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Modeling and optimization of controlled landfill gas performance using LandGEM

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Abstract Modeling with LandGEM offers a large field to quantify emissions from the decomposition of organic waste, consequently prediction of energy generated from gas emissions especially those of methane. Where, the simulation results makes it possible to define the reasons of malfunction concluded by comparing between the LandGEM simulation and the experimental methodology for estimation of methane gas emissions, whose offer a huge knowing, accuracy assessment, and detailed analysis to landfill site state in terms of the production of methane, the tightness, the progress of the anaerobic degradation, the existence of sulfur compound. This study accomplished in site the methane production at 80%, a tightness of 84% compared to the 100% given by LandGEM, and an hydrogen sulfide content which far exceed the recommended limit, cause of corrosion attacking especially the biogas compressor which provoke a complete shutdown to product the electrical energy. Unlike the LandGEM digital model, whose site must produce $3,145.10^7$ m^3 of methane with 100% site tightness, a hydrogen sulfide content equivalent to 40 ppm, for a production of electrical energy equivalent to $10,941.10^7$ kWh according to the year 2022. To optimizing landfill gas performance, we forecast the installation of automatic analyzer sensors to anticipate of an alert for intervention, generated by accidental loss of methane in the air, infiltration of oxygen inside the lockers, disruption of the stability of the fermentation process, or existence of high sulfur contents in organic matter.

Keywords LandGEM Model, Biogas, Optimization, Methane, Electrical Energy, Controlled Landfill Site

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1. Introduction

Currently, the creation of controlled landfills constitutes one of the very effective solutions to develop a waste resource which represents the major material to progress the anaerobic digestion reaction [1], it is a modern system designed to collect biogas generated from biomass or organic waste buried in the landfill waste cells [2].

landfill gas or Biogas is extracted from landfill sites using a series of collectors which direct the collected gases to a central point where they are transformed and treated to be flared, used to produce electricity, replace fossil fuels in industrial sector and manufacturing activities or be used directly in place of alternative vehicle fuel [3], in addition, it is a new concept whose the production of the electrical energy is carried out with reduced operating costs [4].

Biogas, being the product of the methanation reaction, contains high levels of toxic pollutants, mainly methane (CH_4), carbon dioxide (CO_2), and hydrogen sulfide (H_2S), which cause respiratory illnesses and contribute to climate change by their nature as greenhouse gases if they are exposed to ambient air [5]. This is why technical landfill centers accompanied by treatment and energy recovery units have the double advantage of simultaneously being a green and clean renewable energy production sector, via biogas like a source of green energy and alternative

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to replace fossil fuel as natural gas, coal and oil, and a solution to mitigate the risks of global warming linked to greenhouse gas emissions [6], whose the major preoccupation of lot of countries to adopt a new approaches to develop a proper energy, and to improve practices for emission reduction [7].

The performance of biogas produced from biological degradation extends to its composition in methane, oxygen, carbon dioxide and hydrogen sulfide to be valorized in terms of energy [8]. This phenomenon is presumed in four biochemical reactions to be had: hydrolysis, acidogenesis, acetogenesis and methanogenesis [9].Scientific research and technical optimization in the biomass field in general, and anaerobic digestion reaction in particular, are time consuming relatively due to the long processing period [10]. Theoretical model is one of the prediction methods, using Boyle methodology, ultimate analysis, and calculation from the reaction of the decomposition of a generic compound organic composed to calculate the theoretical methane volume generated [11]. Nevertheless, this method consist to repeat analyzes of the organic load to adjust the prediction to the real conditions of landfill site [12].Today, several research studies favor numerical modeling as being the most suitable and which describes the reaction phenomenon of methanation or production of biogas (70% of methane) by anaerobic digestion with more precision [13]. Generally the production of biogas can be modeled according to a zero-order equation, of the first or second order [14, 15]. However, the data obtained during experimental observations in the laboratory and on site recommends that the order kinetics of decomposition organic matter is similar to the first-order [15]. Among the first-order models most popular in scientific literature we find the Intergovernmental panel on climate change model (IPCC) and Landfill gas emissions model (LandGEM), the latter is developed by the United States Environmental Protection Agency (USEPA) constitutes the fastest and precise compared to other models [15]. This numerical model is adopted to predict a biogas production and these components, and to design and modeling of energy recovery units [16].

