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Evaluation of the Activity of a Municipal Waste Landfill Site in the Operational and Non-Operational Sectors Based on Landfill Gas Productivity

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Abstract: This research identifies the productivity of landfill gas actively captured at a municipal waste landfill site with a waste mass exceeding 1 million Mg from sectors in the operational and non-operational phases, considering meteorological conditions. Based on the analysis of landfill gas, including emissions and composition (CH_4, CO_2, O_2, and other gases), the processes occurring demonstrate the impact of the decomposition of deposited waste on the activity of the deposit. With average monthly gas emissions exceeding 960,000 m^3, the average content of CH_4 (30–63%) and CO_2 (18–42%) and the varied content of O_2 (0.3–9.8%) in individual sectors of the landfill site were significant. The statistically significant relationship between CH_4, CO_2, and landfill gas emissions exhibited a noticeable decrease in methane content. Despite the abandonment of waste storage, a high correlation is present between the emission level and methane content (0.59) and carbon dioxide (0.50). In the operational part of the landfill, this relationship is also statistically significant but to a lesser extent; Spearman's *R*-value was 0.42 for methane and 0.36 for carbon dioxide. The operational and post-operational phases of the municipal waste landfill demonstrated a noticeable impact from the amount of precipitation, relative humidity, and air temperature, on landfill gas productivity. The generally progressive decline in the activity of the waste deposit, which reflects a decreasing trend in the methane content of approximately 2% annually in the total composition of landfill gas, as well as the share below 50%, indicates the need only to utilise landfill without producing energy.

Keywords: landfill; landfill gas; municipal waste; methane; statistics

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1. Introduction

Approximately 2 billion tons of municipal solid waste is generated annually worldwide, of which at least 33% is not managed in an environmentally safe manner [1]. In Europe, over 1 billion tons of waste is generated each year, with the largest share being from construction and municipal management [2]. Generally, in developed countries, the continuous increase in generated waste calls for its reuse to minimise its impact [3]. A closed-circuit economy is advisable, characterised by a greater accumulation of selectively collected waste and rational conversion of residues into energy [4]. The hierarchy of waste management, which has been included in international and national regulations as a priority, indicates the following sequence of activities in waste management: prevention, preparation for reuse, recycling, other recovery (including energy recovery), and disposal [5]. Waste management and the 3R strategies (i.e., reduce, reuse, and recycle) are preventive activities that optimise the use of resources in activities related to raw materials management [6]. Landfilling of waste is considered the worst method and at the lowest level in the waste management hierarchy, increasing the impact on the environment [7,8].

In the construction of a landfill site, the sealing of the landfill floor, leachate intake and disposal, and landfill degassing system play important roles [9]. An active landfill gas (LFG) intake system includes a suction cup connecting collection points (i.e., vertical or horizontal perforated pipes) and a flare as an alternative solution. Vertical collection wells are an effective and widely used method of recovering LFG resulting from waste decomposition. In the case of vertical wells, their horizontal spacing is a critical design parameter [10]. The efficiency of captured LFG depends on waste coverage. Three types of covers are usually used in landfills: daily, intermediate, and final covers of various thicknesses [11]. To reduce surface emissions of CH_4 (methane) and its components into the atmosphere, horizontal seals made of geomembrane and geotextile with low filtration rates are introduced into the landfill site structure [12,13].

The guidelines of the European Commission indicate the need to minimise the amount of municipal waste deposited in landfill sites [14], including a maximum of 10% of the total amount of waste generated [15]. This forces an increase in the recovery of biodegradable waste in particular [16]. Municipal solid waste contains 150–250 kg of organic carbon per tonne, which anaerobic microorganisms convert into LFG [17]. Organic matter in landfill sites is degraded mainly in an anaerobic environment, resulting in the formation of products such as leachate or biogas, of which methane (CH_4) and carbon dioxide (CO_2) are critical components [18]. Methane is classified as a toxic and explosive gas [19], and in biogas obtained from a landfill site, it has a value of 1.25 about CO_2 and differs from that produced in a sewage treatment plant [20].

The remaining gas components include oxygen (O_2) and, in smaller amounts, acidic gases and pollutants, such as nitrogen (N_2), water vapour (H_2O), and trace amounts of other volatile organic compounds (VOCs) [21,22]. Oxygen affects the biodegradation of waste, which is classified as an aerobic or anaerobic process, depending on its content [23]. In the anaerobic fermentation process, an acidic, methanogenic phase can be separated by regulating the landfill operation parameters [24]. Acidic and methanogenic bacteria in the two-phase anaerobic fermentation process require optimal conditions for their development to achieve process stability [25]. Anaerobic conditions indicating a stable state of the landfill site (a constant phase of methanogenesis) change as the organic matter is consumed by bacteria [26]. Complete biological, anaerobic stabilisation of a waste landfill can be achieved even after 15 years [27]. The leachate level in the waste deposit also influences the formation of CH_4 and its emission [28]. Another factor is the recirculation of leachate in the landfill site, which may increase the biogas productivity by even double [29]. Castrillón et al. [30] compared new leachate with old and showed that the former had a more balanced mix of anaerobic microbial consortium with a significantly higher methanogen content.

