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Estimation of emissions and modeling of the environmental behavior of greenhouse gases for a landfill.

Estimación de emisiones y modelización del comportamiento ambiental de los gases de efecto invernadero para un relleno sanitario.

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ABSTRACT

The study addressed the problem of greenhouse gas (GHG) emissions at the La Cortada Landfill (RSLC) in Pamplona, Norte de Santander. Since its creation in 2006, this landfill has received a significant amount of waste daily, contributing to the constant release of GHGs. The main objective was to estimate GHG emissions, understand their trajectories and model their dispersion in the environment. To achieve this, specialized tools such as LandGEM, Hysplit and Aermod were used, satellite images from the OLI sensor on board the Landsat 8 satellite were selected in periods between August and October from 2016 to 2020. An empirical methane estimation model was also applied. (estimated CH4), which relates land surface temperature (LST) to methane concentrations measured in the field between 2021-2023 (observed CH4). The results showed that measurements using satellite images gave lower values than those obtained in the field (0.007 mg/m3 per year, annual average of Estimated CH4) and (0.05 mg/m3 per year, annual average of observed CH4). In conclusion, The RSLC represented a significant source of GHGs, and this estimation approach based on satellite imagery and field measurements validated the importance of addressing these emissions to promote more sustainable solid waste disposal practices and protect air quality and regional well-being. , likewise allows arguing the implementation of biogas capture systems in the landfill to reduce methane (CH4) emissions, and the exploration so that this resource can be used as a source of renewable energy to produce heat or electricity, which would contribute to sustainability and emissions reduction.

Keywords:

Methane Emissions, Greenhouse Gases (GHG), LANDSAT, Environmental Mitigation, Environmental Modeling, Landfill, Gas Trajectories.

RESUMEN

El estudio abordó el problema de las emisiones de gases de efecto invernadero (GEI) en el Relleno Sanitario La Cortada (RSLC) de Pamplona, Norte de Santander, desde su creación en 2006, este vertedero ha recibido una cantidad significativa de residuos diariamente, contribuyendo a la liberación constante de GEI. El objetivo principal fue estimar las emisiones de GEI, comprender sus trayectorias y modelar su dispersión en el entorno. Para lograrlo, se utilizaron herramientas especializadas como LandGEM, Hysplit y Aermod, se seleccionaron imágenes satelitales del sensor OLI a bordo del satélite Landsat 8 en períodos entre agosto y octubre de los años 2016 al 2020. También se aplicó un modelo empírico de estimación de metano (CH4 estimado), que relaciona la temperatura superficial terrestre (LST) con las concentraciones de metano medidas en campo entre 2021-2023 (CH4 observado). Los resultados mostraron que las mediciones mediante imágenes satelitales arrojaron valores inferiores a las obtenidas en campo (0.007 mg/m3 por año, promedio anual de CH4 Estimado) y (0.05 mg/m3 por año, promedio anual de CH4 observado) .En conclusión, el RSLC representó una fuente significativa de GEI, y este enfoque de estimación basado en imágenes satelitales y mediciones en campo validó la importancia de abordar estas emisiones para promover prácticas más sostenibles en la disposición de residuos sólidos y proteger la calidad del aire y el bienestar regional, de igual forma permite argumentar la implementación de sistemas de captura de biogás en el relleno sanitario para reducir las emisiones de metano (CH4), y la exploración para que este recurso pueda utilizarse como fuente de energía renovable para producir calor o electricidad, lo que contribuiría a la sostenibilidad y la reducción de emisiones.

Palabras clave:

Emisión de Metano, Gases de Efecto Invernadero (GEI), LANDSAT, Mitigación Ambiental, Modelización Ambiental, Relleno Sanitario, Trayectorias de Gases.

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1. Introduction

Even though several internationally agreed efforts have been made to tackle climate change, some challenges remain and others, have become more intense. The phenomenon of global warming is on the rise, with the concentration of greenhouse gases (GHG) in the atmosphere escalating at a concerning pace. This poses a dual hazard, jeopardizing both the ecological equilibrium of our planet and the well-being, economics, and security of societies worldwide. Colombia collects and disposes of 26,975 tons of solid household waste in landfills every day. Bogotá is the city with the highest trash production, with approximately 6.3 tons on a daily basis, which is followed by the department of Antioquia, which produces 3,260 tons per day, Valle del Cauca with 3,072 tons per day, and Atlántico with 1,907 tons per day. As far as the emissions, the waste accounts for 6% of the target reduction of emissions by 20% in 2030 under the climate change framework [1], with a particular focus on methane, a gas known for its great heat-trapping ability in the atmosphere.

