

## Chemistry

# Mitigation of CH<sub>4</sub> emissions in sanitary landfills: An efficient technological arrangement to reduce Greenhouse gas emission

MITIGAÇÃO DE EMISSÕES DE CH<sub>4</sub> EM ATERROS SANITÁRIOS: Um arranjo tecnológico eficiente para reduzir a emissão de gases de efeito estufa

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## ABSTRACT

Problems related to the solid waste have been shown a relevant subject, by contributing to global warming and climate change. The MSW is one of the main sources of Greenhouse Gases (GHG) emissions, especially the methane gas (CH<sub>4</sub>). Towards this concern, the general objective of this research is to estimate CH<sub>4</sub> emissions produced at the Dom Antonio Barbosa II Sanitary Landfill, situated in the City of Campo Grande, state of MS. Its aim, specifically, is to verify the gravimetric composition of these residues, as well as measure the amount of the MSW already existing and also the volume placed in the mentioned sanitary landfill. The CH<sub>4</sub> emissions were estimated in an accumulated total of 2,364,556.28 tCO<sub>2</sub>eq. It was obtained a total reduction of 1,479,693.87 tCO<sub>2</sub>eq by methane burning, transforming it into CO<sub>2</sub>, thus it was possible mitigating the emissions of 62.65% of CH<sub>4</sub> generated in DAB II landfill. It is expected that the results from this research contribute to the attenuation of the problems related to the MSW impact on the environment, as well as reflect on the effectiveness of the current adopted technological model.

**Keywords:** Public Policies; Greenhouse Gas; Climate Changes

## RESUMO

Os problemas relacionados aos resíduos sólidos têm se mostrando um assunto relevante, por contribuir para o aquecimento global e as mudanças climáticas. O RSU é uma das principais fontes de emissão de Gases de Efeito Estufa (GEE), principalmente o gás metano (CH<sub>4</sub>). Nesse sentido, o objetivo geral desta pesquisa é estimar as emissões de CH<sub>4</sub> produzidas no Aterro Sanitário Dom Antonio Barbosa II, situado na cidade de Campo Grande, Estado de MS. Pretende-se, especificamente, verificar a composição gravimétrica destes resíduos, bem como medir a quantidade de RSU já existente e também o volume

depositado no referido aterro sanitário. As emissões de CH<sub>4</sub> foram estimadas em um total acumulado de 2.364.556,28 tCO<sub>2</sub>eq. Obteve-se uma redução total de 1.479.693,87 tCO<sub>2</sub>eq pela queima do metano, transformando-o em CO<sub>2</sub>, assim foi possível mitigar as emissões de 62,65% do CH<sub>4</sub> gerado no aterro DAB II. Espera-se que os resultados desta pesquisa contribuam para a atenuação dos problemas relacionados ao impacto do RSU no meio ambiente, bem como reflitam sobre a eficácia do atual modelo tecnológico adotado.

**Palavras-chave:** Políticas públicas; Gás de efeito estufa; Mudanças climáticas

## 1 INTRODUCTION

The increase of the production and consumption, associated with the excessive generation of residues are ones of the great problems faced by humanity, in the contemporary age. The production of the municipal solid waste (MSW) comes, mainly, from an urban phenomenon (CASTILHO; PONTES; BRANDÃO, 2018). This problem is intensified with the expansion and the urban densification since the infrastructures of big cities and metropolises do not follow the growth of the solid waste production (VIDA; JESUS-LOPES, 2020).

The literature announces that since Industrial Revolution, natural resources have been intensively explored. This fact is due to a technology development not necessarily clean, which aims at the production of consumer goods. However, in the last five decades, the evidence and the scientific agreement on the natural resources are finite and need to be better used, have made the concern at the environmental preservation and the quality of life of future generations be widely argued (RISSATO *et al.*, 2018; SILVA *et al.*, 2018).

The problems related to the MSW have been shown be a significant subject, in a worldwide scale, both in developed and developing countries, because they importantly contribute to the global warming and climate changes in the Earth (SILVA FILHO *et al.*, 2017). The trends of urbanization without precedents bring the potential to transform the cities into exclusive centers of services and to fulfill the promise of inclusion and better social and economic chances for everyone. Nevertheless, if they do not be adequately managed and planned, the urban systems can suffer a strong pressure, in accordance with UN-Habitat (2017).

GHG are gases are present in the Earth's atmosphere and possess the property to block part of infrared radiation. As consequence of the human activities, the Earth's biosphere has presented an increase in the concentration levels of some of these gases, causing the anthropic greenhouse effect, i.e., caused by the man, responsible for the climate changes through the planet (MCT, 2004).

The Intergovernmental Panel on Climate Change - IPCC (2006) explains that the increase in the emission of gases such as CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, HFCs, PFCs, CFCs, NF<sub>3</sub>, SF<sub>6</sub>, SF<sub>5</sub> and CF<sub>3</sub>, halogenated ethers and other halocarbons, which are considered to be the main GHG, with emissions from anthropogenic sources, has been a major contribution to global warming and climate change.

