

## Article

# Accounting Greenhouse Gas Emissions from Municipal Solid Waste Treatment by Composting: A Case of Study Bolivia

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**Abstract:** Waste generation is one of the multiple factors affecting the environment and human health that increases directly with growing population and social and economic development. Nowadays, municipal solid waste disposal sites and their management create climate challenges worldwide, with one of the main problems being high biowaste content that has direct repercussions on greenhouse gases (GHG) emissions. In Bolivia, as in the most developing countries, dumps are the main disposal sites for solid waste. These places usually are non-engineered and poorly implemented due to social, technical, institutional and financial limitations. Composting plants for treatment of biowaste appear as an alternative solution to the problem. Some Bolivian municipalities have implemented pilot projects with successful social results; however, access to the economic and financial resources for this alternative are limited. In order to encourage the composting practice in the other Bolivian municipalities it is necessary to account for the GHG emissions. The aim of the present study compiles and summarizes the Intergovernmental Panel on Climate Change (IPCC) guidelines methodology and some experimental procedures for accounting of the greenhouse gases emissions during the biowaste composting process as an alternative to its deposition in a dump or landfill. The GHG emissions estimation results by open windrow composting process determined in the present study show two scenarios: 38% of reduction when 50% of the biowaste collected in 2019 was composted; and 12% of reduction when 20% of the biowaste was composted.

**Keywords:** municipal solid waste; SWDS; composting process; DOC; IPCC guidelines; GHG emissions



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## 1. Introduction

Climate change has become a crosscutting issue in the management and direction of public policies worldwide, and the waste sector is an important contributor reflected in the GHG inventories. In Bolivia, according to the Plurinational Authority of Mother Earth (APMT), methane (CH<sub>4</sub>) generated at solid waste disposal sites is responsible for approximately 10% of the annual global anthropogenic greenhouse gas emissions [1]. Additionally, according to the National Statistics Institute of Bolivia (INE), the Municipal Solid Waste (MSW) generation was 1,600,938 tons in 2019, of which 88% is generated in the urban area with a generation rate of 0.53 kg per inhabitant-day [2].

The Solid Waste Disposal Sites (SWDS) in Bolivia are mainly dumps, being approximately 6.8% disposed in sanitary landfills, 4.1% in controlled dumps and 89.1% in dumps [3]; of which about 30% are close to bodies of water that are used for human consumption and irrigation; these unsustainable practices generate leachates (percolated liquids), pollution of water, soil and atmosphere, and GHG emissions that affect the population health of the country [4]. A possible way of mitigating the MSW problem is firstly the differentiated collection to later compost it and allocate its nutrients for agriculture and forestry, through domestic use in gardens or orchards, and municipal use in gardening, landscaping, and recovery of degraded areas [5].

According to the IPCC guidelines, the composting process in general is given in aerobic conditions where a large part of the degradable organic carbon (DOC) in the waste material is transformed to carbon dioxide (CO<sub>2</sub>). CH<sub>4</sub> is generated in anaerobic sections of the composting process [6]. According to Ahn [7], the GHG monitoring results in well managed composting plants, which show that the CO<sub>2</sub> produced is biogenic, and CH<sub>4</sub> and N<sub>2</sub>O gases production are negligible. However, if proper composting conditions are not managed, CH<sub>4</sub> and N<sub>2</sub>O emissions could potentially increase.

## 2. Methodology

The methodological steps provide a resume of the IPCC guidelines for the waste sector and the experimental procedure to determine the composting process GHG emissions when a municipality has separate biowaste collection and composting process such as MSW management strategy. After showing the calculation methodology, a study case for the Bolivian context is presented.

### 2.1. GHG Emission Sources

The IPCC guidelines present an internationally-approved methodology for the national GHG emissions and removals calculation and reporting [8]. Up until today, there are two IPCC reference guidelines, 1996 and 2006, and there is a 2014 refinement to the 2006 report that does not include refinement to the biological treatment in the waste sector.

In some cases, the Global Warming Potential (GWP) in the 2006 guidelines (Fifth Assessment Report) increased in comparison with 1996, such as with CH<sub>4</sub>, and this particularity makes the specification of the guide important to use when a country reports its GHG inventory. In addition, in order to reduce double emissions accounting and to improve the coherence and completeness of the inventory, the 2006 guideline reduces from six groups of GHG emission sources to four: energy, Industrial Processes and Product Use (IPPU), Agriculture, Forestry and Other Land Use (AFOLU), and the waste sector.