The production of these gases is influenced by variables such as the age of the waste and the specific weather conditions in the area [2].

The advancement of society and the successful resolution of global challenges heavily rely on scientific research and accumulated knowledge. In this regard, it is crucial to comprehend the connections among different components, elements, issues, and aspects pertaining to solid waste management, climate change mitigation, and environmental preservation. This proposed research aims to investigate these relationships and tackle crucial issues in these domains by conducting a comprehensive review of the state-of-the-art and original research.

The state-of-the-art offers a comprehensive summary of prior research that has tackled fundamental topics in these areas. Some noteworthy studies have been conducted by Colomer (2017) which compare different mathematical models used to estimate biogas production from the HASAR landfill in Jalisco, Mexico. The results obtained from these models were contrasted with the actual data collected between 2009 and 2011 regarding biogas generation. One of the models that was compared was LandGEM, whose conclusion was that LandGEM overestimates the generation of gases [3]. On the other hand, Vega (2019) [4] conducted an estimation of GHG emissions and their trajectories in large forest fires in Catalonia, Spain, which was also presented the estimation of GHG generated in these wildfires over the past 10 years in that region. Also, it was used the HYSPLIT program to determine the trajectories of smoke columns revealing that they were displaced over long distances.

Tello (2019) conducted a study on the assessment of methane gas emissions in landfills in Colombia. The authors also investigated the environmental strategies implemented on university campuses [2]. Additionally, Sanchez (2023) addressed the geotechnical characterization of the La Cortada Regional Landfill subsoil in Pamplona, Norte de Santander [6]. On the other hand, Sofan´s study (2022) focused on estimating energy derived from landfill biogas [7]. In addition, the study evaluates the potential methane gas production in the solid waste landfill of the Patate-Pelileo commonwealth in Ecuador [8]. Furthermore, Ballesteros (2021) developed a degree project for detecting hydrogen sulfide as a pollutant, and Vergara conducted a study on the impact of climate change in the sub-basin of the Chagres River in Panama [9] [10].

The significance of this review of the current state of knowledge hinges on the fact that these prior studies make a substantial contribution to comprehending environmental challenges and provide valuable insights that inform the advancement of our own research. Besides, Fundamental topics have been addressed such as the assessment of greenhouse gas emissions in landfills, the implementation of environmental strategies in educational institutions, the geotechnical analysis of the subsoil, the generation of energy from biogas, air quality in proximity to landfills, and the impact of climate change on river basins.

The significance of understanding these elements is in their immediate influence on environmental sustainability, solid waste management, and climate change mitigation. The results of these prior investigations emphasize the importance of successfully tackling these problems in order to foster sustainable development and enhance human welfare [17].

The main goal is to build upon the existing foundation of knowledge and gain a deeper understanding of the connections between various components, elements, issues, and aspects. Therefore, the objective is to assess emissions and simulate the environmental impact of greenhouse gases in a landfill, with the aim of aiding in the effective management of solid waste and the strategic planning of future landfill expansions or modifications. This research, which is backed up by robust and up-to-date research, is at the forefront of the fight against climate change and the promotion of sustainable practices in solid waste management [15].

Research on pollutant emissions from combustion systems and environmental restrictions has been growing in recent years, which has resulted in the creation of equipment that can run using fuels derived from both fossil and renewable sources. These fuel combinations effectively decrease carbon dioxide emissions (which is considered a trigger for greenhouse gas), in the atmosphere due to the inclusion of hydrogen (H2) and synthesis gas [18].

2. Methods and Materials

The La Cortada Regional Landfill is located in the Chichira rural district, northeast of the Pamplona-Chitagá highway. Its geographical coordinates fall within the range of North 1,307,000 and 1,308,000, and East 1,159,000 and 1,160,000 and it has an average altitude of 2,375 meters above sea level (masl) (Sánchez et al., 2020).