Besides diverse local environmental impacts on the health and quality of life of the population, MSW contributes to environmental impacts in global levels, therefore constitutes a significant source of CH<sub>4</sub> emissions ICLEI (2009, p. 7). Thus, how MSW is related to the climate alterations and anthropic emissions of GHG? According to the United States Environmental Protection Agency - EPA (2002), MSW represents what remains after a long series of steps, from the extraction to the use by consumers and the management of residues. In accordance with EPA (2002, p. ES-3) four are the main forms of relation between Municipal Solid Waste - MSW and GHG,

Energy consumption (specifically, combustion of fossil fuels) associated with making, transporting, using, and disposing of the product or material that becomes waste. Non-energy-related manufacturing emissions, such as the CO<sub>2</sub> released when limestone is converted to lime (which is needed for use in aluminum and steel manufacturing). CH<sub>4</sub> emissions from landfills where the waste is disposed. Carbon sequestration, which refers to natural or man-made processes, that remove carbon from the atmosphere and store it for long periods or permanently.

A form to generate such gases refers to the treatment phases and/or final disposal of MSW, which emit CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub> (GOUVEIA, 2012). The uncontrolled emission of CH<sub>4</sub> deriving from the decomposition of the organic matter present in

the MSW is one of the precursors of the GHG production, related to the global warming, and has been in the recent years a subject for great debates (FERNANDES *et al.*, 2009).

Global emissions of CH<sub>4</sub>, proceeding from residues, had been estimated at approximately 40 million tons per year (RAHMAN, SHAMS, MAHMUD, 2009). As a climate changes effect, the IPCC (2014) indicates that the types of hydrological changes cited include effects on the snow, ice, and frozen ground; on the number and size of glacial lakes, on the increase in drainage of several glacier rivers, on the thermal structure and on quality of water of rivers and lakes, and also on dry and rainy seasons more intense in some regions.

Because of these impacts, it has been developed mechanisms in order to decrease the pressure that the human beings exert on the environment, and in such a way to cheat the conciliation between the development with the conservation and the environment protection (GOUVEIA, 2012). This way, it is believed that flexible strategies, combined with financial incentives can expand the actions for the MSW management, becoming possible to reach goals for GHG mitigation.

The assumption of the directive indicated by the National Policy of Solid Waste (PNRS), instituted by the Law 12,305/2010, for guaranteeing the environmentally appropriate final disposal of the MSW occurs in order to prevent damages or risks to the public health and the security, and besides to minimize adverse environmental impacts: how possible is to mitigate CH<sub>4</sub> emissions, proceeding from the MSW sphere? Before the exposed concern, the objective of this study is to estimate the reduction of CH<sub>4</sub> emissions, based on the burning of this gas, generated in Dom Antonio Barbosa II landfill, in the City of Campo Grande, state of MS.

This research is justified by presenting a different bias from the other studies in this area, therefore it aims at not only determine the reductions of the emissions, in the final phase of MSW disposal but also to argue the current social standards

of consumption, as well as the efficiency and the effectiveness of municipal solid waste management process. It is expected, as such, that public managers, companies, and society have a wider look at the problematic here analyzed since the boarded debates are capable to indicate its relative impacts.

The content of this paper is composed, furthermore this introductory part, of the interdisciplinary theoretical set, which will give support to the necessary reflections for the best understanding of the topic. After that, the methodological procedures applied for meeting the research proposal are explained. The comments and conclusion remarks are described as well. Funding and declaration of competing interest come before by the references.

## **2 THEORETICAL REFERENCES**

### **2.1 GHG Emissions and Mitigation Measurement in the Solid Waste Sector**

A significant percentage of the solid waste generated in the developing countries rests in uncontrolled landfills or illegal dumping. This situation provokes environmental and health concerns in life. The implementation of waste management allows developing countries to improve the public health and protect the environment; meanwhile, they reduce GHG emissions (ISWA, 2009).

Registering and reporting GHG emissions from the waste management is particularly challenging. The activities of the waste sector generate emissions of CH<sub>4</sub>, CO<sub>2</sub>, and N<sub>2</sub>O, and the industry, in turn, is responsible for the reduction of these impacts, by means of the recovery of materials and energy generation (ISWA, 2009).

The IPCC (1996) recommends that the studies on GHG emissions give priorities to CH<sub>4</sub>, CO<sub>2</sub>, and N<sub>2</sub>O gases, due to the concentration level of some of these gases and their current contribution with global atmospheric balance. CH<sub>4</sub> global atmospheric concentration increased from 715 ppb to 1,732 ppb in early

years 90, reaching 1,774 ppb in 2005, being that the variation of this concentration in the last the 650 thousand years is from 320 ppb to 790 ppb (IPCC, 2013).

In Brazil, according to data of Third Brazilian Inventory of Greenhouse Gases, published by the Ministry of Science, Technology and Innovation – MCTI (2016), the GHG emissions related to the sector of treatment of municipal solid waste represented 14.8% of CH<sub>4</sub> total emissions, in 2010, and the solid waste disposal, in turn, was responsible for 53.9%, what corresponds approximately to 1,327 tCH<sub>4</sub>. In the period from 2005 to 2010, CH<sub>4</sub> emissions from the sector of treatment of solid waste had an increase of 7.3%. The CDM can be applied to the activities of management of municipal solid waste and can help to surpass some barriers to development. The sales revenue of CRE can contribute to the advance of waste management practices environmentally suited (ISWA, 2009).