### 2.2. Estimation Method

According to the 1996 and 2006 IPCC guidelines, the estimation method for accounting the GHG emissions is given by the Equation (1), where *AD* is the activity data that considers human activity with coefficients, and *EF* are the emission factors that quantify the emissions or removals per unit activity; the *EF* varies from default values (Tier 1) until more estimation complex methods (Tier 3); the parties members of the United Nations Framework Convention on Climate Change (UNFCCC) will choose their tier depending of their national circumstances and data availability [9].

$$Emissions = AD \times EF \quad (1)$$

The GHG emissions estimation from the waste sector compiles activity data on its generation, composition and management. Solid waste management takes into account its collection, recycling, disposal sites, biological and other treatments, and incineration and open burning options [10]; CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emissions estimation are considered for the waste sector GHG accounting. According to the 2006 IPCC guideline, it considers SWDS, biological treatment of solid waste, incineration and open burning of waste, and wastewater treatment and discharge categories. The accounting for CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emissions varies according to the source categories as detailed in the Table 1.

As this study has focus on composting GHG accounting; SWDS and biological treatment of solid waste categories are reviewed [10].

#### 2.2.1. Solid Waste Disposal Sites

The Revised 1996 IPCC Guidelines describe the mass balance method (Tier 1) and the First Order Decay (FOD) method (Tier 2) for estimating CH<sub>4</sub> emissions from SWDS. In 2006, a guidelines Tier 1 is given by the FOD method because it produces more accurate estimates of annual emissions [12]. In the FOD method the DOC content decays slowly

in a few decades where CH<sub>4</sub> and CO<sub>2</sub> are produced; usually waste in a SWDS produces high amounts of CH<sub>4</sub> for the first years after its deposition. In order to achieve acceptably accurate results, the collected or estimated data should consider waste historical disposals over a time period of 3 to 5 half-lives and use disposal of at least 50 years [13].

**Table 1.** GHG source and emissions categories related to solid waste included in the IPCC 2006 guidelines [11].

| Category                                  | GHG              | Inclusion in the Emissions Report | Comments  |
|---|------------------|-----------------------------------|---|
| 1. Solid waste disposal                   | CO <sub>2</sub>  | No                                | Biogenic origin and net emissions are accounted for the AFOLU Sector. Fugitive emissions derived from the anaerobic decomposition of waste. Presumed insignificant.   |
|   | CH <sub>4</sub>  | Yes                               |   |
|   | N <sub>2</sub> O | No                                |   |
| 2. Biological treatment of solid waste    | CH <sub>4</sub>  | Yes                               | Considers CH <sub>4</sub> and N <sub>2</sub> O emissions for composting process; and CH <sub>4</sub> emissions for biogas production. If the biogas generated is used to produce energy, it will be reported in the energy sector and its N <sub>2</sub> O emissions are presumed negligible. |
|   | N <sub>2</sub> O | Yes/No                            |   |
| 3. Incineration and open burning of waste | CO <sub>2</sub>  | Yes                               | The GHG emissions from waste incineration with energy recovery are reported in the Energy Sector, in the other case are reported in the waste sector; Only CO <sub>2</sub> emissions from fossil origin must be reported.   |
|   | CH <sub>4</sub>  | Yes                               |   |
|   | N <sub>2</sub> O | Yes                               |   |

For this category, Tier 1 estimation values are based on default activity data and parameters from the IPCC FOD method; Tier 2 use the IPCC FOD method and some default parameters; however, it requires good quality country-specific AD (statistics, surveys or other similar sources) for at least 10 years or more on historical waste in SWDS; Tier 3 is based on good quality country-specific AD and the FOD method is used with developed or measured country-specific parameters. In addition, another method with equal or higher quality to the Tier 3 method can be used [10].

