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Sustainable Management of Landfill Methane Emissions in Poland: The Role of the Pollutant Release and Transfer Register

Józef Ciuła [1], Elżbieta Sobiecka [2,*], Tomasz P. Olejnik [3], Anna Kochanek [1] and Agnieszka Dorota Woźniak [4]

[1] Faculty of Engineering Sciences, State University of Applied Sciences in Nowy Sącz, Zamenhofa 1A, 33-300 Nowy Sącz, Poland; jciula@ans-ns.edu.pl (J.C.); akochanek@ans-ns.edu.pl (A.K.)
[2] Institute of Natural Products and Cosmetics, Faculty of Biotechnology and Food Sciences, Lodz University of Technology, ul. Stefanowskiego 2/22, 90-357 Lodz, Poland
[3] Department of Occupational Safety Engineering, Faculty of Process and Environmental Engineering, Lodz University of Technology, ul. Wolczanska 213, 93-005 Lodz, Poland; tomasz.olejnik@p.lodz.pl
[4] State University of Applied Sciences in Krosno, Rynek 1, 38-400 Krosno, Poland; agnieszka.wozniak@pans.krosno.pl
* Correspondence: elzbieta.sobiecka@p.lodz.pl

Abstract

Waste management is a vital component of modern economies, requiring not only technological solutions, but also economic and social approaches that reflect human needs while minimizing environmental harm. Within the European Union, sustainable development remains a central objective, promoting strategies in which waste is not merely disposed of, but is also recovered and reused whenever feasible. Landfill gas, primarily composed of methane, can be captured and managed in a controlled way. If left unregulated, methane emissions present serious risks to human health and contribute significantly to environmental degradation. At the same time, methane represents a valuable yet underutilized renewable energy source. In Poland, emission monitoring is conducted through the National Pollutant Release and Transfer Register, which operates as part of a broader European system. Landfill operators must report methane emissions and pay associated environmental fees. This study aimed to estimate methane emissions across Polish voivodeships from 2019 to 2023, considering both economic and social dimensions of sustainability. The analysis relied on official register data and landfill documentation, enabling evaluation of reporting accuracy and regulatory effectiveness. The findings indicate that current policies insufficiently encourage emission reductions, highlighting the need for systemic reforms, improved transparency, and clearer regulatory thresholds to drive meaningful environmental progress.

Keywords: sustainable management; environmental policy instruments; environmental and socio-economic sustainability; landfill gas; methane emission

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1. Introduction

Methane (CH_4) is the second most harmful greenhouse gas emitted by humans after carbon dioxide (CO_2). It contributes significantly to global warming, thereby affecting the entire ecosystem. The Global Warming Potential (GWP) values from the IPCC Sixth Assessment Report (AR6) for methane (CH_4), covering biogenic sources over 100-year timeframes, have been updated, and methane is now 28 times more harmful than carbon dioxide. [1,2]. The International Energy Agency (IEA) predicts that a 75% reduction in methane emissions from the fuel and energy sector by 2030 is one of the key conditions for limiting global warming to 1.5 °C. Moreover, methane indirectly contributes to air pollution as a precursor of tropospheric ozone, which has adverse long-term effects on human health [3,4]. In 2024, the global fossil fuel sector emitted approximately 200 billion cubic meters of methane. Reducing the scale of this phenomenon would not only benefit the rapidly warming climate but also increase the available supply of natural gas [5,6]. The European Union's (EU) approach to reducing methane emissions remains a continuing challenge arising from the complex issue of methane's impact as a potent greenhouse gas. Methane accounts for about 12% of total greenhouse gas emissions in the EU, equivalent to 17 million tons of CO_2 equivalent. Once released into the Earth's atmosphere, methane has a much higher heat-trapping capacity than carbon dioxide. This fact makes reducing its emissions crucial for achieving climate goals [7]. In the energy sector, which is responsible for about 19% of methane emissions in the EU, greater progress has been achieved thanks to regulatory measures and market developments [8,9]. Currently, a significant portion of municipal waste worldwide is still disposed of in landfills, which emit anthropogenic methane. This situation calls for decisive action to accurately estimate greenhouse gas emissions from landfills, particularly methane [10,11].

For this reason, it is concluded that achieving air quality standards for ozone will require a reduction in methane emissions [12,13]. The management of municipal waste, selectively collected into biodegradable fractions, requires the implementation of appropriate processing methods within the framework of a circular economy. This particularly concerns the treatment and neutralization processes of waste deposited in landfills, both currently stored and those deposited in previous years, which generate numerous environmental and public health problems. Among these risks is the release of methane resulting from the processing of municipal waste in waste treatment facilities and from landfill surfaces [14,15]. Considering environmental aspects, photovoltaic installations are increasingly being used at landfill sites as part of their energy balance, enabling the use of renewable energy sources [16,17].

1.1. Legal Framework

Methane emissions from landfills represent 40–60% of the methane contained in landfill gas, which is often not utilized for on-site energy production. Consequently, this issue has been regulated under the Environmental Protection Law [18,19]. This law establishes the National Pollutant Release and Transfer Register (PRTR), hereinafter referred to as the National Register, which forms part of the European Pollutant Release and Transfer Register (E-PRTR), as set out in Regulation (EC) No. 166/2006 on the establishment of the European Parliament and of the Council of 18 January 2006 concerning the establishment of a European Pollutant Release and Transfer Register and amending Council Directives 91/689/EEC and 96/61/EC (OJ EU L 33, 4 February 2006). The National Register is maintained by the Chief Inspector of Environmental Protection. Any operator of an installation carrying out at least one of the activities listed in Annex I of Regulation 166/2006, who operates the installation above the performance thresholds specified in that annex, must submit a report to the Regional Inspector of Environmental Protection. This report includes data on threshold exceedances for pollutant releases and transfers referred to in Annex II of Regulation 166/2006, as well as waste transfers specified in Article 5(1)(b) of that regulation, taking into account the scale of production. The report must be submitted by 31 March of the year following the reporting year. The Regional Inspector of Environmental Protection assesses the quality of the data provided by operators and forwards it to the Chief Inspector of Environmental Protection, who then submits the relevant report to the European Commission [20,21].

