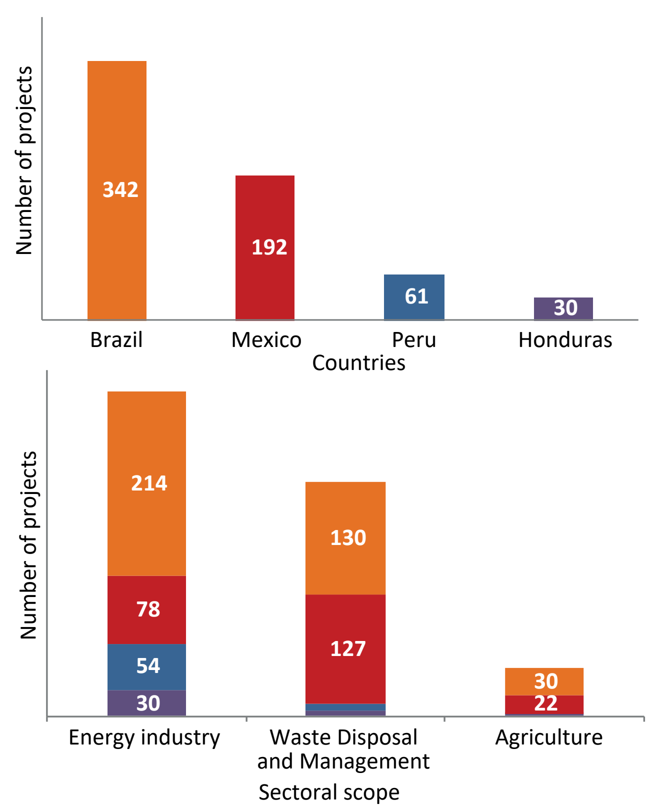

Figure 1. Major CDM projects by country and sector scope
Source: Adapted from Benites-Lazaro and Mello-Théry, 2019

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What still causes difficulties in the elaboration of new projects is the lack of knowledge of landfill managers and the responsible public entities regarding the procedures for preparing projects. However, federal government initiatives already exist, such as manuals for the preparation of a Project Design Document (PDD), which is the first step for postulating CDM projects (Gomes Neto, 2007).

2.2 LandGem Model

Landfill gases are mainly composed of methane (40-60%) and carbon dioxide (40-50%) (Hamini et al., 2012). For landfill gas calculation, the LandGem model created by the EPA was used. This model is specific for calculating gases in landfills that receive municipal solid waste. LandGem is based on a first-order decomposition equation (Equation 1), according to which, as organic matter is consumed, there is proportional methane production.

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k L_0 \left(\frac{M_i}{10}\right) e^{-k t_{ij}} \quad \text{(Equation 1)}$$

Where variables are:

Q_{CH4} = annual methane generation in the year of calculation (m^3/year);

i = time increment of one year;

n = (year of calculation) - (year of start of operation of the landfill);

j = 0.1 time increment;

k = methane generation rate ($year^{-1}$);

L_o = methane generation capacity potential (m^3/Mg);

M_i = waste acceptance mass in year i_{th} (Mg);

t_{ij} = age of section j_{th} of waste mass accepted in year i_{th} (decimal years, e.g. 3.2 years) (EPA, 2005).

Organic waste, such as food or weeding waste, contributes to rapid waste decay and high methane production; wood, paper, rubber and leather contribute to medium decay and low decay, respectively, and do not favor methane production (Kumar; Sharma, 2014). L_0, in turn, is related to the humidity of the site and the proportion of organic materials.

The LandGem model considers that landfill gases are composed of a 50% methane and 50% carbon gas ratio, as well as traces of other non-methanogenic components (NMOC) (EPA, 2005). In 2009, a study was conducted in which the authors analyzed emissions from 35 Canadian landfills and used different methane production estimation models. The model ranked among the three most effective, with conservative estimation rates (Thompson *et al.*, 2009).

3. MATERIALS AND METHODS

3.1 Study area

The municipal solid waste landfill MTR Santa Maria Madalena, which is located in the municipality of Santa Maria Madalena, in the state of Rio de Janeiro, Brazil, was chosen (22°2’57.00”S, 41°53’35.16”O).