Considering that CH<sub>4</sub> is generated with the organic material degradation under anaerobic conditions, in the cover of the SWDS part of the CH<sub>4</sub> is oxidized and can be recovered for energy or flaring. Given this fact, the CH<sub>4</sub> emissions from SWDS for a single year only consider the fraction of CH<sub>4</sub> that is not recovered and can be estimated with the Equation (2).

$$CH_4 \text{ Emissions} = \left[ \sum_x CH_4 \text{ generated}_{x,T} - R_T \right] * (1 - OX) \quad (2)$$

where  $CH_4 \text{ Emissions}$  are the total CH<sub>4</sub> emissions in the year of reference  $T$  in generated CH<sub>4</sub>;  $x$  is the waste category or type of material;  $R_T$  is the total amount of CH<sub>4</sub> recovered in the year of reference,  $OX$  is the oxidation factor (fraction) in the year of reference  $T$  [12]. CH<sub>4</sub> generation depends on MSW information (waste and SWDS types) and it can be determined for the following equations:

$$DOC = \sum_i (DOC_i * W_i) \quad (3)$$

$$DDOC_m = W * DOC * DOC_f * MCF \quad (4)$$

$$DDOC_{maT} = DDOC_{mdT} + (DDOC_{maT-1} * e^{-k}) \quad (5)$$

$$DDOC_{m \text{ decomp}T} = DDOC_{maT-1} * (1 - e^{-k}) \quad (6)$$

$$CH_4 \text{ generated}_T = DDOC_{m \text{ decomp}T} * F * 16/12 \quad (7)$$

where  $DOC$  is the fraction of degradable organic carbon in bulk waste in Gg of C/Gg of waste given by Equation (3), that considers  $DOC_i$  as the fraction of  $DOC$  in waste type  $i$ ; and  $W_i$  as the fraction of waste type  $i$ . The Decomposable Degradable Organic Carbon ( $DDOC_m$ ) is defined by Equation (4), considering  $W$  as the waste mass deposited in Gg;  $DOC$  as the degradable organic carbon in the year of deposition Gg of C/Gg of waste in

fraction;  $DOC_f$  as the  $DOC$  fraction that can be decomposed in fraction (recommended default value 0.5 considering that SWDS environment is anaerobic and  $DOC$  values include lignin); and  $MCF$  as the  $CH_4$  correction factor in aerobic conditions in the year of deposition in fraction (default values provided by IPCC for SWDS managed in anaerobic conditions and unmanaged in less than 5 m of high are 1 and 0.4, respectively) [12,14].

Additionally, the FOD basis is the first order reaction, where the  $CH_4$  generation only depends on the total mass of decomposing material currently in the site. For this reason, the FOD calculations can be done by the Equations (5) and (6), being  $DDOC_{maT}$  and  $DDOC_{maT-1}$  the  $DDOC_m$  accumulated in the SWDS at the end of the year of reference  $T$  and  $T-1$  respectively in Gg;  $DDOC_{mdT}$  the  $DDOC_m$  deposited in the SWDS in the year of reference  $T$  in Gg;  $DDOC_{m\ decompT}$  the  $DDOC_m$  decomposed in the SWDS in the year of reference  $T$  in Gg; and  $k$  the reaction constant, for Tier 1,  $k$  values for tropical sites up than  $20\ ^\circ C$  are 0.07 for paper; 0.17 for garden and park waste; and 0.4 for food waste in most and wet conditions [13].

Finally, the  $CH_4$  generation is given by the Equation (7), considering  $F$  as the fraction of  $CH_4$  (vol/vol) generated in the landfill; and the factor  $16/12$  as the molecular weight ratio  $CH_4/C$  [14].

### 2.2.2. Biological Treatment of Solid Waste: Composting Process

Composting involves biological treatment where organic material is degraded through microorganisms; leading to the compost production that can be used as a natural fertilizer or to improve soil structure [15]. During the process oxygen availability, C/N ratio, humidity, and temperature are the most important parameters that should be controlled under its three phases: Thermophilic, maturing and cooling. Under the thermophilic phase the material is decomposed, and the pathogens and bacteria are reduced by high temperatures above  $55\ ^\circ C$  [16]; in the maturing phase the temperature decreases for the low biological activity; and in the cooling phase the material gets very stable and mature [17].

The microbial activities under anaerobic and aerobic conditions during the composting process leads to the production of  $CO_2$ ,  $CH_4$ ,  $N_2O$ , and  $NH_3$ , with the  $CO_2$  and  $CH_4$  production given by the insufficient diffusion of  $O_2$  [18]; the  $N_2O$  production depends on the temperature, nitrate content and the aeration rate [19], and  $NH_3$  production has a direct relation with the temperature and pH [20].