According to a survey from UNFCCC, the projects of CDM registered, until August 2017, have reached 1,009. There are 259 projects when considering municipal solid waste and the activities focused on the final disposal of it in landfills. Brazil houses about 19% of these projects of CDM, registered by UNFCCC, and a potential for reduction of 12,437,068 of tCO<sub>2</sub>eq..

Still in accordance with the analysis developed by the referred entity, by means of its database of registered projects of CDM, the main activities used for direct mitigation of GHG emissions, aimed at the final disposal of the MSW, are two: the first one is the capture and burning in flare of biogas of landfills and the second, the recovery energy of biogas or of CH<sub>4</sub>.

## **2.2 Contemporary Corporate Model and Solid Waste Generation**

One of the proposals presented for the resolution of the generation of municipal solid waste is made under the perspective of the use of technological tools, which aim at mitigating the problems of the generation of these residues. Regarding this topic, Angelis Grandson (1999) proposes a reflection, although

recognizing that the production of municipal solid waste is an inevitable phenomenon, where points as necessary to observe the relation between the society and the production processes and consumption standards. With regard to the productive process that causes an impact on the environment, Pethig (1991) apud LOPES (2007) indicates that human beings, in order to take care of a diversity of production and consumption, and thus to support the contemporary society lifestyle, explore the environment intensely (RISSATO *et al.*, 2018; SILVA *et al.*, 2018).

For Lopes (2007), the available technologies are insufficient for reducing the MSW production. However, once understood this phenomenon as also social, one perceives clearly that such resolution will not take place unique and exclusively by the available techniques or by those which will be developed in the next future, but, overall, by other social and politic forces, such as the cultural change of consumption. For him, the increasing generation of residues is due to the logic of the standard consumption of the contemporary society, which comprehends the extraction cycle of raw material, the production, and post-consumption.

Lopes, (2007), based on the reflections of Rodrigues (1998), Lima (2002) and Angeliz Neto (1999), conceives that the contemporary society, didactically, can be divided into three categories. They are: 1) the society of production and consumption; 2) the disposable society, and 3) the throwaway society. According to Angelis Grandson (2007), the consumer society is characterized by the individualistic actions of human beings, once the man acts and behaves in the urban environment much more as an individual. This individual has a compulsion for the consumption in order to satisfy their anxieties, but at the same time, this act represents the power, lifestyle, status, which make them believe they are different from the other individuals.

For Lima (2002), the society of consumption is also, for extension and consequence, the disposable society. It is a society consisting in the logic of consumerism of the newest, therefore, of replaceable goods in short-term, strategically designed for this aim. In this point, according to Schneider *et al.* (2004),

the discarding society is characterized by the wastefulness of the industrialized countries, where the social structures are responsible for stimulating the frequent renewal of the consumption goods.

The throwaway society is characterized by Rodrigues (1998), as that one which effectively wastes the natural resources and their own energy, such elements that, in the period of after-consume, stay disposed of in landfills, water bodies and in the seas, expanding contaminations. These complex relations are the ones which take Lopes (2012) to understand that the environmental changes, and as consequence the climate changes, are products from social actions on the natural resources and, simultaneously, from the social relationships, both imposed by the production ways and contemporary consumption, and not only issues related to the nature.

### **2.3 Municipal Solid Waste (MSW)**

According to Gouveia (2012), the economic development, the population growth, the processes of urbanization and the technological development cause changes in lifestyle, as well as in the ways of production and consumption of the global population. As a direct result of these processes, it has been observed an increment, both in amount and in the diversity of the Municipal Solid Waste production (MSW). For Keser *et al.* (2012) and Weng and Fujiwara (2011) apud Saifullah and Islam (2016), the generation of residues in urban areas is widely influenced by many factors, such as geographic condition, frequency on residues collection, stages of social and economic development and weather conditions.

ISWA (2015) indicates that, historically, the quantity of per capita generation of MSW had a direct relationship with the population income in the country. However, along two last decades, the MSW generation in countries with higher incomes reached its maximum level, and the income levels seem to have been disconnected from the residues generation. Despite stimulated for the population



increase, urban expansion, and economic growth, it is expected that the levels of residues generation significantly appear in the next decades in low-income countries.

As Hoornweg, Bhada-Tata and Kennedy (2009), as long as the urban expansion occurs, the global generation of MSW speeds up. In 1900, the world had 220 million urban inhabitants, 13% of the population. They had produced less than 300,000 tons of MSW per day. In 2000, the 2.9 billion people who lived in the cities, 49% of the worldwide population, generated more than 3 million tons of MSW, per day.

According to International Solid Waste Association data - ISWA (2015), the annual global generation of MSW represents from 7 to 10 billion tons in the total, of which approximately 2 billion are classified as MSW. The Association of Public Cleaning and Special Residues Companies - ABRELPE (2016), presented a generated volume of MSW in Brazil, in the range of 79.9 million tons in the year of 2015, which represented a 1.7% growth, in relation to the previous year.

In accordance with the IPCC, (2006), the standard composition of MSW presents about 50% to 60% of food residues. Still, Food and Agriculture Organization of the United Nations - FAO (2013) presents a study on the food wastefulness and indicates that the consumption phase, which reflects the MSW generation, is the third greatest responsible for food waste, corresponding to approximately 350 million tons.