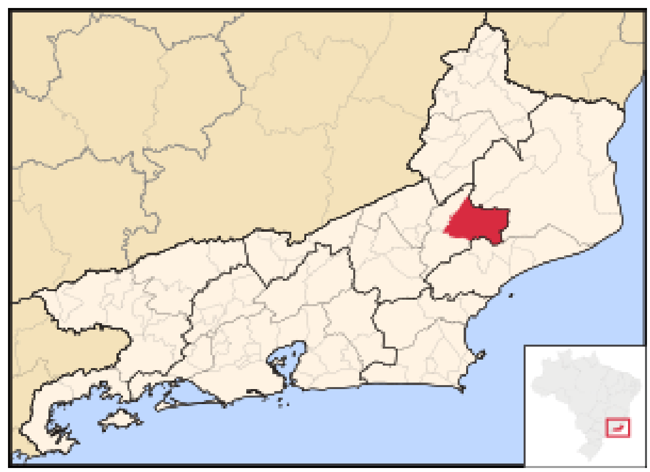

Figure 2. State of Rio de Janeiro, highlight of the municipality of Santa Maria Madalena.

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Figure 3. MTR Madalena Location, 22° 2’57.00”S, 41°53’35.16”O.

This landfill has no structure to mitigate methane release and receives waste through the municipal consortium of 11 municipalities in the interior of the state: Bom Jardim, Cantagalo, Carapebus, Conceição de Macabu, Cordeiro, Duas Barras, Macuco, Quissamã, Santa Maria Madalena, São Sebastião do Alto, and Trajano de Morais. These municipalities are considered small because they have populations ranging from 5,000 to 25,000 inhabitants.

Inland city waste is highly organic, which favors methane production; in the state of Rio de Janeiro, the proportion of small town organics comprises 56.72% of the total waste (Plano Estadual de Resíduos Sólidos do Estado do Rio de Janeiro, 2013).

Table 1. Waste gravimetry of small cities (up to 100 thousand inhabitants), in the interior of Rio de Janeiro state, Brazil

Waste Category	Composition
Organic matter	56,72%
Paper, cardboard	13,45%
Plastic	18,63%
Glass	2,83%
Metal	1,58%
Others	6,79%

Source: Adapted from Plano Estadual de Resíduos Sólidos do Estado do Rio de Janeiro, 2013.

3.2 Parameters and input data in the LandGem model

The input data from the model, as exposed in Equation 1, are total mass of waste received per year (M_i), methane generation rate (k) and methane generation capacity (L_0). The values of (k) vary according to ph, temperature and type of residue.

3.2.1 Parameter Estimation

The parameters L_0 and k were estimated according to the locational characteristics and proportion of organic waste received by the landfill. The amount of organics is directly related to methane generation capacity. The EPA and the Handbook for the Preparation of Landfill Gas to Energy Projects in Latin America and the Caribbean (World Bank, 2004), provide a specific study on Latin American landfills, including Brazilian landfills, and suggest that values of k and L_0 can be adopted according to precipitation and proportion of organic waste received by the landfill (Table 2).

As these are small towns that send their waste to the site, gravimetry shows that most of the waste is organic (Table 1). From these data, the residues were considered as moderately compostable. The average locational precipitation of Santa Maria Madalena, necessary to estimate the value of the parameter k, was analyzed using data from the National Institute of Meteorology (INMET – *Instituto Nacional de Meteorologia*). The Santa Maria Madalena – A630 meteorological station had a rainfall accumulation index of 850 mm last year. Therefore, a value of L_0 = 200 and k = 0.05 was adopted.

3.2.2 Total mass of waste

The amount of waste received by the landfill from each municipality was estimated. For this, per capita production and population data provided by the Rio de Janeiro State Solid Waste Plan (PERS – *Plano Estadual de Resíduos Sólidos do Rio de Janeiro*) and the Brazilian Institute of Geography and Statistics (IBGE – *Instituto Brasileiro de Geografia e Estatística*) were used. With data from the IBGE population censuses, from 1991, 2000 and 2010, it was possible to elaborate a population growth and/or decrease rate of each municipality, using geometric progression. The per capita waste generation data were taken from the 2013 PERS (Table 3).

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Table 2. Estimates of parameters k and L_0 by waste category and annual precipitation

Waste Category	k (year-1)				L0	
	Annual Precipitation (mm)					
	<250	250-500	500-1000	>1000	Minimum	Maximum
Relatively inert	0,01	0,01	0,02	0,02	5	25
Moderately compostable	0,02	0,03	0,05	0,06	140	200
Highly compostable	0,03	0,05	0,08	0,09	225	300

Source: Adapted from World Bank, 2004

Table 3. Index of municipal waste generation per capita

Municipality	Per Capita Generation Index
	(Kg/inhab.day)
Bom Jardim	0,70
Cantagalo	0,68
Carapebus	0,85
Conceição de Macabu	0,76
Cordeiro	0,71
Duas Barras	0,65
Macuco	0,61
Quissamã	0,65
Santa Maria Madalena	0,67
São Sebastião do Alto	0,73
Trajano de Morais	0,72

Waste produced annually by each municipality was estimated by multiplying the annual municipal population forecasts by the per capita waste production available in the Rio de Janeiro State PERS (Plano Estadual de resíduos Sólidos do Estado do Rio de Janeiro, 2013). The final amount disposed at the MTR Santa Maria Madalena landfill was estimated by the sum of the annual waste produced by each municipality.