The IPCC methodology for biological treatment of solid waste is given in the 2006 guideline that includes  $CH_4$  and  $N_2O$  emissions from compost preparation considering the Mechanical–Biological (MB) treatment and the composting process. MB treatment involves separation, shredding and crushing operations on the organic material;  $CH_4$  and  $N_2O$  production during the MB treatment depend on the specific operation and the time process [14]. The  $CH_4$  and  $N_2O$  emissions estimation can be determined by the following steps:

Step 1: Data collection on the amount of solid waste that is composted (regional and country-specific default data for some countries is given in the 2006 IPCC guideline) [14];

Step 2: Estimate the  $CH_4$  and  $N_2O$  emissions from composting process with Equations (8) and (9). The EF must be considered according to the facilities to get the specific information (tiers).

$$CH_4\ Emissions = M * EF * 10^{-3} \quad (8)$$

$$N_2O\ Emissions = M * EF * 10^{-3} \quad (9)$$

where:  $CH_4\ Emissions$  and  $N_2O\ Emissions$  are the total  $CH_4$  and  $N_2O$  emissions per year in Gg respectively, considering  $M$  as the mass of organic waste processed in Gg; and  $EF$  in g of  $CH_4/kg$  and g of  $N_2O/kg$  of waste treated, respectively.

The  $CO_2$  emissions are not considered given its biogenic origin [6],  $CH_4$  and  $N_2O$  GWP are 28 and 265 times higher than  $CO_2$  respectively [21].  $CH_4$  generation can occur at the beginning of the composting process under anaerobic conditions [22]; and  $N_2O$  generation can take place at various stages of the process by-product of nitrification or de-nitrification.

The EF by default or Tier 1 for CH<sub>4</sub> and N<sub>2</sub>O emissions, and its uncertainty are given in the Table 2, during mechanical operations the GHG emissions can be considered negligible. EF for Tier 2 should be based on applied country representative measurements during the composting process; and EF for Tier 3 would consider facility/site-specific measurements (on-line or periodic) that are more reliable than Tier 2.

**Table 2.** Default emission factors for CH<sub>4</sub> and N<sub>2</sub>O emissions from composting process [14].

| Type of Basis   | CH <sub>4</sub> Emission Factors<br>(g of CH <sub>4</sub> /kg Waste Treated) | N <sub>2</sub> O Emission Factors<br>(g of N <sub>2</sub> O/kg Waste Treated) | Remarks  |
|-----------------|--|---|--|
| On a dry weight | 10<br>(0.08–20)  | 0.6<br>(0.2–1.6)  | Assumptions: 25–50% DOC in dry matter. 2% N in dry matter, 60% moisture content. |
| On a wet weight | 4<br>(0.03–8)  | 0.24<br>(0.06–0.6)  |  |

### 2.3. Sampling Methods

Experimental composting measurements are oriented to collect more affordable information for the EF such as with Tier 2 and Tier 3. Two experimental methods for sampling GHG emissions from open windrow composting are reviewed: flux chamber and funnel.

#### 2.3.1. Flux Chamber Method

The flux chamber method has been successfully used for measuring GHG emissions in composting piles with organic household wastes [23], which basically uses inverted boxes or cylinders (with known dimensions) situated over the compost pile surface where the gases produced concentration is measured by several instrumental techniques [24]. This method can be done by closed and open chamber types, and non-reactive materials (stainless steel, aluminum, PVC, polypropylene, polyethylene, or plexiglass) are recommendable to construct the flux chambers [25].

The closed chambers shapes usually are cylinders with 10 to 400 L of volume [23] where gases concentration are sampled from 10 to 30 min intervals depending on the instrumental technique. Gas analysis can be done on site (sample return into the chamber) in order to avoid pressure changes or off-site, being the samples stored and analyzed in the laboratory generally by gas chromatography technique. The EF determination is determined by the following equations:

$$E_{Flux\_chamber} = \frac{dC_{gas}}{dt} * V_{chamber} \quad (10)$$

$$EF_{gas} = \frac{\sum \int_{t_2}^{t_1} E_{Flux\_chamber} * dt}{m_{input\_waste}} \quad (11)$$

where, the gas emission fluxes ( $E_{Flux\_chamber}$ ) in kg/h [18] considers  $dC_{gas}/dt$  as the change in the concentration  $C_{gas}$  over time in kg/s·m, and  $V_{chamber}$  as the total volume inside the chamber in m<sup>3</sup>. The emission factor of the gases ( $EF_{gas}$ ) integrates over time (time between measurements) and summarize over the entire year of composting the  $E_{Flux\_chamber}$  considering  $m_{input\_waste}$  as the total input organic waste amount in Mg being its units kg/Mg.