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Waste management in Poland is implemented on the basis of the Waste Act, which defines measures aimed at protecting the environment, as well as human life and health, by preventing the generation of waste, reducing its quantity, and minimizing the negative impact of waste production and management. The Act indicates possible approaches to reduce the overall impact of resource use and to improve the efficiency of such use in order to move towards a circular economy. These actions are consistent with the circular economy strategy and the ESG reporting system, which, at the level of vehicle production in the automotive industry, imposes requirements regarding the impact on climate change [22,23]. The detailed scope and method of reporting are specified in the Regulation of the Minister of Climate and Environment of 22 February 2022, on data included in the National Pollutant Release and Transfer Register (NPRTR). The regulation defines the format of the report containing data on exceeding threshold values for pollutant releases and transfers. Additionally, it specifies the detailed scope of data necessary to identify the facility where the installation operates, as well as the technical conditions, form, procedure, and method of submitting the report and data required for facility identification [24,25].

1.2. Environmental Considerations

Landfill gas generated within a waste deposit through anaerobic processes contains about 50% methane, a flammable gas which, if not properly captured and utilized (for example, for energy purposes), can have an adverse impact on the environment [26,27]. Due to landfill leakages, the gas may migrate into the soil, displacing air in the root growth zone and creating anaerobic conditions. Additionally, landfill gas negatively affects soils by altering their mineral composition, which also impacts vegetation [28,29]. The main component of landfill gas, alongside carbon dioxide, is methane, a flammable gas that poses a serious explosion risk within the landfill and its surroundings when it forms explosive mixtures with air. Therefore, during landfill operation, it is necessary to implement active landfill degassing systems, manage the biogas produced, and conduct continuous monitoring [30,31]. Landfill biogas and the methane it contains can also pose a potential threat to the quality of surface and groundwater. The degree of water contamination depends primarily on the distance between the waste deposits and watercourses, as well as on geological and hydrological conditions [32,33]. Landfill gas, which contains two main components, carbon dioxide and methane, as well as volatile nitrogen, sulfur, and chlorine compounds, is classified among the most significant greenhouse gases with a potential impact on global climate change. According to the Kyoto Protocol, the emission of 1 Mg of methane is equivalent to the emission of 21 Mg of carbon dioxide, which is considered the main greenhouse gas on Earth [34,35].

1.3. Landfill Emissions—Health Aspects

Methane, which is an odorless gas, undergoes self-ignition at a temperature of 235 °C, resulting in the formation of additional compounds mainly associated with the material being combusted. The impact of methane on the health of people living in the immediate vicinity of landfills and of workers employed at these sites is an important but complex area of scientific research [36,37]. These studies face many methodological limitations, including difficulties in assessing human exposure to methane because such an assessment requires long-term analysis. Methodological challenges also result from the fact that individuals may be exposed to multiple other factors simultaneously, which can influence their health condition. From a methodological point of view, population migration is also significant, both toward and away from areas near landfills [38,39]. This makes it difficult to conduct prospective studies that require reliable and long-term observation, such as research assessing carcinogenic effects, which require many years of monitoring. The

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relationship between waste disposal and human health is often discussed, but scientific studies do not provide conclusive evidence because researchers have obtained different results in the course of their analyses [40,41].

Legislative regulations in the area of waste landfilling introduced over the past 20 years have significantly reduced its negative impact on the environment and human health, contributing to improved living conditions and health safety for both employees working at these sites and residents of nearby areas. However, it is important to intensify research enabling the assessment of risks associated with methane exposure among workers and residents living in the vicinity of waste landfills, taking into account lifestyle factors and socio-demographic variables, which are often overlooked in such studies. These findings would constitute an important argument in the process of determining suitable locations for landfills [42,43]. Methane contributes to air pollution as one of the precursors of tropospheric ozone (O_3). Tropospheric ozone damages human tissues and indirectly causes approximately one million deaths worldwide each year [44]. Methane is a flammable, explosive, and toxic gas, a fact that correlates with its energy properties. Human exposure to this gas can result in shortness of breath, coughing, and a burning sensation in the mouth. Therefore, appropriate procedures should be implemented, including risk assessment along with proposed tools and techniques to protect human health when exposed to methane [45]. The long-term effects of emissions from landfills have a significant impact on human health and can lead to many diseases. Methane primarily affects human health indirectly through air pollution. A significant effect of its presence is the formation of tropospheric ozone, which is extremely harmful. This compound is linked to respiratory problems. Elevated ozone levels can result in serious conditions such as asthma, bronchitis, and emphysema. Numerous research findings suggest that reducing methane emissions could alleviate lung diseases affecting hundreds of thousands of people worldwide [46]. Research on emissions from landfills and their impact on human health primarily focuses on methane and volatile organic compounds—air pollutants that are potentially hazardous to humans. When considered locally, this problem affects landfill workers and people living near the landfill who are exposed to inhaling pollutants in the air, which can cause acute or chronic illnesses [47]. One method of neutralizing methane present in landfill gas at waste landfills is the use of a biological filter to oxidize the methane. Accordingly, relevant studies were conducted in this work, which confirmed the effectiveness of this solution, resulting in a reduction in the risk of cancer by an average of 79% and in the hazard ratio by an average of 92% [48].

1.4. Economic and Social Aspects

In Poland, the amount of methane emissions into the atmosphere reported in the PRTR (Pollutant Release and Transfer Register) is subsequently declared by the landfill operator as pollution released into the air due to gas emissions, subject to a fee pursuant to the Notice of the Minister of Climate and Environment on the rates of fees for the use of the environment for a given calendar year [49,50]. Methane emissions in Poland in 2023 amounted to 1.9 million Mg, which corresponds to 40.09 million Mg of CO_2 equivalent. Emissions in 2023 were 48.8% lower than in 1988 and 2.1% lower than in 2022. The share of methane in Poland's total greenhouse gas emissions in 2023 was 11.5%. The three main sources of methane emissions fall into the following categories: fugitive emissions from fuels—42.4%, agriculture—40.7%, and fuel combustion—9.0% [51]. Greenhouse gas emissions, including methane, and their consequences, apart from environmental and social aspects, should also include an economic analysis on both micro and macro scales, along with an assessment of financial impacts. To date, existing economic mechanisms have not reflected the actual harmfulness of methane emissions.

