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# Estimation of Landfill Gas and Its Renewable Energy Potential from the Polesgo Controlled Landfill Using First-Order Decay (FOD) Models

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## Abstract

Methane generation in landfills and its inadequate management represent the major avoidable source of anthropogenic methane today. This paper models methane production and the potential resources expected (electrical energy production and potential carbon credits from avoided $CH_4$ emissions) from its proper management in a municipal solid waste landfill located in Ouagadougou, Burkina Faso. The modeling was carried out using two first-order decay (FOD) models (LandGEM V3.02 and SWANA) using parameters evaluated on the basis of the characteristics of the waste admitted to the landfill and weather data for the site. At the same time, production data have been collected since 2016 in order to compare them with the model results. The results obtained from these models were compared to experimental one. For the simulation of methane production, the SWANA model showed better consistency with experimental data, with a coefficient of determination ($R^2$) of 0.59 compared with the LandGEM model, which obtained a coefficient of 0.006. Thus, despite the low correlation values linked to the poor consistency of experimental data, the SWANA model models methane production much better than the LandGEM model. Thus, despite the low correlation values linked to the poor consistency of the experimental data, the SWANA model models methane production much better than the LandGEM V3.02 model. It was noted that the poor consistency of the experimental data justifies these low coefficients, and that they can be improved in the future thanks to ongoing in situ measurements. According to the SWANA model prediction, in 27 years of operation a biogas plant with 33% electrical efficiency using biogas from the Polesgo landfill would avoid 1,340 $GgCO_2e$. Also, the evaluation of revenues due to electricity and carbon credit gave a total revenue derived from methane production of US$27.38 million at a cost of US$10.5/tonne $CO_2e$.

## Keywords

First-Order Decay, Methane, Modeling, Landfill, Renewable Energy

## 1. Introduction

There is growing concern worldwide regarding Municipal Solid Waste (MSW) generation. In Africa, the key drivers of solid waste generation are rapid urbanization and growing populations [1]. Although currently ranked as the least urbanized region of the world, Africa is the most rapidly urbanizing continent globally [1]-[3]. As an illustration, it's projected that in the next few decades, the continent will have more than half of its population living in urban settings [2]. The estimated quantity of MSW generated worldwide is 2.01 billion tons every year [4] [5]. Without change, this figure could increase to 3.4 billion tonnes by 2050 [4]. Research has shown that in many cases, developing countries experience poor municipal solid waste management because cities and municipalities are not well equipped and there are not enough financial resources to manage waste in a sustainable way. Less than 70% of waste generated in low-income countries is collected and more than 50% of the collected waste (less than 35% of the generated waste) is often disposed of through uncontrolled landfilling while about 15% is processed through unsafe and informal recycling [4].

In sub-Saharan African (SSA) cities, like in other developing regions, rapid population growth as well as expansion of service and manufacturing sectors have led to an increase in waste generation (quantity and variety), while its management has remained highly deficient [6]-[8]. Landfilling remains the primary treatment option for municipal solid waste (MSW) and other non-hazardous wastes in most parts of the world [7]-[11]. According to [1] about 85% of the world's MSW is deposited in controlled and uncontrolled landfills.

The degradation of landfilled organic waste will inevitably generate landfill gas (LFG) [12]. Hence, the MSW disposed of in Ouagadougou comprises biodegradable material (>60%) [13] which undergoes anaerobic digestion producing LFG. LFG is a complex mixture of different gases formed by the action of microorganisms within a landfill [14] [15]. Landfill gas (LFG, or biogas) fugitive emissions are one of the major environmental issues related to sanitary landfills [15]. LFG is roughly composed of 60% - 65% methane ($CH_4$), 35% - 40% carbon dioxide ($CO_2$) [9] [16]-[18] and more than 150 trace compounds. As a main component of LFG, $CH_4$ has a global warming potential (GWP) 28 - 34 times greater than $CO_2$ over a 100-year period (not considering climate feedback) [19], 86 times over 20 years

[20]. From this point of view, controlling $CH_4$ emissions from municipal solid waste landfills is an urgent task.

Mismanagement of landfills can lead to uncontrolled emissions of LFGs such as $CH_4$ and $CO_2$ which contribute enormously to climate change [18] [21]; pungent odors, litter, and dust in the vicinity; seepage of leachate formed in the landfill into groundwater and surface water. It is estimated that 30 - 70 million tons of methane gas are emitted per year from landfills throughout the world.

Research has shown that landfills are not the solution to a city's waste management problems, given the damage they cause. In almost all cities where they exist, old landfill sites have become environmental and health hazards [22]. By way of illustration, in 2011, the United States recorded 1908 landfills which generate approximately $1.03 \times 10^8$ metric tonnes of carbon equivalent of $CH_4$, which accounts for 17.7% of the total $CH_4$ emitted from the United States into the atmosphere. In 2013, China recorded 580 landfills and the $CH_4$ emitted from these landfills accounted for 13% of the total $CH_4$ emitted from China. In Europe, landfills recorded the second-largest source of $CH_4$ emitted from anthropogenic activity, which was 20% of estimated $CH_4$ from waste disposal sites [23]. Africa is the most vulnerable part of the world in relation to the consequences associated with uncontrolled emission of LFG. The total potential methane generated from Africa in 2012 was $10{,}496 \times 10^6$ $m^3$ (assuming all the waste generated is landfilled), therefore management of LFG generated is of great importance [1]. In Burkina Faso, there is a scarcity of data in this area. The Polesgo landfill, located in the capital emitted 24.966 and 40.025 $GgCO_2e$ in 2017 and 2018 respectively [7].

Different research programs have been launched in the past decades to optimize landfill operation and to mitigate fugitive landfill greenhouse gas (GHG) emissions through the landfill cover, which constitutes one of the largest anthropogenic sources of $CH_4$ in the U.S.

Considering the sad state of MSW management in SSA cities, particularly in Ouagadougou (Burkina Faso), the landfills and the growing problem of climate change, the assessment of $CH_4$ generation and emission potential from landfills has become extremely important. This will further help in taking appropriate measures for recovery of methane for electricity generation or other uses, thereby avoiding methane emissions into the atmosphere.

To gain a better understanding of $CH_4$ generation and migration in soil or biocovers in landfill sites, several models and measurement techniques for $CH_4$ emissions have been developed by different researchers over the years but none of them has been recognized as an international reference method [23]. In most of the landfill gas generation models, zero, first or second order decay equations are employed to determine the amount of LFG that is generated [24] [25]. A comprehensive review of the LFG generation models was discussed by [24] [26]. The zero order models are based on the assumption that the gas generation rates are constant over a period of time, unaffected by the age of waste or the waste breakdown. Some of the commonly used zero order models are European Pollutant

Emission Register (EPER Germany), Solid Waste Association of North America (SWANA) and Intergovernment Panel on Climate Change (IPCC) zero order [26]. The first order decay models account for the physical and chemical waste characteristics and the quantity of the waste under consideration based on the data obtained from landfills along with site-specific conditions [24]. This makes the use of first-order decay models a more realistic approach by which to determine the LFG generation rates. Some of the first order models include LandGEM, GasSim, Afvalzorg, IPCC, EPER France, SWANA, TNO and Mexico [24] [26] [27] with LandGEM the most widely used gas generation model as it is specific for MSW landfills in the US.