LFG was examined by Carriero et al. [31], Ciuła et al. [32], Garcia et al. [33], Przydatek i Ciągło [34], Przydatek et al. [35], and Njoku et al. [36]. Scientists from various countries have shown that landfill sites are a major source of greenhouse gas (GHG) emissions [37]. The content of GHGs CH_4 and CO_2, the main components of biogas, depends essentially on the amount of stored waste, its chemical composition, and the moisture of the waste deposit [38]. Methane is a GHG with the potential to create a greenhouse effect 28 times greater than that of CO_2; hence, landfill sites contribute to global warming [39]. Methane is the second most potent anthropogenic GHG after carbon dioxide, with a global warming factor 32 times greater than that of CO_2 over the last 100 years [40]. A significant reduction in GHG emissions is the main goal of the United Nations in the Paris Agreement on Sustainable Development [41]. Therefore, European Union (EU) member states have committed to reducing GHG emissions by at least 55% by 2030 compared to 1990 [42].

Of note, the decomposition rate and, thus, the amount of emissions depends on not only the composition of waste [43] but also climatic conditions [44]. These include temperature, precipitation, humidity, and solar radiation [45–47]. Atmospheric pressure is also a tested biogas productivity factor [48].

In addition to waste composition, the age of deposited waste (<10 years) significantly influences LFG production. Most LFG is produced within five to seven years of waste being deposited in landfills [49].

In Europe, biogas recovered from landfill sites accounts for approximately 17% [50]. The essential parameters of biogas as a fuel include elemental composition, calorific value, minimum demand for air for combustion, flammability, and methane number values [51]. An organised collection of biogas from landfills results in reduced emissions. Therefore, the activities undertaken related to capturing biogas and its use for heating and energy production can help limit harmful emissions into the atmosphere [52]. However, according to Dos Santos et al. [53], economic efficiency remains a barrier to generating energy from biogas.

Anaerobic waste landfill sites where LFG is produced from the decomposition of organic material can be used as sources of energy production [54]. GHG energy recovery converts waste to energy (WTE) through a high-tech chemical process [55] in which non-recyclable solid waste is converted into useful electricity, heat, or fuel through combustion, gasification, and anaerobic fermentation [56]. Ultimately, biogas whose parameters change requires utilisation through combustion to minimise hydrocarbon content, among others [57].

This article aims to assess the activity of a municipal waste landfill deposit site in the operational and non-operational phases, taking into account the LFG components and local meteorological parameters in 2012–2018.

2. Materials and Methods

2.1. Facility

The tested landfill site is located in southeastern Małopolska (Figure 1).

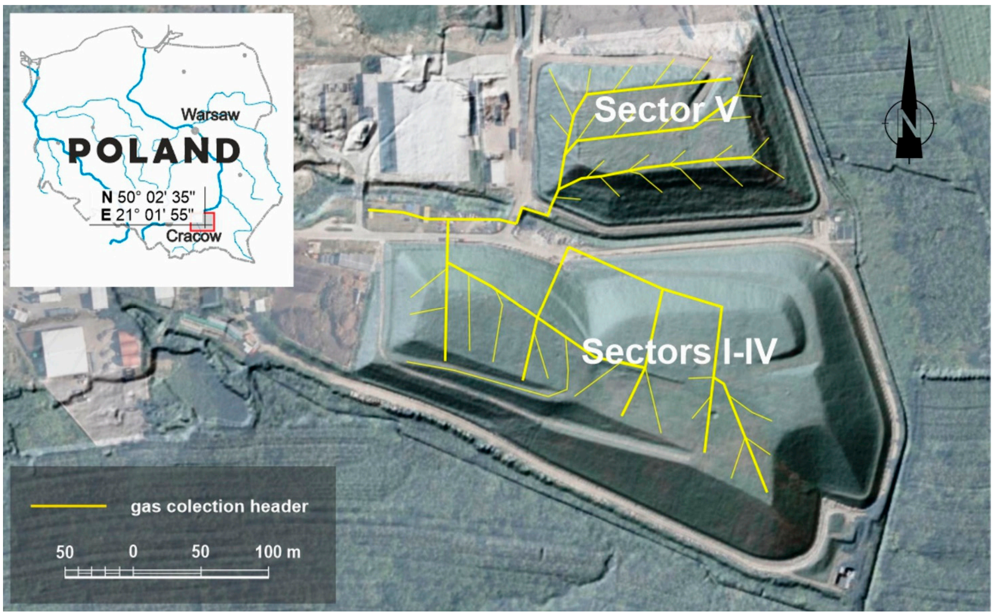

Figure 1. Installation of an LFG intake in the operational and non-operational parts of the landfill site (southeastern Lesser Poland, Poland).

The facility, which has been operating since the 1980s, is where municipal waste has been deposited, with particular emphasis in recent years on other waste. The site is located at the geographical coordinates of N 50°02′35″ and E 21°01′355″. This paper presents meteorological conditions at the landfill site in 2012–2018 based on monthly values of average air temperature (°C), total sunshine (h), total rainfall (mm), average wind speed (m/s), average humidity relative air pressure (%), and mean atmospheric pressure at station level (hPa). Meteorological data were obtained from the meteorological station of the Institute of Meteorology and Water Management (N 50°01′59″, E 20°59′04″) located near the landfill.

In the same period, LFG obtained separately from two sections was examined: sectors I–IV (non-operational sections) and sector V (operational sections). As part of the composition of LFG, the average monthly percentages of CH_4, CO_2, O_2, and other gases were determined. The gas volume (total quantity) was measured collectively for all sectors before disposal, and the gas composition was tested at two outlets from sectors I–V. Because of two technical breaks, the results are the amount of gas captured cover 76 months. Data on LFG and its components (CH_4, CO_2, O_2, and other gases) were made available by the landfill administrator for the years 2012–2018.