The economic aspects of sustainability reporting in the context of the environment, society, and corporate governance (ESG) were presented in the study by Matuszak-Flejszman et al., who demonstrated how commercial banks in Poland report such activities. The authors, specifying environmental factors, referred to how economic activity affects climate change through greenhouse gas emissions, pollution and waste management, as well as the impact on biodiversity and the natural environment [52,53]. In their research, the team presented sustainability reporting based on data obtained from Polish banks, taking into account different approaches and scopes of data presentation. It was found that a positive effect of ESG reporting is the improvement of indicators, such as the reduction in greenhouse gas emissions, the elimination of exposure to the extractive sector, and the increase in green financing in investments [54].

Studies conducted by Kluczek et al. [9] showed how the diversification of energy policies in individual countries affects key economic outcomes in European countries, with particular emphasis on the economic aspects of the relationships between energy prices, climate regulations, and greenhouse gas emissions. The research results present a new framework for assessing the economic implications of the diversification of energy and climate policies at the EU level in relation to climate change. The economic and energy efficiency of agricultural holdings in Poland, in the context of climate change and its negative environmental effects, were addressed in the study by Wysokiński et al., who demonstrated a conflict between economic and environmental interests. The study used an indicator of economic and energy efficiency, which enables a combined assessment of technical and economic performance [55]. The authors demonstrated the need for food production characterized by low energy consumption and a positive energy balance, emphasizing the necessity of developing a support system for agricultural holdings with the highest levels of economic and energy efficiency. The economic costs and social benefits resulting from methane emission reduction were presented in the study by Qi and Feng [56], who discussed the current challenges in achieving CH_4 emission reductions and proposed possible technical pathways for future climate change mitigation actions. The analysis of emission volumes and reduction methods showed that approximately 47% of anthropogenic methane emissions can be mitigated, and the negative effects reduced, using available technologies, most of which can be implemented at relatively low financial costs [57,58].

1.5. Sustainable Development and Renewable Energy

Municipal waste management is closely related to the concept of sustainable development. This also applies to renewable energy generated from biodegradable waste through anaerobic digestion processes in closed bioreactors, as well as at municipal waste landfills [59,60]. Biodegradable waste deposited in previous years at landfills is the source of biogas, a renewable energy carrier containing approximately 50% methane [61,62]. The generation of electricity and heat from landfill gas is a process that optimizes energy management and diversifies energy sources. Renewable energy constitutes an important supplement to the energy mix both at the local and national levels [63,64].

Renewable energy derived from methane contained in landfill biogas should be captured and used for energy purposes at landfill sites as a mechanism supporting sustainable development. In contrast, uncontrolled methane emissions into the atmosphere represent a hazardous phenomenon with negative consequences for both the environment and human health [65,66]. Numerous studies have reported disturbances in methane emission reporting and a decrease in the level of methane released into the atmosphere during the COVID-19 period, including in rural areas. This situation resulted from a decline in production activities, such as agriculture and industry, as well as limited mobility of personnel responsible for emission measurements and reporting, which hindered data collection [67,68].

Locally generated renewable energy ensures energy security, primarily for micro-scale prosumers, provided that their locations are optimized through the use of information technology tools such as Geographic Information Systems (GIS). This applies to biogas production technologies used at waste landfills as well as in agricultural biogas plants, which in the agricultural sector help to offset methane-related burdens from animal and crop production [69,70]. The integration of renewable energy sources with sustainable development goals is one of the key tasks confronting countries implementing circular economy strategies [71,72].

Renewable energy sources provide emission-free energy production, yet at the same time they require new competencies, new business models, and improved energy distribution systems. In this way, they become a cornerstone of sustainable development, supporting the achievement of global climate objectives and the energy transformation of the economy [73,74].

The research fills a gap in publications on national-level balancing of methane emissions from landfills covered by the European Pollutant Release and Transfer Register. In addition, it points to the low level of fees paid by landfill operators to compensate for these methane emissions. The study also draws attention to the need to verify the reliability of data and the methods used to calculate it [75,76]. The main objective of the study is to present control mechanisms for that portion of landfill gas which, for economic and technological reasons, cannot be captured or utilized at landfills. In this context, the PRTR system serves as a tool for monitoring and managing emissions within the framework of sustainable development in waste management. This primarily concerns diffuse (uncontrolled) emissions from the surface of landfills. Uncontrolled methane emissions from municipal landfills result mainly from the way the landfill is operated and the type of degassing system. These emissions occur both at active landfills currently in operation and at those that have already been reclaimed. Leaks in the degassing system can be an additional source of uncontrolled emissions. The magnitude of uncontrolled emissions depends, among other things, on the type of landfill and the sealing layer technology used. A key factor in landfill operation is the degree of waste compaction, achieved using appropriate equipment such as compactors. Available technical solutions do not guarantee 100% capture of landfill gas generated at the waste landfill; however, they demonstrate degassing system efficiency in the range of 60% to 80%. This range is the subject of reporting on methane emissions to the air. The novelty of this study regarding emissions recorded in the PRTR system is that it highlights the disproportionate burden of fees for emitting 1 Mg of methane into the air compared to the social impact. The aim of this study was not only research-oriented but also practical and social, allowing for a broader perspective on the issue. The results of this study should spark a discussion regarding the determination of unit fees for emissions of one ton of methane in relation to potential social and economic impacts. Additionally, the discussion should address the appropriateness of the method chosen by the landfill operator to estimate emission levels in order to ensure the reliability of the final results.