Figure 1. Location of Study Area

According to Decree 1784 of 2017 [11], It is classified as category I, and it is crucial for solid waste management in several localities and municipalities, providing benefits to about 114,000 residents. It is anticipated to remain in operation until 2034, which turns it into a significant spot for assessing greenhouse gas (GHG) emissions.

The strategic positioning of the landfill is influenced by the specific weather conditions in the area, including temperature, humidity, precipitation, and sunshine hours, which have a direct impact on temperature and cloud cover, which are also crucial for the processing of satellite images. Hence, the months from August to October were selected as an opportune timeframe for conducting the study.

Even though the local solar day is affected by various significant factors during the daytime, the one thing that makes the difference is its location in a valley surrounded by mountains. In such a scenario, the solar radiation does not reach that point until after the initial minimum tilt angle, and then the radiation is obscured. This situation is expected to occur in the study area due to its geographical position [19].

A Garmin 64s GPS device with an accuracy of +/- 12 feet (+/- 4 meters) [16] was utilized to collect geo-referenced data that was rectified and superimposed using Magna Sirgas V 5.1 software to define the study region onto satellite images. Furthermore, a KML-formatted file was utilized, derived from the topographic plan accessible at the landfill's entrance.

For the modeling of greenhouse gas (GHG) trajectories and concentrations, homologous periods per year and dispersion approach were utilized to establish precise correlations between GHG concentration and the trajectory and dispersion of pollutants originating from La Cortada Landfill.

It is worth mentioning that the initial results, both from in situ observations and satellite images, were given in parts per million (ppm), which were converted to grams per cubic meter (g/m^3), for further consistency and practicality in this research.

2.1. Experimental Methodology and Statistical Analysis

The project aims to analyze the emissions, trajectories, and environmental impact of Greenhouse Gases (GHG) originating from the La Cortada landfill in Pamplona, Norte de Santander, Colombia.

To tackle this issue comprehensively, three internationally known models will be employed: LandGEM, Hysplit, and LANDSAT-8 for image processing and analysis. The methodology is arranged into four essential steps.

During the initial phase, our focus will be on characterizing the landfill in order to gain a comprehensive understanding of its unique features and functioning. In the subsequent stage, greenhouse gas (GHG) emissions will be estimated, with a specific emphasis on methane gas (CH4). This estimation will take into account factors such as waste composition and age, aligning with previous research conducted by Tello et al. (2019) on landfills, which will allow for the establishment of a baseline for our research.

The modeling of greenhouse gas (GHG) trajectories will be conducted in the third stage. The Hysplit model will be utilized to assess the dispersion and transportation of the generated pollutants, considering the local meteorological conditions and based on previous studies conducted in relevant research locations [5][9].

Lastly, the fourth phase will focus on the processing and analysis of LANDSAT-8 images. On this stage, the correlation will be assessed between environmental factors, such as surface temperature, and soil cover, and greenhouse gas (GHG levels in the study area, aligned with Vergara's methodology the integration of these models and approaches will provide a comprehensive understanding of GHG emissions and behavior at La Cortada landfill, which will contribute to effective solid waste management and offer valuable insights for future planning and modifications at the site [6].

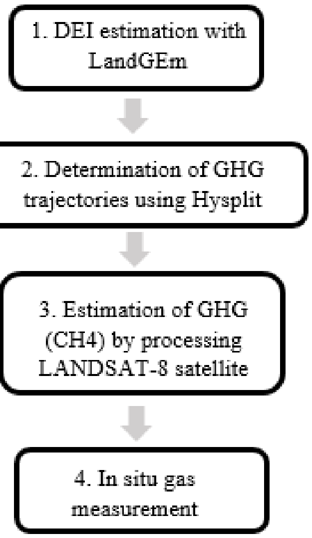


Figure 2. Methodology Stages

The analysis of Greenhouse Gas (GHG) trajectories and concentrations at the landfill will focus on a two-year period, specifically from August 21, 2019 to August 21, 2021, which will allow us to capture the temporal and seasonal fluctuations in GHG trajectories. Four times a day (00:00, 06:00, 12:00, and 18:00), trajectories will be assessed using a 6-hour analysis to account for daily fluctuations in both daytime and nighttime, as well as changing weather conditions that impact the spread of pollutants. This evaluation will specifically focus on methane (CH4) as the primary greenhouse gas (GHG) due to its compressibility and factors that can be measured using LANDSAT-7 and LANDSAT-8 imagery.