2.2. Statistics

Statistical parameters were determined for the examined meteorological elements and the amount and composition of LFG: minimum and maximum value, arithmetic mean, standard deviation, and variability index. The annual variability of meteorological conditions (relative air humidity, precipitation, and temperature) and the percentage of GHGs (methane and carbon dioxide) in the captured biogas from the landfill site were determined based on average monthly values. Statistical inference about the significance of differences in the percentage of GHGs obtained from sectors in the operational and non-operational phases was carried out using the non-parametric Mann–Whitney U test. The time trend of the percentage of methane content in the gas collected from the municipal waste landfill site was determined.

The dependence of the amount and composition of LFG in sectors I–IV and V on meteorological elements was determined. Correlational relationships were developed using Spearman's rank method because of the lack of normality of the distribution of the values of the analysed parameters according to the Shapiro–Wilk test results and the lack of equality of variances using the Fisher–Snedecor test. The Spearman R correlation coefficient is a non-parametric equivalent of the Pearson coefficient p that determines the strength of the correlation between variables (where $p < 0.05$ indicates statistical significance). Additionally, the dependences of the percentage contents of CH_4, CO_2, O_2, and other gases on the volume of the obtained gas were determined. The number of research samples ranged from 76 to 83. Statistical analyses were performed in the Statistica 12 program by StatSoft (Statsoft Inc., Tulsa, OK, USA; 12 for Windows).

2.3. Characteristics of the Landfill

The analysed landfill site is equipped with an installation for the capture, discharge, and utilisation of LFG. The degassing installation includes vertical degassing wells located in the waste bed. They are connected by a network, allowing the biogas to be discharged to the flare. The gas is actively extracted using a suction. The network includes more than 50 wells made of perforated pipes (polyethylene) covered with gravel, ending with heads. They are connected via pipes to a flare where the LFG is burned. The landfill sectors are sealed at the bottom and slopes. The insulation is made of a polyethylene geomembrane, geotextile, and a 1 m thick layer of clay. Sectors I–IV were closed during the research period and have remained at the recultivation stage. Waste was collected in sector V from November 2009 to the end of August 2017, and in 2018, the sector was subjected to technical and biological recultivation. The increasing amount of waste deposited in the landfill site exceeded 1,000,000 Mg and 92,000 m^2 over the study period.

3. Analysis of Research Results

3.1. Meteorological Parameters

The average monthly air temperature is 9.9 °C, ranging from −7.2 to 22.3 °C. The average monthly sunshine is 157.9 h, with a minimum value of 18.9 h. The monthly rainfall ranges from 0 to 211.4 mm, with a mean of 54.4 mm and a standard deviation of 40.1 mm. The monthly average wind speed is 1.6 ± 0.3 m/s, while the average relative humidity is 76.1 ± 5.8%, and atmospheric pressure is 991.6 ± 3.4 hPa. The meteorological elements used to measure altitude at the station include the coefficient of variation of 0.3% and relative air humidity of 8%. The highest correlation coefficient of >70% is for the relationship between the monthly air temperature and rainfall. Among the analysed meteorological parameters, the highest average value was atmospheric pressure (991.6 hPa). The highest standard deviation was observed in total monthly sunshine (93.5 h). The other variability index with the highest value was the average monthly temperature (77%) (Table 1).

Table 1. Basic statistics of the meteorological elements.

Parameters	Unit	Quantity	Min–Max	Average	Standard Deviation	Coefficient of Variation [%]
Monthly average temperature	°C	80	−7.2–22.3	9.9	7.7	77
Monthly average sunshine	hours	79	18.9–326.7	157.9	93.5	53
Monthly average rainfall	mm	83	0.0–211.4	54.4	40.1	74
Monthly average wind speed	m/s	70	1.0–2.4	1.6	0.3	19
Monthly average relative humidity	%	79	61.7–87.2	76.1	5.8	8
Monthly average pressure	hPa	79	982.5–1002.9	991.6	3.4	0.3

Annually, the warmest months are June, July, and August, with an average monthly air temperature above 17 °C. The coldest months are January and February, with an average monthly air temperature below 0 °C. The highest monthly rainfall above 70 mm falls in May, June, July, and September, and the lowest—below 40 mm—is in the winter period (November to March). The highest relative air humidity, with a monthly average of around 80%, occurs from September to February (Figure 2).

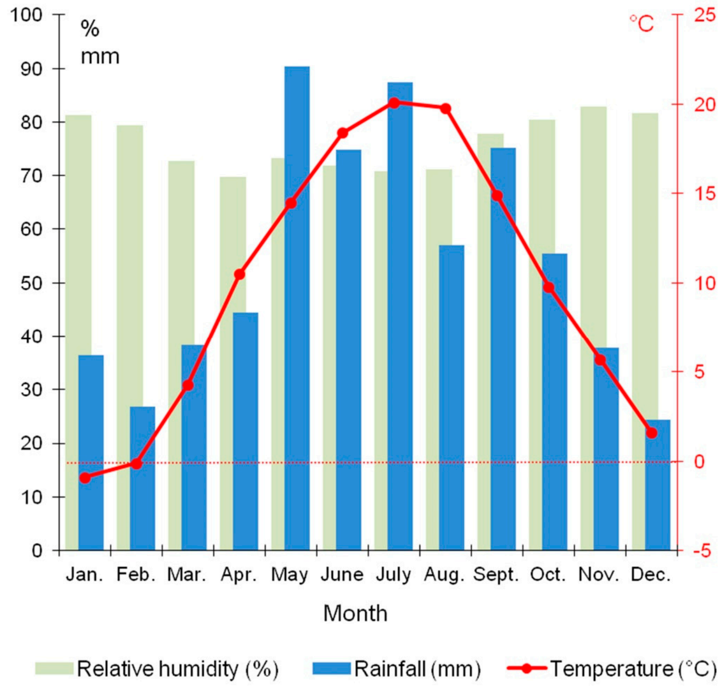

Figure 2. Average monthly values of meteorological elements in 2012–2018.