Estimated total waste quantities annually for 20-year durability of the landfill, which is the estimated time of its activity, can be seen in Table 4 (results with total municipal estimates are in Appendix A). Subsequently, as input data into the LandGem model, these annual quantities were used from the start-up period in 2007 to the planned closure year 2027.

Table 4. Annual estimate of waste sent to Santa Maria Madalena landfill

Years	Municipal waste production per year (tonne)
2007	107864,81
2008	108608,66
2009	109372,56
2010	117490,70
2011	125579,83
2012	127581,58
2013	129647,68
2014	131780,64
2015	133983,11
2016	136257,83
2017	138607,67
2018	141035,59
2019	143544,71
2020	146138,27
2021	148819,62
2022	151592,30
2023	154459,95
2024	157426,39
2025	160495,60
2026	163671,72
2027	166959,07

4. RESULTS AND DISCUSSION

According to the CDM methodologies application manual, the base scenario (BE_y) is the current scenario of the enterprise; The project scenario (PE_y) is the scenario with the emission reduction project implemented; and emission reduction (ER_y) is the difference between emissions in the base scenario and the project scenario (Equation 2) (UNFCCC, 2012).

$$ER_y = BE_y - PE_y \quad \text{(Equation 2)}$$

For the calculation of methane produced in BE_y, the values found in LandGem were used, since this first-order decay model was proven closer to the actual methane gener-

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ation rates (Bianek *et al.*, 2018; Thompson *et al.*, 2009). The constant , which represents the global warming potential of methane in the commitment period, is considered to find the amount of carbon equivalent to methane. The value of this constant is established by the United Nations (UN), as: = 21 x , that is, CH_4 21 times more harmful than CO_2.

About 80% of methane can be captured through the landfill gas collection system and destroyed in flares, with methane reduction efficiency of 90% in closed flares and 50% in open flares (Tayyeba et al., 2011; UNFCCC, 2006). To calculate CO_2e in PE_y, a design scenario with closed flares was considered.

It is possible to observe the difference between the amount of carbon emitted without the installation of flares (BE_y) and the installation of closed flares (PEy) (Table 5 and Graph 1). The peak of CO_2e emission generation occurs shortly after the landfill closes in 2028.

Table 5. Estimated methane generated annually from 2007 to 2028, with respective CO_2e values in the base scenario and project scenario

Year	Methane (Mg/year)	BEy	PEy	ERy
		CO^2e (Mg/ year)	CO^2e (Mg/ year)	CO^2e (Mg/ year)
2007	0	0	0	0
2008	2520,20	52924,23	14818,78	38105,45
2009	4932,48	103582,04	29002,97	74579,07
2010	7242,52	152092,98	42586,03	109506,94
2011	9455,76	198570,94	55599,86	142971,08
2012	11577,35	243124,44	68074,84	175049,59
2013	13612,23	285856,85	80039,92	205816,93
2014	15565,08	326866,71	91522,68	235344,03
2015	17440,38	366247,93	102549,42	263698,51
2016	19242,38	404090,01	113145,20	290944,81
2017	20975,16	440478,31	123333,93	317144,38
2018	22821,70	479255,64	134191,58	345064,06
2019	24775,74	520290,60	145681,37	374609,23
2020	26683,38	560350,94	156898,26	403452,68
2021	28548,44	599517,20	167864,81	431652,38
2022	30374,63	637867,26	178602,83	459264,43
2023	32165,55	675476,60	189133,45	486343,15
2024	33924,69	712418,39	199477,15	512941,24
2025	35655,41	748763,71	209653,84	539109,87
2026	37361,03	784581,70	219682,88	564898,82
2027	39044,75	819939,73	229583,12	590356,61
2028	40709,69	854903,54	239372,99	615530,55

Considering landfill emissions with the maintenance of the current scenario (BE_y), i.e. without any use or destruction of methane, there would be a total of 854,903.54 mega grams (Mg) of carbon equivalent (CO_2e) being generated at the peak of gas production. In the scenario with the closed flare system project implemented (PE_y), it is possible to observe a 72% reduction in CO_2e (ER_y) emission, generating a total of 239,372.99 Mg, in which the avoided emissions are directly related to system capture efficiency and flare capacity. After the landfill is closed there is still considerable gas emission for about 80 years.