In Morocco, organic materials represent 70% of the total weight of waste, a strategic area for the extraction of biogas, which the Fez city, our case study constitutes the most responsive controlled landfill in terms of energy recovery from biomass fermentable, however over the last five years of operation there have been shutdowns of bioelectric units without knowledge of the cause [17, 18].

In this work, we will study the composition of biogas obtained experimentally from the field by taking samples to carry out an overall evaluation of landfill gas, its circuit, its withdrawal and distribution network to other energy recovery units. Research to reconcile the experimental results and the LandGEM digital model will be carried out to identify the reasons of dysfunctional of the technical landfill recovery units and to propose the most appropriate solutions for our study case.

2. Materials and methods

2.1. Experimental methodology and assessment of the landfill site

The landfill site subject to study is located in a basin on an 80 m layer of clay which helps prevent the infiltration of biogas and leachate into the water table; it is protected by water drainage network rainwater of 4 km around the landfill [19]. The surface area of the site is 110 hectares, the capacity is more than 1000 tons of waste per day, and a lifespan of 30 years which extends from 2004 to 2034 [20].

The construction of the site as mentioned in Fig. 1 including access roads, rainwater collection and evacuation works, biogas collection and treatment works, lockers and collection and treatment works leachate, in addition to the bioelectric station shut down for more than 5 years, the biogas withdrawal stations, and the flares to burn excess biogas and minimize greenhouse gas emissions [20]. The methodology used for the experimentation is the estimation of methane gas emissions from landfill site and quantify the energy potential [21]. This method re-quires that the assessment of the landfill site targeted two major areas, the first being the tonnage of waste at the entrance to the site, the weight measurements of municipal solid waste in particular were carried out every day throughout 2022, and the second being the landfill lockers where the 25 well heads are located connected to the main biogas collector, the measurements of the concentrations of the biogas components were taken every month of the year 2022 using of the biogas analyzer apparatus.

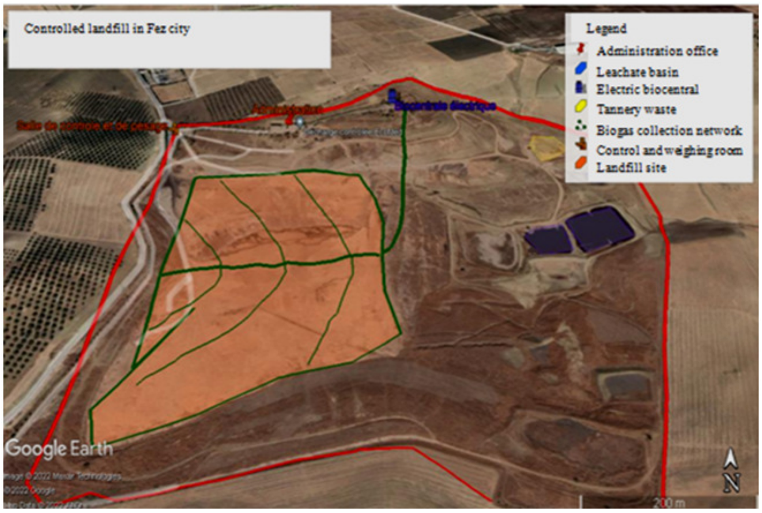

Figure 1. Location and construction of the controlled landfill in Fez city by Google Earth.

Item	Value Biogas Components			
	CH_4	O_2	H_2S	CO_2
Measurement range	0–100%	0–25%	0–9999ppm	0–100%
Precision	$\pm 2\%$	$\pm 4\%$	$\pm 4\%$	$\pm 2\%$
Speed (Response time T90 in seconds)	≤ 10	≤ 20	≤ 30	≤ 10
Resolution	$0,01\%$	$0,01\%$	1ppm	$0,01\%$

Table 1. Technical characteristics of the biogas analyzer type GAS 3000 [21].

The biogas analyzer type GAS 3000 used for monthly measurements of biogas components namely oxygen, methane, carbon dioxide and hydrogen sulfide is characterized according to the technical specifications indicated in Table 1.

2.2. Numerical Model by LandGEM

This model uses kinetics described in a first order equation, That include critical factors like Lo a potential methane generation capacity in m^3/Mg unit, and k a first order methane generation rate according to year–1 as mentioned in equation (1) [16, 22].