The study will employ the Avdan and Jovanovska (2016) methodology to establish a relationship between Land Surface Temperature (LST) and methane concentration to enable a better understanding of the environmental factors that impact the dispersion of greenhouse gases (GHGs) in the study area. Mathematical Modeling for calculating LST.

Table 1. Mathematical Modeling for calculating LST.

Factor	Mathematical Model Proposed	Development for GIS
TOA (Top of Atmospheric) radiancia espectral	$L\lambda = M_L * Q_{cal} + A_L - O_i$	TOA =0.0003342 * "Band 10" + 0.
BT Brightness Temperature	$BT = \frac{K_2}{\ln[(K_1/L\lambda)+1]} - 273.15$	BT =(1321.0789/Ln ((774.8853/"%TOA) +1) 273.15
Normal Difference Vegetation Index (NDVI)	$NDVI = \frac{NIR\,(band\,5) - R\,(band\,4)}{NIR\,(band\,5) + R\,(band\,4)}$,	NDVI =(Banda 5–Band 4)/(Band 5+Band 4)
Proportion of Vegetation (Pv)	$P_v = \left(\frac{NDVI - NDVI_s}{NDVI_v - NDVI_s}\right)^2$	Pv= Square ((NDVI – NDVImin) / (NDVImax– NDVImin))
Land Surface Emissivity (Ɛ)	$\varepsilon_\lambda = \varepsilon_{v\lambda}P_v + \varepsilon_{s\lambda}(1-P_v) + C_\lambda$,	ε = 0.004 *Pv+ 0.986
Land Surface Temperature (LST)	$T_s = \frac{BT}{\{1+[(\lambda BT/\rho)\ln\varepsilon_\lambda]\}}$,	LST = (BT / (1+(0.00115 *BT / 1.4388) *Ln(ε)))

Note. Taken and modified from [14].

Table 2 provides the necessary changes for the creation of the mathematical modeling based on the implementation of an empirical model in CH4 estimation, as proposed by Cortez (2013) and Agarwal and Garg (2009):

Table 2. Mathematical Modeling for CH4 Emission Analysis.

Factor	Mathematical Model Proposed	Development for GIS
Ft, temperature factor	$F(Ts) = \frac{e^{0.334(TLS-23)}}{1 + e^{0.334(TLS-23)}}$	(Power(2.71828182845,0.334* ("LST.TIF" -23))) /(1 + Power(2.71828182845,0.334 * ("LST.TIF" -23)))
E_{CH4} Methane estimation	$E_{CH4} = E_{obs} * Ft * A$	Ft * 0.0093

Note. Taken and modified from [12] [13].

The gases emitted from the La Cortada landfill were gauged using the Industrial Scientific Ibrid MX6 Gas Multidetector, a cutting-edge instrument that adheres to rules and ensures precise and dependable measurements, hence improving the trustworthiness of the findings.

3. Results

3.1. Estimating GHG emissions using LandGEM

The study's findings indicate that the La Cortada landfill releases a substantial quantity of Greenhouse Gases (GHG), particularly methane (CH4) and carbon dioxide (CO2) emissions. These emissions are not consistent, but instead fluctuate over time and are influenced by several factors that affect their intensity, among these factors are the type of trash being put in the landfill, the local weather conditions, and the waste management methods utilized at the site.

The analysis indicated that there will be a noteworthy increase in greenhouse gas (GHG) emissions around the year 2035, reaching considerable levels. More precisely, the predicted annual carbon dioxide (CO2) emissions are expected to be approximately 6x105 cubic meters, while methane (CH4) emissions could reach roughly 1.20x106 cubic meters per year.

The values provided indicate the importance of tackling GHG management at La Cortada landfill in order to reduce its impact and promote more sustainable environmental practices in solid waste disposal. Figure 2 displays the outcomes of the LanGEM estimations.