There is nowadays a lot of scientific evidence to explain a number of phenomena in landfills. These achievements include the development of tools for modeling methane production and emissions in landfills. Although some authors argue that this scientific knowledge is limited, it remains a solid foundation for landfill decision-making. However, a considerable gap is noted. This relates to the validation and reliability of the above-mentioned modeling tools to reproduce or predict reality. To this gap is transposed the problem of the transferability of these models in relation to the climatic conditions specific to developed countries in developing countries, more specifically in Burkina Faso.

The aim of this study was to examine the transferability of landfill methane production models developed in industrial countries to climate conditions in developing countries, in order to determine whether landfill methane production models are compatible with climate conditions in developing countries. Two first-order models (LandGEM and SWANA) have been used with the specific conditions of the study site and compared with experimental in situ data. The choice of these models was guided by the frequency of their use in other countries and also taking into account the specific climatic conditions in the study area. The model closest to the experimental data is then used to project the use of landfill gas energy and the potential benefits this option would bring (renewable electricity potential and avoided greenhouse gases).

## 2. Material and Methods

### 2.1. Site Description

The study area for this research was Polesgo landfill, ranging from 12˚25'08" to 12˚25'53"N and from 1˚30'41" to 1˚31'12"W. The Polesgo landfill was built and commissioned in 2005. It has a capacity of 6.1 million cubic meters of waste and offers an operating capacity of twenty (20) years. It covers an area of 70 hectares and is located about ten kilometers north of the city center. The Polesgo landfill has two missions: firstly, solid waste burial and secondly, solid waste valorization (*i.e.* composting, plastic recovery). Twenty-four wells are integrated into landfill for future in situ measurement. **Figure 1** gives an aerial view of Polesgo landfill, which was named Polesgo Waste Treatment and Recovery Centers, according to this second mission.

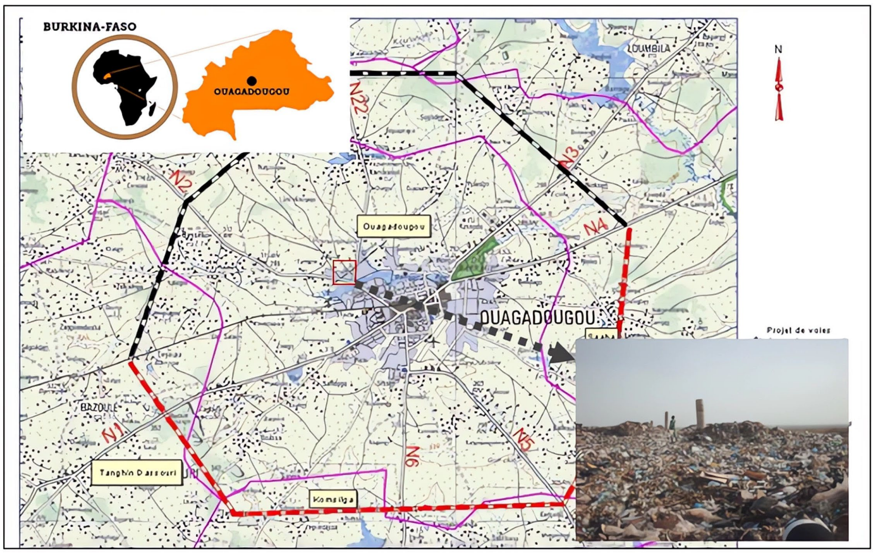

**Figure 1.** Geographic location of Polesgo's landfill.

## 2.2. Landfill Gas (LFG) Generation Modeling

LFG generated in a landfill will have different pathways, as illustrated in Equation (1). If $CH_4$ generation is significant (in the LFG), LFG can be collected and utilized for power and/or heat production, upgraded to biogas or flared for thermal conversion to $CO_2$ (Stegmann, 1996). Part of the LFG will migrate to the top cover, where it can be oxidized to $CO_2$ by methanotrophic bacteria in the cover soil. However, some of the migrating LFG may also escape into the atmosphere without any oxidation and add to anthropogenic $CH_4$ emission and accumulation in the atmosphere. LFG can also migrate laterally to surrounding areas, and finally some will be temporarily stored inside the landfill. This can be summarized in the following $CH_4$ balance for a landfill [28] (with all units in mass time$^{-1}$)

$$\begin{aligned} \mathrm{CH_4\ generated} &= \mathrm{CH_4\ emitted} + \mathrm{CH_4\ oxidised} + \mathrm{CH_4 recovered}\ \left(\text{flared or utilised}\right) \\ &\quad + \mathrm{CH_4\ migrated} + \Delta \mathrm{CH_4\ storage} \end{aligned} \tag{1}$$

Recorded $CH_4$ is based on flow and $CH_4$ concentration measurements, generated $CH_4$ is often modeled based on landfilled waste amounts and waste compositions, using different models for LFG generation [29]. The emission of $CH_4$ can be quantified by using either remote methods, such as tracers gas dispersion, DIAL (Differential Absorption LiDAR) or radial plume mapping [30] [31], or surface-based point measurements (e.g. flux chamber measurements) that integrate total emissions [28] [32].

### 2.2.1. First Order Decay Model

Most available global models which predict biogas generations from landfills are among the ones developed based on first-order decay models. These models consider quality of waste (*i.e.* moisture content, carbon content, age of waste and ability of waste to be digested), waste quantity and condition of the landfill (*i.e.* climate, temperature, precipitation) implicitly. In order words, the effect of depletion of carbon in the waste through time is accounted for in a first-order model.