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_o \, [\frac{M_i}{10}] e^{-kt_{ij}}$$

Whose, the annual methane generation symbol is Q_{CH_4} in m^3/year measure unit, the n symbolizes the year of the calculation minus the initial year of waste acceptance, j shows the 0.1–year time increment, i shows the yearly time increment, t_{ij} symbolizes the age of the j^{th} section of waste mass M_i buried in the i^{th} year in decimal years measure unit, M_i indicates weight of waste accepted in the i^{th} year in Mg measure unit [16, 22]. To calculate the production of methane and other components of biogas from the LandGEM numerical model, we have to introduce input parameters of yearly municipal solid waste tonnages, the year of opening and closing, and previous years as mentioned in the Fig.2. From the LandGEM tool guide, the input parameters L_o, 'k', NMOC concentration, and methane content are taken by default as indicated in the Fig.2 [23]:

From the quantity of methane generated in the sanitary landfill, the electricity production can be calculated using equation (2), which offers two possibilities, namely, an estimate of the quantity of electricity that can be produced

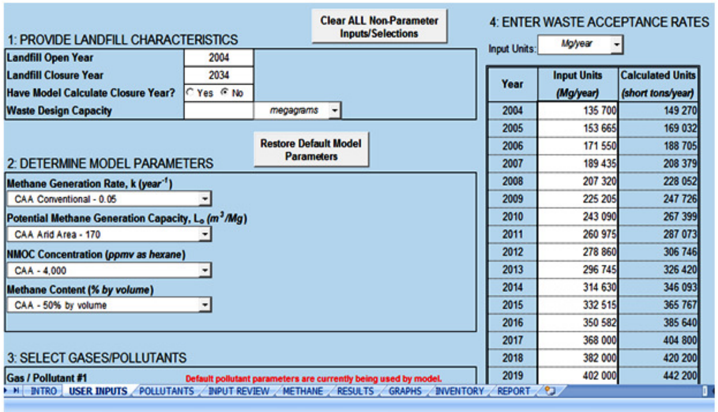

Figure 2. Interface Input parameters of LandGEM model Version 3.02.

from field data (experiment), and a prediction using the LandGEM digital model [24].

$$P_e = P_t \ \times r \ \times \eta_e$$

Where, P_e denotes annual production of electricity in (kWh/year), r symbolizes calculation of volume methane quantity in the year of the study in m^3/year measure unit estimated by the experiment or predicted by LandGEM numerical model, η_e symbolizes the electrical system efficiency, whose the value recommended be-tween 30% and 40%, and P_t is a lower calorific value of methane from controlled landfill site equivalent to 9,94kWh/m^3 [19, 24].

3. Results, discussions and validation

3.1. Results and discussions

In this field of activity, the experimental measurements of methane, oxygen, carbon dioxide and hydrogen sulfide, offer a large knowing and analyzing landfill site state in terms of the production of methane, the tightness, the stability of the progress of the anaerobic degradation process, and the existence of sulfur compound, to search a future improvement to optimize the performance of the biogas landfill site in terms of methane quantities and quality, in addition to electrical energy generated.

From where, monthly experimental measurements of biogas components using the biogas analyzer type GAS 3000 are presented in the following results. The objective is to compare the experimental results with those of LandGEM numerical modeling. According to the evaluation of the results and the representation Fig.3, we note that 84% of landfill areas generate methane whose percentage is between $50\%\pm2\%$ and $70\%\pm2\%$ indicated by blue and orange colors. While the remaining 16% of landfill areas produce biogas whose methane levels are within a range of $20\%\pm2\%$, and $50\%\pm2\%$ shown by the small areas of green, dark blue and purple colors.

The calculation carried out by the LandGEM model shows, as mentioned in Fig.4, that the landfill site under study must produce a quantity of methane of $3,145.10^7\ m^3$ corresponding to the year 2022. While the average quantity of methane produced according to experimental field calculations based on the average biogas flow rates and the corresponding methane contents reaches a value of $2,508.10^7\ m^3$ relating to the year 2022. This implies a difference of $6,37.10^7\ m^3$ corresponding to the year 2022 between the numerical model and the experiment.

This difference could be explained by the fact that the site has certainly suffered air infiltration in some landfill areas, hence the inhibition of the production of methane in the presence of oxygen. Thus, the generation of methane given by LandGEM reaches a greater value than that achieved by the experiment because the numerical model uses ideal conditions concerning the sealing of the landfill site.