The UN classifies as large-scale projects when the difference between annual CO_2e emissions in the base scenario, which is the current landfill scenario (BE_y) and in the project implemented scenario (PE_y), is greater than 60kt. Therefore, the large-scale ACM001 methodology, which focuses on GHG destruction, is suggested. (UNFCCC, 2018).

The ACM001 methodology is directed to landfill methane capture and combustion projects. Some important conditions for its application are considered, such as: a) solid waste management should not be controlled to generate more methane; (b) Emissions calculated for the baseline scenario (BE_y) shall disregard national regulations and legal requirements for GHG emissions (not applicable to Brazil as there is no national legislation regulating landfill methane emissions); c) the effect of methane oxidation in the base scenario (BE_y) and the absence of this effect in the scenario with the implemented project (PE_y) should be considered (Figure 4 and Figure 5). The parameters to be monitored are: a) amount of methane captured; b) methane fraction that makes up the gases emitted by the landfill; c) flare efficiency; d) If a methane recovery project is implemented for electricity generation, the generation of electricity should be monitored; e) monitoring in the case of use for natural gas supply to consumers, vehicles, or gas pipeline.

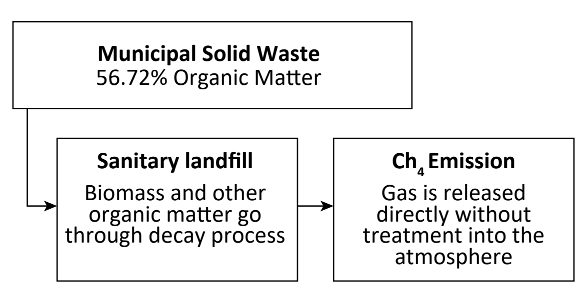

Figure 4. Base scenario where waste is landfilled and methane is released directly into the atmosphere

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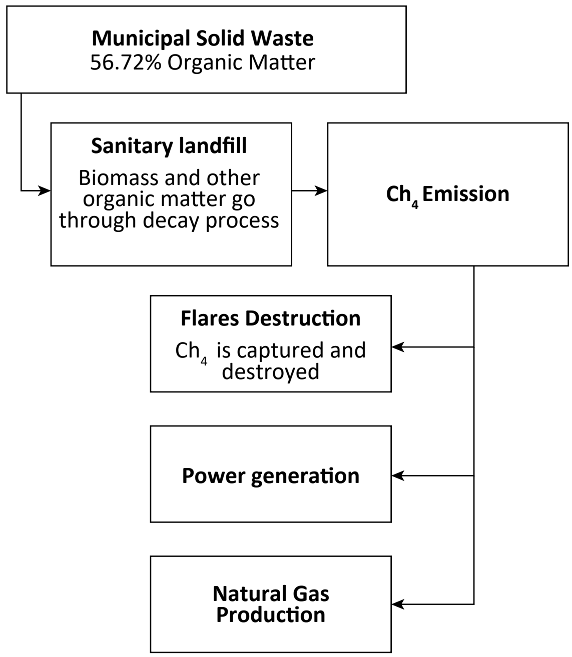

Figure 5. Project scenario where methane is captured and destroyed in flares or used for power generation or natural gas production

5. CONCLUSIONS

This study introduces a method that can be applied to different types of landfills due to the applicability of the LandGem model and the presentation of methodologies in the CDM parameters, which are feasible not only for gases, but for all waste management.

Literature analysis and calculation of the amount of gas emitted at the Madalena landfill made it possible to evaluate biogas characteristics in small city landfills, as well as environmental advantages with the implementation of a methane gas mitigation project.

Inland cities have a considerably high amount of organic waste, which favors the production of methane. In addition, factors such as high rainfall in the studied region are favorable to the production of this gas.

Brazilian law obliges the person in charge for the landfill to continue his management even after its closure. Therefore, applying a methodology that mitigates the methane produced would be environmentally advantageous, since the gas has its peak production one year after the closure of the landfill, and it continues to be produced for up to 80 years after the closure of activities.

The range of UN methodologies can be applied to different types of activities; however, it is a theme that needs to be explored by academia, with a case study approach with real applications and economic advantages for landfill managers. From an environmental point of view, the case study explored in this article showed that the amount of CO_2e that was no longer emitted with the installation of flares alone was high: around 72%.

Initiatives that bring public and private power together are essential to getting these projects off the ground, as well as partnerships between underdeveloped and developed countries to be willing to fund GHG emission reductions.

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