**1) US EPA's LandGEM version 3.02**

The LandGEM was developed by the Control Technology Center (CTC) of the United States Environmental Protection Agency (US EPA) [33]. It is an automated tool on MS Excel based interface to determine release rates of total LFG, methane and other contributing gases in LFG. However, it doesn't include the categorization of wastes. LandGEM predicts the LFGs emissions based on a first order decay equation, which assumes that the $CH_4$ generation rate reaches its peak shortly after the initial waste is placed and decreases exponentially after that. The LandGEM model also assumes that the volume emission rate of $CO_2$ and $CH_4$ emissions are the same, with trace amounts of non-methane organic compounds and other air pollutants. In 2005, the current version 3.02 has been released, and it works in Windows Excel Environment. Equation (2) shows the first-order decay equation used to estimate $CH_4$ generation rate ($Q$, in $m^3$/year) [34] [35]:

$$Q_{\mathrm{CH_4}} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k L_0 \left( \frac{M_i}{10} \right) \times \left( e^{-k t_{ij}} \right) \tag{2}$$

where $Q_{\mathrm{CH_4}}$ is the annual methane generation in the year of calculation ($m^3$/year), k is the methane generation constant ($\mathrm{year}^{-1}$), $L_0$ is the methane generation potential ($m^3 \mathrm{MgMSW}^{-1}$), $M_i$ is the mass of waste in the $i^{th}$ year (Mg) and $t_{ij}$ is the age of $j^{th}$ section of waste mass $M_i$ accepted in the $i^{th}$ year.

According to Equation (2), LandGEM model exhibits two input constants: k, the methane generation constant and, $L_0$, the potential methane generation capacity. Default or site-specific values of these constants may be used and are distinguished as "CAA" and "inventory" [36]. The "CAA" defaults are in accordance with the federal Clean Air Act (CAA) regulations for landfills receiving solid household garbage while the "Inventory" is based on emission factors from the "US EPA".

**2) First Order Multi-phase SWANA Model**

This model is described by Van Zanten and Scheepers (1995). It assumes that the methane generation initially may be low. The generation then rises to a peak before declining in what is essentially an exponential fashion. Equation (3) shows the first-order multi-phase decay equation used to estimate $CH_4$ generation rate ($Q$, in $m^3$/year):

$$Q_{\mathrm{CH_4}} = M_i \times L_0 \times \left[ F_{(r)} \times k_{(r)} \times e^{-k_{(r)}(t-t_1)} + F_{(s)} \times k_{(s)} \times e^{-k_{(s)}(t-t_1)} \right] \tag{3}$$

where $Q_{\mathrm{CH_4}}$ is methane generation in $m^3$/year; $M_i$ is waste in place (tons) in the year $i$; Lo is methane yield potential in ($m^3 \mathrm{MgMSW}^{-1}$); t is time after waste placement in years; $t_1$ is lag time (between placement and start of generations) in the year; $k_{(r)}$ is the first order decay rate constant for rapidly decomposable waste; $k_{(s)}$ is the first order decay rate constant for slowly decomposable waste; $F_{(r)}$ is the fraction of rapidly decomposable waste and $F_{(s)}$ is the fraction of slowly decomposable waste.

### 3) Models inputs

The value of the degradation constant of rapidly degradable waste $k_{(r)}$ or slowly degradable $k_{(s)}$ is estimated from Equation (4) [36]-[38]:

$$k_{(r)/(s)} = \sum_{i=1}^{N} k_i \times F_i \tag{4}$$

where $k_{(r)/(s)}$ is the first order decay rate constant for rapidly/slowly decomposable waste; $k_i$ is the first order decay constant degradation of each waste category (rapidly/slowly degradable waste); $F_i$ is the fraction of rapidly or slowly decomposable waste.

The quantity of Municipal Solid Waste ($M_i$) buried in the Polesgo landfill from 2005 to 2023 was provided by the municipal authorities of Ouagadougou. That from 2024 to 2025 was calculated according to Equation (5) [39]:

$$M_i = t_c \times t_e \times n_{ja} \times w_c \times P_0 \times (1+r)^t \tag{5}$$

where $t_c$ (%) is MSW collection rate (41%); $t_e$ (%) is the rate of landfill of waste at the Polesgo landfill (90%); $n_{ja}$ is the number of days in a year (365 days); $w_c$ is the specific daily production of waste in Ouagadougou (0.62 kg/inhabitant/day reported by [13]); $P_o$ (3, 000,000 inhabitants) is the population of Ouagadougou for the year 2020 taken as a reference (in years); $r$ (%) is the population growth rate of Ouagadougou (4.1%) and $t$ is the number of extrapolation years (in year). **Table 1** shows the waste annual tonnage, $Q_{waste}$, at Polesgo landfill from 2005 to 2025.

**Table 1.** Waste annual tonnage, $Q_{Waste}$, at Polesgo landfill from 2005 to 2025. (Under consideration to close)

| Year | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|---|
| MSW | 60,000 | 84,742 | 94,229 | 124,409 | 130,910 | 137,470 |
| Year | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
| MSW | 148,239 | 172,505 | 174,254 | 197,738 | 211,863 | 225,988 |
| Year | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
| MSW | 240,113 | 336,000 | 386,000 | 389,000 | 391,500 | 350,000 |
| Year | 2023 | 2024 | 2025 | | | |
| MSW (tonne) | 229,280 | 231,022$^*$ | 232,778$^*$ | | | |

$^*$Projected with Equation (5).

According to Machado *et al.*, 2009, if waste composition is known, methane yield potential, $L_0$ can be calculated from Equation (6) [40]:

$$L_0 = \frac{BF_w \times C_m}{1+w} \tag{6}$$

where $BF_w$ is waste biodegradable fraction, $C_m$ the methane generation and, $w$ the water content. The values of $BF_w$ and $C_m$ were calculated from Equations (7) and (8). Where $BFw$ is waste biodegradable fraction, $C_m$ the methane generation and, $w$ the water content.

$$BF_w = \sum_{i=1}^{n} BF_i \times FR_i \tag{7}$$

where $BF_i$ is biodegradable fraction of each waste component and $FR_i$ fraction of each component of dry-based waste.

$$C_m = \frac{\sum_{i=1}^{n} BF_i \times FR_i \times C_{m_i}}{BF_w} \tag{8}$$

where $C_{mi}$ is the methane generation of each waste component. Table 2 shows MSW characteristics related to Polesgo's landfill.

Table 2. MSW characteristics related to Polesgo's landfill.

| Fraction of waste | $BF_i$ [40] | $C_{m_i}$ [40] | $FR_i$ [39] |
|---|---|---|---|
| Papers | 0.40 | 418.51 | 3.82 |
| Cardboard | 0.41 | 438.70 | 8.38 |
| Food waste | 0.64 | 505.01 | 29.34 |
| Garden waste | 0.35 | - | 2.73 |
| Yard waste | | 481.72 | 27.21 |
| Wood | 0.17 | 484.94 | 0.67 |
| Textiles | 0.32 | 573.87 | 10.12 |
| Leather | - | 759.58 | - |

Concerning the methane generation constant, *k*, it can be obtained by an empirical expression given by Equation (9) if landfill meteorological data are available (Alexander *et al*., 2005):

$$k = 3.2 \times 10^{-5} \times (x) + 0.01 \tag{9}$$

where $x$ is the average annual rainfall (millimeters). The rainfall data available for Ouagadougou city since 1902 gives an annual average of 784.93 millimeters.