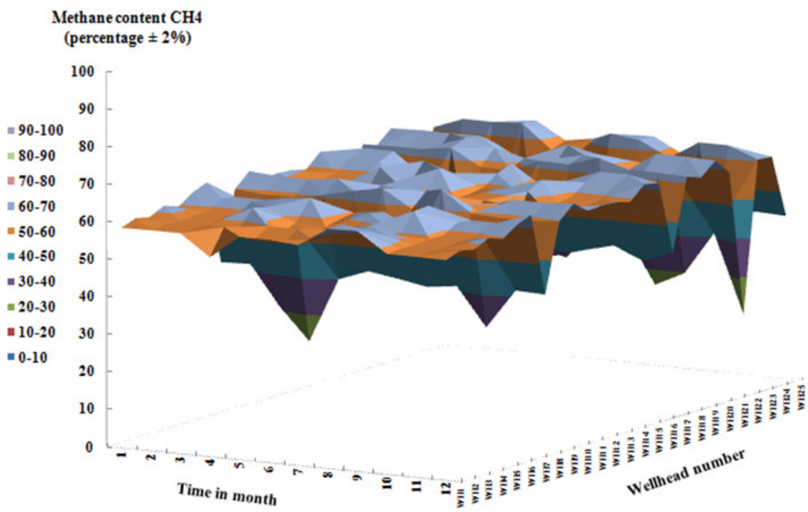

Figure 3. Three-dimensional representation profile of the methane content evolution during the year 2022 according to wellheads zone areas.

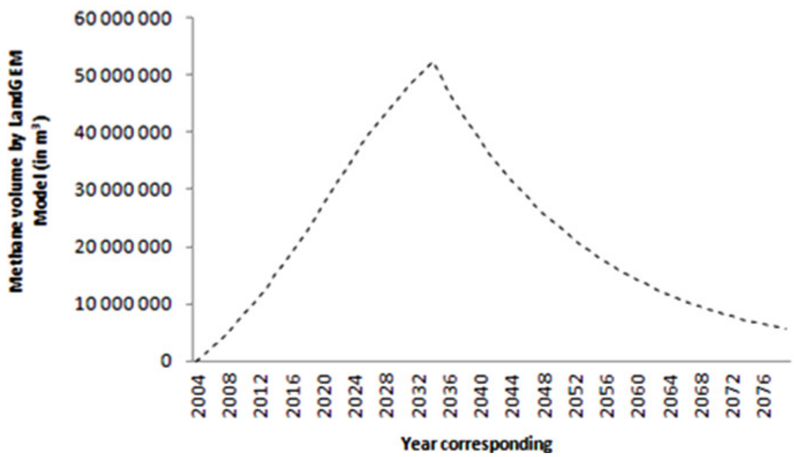

Figure 4. Preview results of methane evolution volume predicted by LandGEM Model in m^3 according to the year corresponding.

Generally, methanization is a reaction whose the absence of oxygen is required for the progress of the reaction process, where the methane produced represents between 50% and 70% of the biogas according to scientific literature [19, 25].

To confirm this, we used oxygen content measurements taken experimentally on site using the biogas analyzer at the same time as the other components, from where the results as shown in Fig.5. We note from the calculations and the representation Fig.5, that 84% of the landfill zones grouped around the wellheads were perfectly sealed against infiltration of areas whose oxygen percentage is between 0,2$\pm 4\%$ and 0,4$\pm 4\%$ indicated in dark blue color. While the remaining 16% of the landfill areas were marked by the presence of oxygen in the landfill bins where the contents indicated values between 10$\pm 4\%$ and 30$\pm 4\%$, mentioned by the green and dark red color areas. According to the above results, it was demonstrated that 84% of the areas of the landfill site studied offer a quality of methane which obeys the standards of the scientific literature, and a quantity of methane which presents 80% of the value calculated by the LandGEM numerical model.

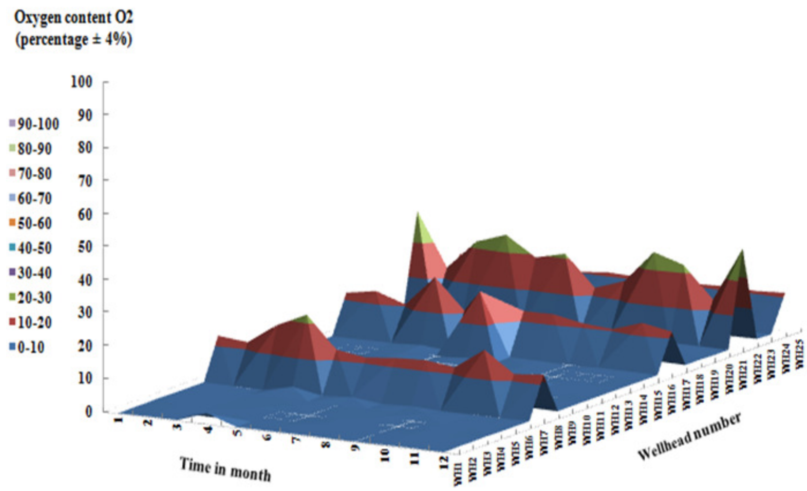

Figure 5. Three-dimensional representation profile of the oxygen content evolution during the year 2022 according to wellheads zone areas.