This method is economic and easy doing as its main advantages. However, the pressure gradients between compost pore space and chamber headspace can be induced, the high height of the chamber may not allow adequate mixing of headspace air [25], and the rate of diffusion of gases can be perturbed or decreased leading to an underestimation of GHG emissions [24].

The open chambers allow the capture of the whole flux of gases generated by the compost process, where the measurements can be collected by different sections and depths of the pile including temperature and oxygen profiles. The daily gas flux from the top, upper or lower side of pile in g/d ( $E$ ) can be calculated by Equation (12) considering

$Q_{sweep}$  as the flow rate of the  $N_2$  sweep gas going into the chamber in L/h;  $C_{sample}$  as the concentration of the gas in vol/vol determined by the gas chromatograph;  $Y_{sample}$  as the concentration of the gas in  $mg \cdot L^{-1}$  that is converted from  $C_{sample}$  assuming ideal gas relations and using chamber air temperature values (measured by a thermocouple thermometer);  $A$  as the bottom of the chamber surface emissions area in  $m^2$ ; and  $B$  as the top, upper or lower side of pile surface area in  $m^2$  [26].

$$E = \frac{Q_{sweep} * \left(1 / (1 - C_{sample})\right) * Y_{sample}}{A} * B * 24 * 1000 \quad (12)$$

The daily average mass-based GHG fluxes should be determined summarizing the  $E$  values of the entire pile divided by the biowaste input weight of the pile and the total composting days. The annual GHG emissions can be determined summarizing the cumulative gas emissions and the total weight of biowaste during a year of compost producing. The EF can be determined with the annual GHG emissions divided by the dry mass of biowaste.

The uncertainty can be determined by the standard deviation of the mean value from three replicates collected in each sampling event using Equation (13), considering  $A$  and  $B$  the standard deviation of the mean value from the three replicates sampled on day  $a$  and day  $a + t$  respectively;  $k$  as the “coverage factor” with value  $k = 2$  for confidence level of almost 95% [26].

$$Uncertainty = \sum \sqrt{\left(\frac{A}{2} * t\right)^2 + \left(\frac{B}{2} * t\right)^2} * k \quad (13)$$

As the air flux rate is affected by the environmental conditions variation this method requires the flow control and correction for changes in temperature and atmospheric pressure being its main limitation [24].

### 2.3.2. Funnel Method

The success funnel method developed by the consulting group Ramboll is used for surface GHG emissions measuring in triangular compost windrows [17]; its measuring instrument can be made of aluminum and resembles where an upside-down funnel covers usually  $1 m^2$  of a windrow and a vent pipe is attached to the top of the funnel [27].

Convection is an important factor in open compost windrows, as the air flows through the windrow and transports gases away from it into the atmosphere [17], given this fact  $EF$  from open compost windrows are difficult to determine considering that usually a small surface is covered and it works as a static chamber that does not allow to measure the gas emissions via convection; in order to overcome this limitation and to improve the accuracy of gas emission estimation, Phong proposed a funnel method covering almost  $50 m^2$  of area, adding forced ventilation from one side of the funnel [17]. With this modification  $EF$  for each gas using the following equations:

$$f_{funnel} = \frac{C_{gas} * v_{air} * A_{vent\_pipe}}{A_{funnel}} \quad (14)$$

$$E_r = \frac{E_{out} - E_{in}}{A_{funnel}} * Q_{funnel} \quad (15)$$

$$EF_d = \frac{E_r * 24}{1000} * \frac{A_w}{M_w} \quad (16)$$

$$EF = \sum EF_d * T \quad (17)$$

The determination of  $EF$  in  $g/Mg$  considers  $T$  as the composting duration in days;  $E_{fd}$  as the emission factor per day in  $g/Mg \cdot d$ ;  $A_w$  as the total surface of the windrow in  $m^2$ ;  $M_w$  as the total mass of the windrow in  $Mg$ ; 24 and 100 as the correction factors from hours to