2. Materials and Methods

2.1. Methodology and Data Sources

The research presented in this study concerns the analysis of the methods for monitoring and reporting methane emissions into the atmosphere from municipal waste landfills, taking into account social, economic, and energy-related aspects. The quantitative analysis was carried out based on data provided by enterprises on the amount of methane emitted into the atmosphere, obtained through the examination and analysis of relevant documentation. The quantitative analysis of methane emissions derived from PRTR reports does not address methane potential, e.g., in energy terms. For this purpose, databases containing information on methane released from landfill surfaces for the years 2019 and 2023 were used. These databases are available in the resources of the Chief Inspectorate of Environmental Protection, in the section PRTR—National Pollutant Release and Transfer Register [77].

Given climate change caused by greenhouse gas emissions and the limited possibilities for reducing methane emissions from landfills, particular attention should be paid to reliable data monitoring. It is also crucial to select the appropriate method for calculating methane emissions depending on the type of landfill, both active and reclaimed. In 2023, a total of 13.4 million Mg of municipal waste was generated in Poland, of which 4.06 million Mg, representing 29.85%, was directed to disposal processes through landfilling. Between 2013 and 2023, the number of active municipal waste landfills showed a decreasing trend, although the rate of decline gradually slowed down. As of 31 December 2023, there were 254 municipal waste landfills operating in Poland, occupying an area of 1632.7 hectares, 21% of which had been reclaimed.

At the end of 2023, there were 236 landfills in Poland equipped with degassing installations, covering 92.9% of all active landfills where municipal waste was deposited. Among these degassing installations, 51.3% discharged gas directly into the atmosphere, 10.6% included systems where landfill gas was combusted with heat recovery, and 27.5% were installations using landfill gas for electricity generation. At the regional level, total methane emissions in Poland reached 1.9 million Mg in 2023, which, according to data from the National Centre for Emissions Management (NCEM), represented around 7.5% of the total methane emissions in the European Union. In the same year, waste landfills accounted for 2.3% of methane emissions into the atmosphere.

Since a municipal waste landfill is a source of air pollution emissions, the operator of such a facility is obliged to report methane releases. The exceedance of threshold values for methane is defined in Regulation (EC) No 166/2006 of the European Parliament and of the Council of 18 January 2006. The operator of any facility carrying out one or more of the activities listed in Annex I, including a landfill that accepts 10 Mg of waste per day or has a total capacity of 25,000 Mg, is required to report air releases of pollutants specified in Annex II, for which the applicable threshold value has been exceeded.

The threshold value for methane (CH_4), identified by CAS number 74-82-8, for air releases is 100,000 kg per year. When this threshold is exceeded, the landfill operator is required to report annually to the competent authority quantitative data, specifying whether the reported figures are based on measurement, calculation, or estimation [10].

The assessment of gaseous pollutant emissions released into the atmosphere from municipal landfills can be conducted based on actual measurements of emission rates or on theoretical estimates, assuming certain parameters. To estimate the volume of methane emissions from the landfill surface, the facility operator may use several methods recommended by the European Commission, as outlined in the guidelines for implementing the European Pollutant Release and Transfer Register [78]. These include: measurement-based methods, an estimation-based method incorporating the standard IPCC methodology, and calculation-based methods. Theoretical calculations use average parameter values; however, the imperfections of measurement methods, their transient nature, and the variability of emissions over time mean that calculations over a longer period are subject to error [79]. Methodologies for determining fugitive emissions from landfills were developed in November 2003 in Luxembourg in the form of a supporting document for the European Pollutant Release and Transfer Register. The developed methodologies are currently used by landfill operators to estimate the final amount of methane emissions [80].

2.2. Statistical Tools

In this study, Statistica software, version 14.1.0.4 (TIBCO Software Inc., Palo Alto, CA, USA, 2023), was used as a tool for the statistical analysis of the research results, performing cluster analysis in the form of a hierarchical tree. Ward's method was applied as the agglomeration technique, representing the distances between clusters and using an analysis-of-variance approach that minimizes the sum of squared deviations between any two clusters. To determine the measure of distance between objects during the agglomeration process in cluster formation, the Euclidean distance was used, representing the geometric distance in multidimensional space. In this method, Euclidean distances (and squared Euclidean distances) are calculated based on raw data rather than standardized data. This study used cluster analysis to identify homogeneous groups of objects based on their characteristics, which allows for the identification of natural data structures and facilitates their further interpretation. Ward's method was used for the cluster analysis because it minimizes the sum of squares within each cluster at every step of the agglomeration process. As a result, it produces the most homogeneous clusters of all agglomeration methods. Additionally, to analyze the interrelationships between annual amounts of fees paid by landfill operators, 3D surface plots were employed for three variable values X, Y and Z, in the years 2019–2023 [81]. Cluster analysis is a tool for exploratory data analysis, the purpose of which is to arrange objects into groups in such a way that the degree of similarity between objects within the same group is as high as possible, and as low as possible with objects from other groups. Cluster analysis has been used to identify data patterns across individual provinces. The literature on the subject cites numerous publications that describe the use of droplet analysis to process research results using Statistica software for similar research topics [82–84].

2.3. Designations Adopted in This Study

To improve the clarity of the tables and figures, this study uses designations for each of the 16 provinces in Poland. Table 1 lists the names of the provinces and their corresponding abbreviations.

Table 1. Names of provinces and their abbreviations.

No.	Province Name	Province Abbreviation
1.	Lower Silesia	V1
2.	Kuyavian-Pomeranian	V2
3.	Lublin	V3
4.	Lubusz	V4
5.	Łódź	V5
6.	Lesser Poland	V6
7.	Masovian	V7
8.	Opole	V8
9.	Subcarpathian	V9
10.	Podlaskie	V10
11.	Pomeranian	V11
12.	Silesian	V12
13.	Świętokrzyskie	V13
14.	Warmian-Masurian	V14
15.	Greater Poland	V15
16.	West Pomeranian	V16385

3. Research Results

The research results present the mechanisms for controlling, monitoring, and reporting on the portion of landfill gas that cannot be captured and utilized at landfills for economic and technological reasons. Even landfills with degassing installations do not guarantee 100% methane recovery. This is due to the diversity of landfill types in terms of the type of seals used, the transfer system, the degree of waste compaction, the storage technology, the method of landfill reclamation, and the leachate drainage system.