However, to optimize methane performance, the landfill site must comply with sealing rules to promote anerobic digestion conditions without the presence of oxygen by air infiltration. To achieve this, automatic analyzer sensors must be attached with the wellheads to send signals directly to the control room indicating an intervention alert to stop propagation at the moment, in the event of loss of CH_4 in the air or infiltration of O_2 inside the lockers, the optimal will be to check after each repair and compare the site values with the LandGEM model.

Among the modulator parameters of the landfill gas we find the ratio CH_4/CO_2, the results found from the on-site experimental analyzes and those of the LandGEM numerical model are represented by Fig.6. This ratio is an indicator of stability and progress of the fermentation process within the landfill site, whose the ratio CH_4/CO_2 must be equivalent to the value (≤ 2) [26].

After viewing the results above Fig. 6, we conclude that the landfill site subject to our study presents stability with respect to the progression of the fermentation process, it also obeys calculated value by the LandGEM numerical model, and the ratio threshold indicated by the scientific literature.

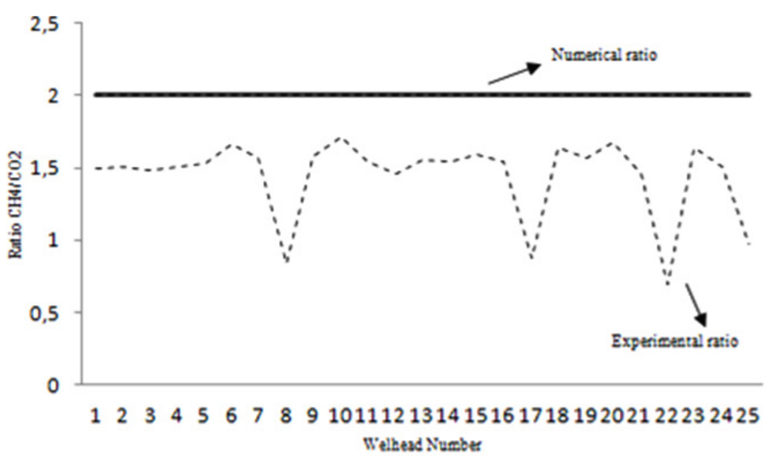

Figure 6. Representation of the numerical calculate ratio by LandGEM Model and experimental ratio content CH_4/CO_2 during the year 2022 .

In addition to the components CH_4, CO_2 and O_2, H_2S constitutes the component that causes corrosion for most metallic equipment such as pipelines, turbines, compressors, motors and other units, in addition to mechanical wear drastically increasing maintenance costs, and posing safety preoccupations and health problems at work by its dangerous characteristics as flammable, colorless, and extremely harmful, in addition, the recommended limit value according by the scientific literature being 1000 ppm [27, 28, 29].

By visualizing the Fig. 7, the H_2S contents evolution during the year 2022 are be-tween 1370($\pm 4\%$) ppm and 8200($\pm 4\%$) ppm, values which largely exceed the recommended limit, and which demonstrates that the biogas contains quantities of H_2S capable of creating repetitive shutdowns for maintenance and corrosion problems attacking pipelines, withdrawal equipment and especially the biogas compressor circulating enormous H_2S contents. These repetitive and unplanned maintenance interventions cost a lot financial, and on the other hand with regard to the ecosystem, by the incineration of biogas very rich in H_2S, and therefore a production of smoke very rich in sulfur which is harmful to the environment.

Unlike the H_2S contained in the biogas affected by the LandGEM model, estimated at 40ppm as mentioned in the Fig. 7, describes the favorable conditions for the proper functioning of the units and for the production of electrical energy, value that is not applied in the field according to the results of the experimentation.