days and from mg to g respectively;  $E_r$  as the emission rate in mg/h·m<sup>2</sup>;  $E_{in}$  and  $E_{out}$  as the concentrations of inlet and outlet in mg/m<sup>3</sup>;  $Q_{funnel}$  as the input air in m<sup>3</sup>/h;  $A_{funnel}$  as the surface under the tunnel in m<sup>2</sup>;  $C_{gas}$  as the gas concentration sampled from the chamber in vol/vol;  $v_{air}$  as the air flow velocity in the vent pipe in m/s; and  $A_{vent\_pipe}$  as the sectional area of the vent pipe in m<sup>2</sup>.

After GHG emissions calculation, the GHG reduction potential can be determined by the Equation (18), being  $E_{SWDS}$  and  $E_{composting\_process}$  the total emissions from biowaste in SWDS and in composting plants respectively in Gg of CO<sub>2</sub>-eq; and  $E_{reduction}$  the total gas reduction for the composting process in Gg of CO<sub>2</sub>-eq.

$$E_{reduction} = E_{SWDS} - E_{composting\_process} \quad (18)$$

### 3. Results and Discussion

The results presented in this section consider the 2006 IPCC methodology as conducive to more affordable characteristics; in addition, as there is not available country specific EF (Tier 2 and Tier 3), Tier 1 EF are used for SWDS category.

In the Bolivian context, MSW information is available since 2003, being the input parameters given by official statistics organization from Bolivia and some default values available in 2006 IPCC guidelines, values that are presented in the Table 3. The  $DDOC_{m\ decompT}$  for the period 2003 to 2019 is presented in the Figure 1, which shows the biowaste that is decomposed each year.

**Table 3.** Input parameters of solid waste disposal sites in Bolivia (self-elaboration).

| No | Parameter   | Symbol  | Unit     | Value | Remarks   |
|----|---|---------|----------|-------|---|
| 1  | Mass of the waste deposited in 2019                         | $W$     | Gg       | 1 601 | Official data of INE Bolivia [28]   |
| 2  | Degradable organic carbon                                   | $DOC$   | fraction | 0.11  | Considering 55.2% of organic waste and 8% of paper [29]                               |
| 3  | Fraction of DOC that can decompose                          | $DOC_f$ | fraction | 0.50  | IPCC default value [13]   |
| 4  | CH <sub>4</sub> correction factor for aerobic decomposition | $MCF$   | fraction | 0.82  | 70% are disposed in controlled sites and 30% are disposed in unmanaged sites <5 m [4] |
| 5  | Reaction constant   | $k$     | fraction | 0.23  | Considering 55.2% of organic waste and 8% of paper; and default values of IPCC [13]   |
| 6  | Fraction of CH <sub>4</sub> in generated landfill gas       | $F$     | fraction | 0.5   | IPCC default value [13]   |
| 7  | Total amount of CH <sub>4</sub> recovered in 2016           | $R_T$   | Gg       | 0     | There is no methane recovery in landfills [29]  |
| 8  | Oxidation factor  | $OX$    | fraction | 0     | IPCC default value [13]   |

The GHG estimated emission from SWDS for the year 2019 is 40.67 Gg of CH<sub>4</sub>, being that this value is in the range of the last Bolivian GHG inventory for the year 2008 (51.14 Gg of CH<sub>4</sub> calculation based on 1996 methodology) [30], the difference between these values can be related to the IPCC methodology use.

In Bolivia, pilot composting plants in some municipalities are processing biowaste since 2006 with 60% of efficiency, in other words, 0.4 tons of compost are produced per ton of biowaste [31]. The GHG emissions estimation from composting facilities is determined considering two scenarios: 50% and 20% of the biowaste collected during 2019 are composted respectively. As there is no experimental measured EF (Tier 2 or Tier 3) from the Bolivian composting plants, experimental EF from other sources are considered; additionally, IPCC default values (Tier 1) is take into account, these EF by method and the GHG emission from the composting process is given in the Table 4.