3.2. LFG

Over the seven years, the annual volume of LFG produced at the facility ranged from 46,626 to 149,569 m^3, with an average of 96,673 m^3. Both the highest average CH_4 content (46.6%) and the highest result (64.3%) occurred in operational sector V. Similarly, the highest average CO_2 content (33.6%) occurred in sector V. In unused sections, i.e., sectors I–IV, the average CH_4 and CO_2 concentrations were lower by 2.20 and 2.60%, respectively. The ratio of CH_4 to CO_2 volumes in biogas obtained in the non-operational sectors was 1.43, and in the exploited sector, it was 1.39. Additionally, the O_2 content in the tested gas ranged from 0.3 to 9.8% at the average concentration (0.69%), standard deviation (1.18%) and coefficient of variation (170%) in sector V. In the inactive part of the landfill, the oxygen content ranged from 0.3 to 6.3%, with an average of 0.66%. In turn, for CO_2, noticeably higher values of the standard deviation (5.0%) and the coefficient of variation (16%) were found in the gas captured in the non-operational sectors of the landfill site (I–IV). These sectors had the highest average other-gas content (24%) (Table 2).

Table 2. Basic statistics of the meteorological elements and the amount and composition of LFG.

Parameters		Unit	Quantity	Min–Max	Average	Standard Deviation	Coefficient of Variation [%]
Gas volume flow		m^3	76	46,626–149,569	96,673	30,712	32
Sectors I–IV	Methane CH_4	%	83	30.1–62.9	44.4	7.4	16
	Carbon dioxide CO_2	%	83	18.6–42.2	31.0	5.0	16
	Oxygen O_2	%	83	0.3–6.3	0.66	0.76	115
	Other gases	%	83	6.5–45.4	24.0	9.1	38
Sector V	Methane CH_4	%	83	31.2–64.3	46.6	7.3	16
	Carbon dioxide CO_2	%	83	17.7–42.1	33.6	4.7	14
	Oxygen O_2	%	83	0.3–9.8	0.69	1.18	170
	Other gases	%	83	3.7–40.3	19.1	9.1	48

Analysis of average monthly GHG values showed that over the seven years in non-operational sectors, the share of methane in LFG ranged from 40.5% in May to 46.3% in October. The amounts of CO_2 were lower, from 29.8% in June to 32.9% in July (Figure 3a). In the operational sector, the methane content ranged from 42.5% (February) to 52% (September), while the share of CO_2 ranged from 32% (March) to 34.6% (April) (Figure 3b).

A comparative analysis of the gas composition between the quarters in the operational (sector V) and non-operational phases (sectors I–IV) exhibited statistically significant differences. The gas obtained from sector V showed a statistically higher content of methane ($p < 0.05$) and carbon dioxide ($p < 0.001$) and a lower content of other gases ($p < 0.001$). The percentage of oxygen in LFG from both sections was at a similar level (Table 3). This is due to the age of the waste deposited in the individual quarters.

Table 3. Comparison of the composition of LFG in sectors of the non-operational (sectors I–IV) and operational (sector V) phases and results of the non-parametric Mann–Whitney U test.

Parameters	Unit	Median		Quartile				Results of Mann-Whitney U Test	
				Q_1	Q_3	Q_1	Q_3		
		I–IV	V	I–IV		V		Values of Statistic (Z)	Probability Test (p)
Methane CH_4	%	43.3	44.9	40.7	47.7	42.1	53.2	−2.12	0.03
Carbon dioxide CO_2	%	31.5	34.4	28.1	34.2	31.3	36.7	−3.71	<0.001
Oxygen O_2	%	0.5	0.5	0.5	0.5	0.5	0.5	−0.66	0.51
Other gases	%	24.5	19.5	18.2	30.5	9.6	24.6	3.40	<0.001

The research period showed a decreasing trend in the percentage of methane content in capturing LFG. According to the trend line, the share of methane in the operational sector was 53% in 2012, decreasing to 39% in 2018. In the non-operational sectors, methane decreased from 50% in 2012 to 38% in 2018 (Figure 4). The annual decrease in the percentage of methane in the total composition of the captured gas was approximately 2%.