The results of researches conducted by Saifullah; Islam (2016) point the presence of great organic fraction in MSW, being observed in many developing countries, as India (40-60%) (SHARHOLY *et al.*, 2008), Turkey (43-64%) (KESER *et al.*, 2012), China (57-62%) (CHEN *et al.*, 2010), Nigeria (52-65%) and Nepal (60-70%) (POKHREL; VIRARAGHAVAN, 2005). ISWA (2009) indicates that the organic components of the residues, for example, paper, cardboard, food residues or garden residues) vary between 30-70% of the total production of MSW. The presence of organic matter in the composition of the MSW is, therefore, the main

responsible for CH<sub>4</sub> emissions and its impacts on the environment (RAHMAN; SHAMS; MAHMUD, 2009).

Many urban areas create unplanned or emergency solutions, as a result of lack of necessary infrastructure to offer the environmentally appropriate destination and disposal for these residues, what originates a series of disorders, which still reflect in serious problems of public health, besides environmental and social ones (WEDGE, 2011). Landfills are one of the main forms of final disposal of residues in Brazil: 58.7% of the MSW collected in 2015 had their final destination considered as environmentally appropriated, in sites as sanitary landfills (ABRELPE, 2016).

Moreover, according to ABRELPE (2016), 3,326 of the 5,570 Brazilian cities, that correspond to 59.71% of the total, still perform the final destination of their residues in improper places, whether open-air landfills or controlled ones. In the State of Mato Grosso do Sul, still, in accordance with ABRELPE (2016), the MSW generated was 2,651,235 tons/year, in 2015. When comparing it with what was produced in 2014, 1.21% of growth is observed. Based on data from the State Court of Accounts in Mato Grosso do Sul, TCE (2016), 62 of the 79 cities of the State carry out the residues disposal in an irregular form in open-air landfills.

## **2.4 National Solid Waste Policy**

In August 2010, Law 12,305 was sanctioned, which institutes the National Solid Waste Policy (PNRS) in Brazil. This document writes about the principles, objectives, and instruments, as well as about the guidelines related to the integrated management and to the solid waste management. Still, in relation to its content, it includes hazardous solid waste, besides the responsibilities shared between managers and the public sector, face to the applicable economic instruments (MENDEZ; MAHLER, 2018).

It presents as main objectives, the protection of the public health and the environmental quality; not generation, reduction, reusing, recycling and solid waste treatment, as well as an environmentally appropriated final disposal of rejects; incentive to the recycling industry, bearing in mind the promotion of raw materials use and inputs derived from both recyclable materials and recycled ones; and the integrated management of solid waste (RODRIGUES *et al.*, 2016).

Regarding the definition of solid waste management, as indicated by Law 12,305/10, it is about the set of exerted actions, direct or indirectly, on the stages of collection, transport, and overflow, treatment and environmentally appropriated final destination of solid waste, as well as environmentally appropriated final destination of rejects. It is created, thus, a chance for elaborating a Municipal Plan of Integrated Solid Waste Management (PMGRS) or a Solid Waste Management Plan (PGRS). This same legal landmark declares what exactly is the process of environmentally appropriated final destination. This is a

destination of residues that includes the reusing, the recycling, the composting, the energy recovery and exploitation or other destinations admitted by the competent agencies [...] such as the final disposal, observing specific operational norms in order to prevent damages or risks to the public health and the security and to minimize adverse environmental impacts. (PNRS, 2011, p.10).

Thus being, it must be considered that the environmentally appropriated final disposal involves the processes of organized distribution of rejects in landfills, observing specific operational standards of health in order to prevent damages or risks for the public health and the security, and also minimizing adverse environmental impacts. The technological arrangement named as MSW sanitary landfill, according to the norm NBR 8419/1992, is set up as

technique of municipal solid waste disposal in the ground, without causing damages for the public health and its security, minimizing the environmental impacts, this latter method, which uses engineering principles to confine solid waste to the lesser area as possible and reduce them to the lesser volume as permissible, covering them with a land layer

in the conclusion of each workday, or at shorter intervals, if necessary. (NBR, 8419/92, p.01).

The current legislation, as well as the diverse standards, can present positive results, under environmental, social and economic perspectives, since it not only tends to reduce natural resources consumption, but it stimulates the opening of new markets, with the implantation of Waste Sorting Plants (UT) or even Waste Treatment Plants (UTR). These activities promote job and income generation for waste pickers, a proposal that converges with the social inclusion program and at the same time diminishes the impacts on the environment caused by the irregular disposal of solid waste. Being thus, the legal content of the Law nº 12,305/10 considers inserting the Brazilian cities in the paradigm of the Sustainable Development, when dealing with actions for the correct and responsible handling of the MSW produced in the country (PNRS, 2011).

### **3 MATERIAL AND METHODS**

#### **3.1 Methodology and the Measuring Instruments**

This work is linked to the Research Group Evolutionary Dynamics of Human Organizations, registered in the Directory Research Council of the National Development Council Scientific and Technological Institute (CNPq), an official member of the Ministry of Education (MEC). Inside that larger investigation, some research has already been carried out with the other minimum themes, required in IN10 / 2012.