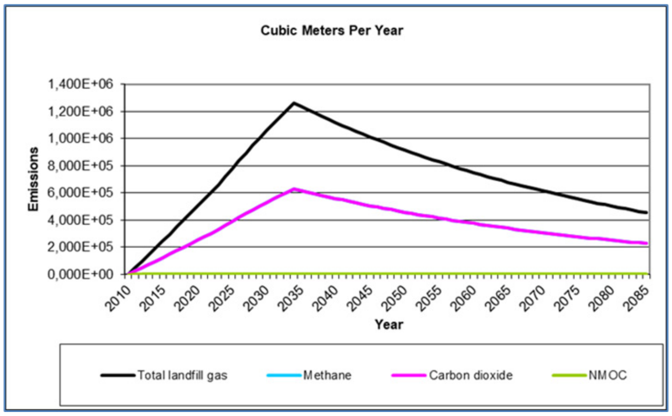


Figure 3. Outcomes of the LanGEM estimations.

Using trajectory modeling, data was collected in August of 2019, 2020, and 2021 at 50 meters elevation, with measurements taken four times a day. This data yielded important insights on the pollutants spreading from the La Cortada Landfill. The project's Geographic Information System (GIS) effectively incorporated the graphical output, which offers a comprehensive geospatial depiction of contaminants, encompassing their concentrations and trajectories.

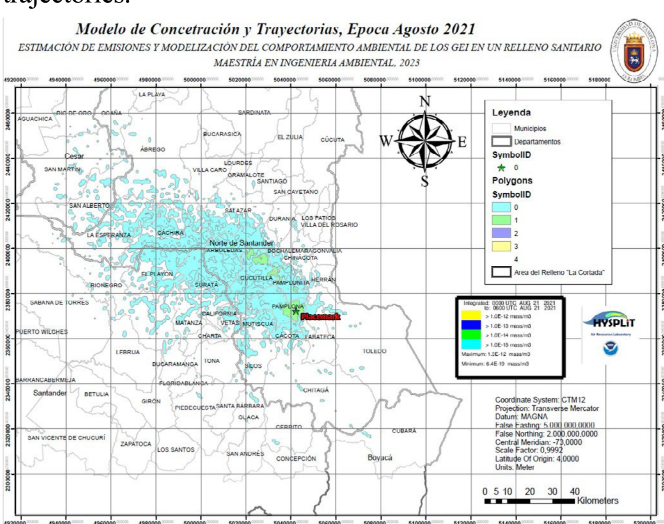


Figure 4. Graphical output of Concentrations and Trajectories Pollutants

The primary trajectories indicate a northwestern (NW) direction, with the main impact being on Pamplona. Additional municipalities such as Pamplonita, Cucutilla, Chinácota, Bochalema, and Arboledas also exhibit indications of pollutants, albeit with lower levels. These findings emphasize the significance of comprehending the dynamics of pollutants and the necessity of controlling and reducing greenhouse gas emissions to safeguard air quality and the well-being of the region.

3.2. Estimating methane levels using the analysis of LANDSAT satellite imagery.

The study utilizes the Land Surface Temperature (LST) method proposed by [10], which offers an effective algorithm for automated mapping of land surface temperature. This method relies on data from the LANDSAT-8 satellite and is crucial for accurately analyzing environmental conditions and obtaining dependable estimates of methane emissions.

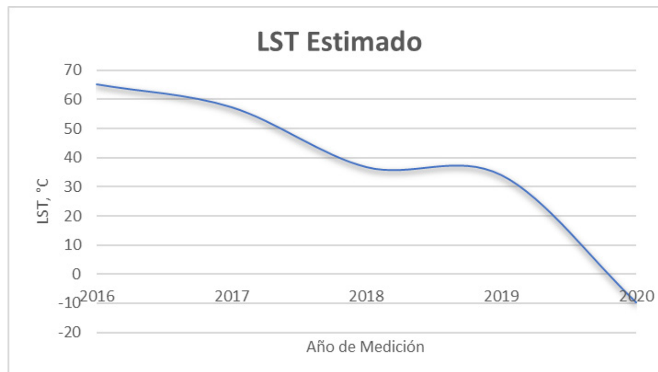


Figure 5. outcomes of LST calculations.

Figure 3 displays the average of Land Surface Temperature (LST) calculated for the time span between 2016 and 2020, covering a wide range of temperatures from 70°C to -10°C. It is crucial to acknowledge that the surface temperature, often known as LST, is distinct from the ambient temperature.

Through the conducted procedure, a map is generated that accurately represents the land surface temperature, which should be differentiated from the surrounding temperature.