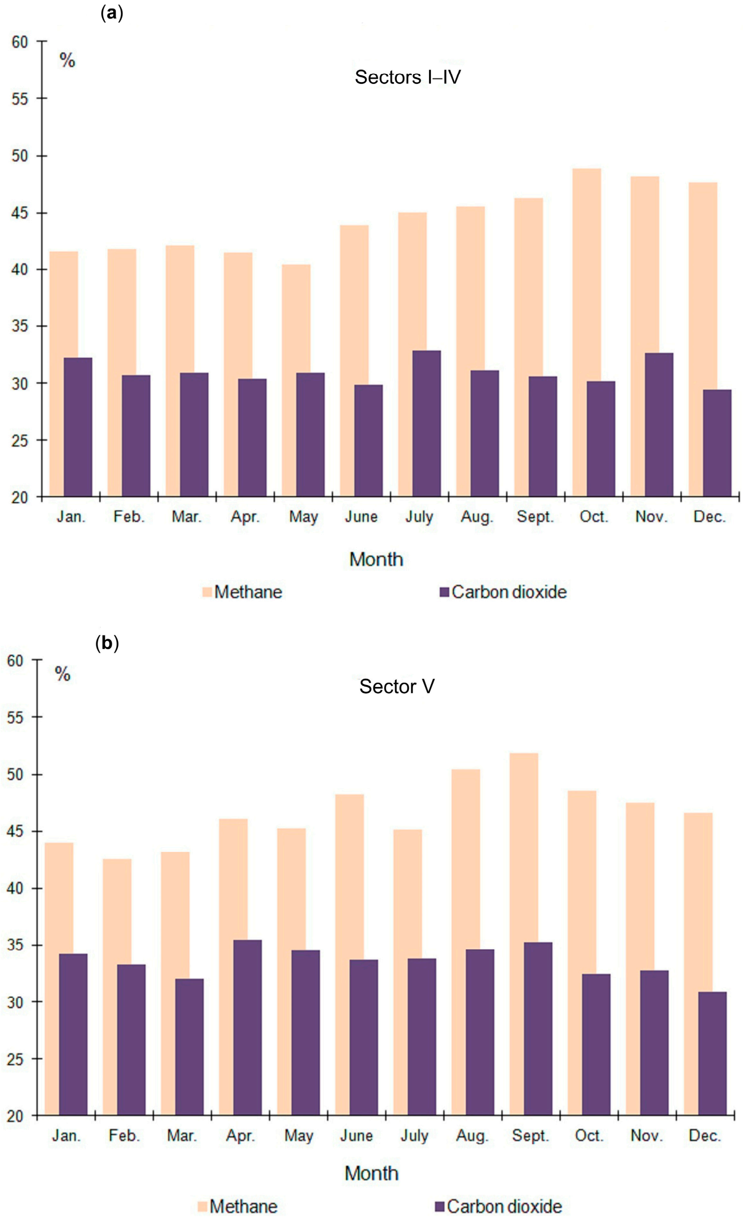

Figure 3. Average monthly percentage of methane and carbon dioxide in LFG for (**a**) non-operational sectors I–IV and (**b**) operational sector V.

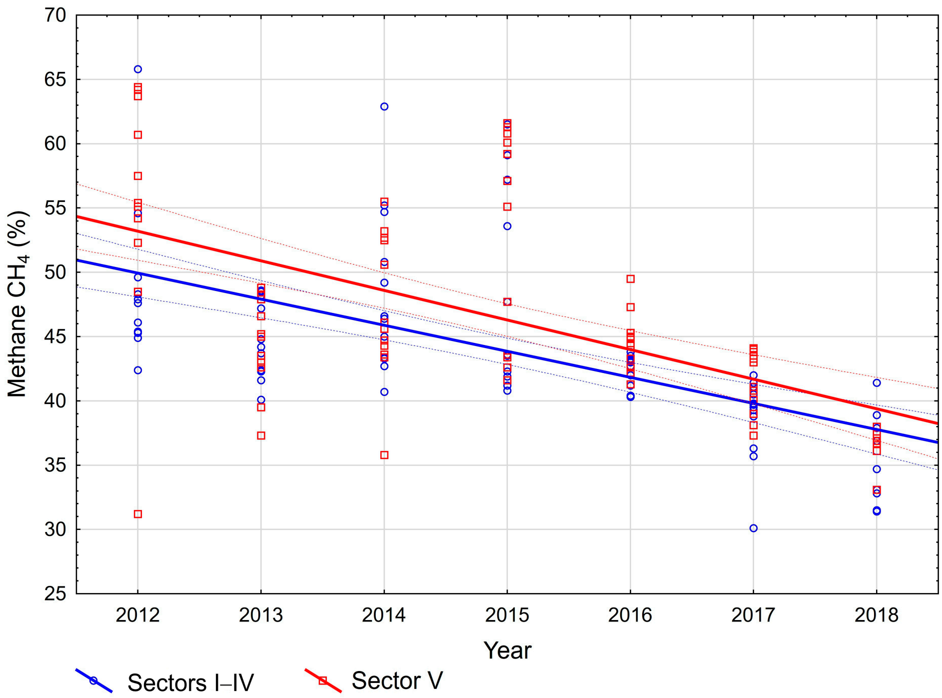

Figure 4. Percentage of methane in LFG along with the trend line in 2012–2018.

3.3. Correlations

Statistically significant relationships between the tested composition of LFG, including the content of CH_4 and CO_2, and the volume of captured gas showed a positive correlation in all sectors. Negative correlations were found for other gases and emissions, indicating that as the amount of captured gas increases, the percentage of other gases decreases (Figure 5a,b).

Statistically significant correlations between total LFG volume and methane content (Spearman's *R* of 0.59) and between LFG volume and carbon dioxide (0.50) occurred in the closed and reclaimed sectors. In contrast, the largest negative correlation occurred between gas emissions and the content of their other components (−0.66) in the non-operational sectors (Table 4). However, in the active sector, several correlations were noticeable but low, such as those between the total LFG captured and its contents of methane (0.42) and carbon dioxide (0.36).

Table 4. Dependence of the amount and composition of LFG in sectors I–IV and sector V on meteorological elements (Spearman's *R* correlation coefficient value).