For the construction and design of this research, the Code of Conduct and Best was consulted Practice Guidelines for Journal Editors (COPE, 2011). Likewise, he followed the instructions described throughout of the Good Practice Manual for Scientific Publication, defended by ANPAD (2018). The ABNT (2018) rules were applied. The existing models for quantification of gases generation in sanitary

landfills can be stoichiometric (static calculation) or kinetic estimates (dynamic simulation).

It was opted, for this inquiry, for the model of research based on kinetic estimates, once for Paraskaki and Lazardis (2005), in kinetic estimates, the gas production taxes are described by models based on mathematical equations, which simulate the biological and physical-chemical process of biogas production in landfills, over time.

The indicated mathematical models are used as a methodology in the Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, IPCC (2000), Tier 2, for quantification of the CH<sub>4</sub> emissions of the disposal residues in sanitary landfills. The raised data refer to the collection and the final disposal of MSW, in the period from November 2012 to December 2016. The projections of the generated residues production in 2017 until the estimated date of DAB II Sanitary Landfill closing had been extracted from the Municipal Plan of Basic Sanitation of the city of Campo Grande (2012). Table 1 presents the quantity of MSW deposited in the Sanitary Landfill, as well as its projections:

Table 1 – Quantity of Residues sent to the Sanitary Landfill

<b>Year</b>	<b>Quantity of residues (t/year)</b>	<b>Kg/inhab/day</b>
2012	46,361.77	0.81
2013	254,499.68	0.84
2014	271,651.74	0.88
2015	269,953.19	0.87
2016	266,245.59	0.85
2017	285,550.72	0.87
2018	294,347.53	0.88
2019	303,211.25	0.90
2020	312,138.88	0.91

Source: SOLURB 2016/PMCG 2012 (Adapted)

The gravimetric composition analyses of the MSW demonstrated in the Technical Reports of the Concessionaire Company in charge of MSW collection are performed quarterly, and they have as a methodological base the Solid Waste Guide of CETESB - Environmental Sanitation Technology Company (1990). Thus, for this research, means were developed based on the quarterly Technical Reports on the residue composition for the years from 2013 to 2016. The estimate of the residues composition for the following years was compiled based on the annual averages of the previous years, being repeated from 2017 to 2020.

### 3.2 The applied formula for the capture of the potential of CH<sub>4</sub> generation

For the calculation of CH<sub>4</sub> generation, in the Sanitary Landfill in reference, it was used the methodology suggested by IPCC (2000), contained in Module 5 - Garbage, from the Good Practice Guide and Uncertainties Management for National Inventories of GHG, referring to the IPCC Reviewed Guidelines (1996). Here the Module 5, Residues, vol. 2 was used as a source of data: Residues Generation, Composition and Data Management; and the Volume 3: Solid Waste Disposal, IPCC (2006).

The IPCC (2000) indicates two methods for estimating CH<sub>4</sub> emissions from the sites of solid waste disposal: 1) The Standard Method (Tier 1); and 2) the First-Order Decay Method (Tier 2). Thus, for this research Tier 2 was adopted since it reflects with more precision the trend of emissions over time. With the adoption of this methodology for the potential determination of CH<sub>4</sub> generation, it had been used the formulas as follow:

$$L_o = MCF * DOC * DOC_f * F * 16/12 \quad (1)$$

Where:

L<sub>o</sub>: potential of CH<sub>4</sub> generation of the residue (tCH<sub>4</sub>/tMSW);

MCF: Methane correction factor (%);

DOC: Degradable organic carbon fraction (tC/tMSW);  
 DOC<sub>f</sub>: Fraction DOC dissimilated (tC/tMSW): 0,50 (IPCC, 2006, vol.3, pg. 13)  
 16/12: Conversion from C to CH<sub>4</sub> (tCH<sub>4</sub>/tC); (IPCC, 1997; IPCC, 2000)  
 MCF = 1 (Landfill well managed);  
 F: Fraction by volume of CH<sub>4</sub> in landfill gas - 50% default (IPCC, 2006, vol.3, pg. 15).

$$DOC=0,40A+0,24B+0,15C+0,43D+0,39E \tag{2}$$

Considering:  
 A: Fraction of paper and textiles;  
 B: Textiles waste;  
 C: Food waste;  
 D: Wood waste;  
 E: Rubber and leather waste.

$$A = \frac{(1 - e^{-k})}{k} \tag{3}$$

Where:  
 A: Correction factor of the summation;  
 k: Decay rate Constant (year<sup>-1</sup>);

$$CH_{4_{generated}} = \sum [L_{o(x)} * MSW_{T(x)} * MSW_{F(x)} * A * k * (e^{-k(t-x)})] \tag{4}$$

Considering:  
 CH<sub>4</sub> generated: CH<sub>4</sub> generated (tCH<sub>4</sub>/year);  
 t: initial year of disposal or of initial calculation;  
 x: years for which input should be added;  
 A: summation correction factor;  
 MSWT: total municipal solid waste generated in year x (t);  
 MSWF: fraction of organic matter disposed of in the residue in year x (t);  
 k: decay rate constant (year<sup>-1</sup>);  
 Lo(x): CH<sub>4</sub> generation potential (tCH<sub>4</sub>/tMSW);

$$R_{(t)} = (CH_{4_{generated}} * CH_{4_{rec. fraction}}) * Ef_{burn} \tag{5}$$

Considering:  
 R<sub>(t)</sub>: Recovered CH<sub>4</sub>;