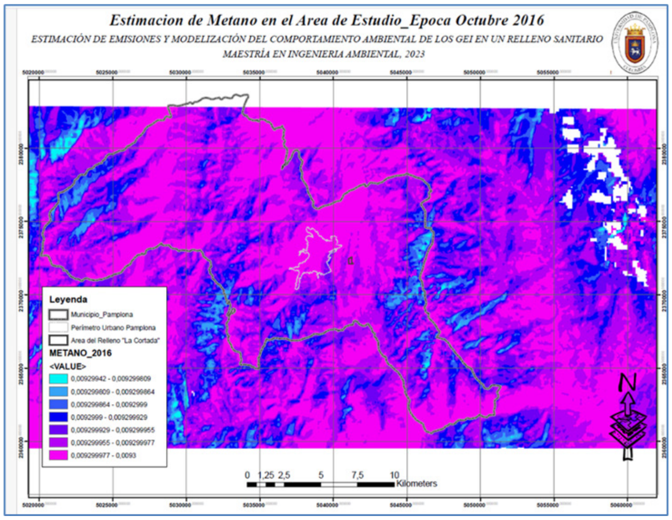


Figure 6. CH4 Estimation Map.

The analysis and processing of LANDSAT8 imagery from 2021 to 2023 allowed for the estimation of methane emissions at various times when in situ methane measurements were conducted using the Multidetector Equipment.

The findings of the LANDSAT-8 image processing for methane estimation in October 2016 are shown in Figure 5. As the interpretation indicates, the measurements in the research region have a maximum value of 0.093.

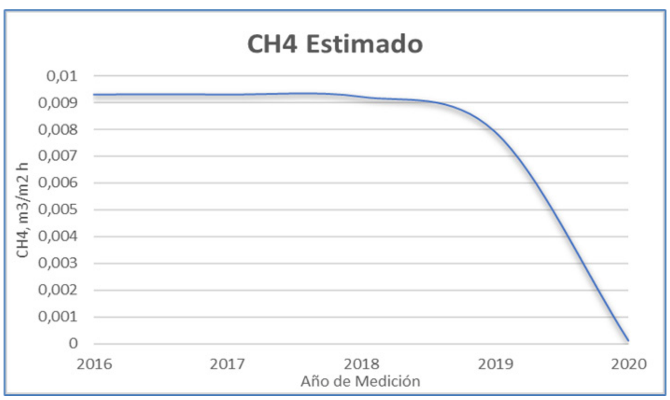


Figure 7. Analysis of estimated CH4 using LANDSAT-8

As shown in Figure 6, the methane (CH4) emissions were estimated using satellite images from Landsat 8 (ETM+) sensors from 2016 to 2020. These estimates were then compared to in situ measurements conducted at La Cortada Landfill.

It is essential to acknowledge that while the LANDSAT-8 estimate is a historical measurement, the in situ measurements were conducted at various time points (from 2021 to 2023). This comparison aimed to establish a benchmark for methane levels using different measurement methods. It is worth noting that the satellite images indicate lower values compared to the measurements taken in the field.