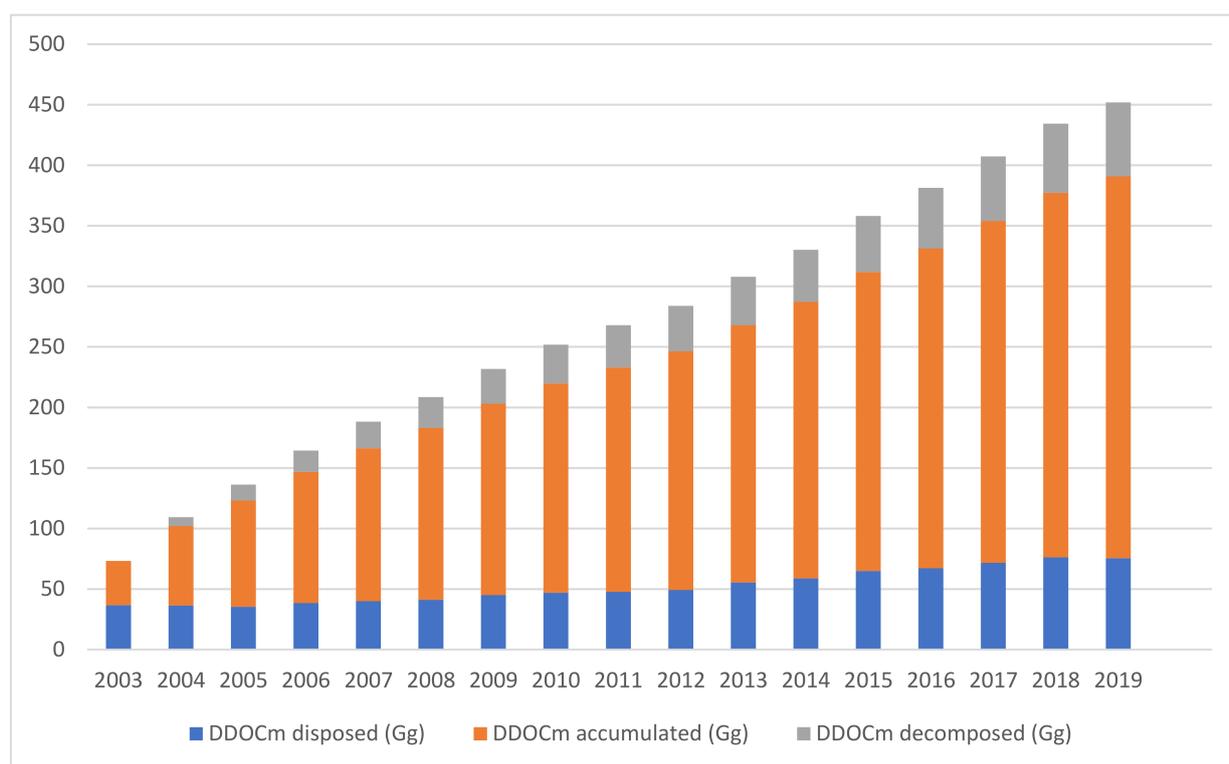


Figure 1. FOD method for solid waste disposal sites in Bolivia (self-elaboration).

Table 4. GHG emissions in open windrow composting plants of Bolivia (self-elaboration).