CH<sub>4</sub> generated: emissão de gás CH<sub>4</sub> (tCH<sub>4</sub>/ano);

CH<sub>4</sub> rec.fraction: recovered fraction CH<sub>4</sub>: 65% (ICLEI, 2009, p.54);

Ef. burn: burn out efficiency of combustion in flares: 90% (ICLEI, 2009);

## 4 RESULTS AND ANALYSES

The application of the methodology for the potential determination of CH<sub>4</sub> production (Tier 2) started with the treatment data of the MSW composition. The gravimetric composition for the years from 2017 to 2020 was developed based on the MSW composition averages from 2013 to 2016. The data on residues composition had been classified, as indicated in Good Practice Guidance 2000, in the following corresponding fractions of residue: papers, textiles, food, wood, rubber and leather, and other inert materials, as shown in Table 2:

Table 2 – Table of Residue Composition

<b>Residue Composition</b>	<b>2013</b>	<b>2014</b>	<b>2015</b>	<b>2016</b>	<b>2017</b>	<b>2018</b>	<b>2019</b>	<b>2020</b>
A – Paper	12.12%	17.62%	18.89%	14.83%	16.23%	16.23%	16.23%	16.23%
B – Textiles waste	3.40%	7.96%	6.09%	2.39%	4.75%	4.75%	4.75%	4.75%
C – Food waste	51.97%	37.86%	41.60%	52.71%	46.79%	46.79%	46.79%	46.79%
D – Wood	0.47%	0.39%	0.00%	0.80%	0.43%	0.43%	0.43%	0.43%
E – Rubber or leather	0.00%	1.45%	0.11%	0.08%	0.10%	0.10%	0.10%	0.10%
Other inert materials	32.04%	34.72%	33.31%	29.19%	31.72%	31.72%	31.72%	31.72%

Source: The author (2017).

It can be observed in Table 2 that the residues composition has its great fraction composed of food residues. These types of residues are responsible, mainly, for the CH<sub>4</sub> emissions. Each type of material that composes such residues presents a different Degradable Organic Carbon (DOC) content, being the main factor for determination of the quantity of generated CH<sub>4</sub> during its decomposition.



The percentages presented in Table 2 had been used, for DOC calculation, and its results are demonstrated in Table 3.

Table 3 – DOC – Degradable Organic Carbon in Year (tCH<sub>4</sub>/tMSW).

Years	2013	2014	2015	2016	2017	2018	2019	2020
[tCH <sub>4</sub> /tMSW]	0.1366	0.1537	0.1530	0.1478	0.1486	0.1486	0.1486	0.1486

Source: The author (2017).

With the results of the DOC contained in the residues, the calculations of the potential of CH<sub>4</sub> generation of the residue (L<sub>0</sub>) were developed, for each year, the CH<sub>4</sub> generation in the base years, its emissions based on its oxidation tax and also its emissions decay, year after year, considering the CH<sub>4</sub> density (0°C and 1.013 bar) as 0.0007168 t/m<sup>3</sup> (FIGUEIREDO, 2007). For the purpose of calculation, the data related to the residues disposed of during november and december 2012, had been added to the ones of 2013, strictly for the cited intend. Table 4 presents CH<sub>4</sub> generation, which points the outflow (m<sup>3</sup> CH<sub>4</sub>/h), year after year, for a period of 30 years, since the implantation of Dom Antonio Barbosa II Sanitary Landfill.

Table 4 – CH<sub>4</sub> Generation and Recovery, and CO<sub>2</sub>eq. Emission from Dom Antônio Barbosa II Sanitary Landfill

Years	CH <sub>4</sub> Generated (tCH <sub>4</sub> /year)	CH <sub>4</sub> Recovered (tCH <sub>4</sub> /year)	CH <sub>4</sub> Emission (tCH <sub>4</sub> /year)	CO <sub>2</sub> eq. Emission (tCO <sub>2</sub> /year)
2013	2,141.92	1,253.02	800.01	16,800.16
2014	3,845.58	2,249.66	1,436.32	30,162.78
2015	5,396.81	3,157.13	2,015.71	42,329.89
2016	6,686.28	3,911.47	2,497.33	52,443.85
2017	7,853.49	4,594.29	2,933.28	61,598.88
2018	8,936.39	5,227.79	3,337.74	70,092.59
2019	9,919.58	5,802.95	3,704.96	77,804.20
2020	10,819.14	6,329.20	4,040.95	84,859.92

To be continued...