Methane Emissions and Reporting in 2019–2023

Based on data obtained from the resources of the Chief Inspectorate of Environmental Protection, in the section PRTR National Pollutant Release and Transfer Register, for the years 2019 and 2023, a quantitative analysis was conducted and the results were assigned to individual voivodeships. Table 2 presents the amounts of methane emissions into the air in each voivodeships. Data marked as NR were not included in the analysis and refer to situations in which landfills did not report methane emissions. They were not included in the analysis.

Table 2. Quantities of methane emissions into the air in 2019–2023.

No.	Voivodeship	Years					
		2019	2020	2021	2022	2023	2019–2023
		Methane Emission [Mg/Year]					
1.	V1	1261.00	136.02	131.00	126.66	133.90	1788.58
2.	V2	1038.00	352.00	1183.76	2873.73	3660.70	9108.19
3.	V3	NR *	NR *	NR *	NR *	NR *	NR *
4.	V4	148.00	NR *	106.19	NR *	NR *	254.19
5.	V5	NR *	NR *	NR *	NR *	NR *	NR *
6.	V6	0.00	308.21	NR *	145.63	154.24	608.08
7.	V7	995.00	1298.02	1567.03	1511.90	1180.64	6552.59
8.	V8	1039.00	1186.33	1238.33	1197.19	130.00	4790.85
9.	V9	196.00	3456.00	1028.33	134.30	110.00	4924.63
10.	V10	NR *	NR*	NR *	NR *	NR *	NR *
11.	V11	472.00	878.75	857.7	3463.04	6367.31	12,038.80
12.	V12	1152.00	408.57	657.38	1041.92	349.30	3609.17
13.	V13	NR *	NR *	NR *	NR *	NR *	NR *
14.	V14	533.00	696.67	454.82	801.40	1036.46	3522.35
15.	V15	424.00	1125.53	922.75	834.14	746.22	4052.64
16.	V16	100.00	1369.73	514.80	NR *	125.57	2110.10
Total for Poland		7358.00	11,215.83	8662.09	12,129.91	13,994.34	52,121.84

* NR—not reported.

The results of the study showed that over the five-year period, the highest methane emission into the air occurred in the Pomeranian Voivodeship, amounting to 12,038.80 Mg CH_4. In contrast, the lowest reported emission among the reporting regions was recorded in the Lubusz Voivodeship, amounting to 254.19 Mg CH_4. It should be noted that landfill operators from four voivodeships did not report methane emissions; this applies to the Lublin, Łódź, Podlaskie, and Świętokrzyskie Voivodeships. Such a situation may result

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from the fact that the landfills did not exceed the applicable threshold value for methane emissions, which is set at 100 Mg per year. Figure 1 shows a dendrogram for individual provinces, based on methane emissions expressed in Mg per year for the period 2019–2023.

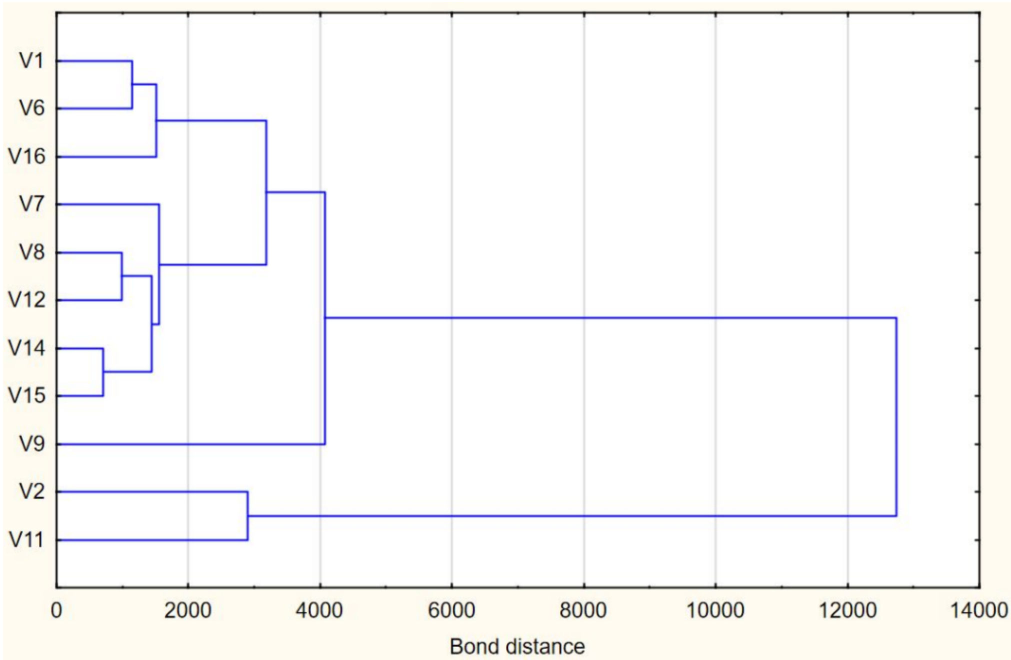

Figure 1. Dendrogram of linkage distances for individual voivodeships in relation to methane emission levels.

The analysis of methane emissions by individual voivodeships in the years 2019–2023 showed that the smallest linkage distance occurred at the level of the first cluster, which included the Lower Silesian (V1), Lesser Poland (V6), and West Pomeranian Voivodeships (V16), with an agglomerative distance of (x = 1539.88; y = 9.72). This indicates that these provinces have the lowest levels of methane emissions from landfills. The second cluster comprised the Masovian (V7), Silesian (V12), Warmian-Masurian (V14), and Greater Poland (V15) Voivodeships, for which the linkage distance was (x = 1575.12; y = 7.71). The third cluster included the Kuyavian-Pomeranian (V2) and Pomeranian Voivodeships (V11), with linkage parameters of (x = 2920.21; y = 1.94), thus representing the greatest linkage distance. It is precisely in these two provinces that methane emissions from landfills are the highest. All clusters were connected by a final linkage with parameters (x = 12,744.04; y = 1.49). Such linkage relationships within the dendrogram indicate a considerable variation in methane emissions across different years and voivodeships. The average methane emission per landfill, reported to the PRTR database in the years 2019–2023, is presented in Figure 2.