Parameters	Unit	Gas Volume Flow (m^3)	Sectors I–IV				Sector V			
			CH_4	CO_2	O_2	Others	CH_4	CO_2	O_2	Others
Average monthly temperature	°C	0.20	0.05	0.14	0.04	−0.10	0.18	***0.31***	−0.11	***−0.25***
Average monthly sunshine	hours	0.09	−0.01	0.05	−0.06	−0.01	0.15	***0.28***	−0.20	−0.21
Average monthly rainfall	mm	***0.31***	0.16	***0.29***	0.10	***−0.26***	0.19	***0.22***	0.08	***−0.24***
Average monthly wind speed	m/s	−0.20	−0.18	−0.15	0.01	0.19	***−0.29***	***0.21***	0.08	***0.33***
Average monthly relative humidity	%	0.23	***0.30***	0.22	0.16	***−0.32***	0.14	−0.01	***0.27***	−0.11
Average monthly pressure	hPa	−0.07	0.08	−0.02	−0.04	−0.04	0.16	0.09	0.01	−0.15
Gas volume flow	m^3	–	***0.59***	***0.50***	0.20	***−0.66***	***0.42***	***0.36***	0.05	***−0.45***

Bold italics indicate a statistically significant value $p < 0.05$.

Taking into account meteorological parameters, statistically significant correlations are also noticeable in the inactive sectors between monthly precipitation and gas emission (0.31), average monthly humidity and methane content (0.30), and average monthly precipitation and CO_2 content (0.29). In the operational sector, the highest correlation was between the average wind speed and other gases (0.33). However, lower correlation values occurred between the CO_2 content and the average monthly temperature, average monthly sunshine, monthly precipitation, and average monthly wind speed, with values of 0.31, 0.28, and 0.21, respectively. The only tested meteorological factor that did not have a significant impact on the composition of LFG is atmospheric pressure.

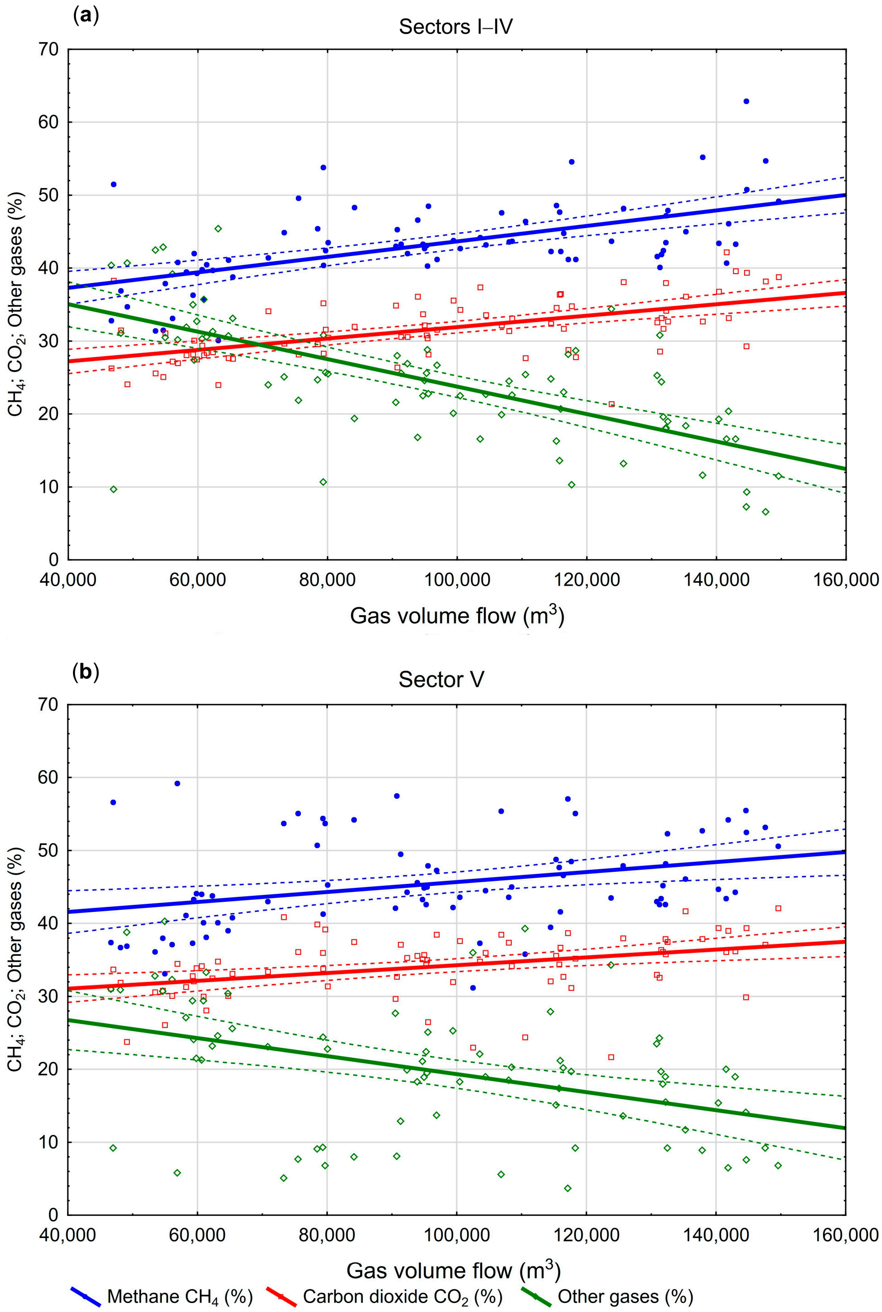

Figure 5. Dependence of the percentage of LFG composition on the amount of captured LFG in (**a**) sectors I–IV and (**b**) sector V.