Table 4 – Conclusion

<b>Years</b>	<b>CH<sub>4</sub> Generated (tCH<sub>4</sub>/year)</b>	<b>CH<sub>4</sub> Recovered (tCH<sub>4</sub>/year)</b>	<b>CH<sub>4</sub> Emission (tCH<sub>4</sub>/year)</b>	<b>CO<sub>2eq.</sub> Emission (tCO<sub>2</sub>/year)</b>
2021	9,127.73	5,339.72	3,409.21	71,593.33
2022	7,700.74	4,504.93	2,876.23	60,400.77
2023	6,496.85	3,800.65	2,426.57	50,958.01
2024	5,481.16	3,206.48	2,047.21	42,991.48
2025	4,624.26	2,705.19	1,727.16	36,270.40
2026	3,901.33	2,282.28	1,457.15	30,600.06
2027	3,291.41	1,925.48	1,229.34	25,816.19
2028	2,776.85	1,624.46	1,037.15	21,780.21
2029	2,342.73	1,370.50	875.01	18,375.20
2030	1,976.48	1,156.24	738.21	15,502.51
2031	1,667.49	975.48	622.81	13,078.92
2032	1,406.80	822.98	525.44	11,034.23
2033	1,186.87	694.32	443.29	9,309.19
2034	1,001.32	585.77	373.99	7,853.83
2035	844.78	494.19	315.52	6,626.00
2036	712.71	416.93	266.20	5,590.13
2037	601.29	351.75	224.58	4,716.19
2038	507.28	296.76	189.47	3,978.89
2039	427.98	250.37	159.85	3,356.85
2040	361.07	211.23	134.86	2,832.05
2041	304.62	178.20	113.78	2,389.30
2042	257.00	150.34	95.99	2,015.77
2043	216.82	126.84	80.98	1,700.65
Total	112,814.74	65,996.62	42,136.31	884,862.42

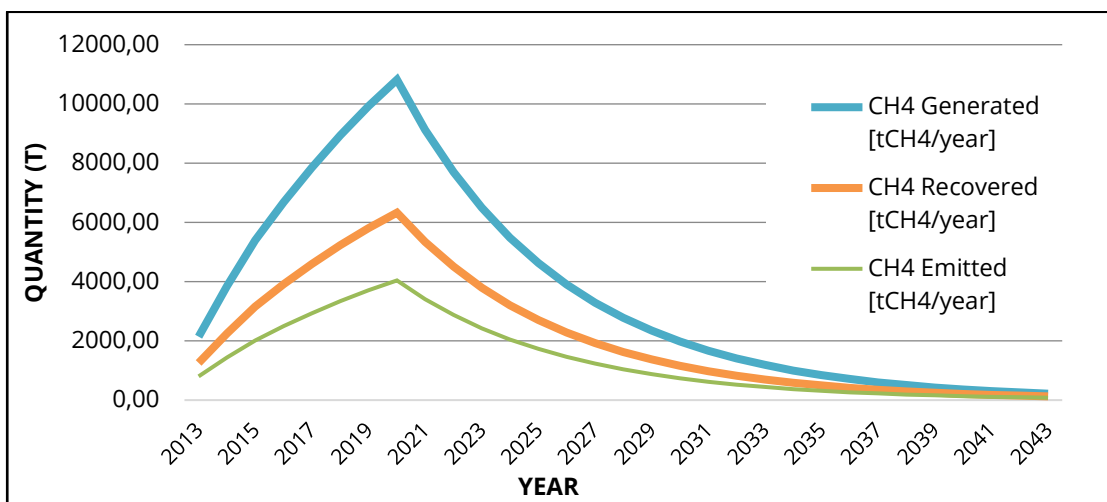
Source: The author (2017).

The recovered amounts of generated CH<sub>4</sub>, according to IPCC studies (2006, p.3.19) varied from 35% to 70% of the capacity range. The efficiency of the burning process varies between 80% and 95%, considering the time of functioning of the equipment, due to maintenance or technical problems, or inactive flare.

As ICLEI (2009, p.54), of the total of CH<sub>4</sub> generated, is estimated that 60% will be collected by the extraction system and that, of this total, 90% will be thermally oxidated in one flare.

It can be noticed that the CH<sub>4</sub> production increases over time of residue disposal, reaching its higher value in the year of the closing of disposal activities as a Sanitary Landfill. In the decay, the curve is conducted by the constant k, referring to the organic matter degradation over time, as presented in Figure 1.

Figure 1 – CH<sub>4</sub> Generation, Recovery, and Emission (t/year)



Source: The author (2017).

In the compilation related to the period from 2012 to 2016 and in the estimates from 2017 to 2020 for the solid waste production to be disposed of in the Sanitary Landfill, there is a reduction in the number of residues in the period that encloses 2015 and 2016, in relation to the previous years. Such situation deserves a further study.

As the gravimetric analysis of the solid waste disposed of in DAB II Sanitary Landfill, the fraction of food residues corresponds to the biggest parcel of its disposal rejects. In that respect, it is possible to observe the great wasted volume of foods and the potential of reduction in face of this wastefulness. Observing the emissions of GHG and their potential of reduction, a relatively high capacity in

terms of reduction of CH<sub>4</sub> emissions is expected. Considering that the foreseen technological arrangement for the DAB II sanitary field presents the CH<sub>4</sub> burning emitted, the gap for future studies on how effective is its functioning remains.

Regarding the existing technological models of MSW disposal, the use of sanitary landfills indicates an advance when GHG emissions mitigation is argued since this system adopts as mitigating procedure the reduction of emissions by means of the CH<sub>4</sub> burn and its conversion into CO<sub>2</sub>, this latter with lower potential of global warming. Other technological models as drains, also known as open-air landfills, do not present any technology for reducing the GHG emissions.

The use of the technologies for mitigating the emission of CH<sub>4</sub>, in sanitary landfills, does not present great social impacts related to the jobs generation. However, the social changes, for the population who previously operated in open-air landfills, as waste pickers, have a greater impact, since they must be redistributed for working through Cooperatives on the recyclable materials sorting, at the Units of Waste Selection (UTR) before being sent to the final disposal in the sanitary landfill.