The results of the analysis showed that in 2023 the highest methane emissions from landfills in Poland were recorded. The average emission from a single landfill in that year amounted to 666.40 Mg of methane per year. In comparison with 2019, the year of the lowest emission, when the emission was 294.32 Mg of methane, the 2023 value was higher by 44.16%.

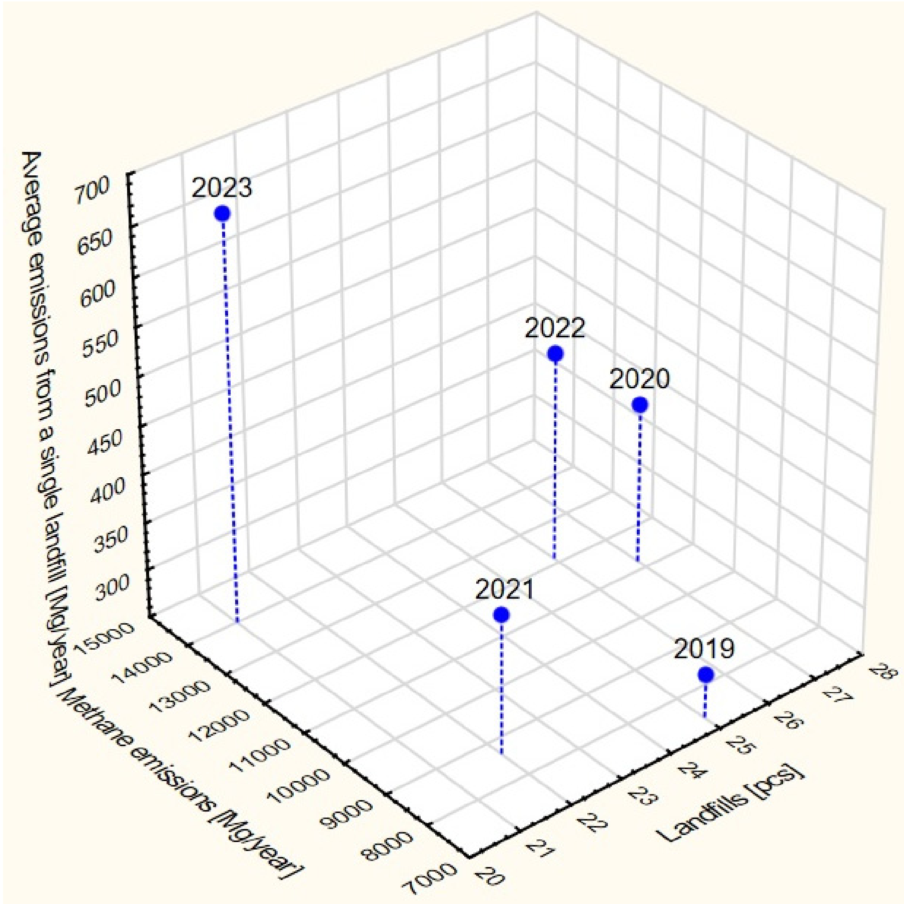

Figure 2. Average annual methane emission from a single landfill in the years 2019–2023.

4. Discussion

4.1. Emission Sources and Their Effects

Fugitive methane emissions occurring at landfill sites do not result from technical faults but are instead the consequence of numerous internal and external factors that influence the generation and release of landfill gas within an open bioreactor system such as a waste landfill. Internal factors include the effectiveness of the landfill's isolation and the morphological composition of the waste stored in the landfill, primarily including the organic fraction content. This fraction is the main determinant of the quantity and quality of biogas production within the landfill and, consequently, the scale of potential emissions into the air. External factors include the degree of waste compaction and the type of materials used to cover the waste, such as soil, clay, and mineral materials. Proper landfill operation and dedicated materials prevent biogas migration to the landfill surface and, consequently, into the air [85]. Therefore, a key element in this process is the accurate diagnosis of the current state, the identification of possibilities for emission reduction, and a realistic estimation of actual methane emissions by the landfill operator. When com-bined with the environmental usage fee, such estimations may partially compensate for the associated social and economic costs. For this reason, a reliable estimation of the actual emission volume by the landfill operator is of key importance. Danish researchers investigated the generation of methane in landfills and its emissions to the air using the validated Afvalzorg model, which incorporates laboratory-determined values for waste from mechanical-biological treatment. Using the mass balance method, the modeled methane emissions were consistent with field measurements, which improves the accuracy and reliability of emission estimates from Danish landfills [86].

It is worth noting that, over a five-year period, the environmental fee for diffuse me-thane emissions increased by only 13% per 1 Mg of methane. However, the legislator does not publish any methodology for indexing this fee, which makes it impossible to conduct a full economic analysis of the adopted parameters. Therefore, it can be inferred that the fee level is not correlated with the actual social impacts of methane emissions. In the context of reducing gas emissions during waste processing, particularly in the processes of aerobic stabilization of the biodegradable fraction, techno-logical solutions based on additives such as biochar play an important role. Research conducted by Malinowski and Famielec demonstrated that the addition of biochar and appropriate airflow conditions during the biostabilization process can significantly re-duce ammonia (NH_3) and carbon dioxide (CO_2) emissions, while simultaneously in-creasing the efficiency of the process [87].

4.2. Limitations of Methane Reporting and Data Reliability

The number of landfills that submitted reports on methane emissions from waste disposal sites in Poland is presented in Table 3.

Table 3. Number of waste landfills reporting methane emissions, 2019–2023.