4. Discussion of the Results

Municipal waste landfill sites are facilities whose activity is described by the volume of emissions released into the environment [58]. During operation and after their closure, waste landfill sites prevent specific areas from being used for many years and require assessment of the course of waste decomposition, in particular, because of the possible emission of GHGs harmful to the climate [59]. Landfill degassing is mainly aimed at the safe capture of LFG in the context of environmental protection, as well as maintaining safety for human life [60]. Unfortunately, some landfill sites still do not employ degassing of the waste deposit [61] to mitigate adverse effects on the environment.

The volume of LFG produced annually in 2012–2018 at the facility ranged from 46,626 to 149,569 m^3, with an average of 96,673 m^3. As mentioned in the introduction, a major source of GHG emissions is municipal waste landfill sites [62]. Components of LFG include methane and carbon dioxide, which are considered harmful anthropogenic GHGs [63]. In the captured biogas from the municipal waste landfill site under study, the operational sector V yielded average contents of CH_4 (46.6%) and CO_2 (33.6%) with small ranges. In the non-operational sectors I–IV, the average CH_4 and CO_2 concentrations were lower by 2.20 and 2.60%, respectively, with significant differences in CO_2 results (18.6–42.2%). Verbeeck et al. [64], for comparison, showed the CH_4 content in LFG at 40–75% and CO_2 at 25–60%. The CH_4/CO_2 content ratio in the tested LFG in the non-operational sectors was 1.43 and 1.39 in the operational sector. However, Lau et al. in 2011 [20] showed a lower CH_4/CO_2 ratio, suggesting a higher CO_2 content in biogas.

In this study, average methane contents exceeding 50% and 40% occurred in autumn in the operational and non-operational phases, respectively. Similarly, Bakkaloglu et al. [65] also showed high concentrations of methane at a closed landfill site. Differences between the components of LFG were also demonstrated by Damanhuri et al. [66]. In another study, Krause et al. [67] confirmed that CO_2 is readily soluble in water/leachate and CH_4 is relatively insoluble; hence, they concluded that its higher concentration in LFG is due to saturated conditions. Other researchers [68] showed that as the temperature increases beyond 55 °C, the methane content decreases because of less methanogenic activity.

Furthermore, a noticeable downward trend was present in the methane content at the tested landfill site. Xiaoli et al. [69] found that the decline in methane concentration progresses with the age of the landfill site, while Stolecka and Rusin [70] concluded that the energy use of LFG requires a CH_4 content of 50–60%. The contribution of another O_2 gas component at an average concentration of 0.69% and coefficient of variation of 170% was dominant in the active sector of the landfill, suggesting fluctuations, aligning with the results of Yilmaz et al. [71].

The waste deposit of the examined landfill site was assumed to be dominated by anaerobic processes, which, according to Sawyer et al. [72], can reduce the landfill area by 4%. In the non-operational sectors I–IV, the average oxygen content was 0.66%. Similarly, Masebinu et al. [73] showed oxygen of 0.40% in a closed landfill site. However, Przydatek et al. [35] recorded a higher average oxygen content in operational and non-operational landfill sites, exceeding 20%. According to Njoku et al. [36], the increased content of oxygen in waste leads to a reduction in methane content.

The relationships between the tested LFG composition, including CH_4 and CO_2 content, and its total volume showed a statistically significant positive correlation in the operational and non-operational sectors of the landfill site. Yang et al. [74] demonstrated a similar positive correlation between the studied GHGs. This study found a statistically significant negative correlation for other gases and emissions. In addition, a high correlation occurred between total LFG volume and methane content (Spearman's R of 0.59) and between total LFG volume and carbon dioxide (0.50) in operational and non-operational sectors. In contrast, the highest negative correlation occurred between gas emissions and the content of its other components (−0.66) in the non-operational sectors.

Other gases in LFG include trace amounts of hydrogen sulphide, hydrogen, carbon monoxide and non-methane organic compounds, of which nitrous oxide is a GHG [75]. Ogata et al. [76], when examining LFG, showed a negative correlation between ammonia and CH_4 and CO_2. Harborth et al. [77] omitted the issue of other gases, including N_2O, arguing that it was not related to climate change. In the operational sector, several correlations were noticeable but low, such as those between the amount of gas captured and its contents of methane (0.42) and carbon dioxide (0.36). Low correlation values between CH_4 and its variables were also obtained by Javadinejad et al. [78]. However, other researchers [79] showed that CH_4 is strongly correlated with economic development and population growth.

Meteorological parameters, such as atmospheric pressure, wind speed, precipitation amount, and temperature, influence LFG emissions [48]. Statistically significant correlations between monthly precipitation and gas flow (0.31), average monthly humidity (0.30), methane content, and precipitation and carbon dioxide content (0.29) were noted in the non-operational part of the landfill site. A similar positive correlation between humidity and methane content was demonstrated by Javadinejad et al. (2019) [78]. A different negative correlation between humidity and methane content was presented by Khaliq et al. (2024) [80]. According to Ruoso et al. [81], the main factors influencing biodegradation are humidity and the organic carbon fraction content. Some researchers [82,83] showed the influence of meteorological factors on the emissivity of LFG, especially temperature and its effect on the CO_2 content. The authors found that the highest average monthly CO_2 content in the studied gas, amounting to 32.9%, occurred in summer with significant precipitation. Gollapalli and Kota [46] also showed higher CO_2 concentrations in LFG during summer.