### 2.3. Landfill Gas (LFG) Generation Measurement

In the second approach, the quantities of generated and collected LFG are related by the collection efficiency as shown in Equation (10) [7]:

$$\mathrm{Q}_{\mathrm{CH}_{4c}} = \mathrm{Q}_{\mathrm{CH}_{4g}} \times \eta_{\mathrm{CH}_4} \tag{10}$$

where $\eta(\%)$ is methane extraction efficiency, $\mathrm{Q}_{\mathrm{CH}_{4g}}$ is methane generated and $\mathrm{Q}_{\mathrm{CH}_{4c}}$ is methane collected. The value of $\eta_{\mathrm{CH}_4}(\%)$ of the Polesgo landfill was assessed in our previous studies. It has been estimated at 27% and 23% in 2017 and 2018 respectively [7]. In this study, an average value of the two determined in our previous study was applied to the other years.

### 2.4. Validation of Model

The models used for modeling of the $CH_4$ production were corroborated by using two statistical parameters; namely (i) coefficient of determination ($R^2$) and (ii) Root Mean Square Error (RMSE). These parameters are comprehensive enough to quantify the accuracy of the models used. $R^2$ was calculated by Equation (11) [8]. It represents the association between experimental $CH_4$ ($Q_{\exp}$) and modeled $CH_4$ ($Q_{\mathrm{mod}}$) at the time i for n number of years. The model with a greater value of $R^2$ establishes the better prediction.

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \left(Q_{\exp,i} - Q_{\mathrm{mod},i}\right)^2}{\sum_{i=1}^{n} \left(Q_{\exp,i} - \overline{Q_{\mathrm{mod},i}}\right)^2} \tag{11}$$

## 3. Potential Electrical Energy Generated According to the Landfill Gas Emission Model

The potential electrical energy generated $Ep_{el}$ (MWh/year) and the electrical power Pel (MW) were estimated from the annual quantity of methane generated according to Equations (12) and (13) respectively [41]-[43].

$$Ep_{el} = \eta_{\mathrm{CH_4}} \times LHV_{\mathrm{CH_4}} \times Q_{\mathrm{CH_4}} \times \eta_{el} \tag{12}$$

where $Ep_{el}$: electrical energy potential in GWh per year.

$Q_{\mathrm{CH_4}}$: annual volume of methane in the year of calculation (m$^3$/year); $LHV_{\mathrm{CH_4}}$: lower calorific value of $CH_4$ (37.2 MJ/m$^3$); $\eta_{\mathrm{CH_4}}$: biogas recovery rate (0.25); $\eta_{el}$: electrical conversion efficiency (0.33) for a given internal combustion engine. A function duration of 27 has been considered in the simulation to be in line with the theoretical duration of a biogas plant.

$$P_{el} = \frac{Ep_{el}}{8760} \tag{13}$$

with:

$P_{el}$: the potential electrical power generated in GW; 8760: number of hours in a year.

Based on the methane generation model, the number of GHGs avoided in the methane recovery hypothesis, expressed in carbon dioxide equivalent ($CO_2e$), was estimated from Equation (14). [7] [44] [45]

$$GHG_{avoided} = Q_{\mathrm{CH_4}} \times \rho_{\mathrm{CH_4}} \times PRG_{\mathrm{CH_4}} \times \eta_{\mathrm{CH_4}} \times 10^{-6} \tag{14}$$

with:

GHG avoided a mass of $GHG_{avoided}$ (Gg$CO_2$e); $\rho$: conversion factor from m$^3$/year to kg/year (0.667); $PRG_{\mathrm{CH_4}}$: global warming potential of methane = 28 compared to that of $CO_2$ which is 1 over 100 years reported by [46]; $Q_{\mathrm{CH_4}}$: annual volume of methane; $\eta_{\mathrm{CH_4}}$: biogas recovery rate ($\eta_{\mathrm{CH_4}}$ = 0.25 for the Polesgo landfill).

In addition, the carbon credit was estimated on the basis of GHG avoided and the current cost of a tonne of $CO_2e$, estimated at US$10.5/tonne.

## 4. Results and Discussions

### 4.1. Models Input Parameters

**Table 3** shows the values of the input parameters of the models used. The value of methane yield potential obtained is close to that of conventional landfills or those located in arid areas and bioreactor type landfills (the value obtained is 0.983 times the conventional value for these types of landfills). Also, the waste degradation constant obtained from rainfall and Equation (9) is close to that given in the inventory for bioreactor type landfills (the value obtained is 0.88 times the conventional value for these types of landfills). This is close to reality insofar as the city of Ouagadougou can be considered an arid zone with respect to the average rainfall recorded (784.93 millimeters and spread over 3 to 4 months out of 12 months).

**Table 3.** Models inputs parameters related to Polesgo's landfill and default values.

| Parameters | Value | Default Values [33] |
|---|---|---|
| Lo ($m^3Mg^{-1}$) | 98.03 | 170 (Clean Air Act for conventional or arid area landfill); 100 (Inventory for conventional or arid area landfill); 96 (Inventory for bioreactor landfill) |
| ks ($year^{-1}$) | 0.003 | - |
| kr ($year^{-1}$) | 0.062 | - |
| Fr (%) | 61.92 | - |
| Fs (%) | 29.02 | - |
| k ($year^{-1}$) | 0.035 | 0.05 (Clean Air Act for conventional or arid area landfill); 0.04 (Inventory for bioreactor landfill); 0.02 (Inventory for conventional or arid area landfill) |

### 4.2. Landfill Gas Production Modeling from Polesgo Landfill

Two predictive models (SWANA and LandGEM) were used to estimate methane emissions from the Polesgo landfill. The methane emission results are shown in **Figure 2**. Note that the model assumes that there is no biogas production in the first year of waste deposition, 2005.

According to models, from $2005 \leq t \leq 2026$, the amount of methane increases linearly with the years, reaching a maximum value in 2026. And for $t > 2026$, the amount of methane produced will decrease exponentially after landfill closure, in parallel with the decrease in the amount of decomposable material in the landfill.

SWANA has predicted maximum methane emission rates of 4,426,559, 4,491,083 and 4,538,419 $m^3$/year for the years 2023, 2024 and 2025 respectively, compared with 8,243,196, 8,733,855 and 9,213,521 $m^3$/year for the same years according to the LandGEM model. The experimental data obtained over this period are 4,191,845 and 4,295,454 $m^3$ in 2022 and 2023 respectively. Data for 2024 are not yet available at the time of writing. Trends in these models show that maximum methane emissions are expected in 2026, one year after the planned closure of the landfill.