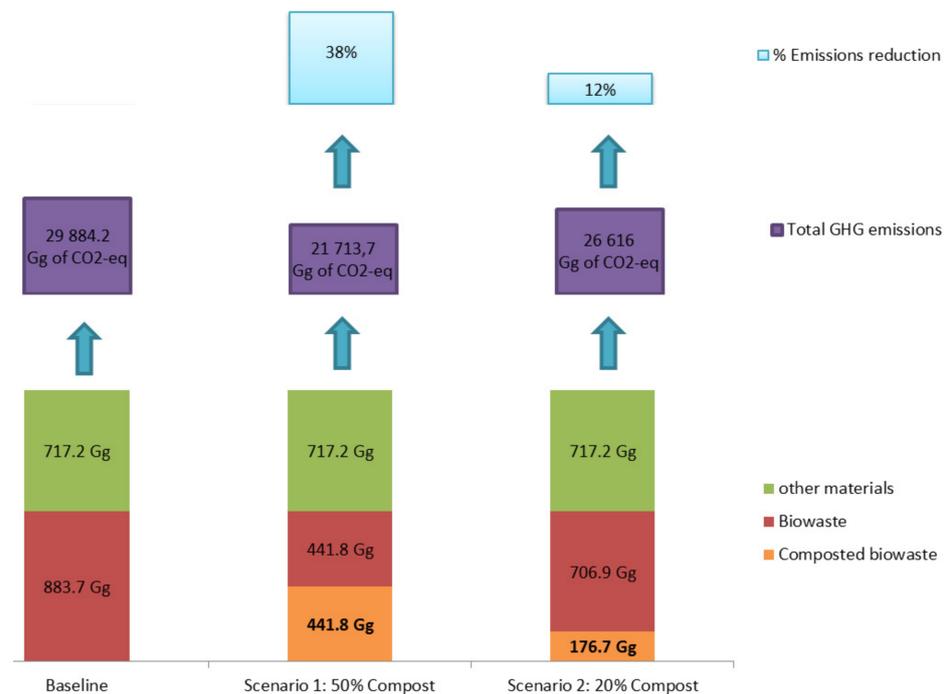
| No | Biowaste Treated in Composting Plants          | Weight Biowaste (Gg) | Method                                | CH <sub>4</sub> Emissions (Gg of CH <sub>4</sub> ) | N <sub>2</sub> O Emissions (Gg of N <sub>2</sub> O) | Total GHG Emissions (Gg of CO <sub>2</sub> -eq) |
|----|--|----------------------|---------------------------------------|--|---|---|
| 1  | 50% of the organic waste collected during 2019 | 441.86               | IPCC default values (Tier 1)          | 1.77   | 0.11  | 77.59   |
|    |  |                      | Flux chamber: Closed chamber (Tier 2) | 0.93   | 0.12  | 58.18   |
|    |  |                      | Funnel (Tier 2)                       | 0.90   | 0.01  | 28.34   |
| 2  | 20% of the organic waste collected during 2019 | 176.74               | IPCC default values (Tier 1)          | 0.71   | 0.04  | 31.04   |
|    |  |                      | Flux chamber: Closed chamber (Tier 2) | 0.37   | 0.05  | 23.27   |
|    |  |                      | Funnel (Tier 2)                       | 0.36   | 0.00  | 11.33   |

The determined emissions in open windrow composting facilities shows that the IPCC default values are overestimated as was found by different authors [17]. Another aspect to consider is that the decomposition of biowaste in SWDS takes almost 100 years according to the IPCC guidelines, in comparison, the composting plants reduce the organic content in months with low GHG emissions, and its residual product is beneficial as a fertilizer for agriculture activities.

In order to show the GHG emissions reduction by the implementation of composting plants in Bolivia as a MSW treatment facility, the Figure 2 shows that over a lifetime of 100 years, the 1601 Gg of waste deposited in SWDS in 2019 generates 1067 Gg of CH<sub>4</sub> or 29,884 Gg of CO<sub>2</sub>-eq in total. However, if the first scenario is considered there is a reduction of 38% of GHG emissions in total, and for the second scenario there is a reduction of 12% (considering Tier 1 EF).

As the results of GHG emissions reduction by composting facilities show, it reduces significantly the GHG emissions and the volume of biowaste that would be cumulated in SWDS. As in Bolivia the main disposal sites are open dumps [3] the benefits to access to biological treatment of biowaste are valuable since the climate change point of view, in

addition, its product properties as a fertilizer can be used for the agriculture activity that contributes around 15% of the national Gross Domestic Product (GDP) [32].



**Figure 2.** GHG emissions reduction by implementing composting facilities for MSW treatment (self-elaboration).

Finally, the main benefits of composting MSW are: the reduction of GHG emissions from the waste sector and the carbon footprint; as a fertilizer it can enrich the soil (compost helps to retain moisture and to suppress pests and plant diseases) promoting higher yields of agricultural crops (with the biodiversity increasing, reducing chemical fertilizer needs); the opportunity to get involved in humus (rich nutrient for plants) production; the potential reduction of leachate produced in SWDS, and the air quality improving (burning yard waste releases harmful chemicals into the air, producing diseases such as asthma); positive environmental and health impacts; and job opportunity creation as social and economic impacts.

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