The correlation between meteorological parameters (precipitation, atmospheric pressure, wind speed, and temperature) and LFG concentration was studied by Delgado et al. [84]. In this study, during landfill operation, a statistically significant correlation was present between the average wind speed and other gases (0.33). A high positive correlation in the landfill was also shown by Kissas et al. [85]. Correlations between CO_2 and temperature, sunshine, and wind speed were slightly lower in the present study. Njoku et al. [36] showed that when the CH_4 content decreases, there is a noticeable increase in CO_2. In turn, Pinheiro et al. [86] explained that CH_4 oxidation in the landfill causes higher CO_2 concentration than CH_4 concentration.

Similarly, Manheim et al. [23] showed statistically significant relationships between CH_4 and CO_2 and meteorological parameters prevailing within the landfill site, indicating that meteorological parameters may, to some extent, influence the CH_4 content [87,88]. The highest average methane content, exceeding 50% in the operational phase and 40% in the non-operational phase, occurred in autumn. Monster et al. [63] confirmed the seasonal variability of methane content in LFG in their study [89].

Using statistical tools, Kasinath et al. [90] showed the relationship between the parameters of the generated biogas and its rational use, taking into account the environmental aspect. The analysed landfill site as a waste disposal facility is a certain type of bioreactor producing biogas, which, for environmental reasons, should be captured and disposed of [91,92]. Biogas is generally treated as a valuable source of renewable energy produced in anaerobic conditions in a waste landfill site, which, because of the CH_4 content, can be recovered in the form of combined energy [93,94] or ultimately flared to protect the atmosphere from harmful emissions.

A noticeable progressive decline in the activity of the waste deposit, reflecting the decreasing trend in the methane content, as well as its content below 50% in the overall composition of LFG, indicates the need for utilisation by burning LFG [95] using a catalyst from a molecular deposit (CuO) to minimise harmful emissions into the atmosphere [96] without the production of energy in the combined form. Amini and Reinhart [97] showed that generating electricity based on biogas reduces GHG emissions by 78% compared to direct flaring in landfill sites.

5. Summary and Conclusions

This research reviewed seven years of data showing the emission and composition of LFG actively captured in a municipal waste landfill site, originating from the operational and non-operational sectors, taking into account meteorological conditions.

The analysis of the results showed that, with the average annual gas emission exceeding 96,000 m^3, the highest average contents of two biogas components classified as GHGs—CH_4 (46.6%), CO_2 (33.6%), and O_2 (0.69%)—occurred in the operational sector of the landfill site. The non-operational sectors of the facility had a higher CH_4/CO_2 ratio (by 0.04) compared to the operational sector. Moreover, in sector V, the oxygen content exhibited significant fluctuations, confirming the dispersion (standard deviation of 1.18%) and differentiation (coefficient of variation of 170%). The average oxygen content below 0.70% implies the dominance of anaerobic processes, which indicates stabilisation of the activity of the waste deposit. However, the significant dominance of anaerobic processes in the waste deposit may be a consequence of the reduction in the landfill area. Therefore, in the non-operational sectors, the average CH_4 and CO_2 contents were lower by 2.20 and 2.60%, respectively.

The varied course of the decomposition process of deposited waste is reflected in statistically significant relationships between the composition of the LFG in terms of CH_4 and CO_2 and emissions, which generally showed a positive correlation. The approximately 2% decrease in CH_4 content is a consequence of the ageing of waste stored since the 1980s. The noticeable high correlations between the total LFG volume and methane content (0.59) and carbon dioxide content (0.50) indicate that changes are still taking place in the waste deposit in the part where waste storage has ceased. An increase in the amount of gas captured from a landfill site results in a statistically significant increase in the percentage share of GHGs (methane and carbon dioxide) and a decrease in the share of other gases.

Based on the analysis of meteorological conditions, a statistically significant correlation (0.31) between precipitation and gas emission was found in the non-operational sectors of the landfill site. In addition, similar correlations were noted between humidity (0.30) and methane content and between precipitation and CO_2 content (0.29), confirming the significant influence of humidity on biodegradation and biogas productivity.

However, in the operational sector, a significant correlation occurred between wind speed and other gases (0.33), which indicates that meteorological parameters may influence the CH_4 content to some extent. Moreover, without reclamation cover, atmospheric conditions significantly affected the CO_2 content in the captured gas. An increase in air temperature, sunshine, rainfall, and wind speed increased the CO_2 content in biogas obtained from the landfill site. Of note, the highest CO_2 content, exceeding 30%, occurred in summer at the highest air temperature, while the highest methane content, exceeding 50%, occurred in autumn, which indicates seasonal variability of the composition of LFG. The highest average temperature and rainfall in summer generally indicate the impact of meteorological factors on the parameters of LFG both during operation and after the cessation of waste storage. In the closed sectors of the tested landfill site, the composition of biogas depends only on the amount of precipitation and the relative humidity of the air.

Generally, a low methane content of <50% and an approximately 2% annual decrease in its content in the overall composition eliminates the energy generation from LFG. However, utilising the gas in a flare through combustion via a catalytic converter can minimise harmful emissions into the atmosphere, including GHGs.

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