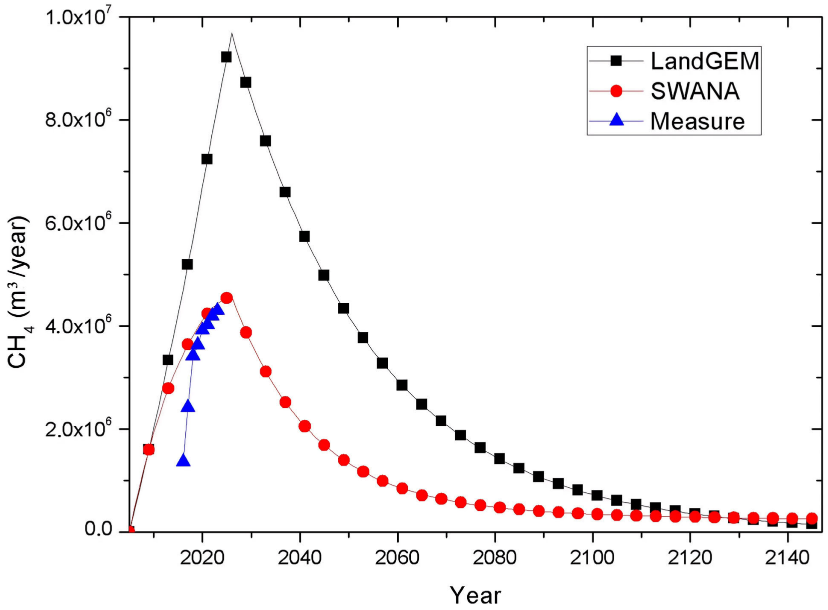

**Figure 2.** Methane generation modeling with LandGEM version 3.02 models and SWANA model versus measurement.

Methane production data obtained from the two above-mentioned models and experimental data showed that the SWANA model better characterizes methane production at the Polesgo landfill. This is because the LandGEM model considers municipal waste to consist of a single category (source). According to this concept, all waste categories degrade in the same way and at the same rate, with the same average methane production potential. This is not realistic in practice [47]. However, when considering municipal waste by category, with the specific characteristics of each category (rapidly degradable, moderately degradable and slowly degradable), as considered in the SWANA model, methane production is overestimated but less exaggerated than with the LandGEM model. The discrepancies observed with the SWANA model (see **Figure 2**) can be explained by the difficulty of obtaining experimental data. As a reminder, the Polesgo landfill does not have a technical platform for monitoring landfill gas emissions. In situ measurements only began in 2016. The consistency of the experimental data remains rather low for a good correlation.

It should be noted that the data on the mass of waste buried in the landfill is approximate, given the weighing methods used in situ. Also, the characteristic data used to come from the 2017 characterization campaign, after the waste was already being degraded in the cells. As a result, there may be discrepancies between the data used and that for waste already landfilled.

In addition, the rate of landfill gas production decreases exponentially after the predicted closure of the landfill (2025), as the amount of decomposable material in the landfill decreases. This is because the model assumes that maximum production normally occurs in the year of closure (2025) or the following year (2026), and that landfill gas production decreases exponentially as the organic fraction of waste is consumed. Biogas concentration decreases with the age of the final landfill site; this fact is included in the model with parameters $k$ and $L_0$.

The results of methane prediction and experimentation at the Polesgo landfill show that there is an untapped energy potential and thus a huge contribution to global warming. It is important to note that this potential can be used for energy purposes and broaden the country's energy mix, as [48] pointed out. Mor & Ravindra, (2023) [49] go further, pointing out that landfill gas-to-energy is an essential component of an integrated municipal solid waste management strategy.

## 4.3. Validation of Model

**Table 4** shows the values of statistical parameters of the two models.

**Table 4.** Statistical parameters of the two models.

| Model | $R^2$ |
|---|---|
| **SWANA** | 0.59 |
| **LandGEM version 3.02** | 0.006 |

Considering methane production rate simulations, SWANA model showed better $R^2$ of 0.59 compared with the LandGEM model which had a value of 0.006 as depicted in **Figure 1** and **Figure 2**. Estimating the rate of methane production in landfills depends largely on the basic and secondary parameters that form the basis for developing equations or computer models. Fewer parameters and/or imprecise data would lead to more inaccurate results than field surveys. More complex and detailed parameters would provide a more accurate estimate [48]. A different mathematical model can be used to evaluate the various parameters, but due to poor analysis or lack of data, the model results are subject to considerable uncertainty. One of the major problems in simulating $CH_4$ emissions from landfills is the quality and abundance of inputs to the models used. This is the case with Polesgo's landfill.

Comparing the measured values against those simulated via SWANA (model data/experimental data), we can see that the ratio evolves from 1.03 to 1.5 between 2017 and 2023. In a similar work, Plocoste *et al*., 2016 had obtained a ratio of 1.94 for the Gabarre landfill [36], less interesting than those of the present work. In view of all these aspects, it should be noted that the SWANA model better reproduces $CH_4$ generation at the Polesgo landfill.

## 4.4. Energy Generation Potential of Polesgo's Landfill

**Figure 3** shows the potential electrical energy generated and carbon dioxide equivalent avoided by the Polesgo landfill in 27 years of operation (between 2024 and 2052).

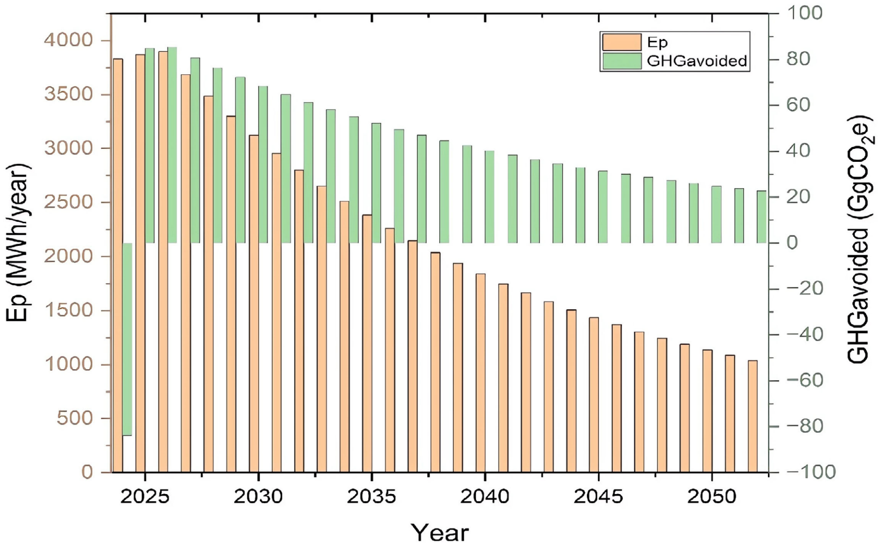

**Figure 3.** Energy generation potential of Polesgo's Landfill.

Knowledge of the biogas generation potential of the Polesgo landfill is essential before implementing a biogas recovery plant for energy production. It should be noted that biogas generation at the Polesgo landfill is continuous due to the anaerobic decomposition of the organic fraction of solid waste. Consequently, if the biogas recovery facility is not operational, there will be an increase in pressure that will cause biogas to be released into the atmosphere. This would pose a real environmental threat, as methane from biogas is a greenhouse gas.