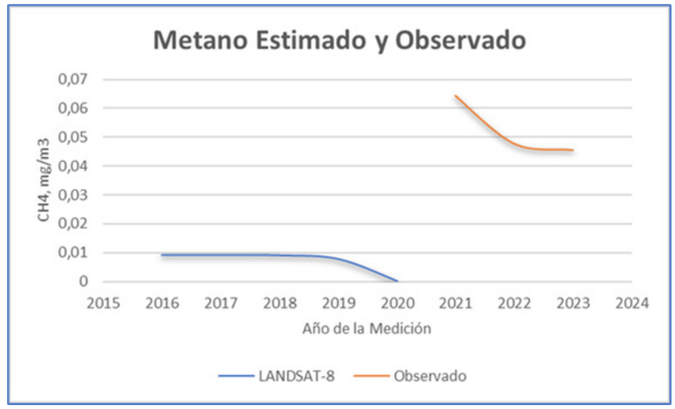


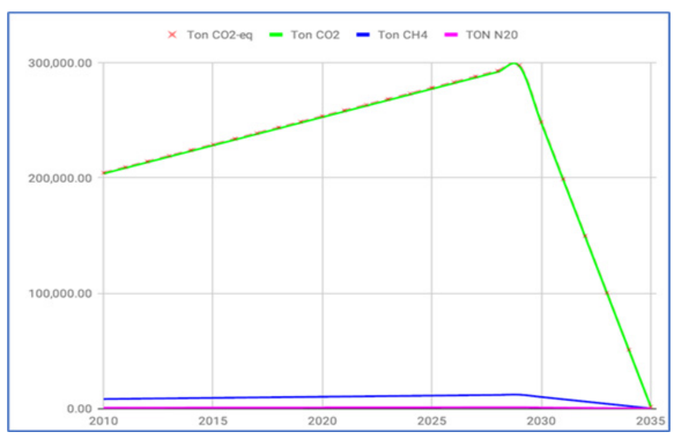
Figure 8. Observed Methane and Estimated Methane.

As previously stated, measurements derived from satellite photography display lower values compared to measurements taken in the field. The diagram depicts the estimated trends in methane concentration from 2016 to 2020 (estimated methane) in comparison to the observed values from 2021 to 2023 (observed methane).

3.3 Landfill Emission Inventory Calculator

As part of this research, a comprehensive computational tool has been produced as free software, in alignment with the set objectives. This tool comprises an emission inventory calculator tailored for landfills and it is hosted on a Google microsite, offering not only access to the calculator but also comprehensive information on the methodology employed, supported by robust theoretical foundations. In addition, the tool is seamlessly integrated with a mobile application (APK), enhancing accessibility to the calculator and providing a concise introduction to the author.

The objective of this tool's development and distribution strategy is to enhance its accessibility and utility by allowing anyone to use it through their mobile devices, which will facilitate wider dissemination and more practical utilization of the landfill emission inventory calculator.



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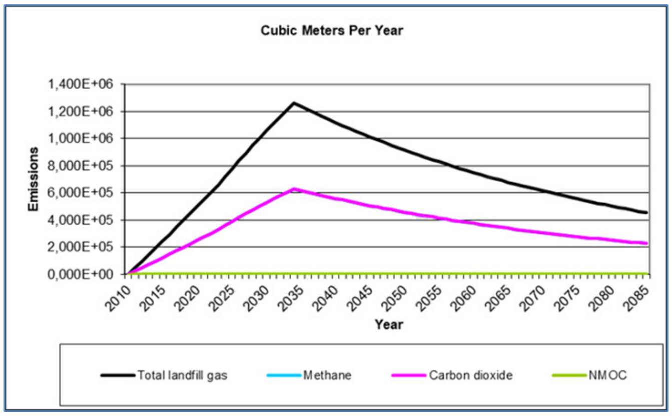

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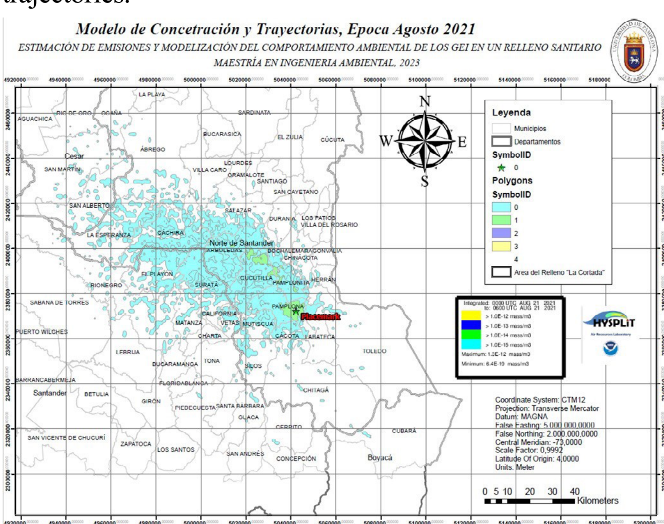

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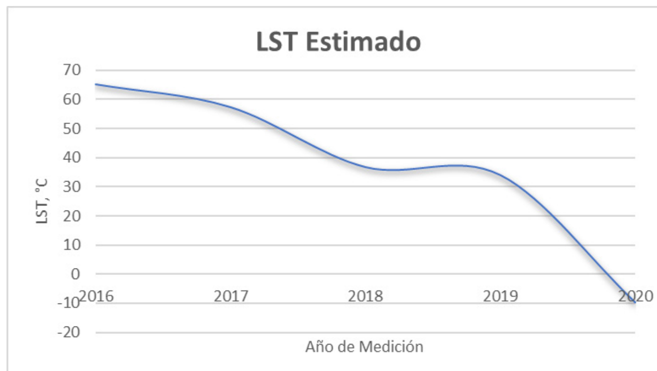