No.	Voivodeship	Year				
		2019	2020	2021	2022	2023
		Number of Reporting Landfills [Units]				
1.	V1	2	1	1	1	1
2.	V2	2	2	3	3	4
3.	V3	0	0	0	0	0
4.	V4	1	0	0	0	0
5.	V5	0	0	0	0	0
6.	V6	0	2	0	1	1
7.	V7	5	5	4	4	3
8.	V8	4	5	5	6	1
9.	V9	1	2	1	1	1
10.	V10	0	0	0	0	0
11.	V11	1	2	1	2	2
12.	V12	4	3	2	2	2
13.	V13	0	0	0	0	0
14.	V14	2	2	2	3	3
15.	V15	2	2	2	3	2
16.	V16	1	1	1	0	1
Total for Poland		25	27	22	26	21

According to data published by the Central Statistical Office (GUS), in 2023 there were 254 municipal waste landfills operating in Poland. The results of the study showed that the highest number of landfills reporting methane emissions, i.e., 27, was recorded in 2020. In relation to the total number of landfills in Poland, this represents 10.63% of all operating facilities. On this basis, it can be concluded that the vast majority of landfills do not exceed the threshold values for methane release into the atmosphere.

Since the authors do not have information on how individual landfill operators ob-tained their data (measurements, calculations, estimates), underreporting may occur in the reports. Underestimates may result from the use of an incorrect method or errors during its application. In this regard, full responsibility lies with the landfill operators who report or state that the emission threshold has not been exceeded (no reporting).

4.3. Financial and Economic Quantification: Fees and Social Cost

The release of methane into the air is associated not only with the obligation to report to the PRTR database but also with a financial burden for the landfill operator. The entity managing a municipal waste landfill, upon exceeding the emission threshold, is required to report quantitative data to the competent authority, including the method of calculation. At the same time, due to the occurrence of such emissions, the entity is obliged to pay a corresponding fee for the environmental burden.

Research on the economic aspects of the financial burden on enterprises resulting from methane emissions into the atmosphere was conducted through the analysis of documents and applicable legal acts. The amount of fees related to the rates for the use of the environment in the years 2019–2023 was analyzed based on the annual Notices of the Minister of Climate and Environment, which constitute the legal basis for charging fees to reporting entities [88–92]. The values for the years 2019–2023 are presented in Table 4.

Table 4. Fees incurred by landfill operators in the years 2019–2023.

Years	Number of Reporting Landfills [Units]	Amount of Methane Released into the Air [Mg/Year]	Unit Fee in a Given Year [EUR/Mg CH_4]	Annual Fee Amount [EUR]
2019	25	7358.00	0.070	514.55
2020	27	11,215.83	0.068	757.83
2021	22	8662.09	0.068	504.69
2022	26	12,129.91	0.068	829.40
2023	21	13,994.34	0.075	1048.03
Total		52,121.84		3654.49

As a result of the conducted research, it was found that environmental usage fees resulting from methane emissions into the atmosphere between 2019 and 2023 ranged from 0.068 to 0.075 [EUR/Mg CH_4] and were indexed annually according to the inflation rate in Poland. The average methane emission over the five-year period amounted to 10,672.03 Mg CH_4, resulting in an average fee value of 747.73 EUR.

The highest estimated fee occurred in 2023, corresponding to the highest methane emissions during the study period.

4.4. Regulatory and Economic Implications for Landfill Operators

The analysis of methane emissions from landfills and the amount of fees paid for methane emissions into the atmosphere showed that landfill operators are not interested in incurring financial costs to reduce these emissions. This results primarily from the operators' economic assessment, as the costs of installing systems to limit uncontrolled methane emissions from landfill surfaces would be disproportionately higher compared to the relatively low environmental fees currently imposed on operators. The economic aspects of methane emissions that constitute the basis for imposing financial charges on landfill operators in Poland do not directly correlate with the social costs generated by these emissions. In the global literature on climate economics, numerous estimates of the social costs of methane emissions worldwide can be found. However, there are currently few scientific publications estimating the social costs of greenhouse gas emissions, and most of them are not directly comparable with current assessments. Examples of publications estimating social costs are provided below.

To correlate the amount of methane emissions with the social costs they generate, it is necessary to refer to the estimation methods developed by researchers. Calculating the Social Cost of Methane (SCM) is more complex than the methods used for CO_2. Many researchers have attempted to estimate the socio-economic costs of methane emissions into the atmosphere, applying appropriate algorithms and indicators.

In their study, Shindell et al. [93] calculated the SCM using a consistent temporal framework that integrated physical and economic processes, while also considering the effects related to climate and air quality. They obtained high SCM values—2000 EUR/Mg CH_4 and 3014 EUR/Mg CH_4 for discount rates of 5% and 3%, respectively. These values are approximately 100 and 50 times higher than the corresponding social costs of carbon dioxide. In turn, Azar et al. proposed a range of 930–9300 EUR/Mg CH_4, with a baseline value estimated at 4420 EUR/Mg CH_4 [94]. Marten and Newbold indicated a value of 1535 EUR/Mg of methane, using an integrated assessment model developed by their team, which combines MAGICC climate data and economic components from DICE to estimate the social cost of CH_4 [95].

A report published in 2023 by the United States Environmental Protection Agency (EPA) presented the social costs of methane emissions at highly variable cost levels. For example, assuming no correlation between climate change damages and consumption growth may lead to overestimation if there is a positive correlation between consumption growth and marginal damages. For methane, the estimate developed with a constant discount rate of 2% amounted to 2186 EUR/Mg [96].

Research conducted by Ericson et al. and published in Nature in 2021 estimated the social cost of methane emissions, based on calibrated reduced-form global climate models, at 850 EUR/Mg [97]. The SCM indicator applied in that study accounts for both the harmfulness of methane as a potent greenhouse gas and its negative impact on human health through its role in the formation of tropospheric ozone.

In Poland, research on the social and economic costs of greenhouse gas emissions, including methane, is not as widespread as in other parts of the world or in Europe. One of the few studies in this area is the work by Prandecki and Gajos, which utilized data on environmental emissions by economic sector for individual European Union countries.

The process of the economic valuation of emissions into the air began with the standardization of emission values in physical units by converting them into carbon dioxide equivalents. For greenhouse gases, the Global Warming Potential (GWP) is calculated, which is expressed in terms of CO_2 equivalents [98].