As with methane production, the estimated energy potential increases from 2024 to 2026. From 2024 to 2026, it rises from 3,829 to 3,896 MWh, with a maximum in 2026. After 2026, the energy potential decreases exponentially. Assuming that the biogas plant starts operating in 2025, by the 27th year of operation (in 2052), the recovered biogas will still be sufficient to generate 1038 MWh, representing a significant energy opportunity for Burkina Faso.

These high values of estimated energy potential could be explained by high values of biogas volume. The increase in energy potential from 2024 to 2026 can also be explained by the increase in methane volume over the same period. The exponential decrease in energy potential observed from 2026 onwards is explained by the exponential decrease in methane volume linked to the gradual reduction in the organic matter contained in landfilled waste.

Producing energy from waste at the Polesgo landfill can help Burkina Faso achieve its energy transition by gradually replacing fossil fuels. Converting waste into energy can become a green, renewable and sustainable energy source. What's more, converting biogas into energy prevents the release of $CH_4$, a greenhouse gas, into the atmosphere. It's important to note that these energy potential values can increase with biogas capture rates, which are currently very low (25%).

**Table 5.** Potential impact of biogas recovery for 27 years of operation.

| Parameters | Units | Cost per unit | Total ($US) |
|---|---|---|---|
| Potential electrical energy generated (MWh) | 61,174 | 0.22$US/kWh | 13,305,345 |
| $CO_2e$ avoided ($GgCO_2e$) | 1,340 | 10.5$US/tonne | 14,071,603 |
| Total income ($US) | | | 27,376,948 |

Over the 27 years of operation of the biogas plant (from 2025 to 2052), energy recovery from biogas at the Polesgo landfill would generate more than 61GWh, avoiding 1,340 $GgCO_2e$ emissions into the atmosphere. Also, the evaluation of revenues from electricity and carbon credits derived from methane production yielded US$27.38 million who reported an average cost of US$10.5 $CO_2e$ /tonne. This income represents a significant added value for the economy of the municipality hosting the landfill.

It was noted that at the Polesgo landfill, in 2026, 1 year after its planned closure, an electrical potential of 3,896 MWh was estimated, with a total of 4,547.040 Gg of waste landfilled since its opening in 2005. This electrical potential corresponds to 857 Wh recovered per tonne of landfilled waste, compared with 84,158 Wh/tonne of landfilled waste at the Akouedo landfill. This difference is explained, on the one hand, by the low biogas collection rate considered at Polesgo (25%) versus (66%) at Akouedo, and, on the other hand, by the difference in waste characteristics, notably the organic loads in the waste from the two landfills (55% - 60% at Polesgo versus 80.09% at Akouedo) and the $CH_4$ production potential (107.56 $m^3CH_4/kg$ at Akouedo [43] versus 98.03 $m^3CH_4/kg$ at Polesgo [39]). In addition to the above, the difference in climates between Côte d'Ivoire (more humid) and Burkina Faso (less humid) should be noted. Humidity is a factor favoring the degradation of waste, and therefore higher $CH_4$ emissions [18] [36] [50] [51].

## 5. Conclusion and Perspectives

The waste disposed of in Polesgo's landfill is rich in organic matter, which is in line with our previous work on the characterization of Ouagadougou waste. This high organic matter content favors a high potential for methane and carbon dioxide emissions. These greenhouse gases represent a real threat to the environment. Two models, LandGEM and SWANA, were used to estimate methane generation at the Polesgo waste treatment and recovery centers based on actual waste data. The parameters of these models are obtained from the characteristics of waste from the city of Ouagadougou. The methane production potential obtained is estimated to be 98.03 $m^3CH_4/kg$ of waste. The waste degradation rate obtained is 0.035 $yr^{-1}$. These data are in the same orders of magnitude as the default Clean Air Act data for conventional or arid area landfills. The results obtained from the two models show that the SWANA model reproduces the results of in situ measurements rather better than the LandGEM model. However, more measured data are required for better simulation validation. Furthermore, studies carried out on this landfill to date have been limited to showing the existence of adverse environmental effects associated with it. However, to the best of our knowledge, no study has yet been carried out on the energy recovery of waste from this landfill.

According to the SWANA model prediction, in 27 years of operation a biogas plant with 33% electrical efficiency using biogas from the Polesgo landfill would avoid 1,340 Gg$CO_2$e. Also, the evaluation of revenues due to electricity and carbon credit gave a total revenue derived from methane production of US$27.38 million at a cost of US$10.5/tonne $CO_2$e. Consequently, we believe it is necessary to continue the present work by assessing the economic viability and return on investment of this landfill biogas recovery strategy. It would also be appropriate to explore other recovery options, such as incineration with heat energy recovery and anaerobic digestion, in order to optimize the most suitable and economically viable choice. As a result, we feel it is necessary to follow up the present work by assessing the energy potential of biogas from landfill waste, as well as other recovery options such as incineration with heat energy recovery.

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## Data Availability

No data was used for the research described in the article.

## Conflicts of 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.

## References

[1] Njoku, P.O., Odiyo, J.O., Durowoju, O.S. and Edokpayi, J.N. (2018) A Review of Landfill Gas Generation and Utilisation in Africa. *Open Environmental Sciences*, **10**, 1-15. https://doi.org/10.2174/1876325101810010001

[2] Njoku, P.O., Edokpayi, J.N. and Odiyo, J.O. (2020) Modeling Landfill Gas Potential and Potential Energy Recovery from Thohoyandou Landfill Site, South Africa. *Journal of the Air & Waste Management Association*, **70**, 820-833. https://doi.org/10.1080/10962247.2020.1778137

[3] Hoornweg, D. and Bhada-Tata, P. (2012) What a Waste: A Global Review of Solid Waste Management. World Bank Urban Development Series Knowledge Papapers.

[4] Kaza, S., Yao, L.C., Bhada-Tata, P. and Van Woerden, F. (2018) What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Urban Development, No. 112,

World Bank. https://doi.org/10.1596/978-1-4648-1329-0

[5] UNEP (2010) Climate and Climate Change.