As reported in the literature, mitigating the GHG emissions derived from the DAB II Sanitary Landfill contributes to the reduction of emissions and, as a consequence, also relieves the impacts of global warming, as well as the effects on the climate changes. The strong presence of the organic matter in the MSW composition is the main responsible for the CH<sub>4</sub> generation in disposal sites.

When analyzing the technological arrangement of final disposal in DAB II Sanitary Landfill, bearing in mind the mitigation of the CH<sub>4</sub> emissions, it can be considered as an efficient model, since the installed technological plant uses the means and the suitable technical procedures for reaching goals and results. Besides, it can be considered as an efficient technological arrangement, because it implies the capacity to mitigate the CH<sub>4</sub> emissions and presents concrete steps to reach them. It also covers the effectiveness, since its benefits run for long-term, as the applied technological procedures result in lower environmental impacts.

Observing the quantity of cities that still have the final destination of their residues in improper sites, whether they are open-air landfills or controlled landfills, and the environment and public health problems which are consequences of those actions, it can be considered that to solve the problem of irregular discarding is an essential initiative for the effectiveness of the process of MSW management. Nevertheless, it is not possible to consider it as an efficient, efficacious and/or effective model, since this process is more including and it involves actions of other agents, different interests, and behavior as well.

## 5 CONCLUDING REMARKS

In the face of the proposed delineation, it was possible to reach the indicated objective, estimating the CH<sub>4</sub> emissions mitigated, in Dom Antonio Barbosa II landfill, during its operation years, between 2013 and 2020, and after its closing until 2043. Moreover, this research also allowed getting information on the MSW management, especially in the final phase of its disposal. Using mathematical models, it was possible to determine the CH<sub>4</sub> emissions from the MSW decomposition, as well as the reductions of CH<sub>4</sub> emissions, when burning and transforming into CO<sub>2</sub>.

The calculation for estimating the CH<sub>4</sub> generation presents in its initial year, 2013, 2,141.92 tCH<sub>4</sub>. On the other hand, in its last year of disposal, 2020, it reached its maximum estimated value of CH<sub>4</sub>, 10,819.14 tCH<sub>4</sub> and an accumulated total from 2013 to 2043, of 112,814.74 tCH<sub>4</sub>, or 2,364,556.28 tCO<sub>2eq.</sub> Using as mitigation proposal the thermal oxidation, by means of the CH<sub>4</sub> burning in a flare, transforming it into CO<sub>2</sub>, is possible to reach a total reduction of 65,996.62 tCH<sub>4</sub>, which represents 58.5% of the CH<sub>4</sub> generated. Besides, when considering the CH<sub>4</sub> oxidation, we have the emission of 42,136.31 tCH<sub>4</sub>, that corresponds to 884,862.42 tCO<sub>2eq.</sub>, 37.35%. Therefore, it is possible to mitigate the emissions of 62.65% of the CH<sub>4</sub> generated in DAB II Sanitary Landfill.

When observing the principle of efficiency mentioned previously, it is possible to indicate that the current technological model, regarding the CH<sub>4</sub> emissions and the technological application for mitigation, proved to be efficient, but not effective, since it remits to the controlled conditions and to the desired results.

It was possible to verify, through the data collections, how much is still important to raise awareness of the society concerning the reduction of the municipal solid waste production, as its impacts on the climate changes are already known. Once more, it is recommended that the Public Administration ups date its general plans to reflect on subjects concerning the sustainability of municipal solid waste, such as goals of reduction of GHG emissions and recovery of the CH<sub>4</sub> emitted in Sanitary Landfills.

It is believed that the data presented here supply a useful vision of the municipal solid waste management, especially respect to the GHG emissions, in the final disposal of municipal solid waste, indicating the effectiveness of the implantation of MDL projects, in the level of the Kyoto Agreement. The Public Administration, independently of the level of actuation, fits with stimulating projects on mitigating GHG emissions, both in the public and in the private sector to reach the global proposals for GHG emission and reductions, especially for the MSW sector.

Even so, an advance in the social standards of production and consumption is necessary, as well as current technological and institutional arrangements need improvements, such as the implantation of options of residues destination which aim at its reusing and recycling. An example is a system of composting for organic matter, searching the effectiveness of the solid residues management.

This work searched for instigating, besides, sources for future inquiries and discussions, mainly, regarding the process of MSW management, efficacy, efficiency, and effectiveness, since other agents and forces involved need to be considered, such as the paper and the conditions of the selective collection, within

the process of MSW management, in the Brazilian cities. It was observed that the resolution of the problems attributed to the municipal solid waste is far from being only technological, but also for questions tied with its management, as well as problems of the contemporary culture in relation to the production of goods and its consumption.

From the present study, it was concluded that the Sanitary Landfill, an object of this paper, is a polluting agent due to its GHG emissions, which contributes, even partially, to the global warming and to the changes in climate regulation. Even though the mitigation mechanisms of CH<sub>4</sub> emissions are efficient and achieve to reduce significantly these GHG emissions, the MSW management still needs to advance.

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## **DECLARATION OF COMPETING INTEREST**

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

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