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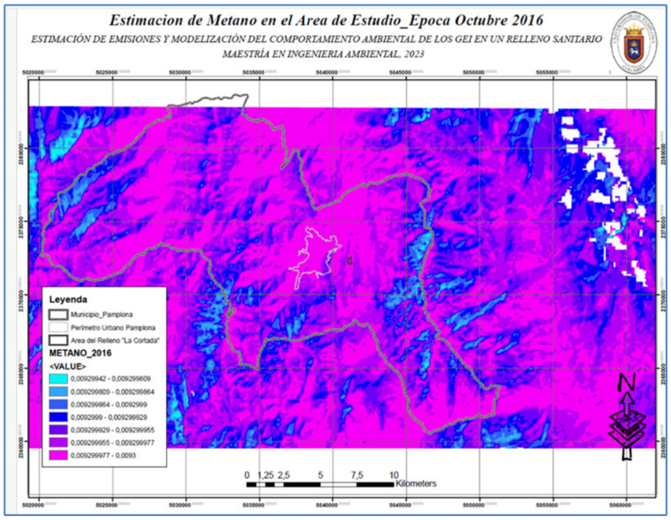

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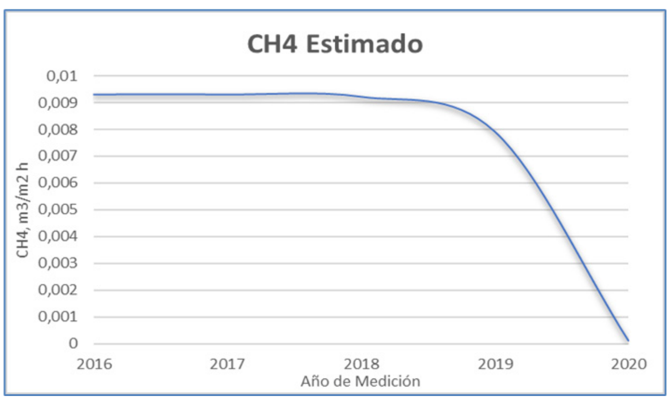

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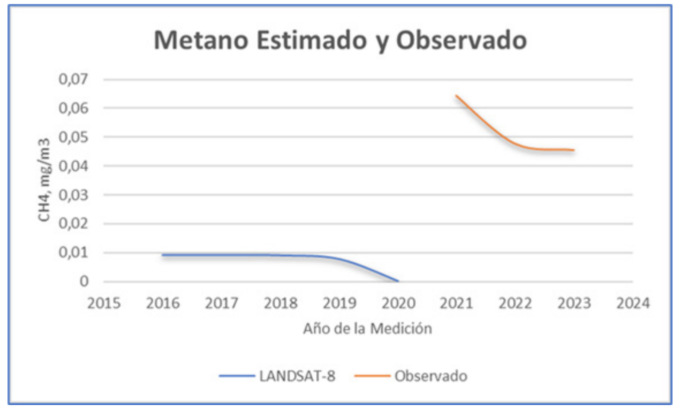

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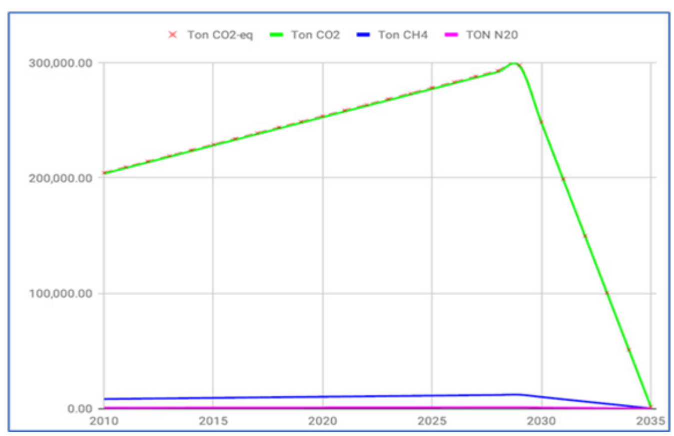

Figure 9. Landfill emission inventory calculator.

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