[6] Achankeng, E. (2003) Globalization, Urbanization and Municipal Solid Waste Management in African. African Studies Association of Australasia and the Pacific 2003 Conference Proceedings—African on a Global Stage, 1-22. http://www.wiego.org/sites/default/files/publications/files/Achankeng_Globalization_Urbanization_MSWMgmt_Africa.pdf

[7] Haro, K., Ouarma, I., Nana, B., Bere, A., Tubreoumya, G.C., Kam, S.Z., *et al.* (2019) Assessment of $CH_4$ and $CO_2$ Surface Emissions from Polesgo's Landfill (Ouagadougou, Burkina Faso) Based on Static Chamber Method. *Advances in Climate Change Research*, **10**, 181-191. https://doi.org/10.1016/j.accre.2019.09.002

[8] Mahar, R.B., Sahito, A.R., Yue, D. and Khan, K. (2014) Modeling and Simulation of Landfill Gas Production from Pretreated MSW Landfill Simulator. *Frontiers of Environmental Science & Engineering*, **10**, 159-167. https://doi.org/10.1007/s11783-014-0685-6

[9] Ghosh, A., Sarkar, J.P. and Das, B. (2019). Sustainable Energy Recovery from Municipal Solid Waste (MSW) Using Bio-Reactor Landfills for Smart City Development. 2019 *IEEE International Conference on Sustainable Energy Technologies* (*ICSET*), Bhubaneswar, 26 February-1 March 2019, 242-246. https://doi.org/10.1109/icsets.2019.8745334

[10] Staub, M.J., Marcolina, G., Gourc, J. and Simonin, R. (2011) An Incremental Model to Assess the Environmental Impact of Cap Cover Systems on MSW Landfill Emissions. *Geotextiles and Geomembranes*, **29**, 298-312. https://doi.org/10.1016/j.geotexmem.2011.01.013

[11] Yang, N., Tao, Y., Wang, X., Zhan, G., He, X., Zhang, L., *et al.* (2021) Impact of Low Temperature on *ex situ* Nitritation/*in situ* Denitritation in Field Pilot-Scale Landfill for Postclosure Care of Leachate Treatment and Gas Content. *Waste Management*, **131**, 61-71. https://doi.org/10.1016/j.wasman.2021.05.036

[12] Di Trapani, D., Mannina, G., Nicosia, S. and Viviani, G. (2018) Biogas from Municipal Solid Waste Landfills: A Simplified Mathematical Model. *Water Science and Technology*, **77**, 2426-2435. https://doi.org/10.2166/wst.2018.193

[13] Haro, K., Ouarma, I., Nana, B., Bere, A. and Koulidiati, J. (2018) Characterization and Potential Recovery of Household Solid Waste in the City of Ouagadougou (Burkina Faso). *Journal of Environmental Protection*, **9**, 309-324. https://doi.org/10.4236/jep.2018.94021

[14] Maciel, F.J. and Jucá, J.F.T. (2011) Evaluation of Landfill Gas Production and Emissions in a MSW Large-Scale Experimental Cell in Brazil. *Waste Management*, **31**, 966-977. https://doi.org/10.1016/j.wasman.2011.01.030

[15] Martin, H. (2008) Développement d'outils de gestion de biogaz produits par les lieux d'enfouissement sanitaire. Thèse de doctorat, Ecole Polytechnique de Montréal.

[16] Chen, Z., Gong, H., Jiang, R., Jiang, Q. and Wu, W. (2010) Overview on LFG Projects in China. *Waste Management*, **30**, 1006-1010. https://doi.org/10.1016/j.wasman.2010.02.001

[17] Fathi Aghdam, E. (2018) Methane Production, Recovery and Emission from Two Danish Landfills. PhD Thesis, Technical University of Denmark.

[18] Aghdam, E.F., Scheutz, C. and Kjeldsen, P. (2019) Impact of Meteorological Parameters on Extracted Landfill Gas Composition and Flow. *Waste Management*, **87**, 905-914. https://doi.org/10.1016/j.wasman.2018.01.045

[19] Jigar, E., Jigar, E., Bairu, A. and Gesessew, A. (2014) Application of IPCC Model for Estimation of Methane from Municipal Solid Waste Landfill. *Journal of Environmental Science and Water Resources*, **3**, 52-58.

[20] Fosco, D., De Molfetta, M., Renzulli, P. and Notarnicola, B. (2024) Progress in Monitoring Methane Emissions from Landfills Using Drones: An Overview of the Last Ten Years. *Science of The Total Environment*, **945**, Article 173981. https://doi.org/10.1016/j.scitotenv.2024.173981

[21] Yong, H., Allen, G., Mcquilkin, J., Ricketts, H. and Shaw, J.T. (2024) Lessons Learned from a UAV Survey and Methane Emissions Calculation at a UK Landfill. *Waste Management*, **180**, 47-54. https://doi.org/10.1016/j.wasman.2024.03.025

[22] Biswas, A., Parida, S., Chaudhary, K., Singh, R., Tewari, S. and Singh, S. (2021) Waste-Wise Cities: Best Practices in Municipal Solid Waste Management. https://www.niti.gov.in/sites/default/files/2021-12/Waste-Wise-Cities.pdf

[23] Mønster, J., Kjeldsen, P. and Scheutz, C. (2019) Methodologies for Measuring Fugitive Methane Emissions from Landfills—A Review. *Waste Management*, **87**, 835-859. https://doi.org/10.1016/j.wasman.2018.12.047

[24] Majdinasab, A., Zhang, Z. and Yuan, Q. (2017) Modelling of Landfill Gas Generation: A Review. *Reviews in Environmental Science and Bio/Technology*, **16**, 361-380. https://doi.org/10.1007/s11157-017-9425-2

[25] Wang, D., Yuan, W., Xie, Y., Fei, X., Ren, F., Wei, Y., *et al.* (2023) Simulating CH4 Emissions from MSW Landfills in China from 2003 to 2042 Using IPCC and Landgem Models. *Heliyon*, **9**, e22943. https://doi.org/10.1016/j.heliyon.2023.e22943

[26] Kamalan, H., Sabour, M. and Shariatmad, N. (2011) A Review on Available Landfill Gas Models. *Journal of Environmental Science and Technology*, **4**, 79-92. https://doi.org/10.3923/jest.2011.79.92

[27] Kamalan, H., Ave, S.W. and Golzar, S. (2016) A New Empirical Model to Estimate Landfill Gas Pollution. *Journal of Health Sciences & Surveillance System*, **4**, 3-9.