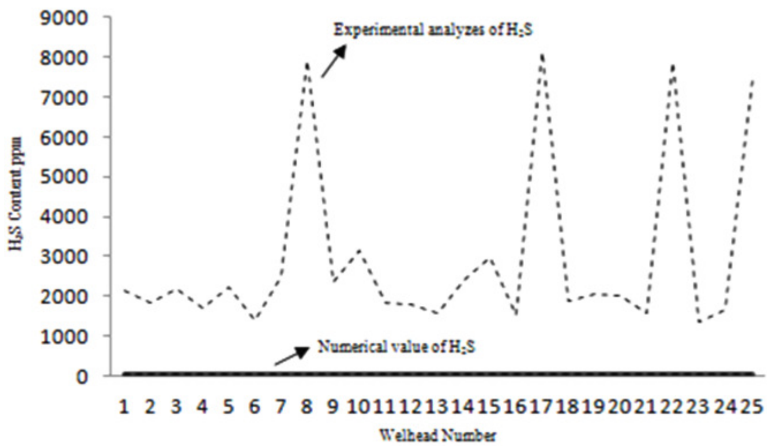

Figure 7. Representation of the numerical value of H_2S by LandGEM Model and experimental analyzes of H_2S during the year 2022 .

This model introduces into these hypotheses that organic matter must not contain organic sulfur compounds [23]. As indicated in Fig.4 by the LandGEM model, the landfill studied must produce a quantity of methane equivalent to $3,145.10^7$ m^3 corresponding to the year 2022, this implies a production of electrical energy equivalent to $10,941.10^7$kWh according to the year 2022, using the equation (2). Such electricity generation is capable of ensuring the electrical needs of the entire site, the city's public lighting, and 30% of the city's electrical needs [30].

To optimize the performance of methane for the production of electrical energy, the discharge must respect the rules of organic matter where sulfur compounds are almost absent or present with only traces. Therefore, provide a methane desulphurization process before its circulation to the recovery units.

3.2. Results validation

The values mentioned in Table 2 resulting from the experimental measurement realized on site, shows –20% of deviation compared to the calculation carried out by the digital model (LandGEM). This is explained by the fraction of CH_4 in the biogas which constantly changes depending on the landfill conditions, in particular those linked to the accidental presence of oxygen or the lack of insulation which inhibits the formation of methanogenic bacteria in an anaerobic environment, whose the results of the analyze, the critique and explanation in the aforementioned representation as Fig.3 and Fig.5. These directly affect the quantity of methane generated and therefore the estimate of the equivalent electrical energy.

Item	Experimental value	Numerical value
Methane generation (m^3)	$2,508.10^7$	$3,145.10^7$
Electrical energy in (kWh)	$8,725.10^7$	$10,941.10^7$

Table 2. Electrical energy and methane volume estimated by experimental method and numerical model (LandGEM) according to the year 2022.

According to the results, the validation is dependent on the operating conditions of the field which must absolutely respect those mentioned in the digital model by LandGEM, mainly the anaerobic environment whose organic load contains only traces of hydrogen sulfide and oxygen, with compliance of the standard in relation to the CH_4/CO_2 ration

4. Conclusion and perspectives

This study has demonstrated the LandGEM numerical model performance, whose offering a reference guide to rule, compare, estimate the gases of the landfill site subject of study, and in this case find the key parameters to respond to the reasons malfunction of the site. We deduced from the calculations of the LandGEM that the site must produce $3,145.10^7 m^3$ of methane in 2022 with 100% site sealing, stable progression of the fermentation process, and an H_2S content equivalent to 40 ppm, for a production of electrical energy equivalent to $10,941.10^7$kWh in 2022. This responds to the causes of malfunction of the existing recovery units on site, which according to experimental analyses, presents a methane production equivalent to $2,508.10^7 m^3$ in 2022 with a tightness of 84%, and an H_2S content between 1370($\pm 4\%$) ppm and 8200($\pm 4\%$) ppm, which far exceed the recommended limit and which creates repetitive shutdowns due to corrosion attacking the pipes, the withdrawal equipment and especially the compressor of biogas which circulates a drastic quantity of sulfur.

Optimization of landfill gas performance involves the installation of automatic analyzer sensors that must be attached to the wellheads to send signals directly to the control room indicating an intervention alert in case the gas content measurements CH_4, O_2, CO_2 and H_2S exceed the limits for reasons following : accidental loss of CH_4 into the air, infiltration of O_2 inside the racks, disruption of the stability of the fermentation process, and existence high levels of sulfur in organic matter respectively. The optimal for the latter will be to install a biogas desulphurization process, which will be the objective of our future research.

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