[28] Scheutz, C., Kjeldsen, P., Bogner, J.E., De Visscher, A., Gebert, J., Hilger, H.A., *et al.* (2009) Microbial Methane Oxidation Processes and Technologies for Mitigation of Landfill Gas Emissions. *Waste Management & Research*: *The Journal for a Sustainable Circular Economy*, **27**, 409-455. https://doi.org/10.1177/0734242x09339325

[29] Mou, Z., Scheutz, C. and Kjeldsen, P. (2015) Evaluation and Application of Site-Specific Data to Revise the First-Order Decay Model for Estimating Landfill Gas Generation and Emissions at Danish Landfills. *Journal of the Air & Waste Management Association*, **65**, 686-698. https://doi.org/10.1080/10962247.2015.1008653

[30] Babilotte, A., Lagier, T., Fiani, E. and Taramini, V. (2010) Fugitive Methane Emissions from Landfills: Field Comparison of Five Methods on a French Landfill. *Journal of Environmental Engineering*, **136**, 777-784. https://doi.org/10.1061/(asce)ee.1943-7870.0000260

[31] Mønster, J., Samuelsson, J., Kjeldsen, P. and Scheutz, C. (2015) Quantification of Methane Emissions from 15 Danish Landfills Using the Mobile Tracer Dispersion Method. *Waste Management*, **35**, 177-186. https://doi.org/10.1016/j.wasman.2014.09.006

[32] Rees-White, T.C., Mønster, J., Beaven, R.P. and Scheutz, C. (2019) Measuring Methane Emissions from a UK Landfill Using the Tracer Dispersion Method and the Influence of Operational and Environmental Factors. *Waste Management*, **87**, 870-882. https://doi.org/10.1016/j.wasman.2018.03.023

[33] Alexander, A., Burklin, C. and Singleton, A. (2005) Landfill Gas Emissions Model

(LandGEM) Version 3.02 User's Guide. United States Environmental Protection Agency. http://www3.epa.gov/ttncatc1/dir1/landgem-v302-guide.pdf

[34] USEPA (2004) Direct Emissions from Landfilling Municipal Solid Waste.

[35] Robertson, T. and Dunbar, J. (2005) Guidance for Evaluating Landfill Gas Emissions from Guidance for Evaluating Closed or Abandoned Facilities. http://clu-in.org/download/char/epa-600-r-05-123.pdf

[36] Plocoste, T. and Jacoby Koaly, S. (2016) Estimation of Methane Emission from a Waste Dome in a Tropical Insular Area. *International Journal of Waste Resources*, **6**, Article 1000211.

[37] Aguilar-Virgen, Q., Taboada-González, P., Ojeda-Benítez, S. and Cruz-Sotelo, S. (2014) Power Generation with Biogas from Municipal Solid Waste: Prediction of Gas Generation with in Situ Parameters. *Renewable and Sustainable Energy Reviews*, **30**, 412-419. https://doi.org/10.1016/j.rser.2013.10.014

[38] Aguilar-Virgen, Q., Taboada-González, P. and Ojeda-Benítez, S. (2014) Analysis of the Feasibility of the Recovery of Landfill Gas: A Case Study of Mexico. *Journal of Cleaner Production*, **79**, 53-60. https://doi.org/10.1016/j.jclepro.2014.05.025

[39] Haro, K., Ouarma, I., Nana, B., Bere, A. and Koulidiati, J. (2017) *In-situ* Measurement and Theoretical Calculations of Annual Biogas Generation: Case of Poles go Landfill at Burkina Faso. *Sardinia* 2017/*Sixteenth International Waste Management and Landfill Symposium*, Cagliari, 2-6 October 2017, 1-11.

[40] Machado, S.L., Carvalho, M.F., Gourc, J., Vilar, O.M. and do Nascimento, J.C.F. (2009) Methane Generation in Tropical Landfills: Simplified Methods and Field Results. *Waste Management*, **29**, 153-161. https://doi.org/10.1016/j.wasman.2008.02.017

[41] Usman, A.M. (2022) An Estimation of Bio-Methane and Energy Project Potentials of Municipal Solid Waste Using Landfill Gas Emission and Cost Models. *Frontiers in Engineering and Built Environment*, **2**, 233-245. https://doi.org/10.1108/febe-06-2022-0021

[42] Idehai, I.M. and Akujieze, C.N. (2015) Estimation of Landfill Gas and Its Renewable Energy Potential in Lagos, Nigeria. *International Journal of Energy and Environmental Engineering*, **6**, 329-343. https://doi.org/10.1007/s40095-015-0178-9

[43] Cyril, K.M., Essi, K., Agboue, A. and Albert, T. (2018) Characterization of the Parameters and Estimation of Potential Biogas of a Landfill in Tropical Area: Case Study of the Principal Landfill of Abidjan Akouedo Landfill. *Research & Reviews: Journal of Ecology and Environmental Sciences*, **6**, 1-7.

[44] Collaguazo, G., Badea, A., Stan, C., Apostol, T., Paraschiv, G. and Pasztai, Z. (2019) Landfill Gas to Energy Conversion from Oradea Municipal Waste Landfill in Romania. *Environmental Engineering and Management Journal*, **18**, 311-320. https://doi.org/10.30638/eemj.2019.030

[45] Collaguazo, G. Badea, A. Marculescu, C. and The, I. (2015) Estimation of the Energetic Potential of Household Solid Waste Based on Two Management Strategies: Landfilling and Thermal Conversion. *UPB Scientific Bulletin*, *Series C*, **77**, 419-431.

[46] Hanson, J.L., Manheim, D.C. and Yeşiller, N. (2023) Geoenvironmental Assessment of Climate Impacts from Landfill Gas Emissions. *Soils and Foundations*, **63**, Article 101279. https://doi.org/10.1016/j.sandf.2023.101279

[47] Idrissi Oukili, A., Mouloudi, M. and Chhiba, M. (2022) Landgem Biogas Estimation, Energy Potential and Carbon Footprint Assessments of a Controlled Landfill Site. Case of the Controlled Landfill of Mohammedia-Benslimane, Morocco. *Journal of*

*Ecological Engineering*, **23**, 116-129. https://doi.org/10.12911/22998993/145410

[48] Rafey, A. and Siddiqui, F.Z. (2023) Modelling and Simulation of Landfill Methane Model. *Cleaner Energy Systems*, **5**, Article 100076. https://doi.org/10.1016/j.cles.2023.100076

[49] Mor, S. and Ravindra, K. (2023) Municipal Solid Waste Landfills in Lower- and Middle-Income Countries: Environmental Impacts, Challenges and Sustainable Management Practices. *Process Safety and Environmental Protection*, **174**, 510-530. https://doi.org/10.1016/j.psep.2023.04.014

[50] Aghdam, E.F., Fredenslund, A.M., Chanton, J., Kjeldsen, P. and Scheutz, C. (2018) Determination of Gas Recovery Efficiency at Two Danish Landfills by Performing Downwind Methane Measurements and Stable Carbon Isotopic Analysis. *Waste Management*, **73**, 220-229. https://doi.org/10.1016/j.wasman.2017.11.049

[51] Fei, F., Wen, Z. and De Clercq, D. (2019) Spatio-Temporal Estimation of Landfill Gas Energy Potential: A Case Study in China. *Renewable and Sustainable Energy Reviews*, **103**, 217-226. https://doi.org/10.1016/j.rser.2018.12.036