To estimate the economic value of methane emissions into the atmosphere, the authors used the purchase price of carbon emission allowances from the EU Emissions Trading System (EU ETS), converted according to the volume of methane emissions. The results of the study showed that the value of one tonne of methane emitted into the atmosphere, calculated based on the average annual price of CO_2 emission allowances under the EU ETS in 2014, amounted to 166.0 EUR/Mg CH_4. This value is significantly lower than the estimates reported globally [99].

The economic and social costs resulting from methane emissions, estimated based on the literature review and conducted research, are presented in Figure 3.

The result of the financial analysis is a value ranging from 166.00 to 4420 EUR per tonne of CH_4, with an average value of 2293.00 EUR/Mg CH_4 [85]. The financial estimates of the social cost of methane emissions presented in selected studies fall within a very wide range. This variability results from the multifaceted nature of methane's impact on global warming, public health damage, and the reduction in yields in agricultural and

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forest ecosystems, as well as from the different range of discount rates applied, ranging from 2% to 5%.

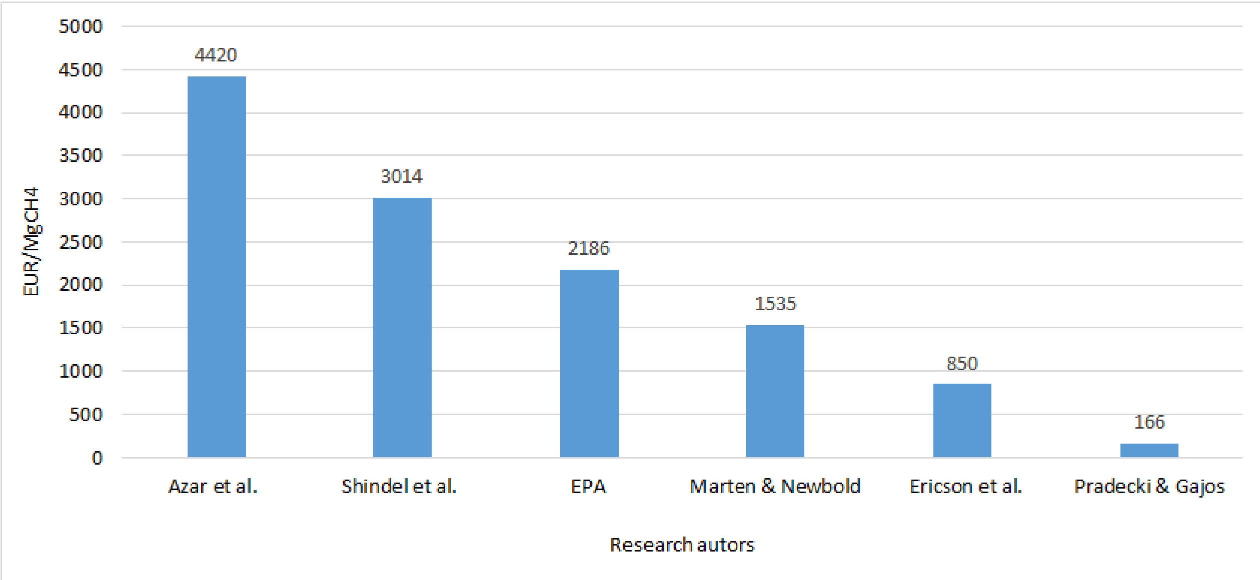

Figure 3. Economic and social costs of methane emissions into the atmosphere [93–98].

The discount rate, in the context of the social costs of greenhouse gases, defines how much value we assign to future benefits or costs compared to their present value. A lower discount rate indicates greater weight placed on the benefits of emission reduction for future generations and increases the social cost of methane. Conversely, a higher rate places more emphasis on the present and decreases the social cost of methane.

Poland's environmental policy does not provide mechanisms that would encourage enterprises to implement measures aimed at reducing methane emissions. The environmental fee currently in force in Poland for methane emissions into the atmosphere remains at a very low level. During the study period conducted by the authors, covering the years 2019–2023, this fee ranged from 0.068 to 0.075 EUR/Mg CH_4, and since its introduction more than 20 years ago, it has been adjusted only for inflation. In 2025, the fee for methane emissions to the atmosphere amounts to 0.10 EUR/Mg CH_4, and in 2026 it will increase to 0.11 EUR/Mg CH_4. Such a low rate does not motivate operators to reduce emissions; therefore, methane emissions in recent years have decreased only slightly [100–103].

Environmental usage fees for methane emissions are transferred to the accounts of regional marshal offices in the voivodeships where landfills are located. If these revenues were sufficiently high, the funds could be invested in subsidy programs supporting methane reduction technologies within a given region. These fees should be reasonably proportional to the environmental and social damages resulting from methane emissions.

One of the main obstacles to increasing the fee is the fact that the waste management sector struggles with a lack of innovative technologies and with financial constraints that limit its ability to implement effective climate mitigation solutions.

When correlating the social cost of methane emissions worldwide and in Poland, it should be stated that the fees imposed in Poland are significantly lower than the estimated social costs. Assuming the lowest estimated social cost of methane emissions in Poland at 166 EUR/Mg CH_4, it is difficult to relate this value to the fee paid by enterprises, which in 2025 amounts to only 0.10 EUR/Mg CH_4. The comparison becomes even more disproportionate when referring to global studies that estimate the average social cost of methane emissions at 2293 EUR/Mg CH_4, compared with 166 EUR/Mg CH_4 estimated for Poland.

In the area of broadly understood methane emissions, the Methane Regulation 2024/1787, adopted by the European Parliament and the Council of the European Union on 13 June 2024, may contribute to improving the current situation [104]. The Methane Regulation primarily covers enterprises operating in the mining, gas, and energy sectors. In practice, this means that the new obligations apply to coal mines (both active and inactive), oil and gas extraction facilities, transmission pipeline operators, gas storage facilities, and LNG installations. However, with regard to methane emissions from waste landfills, no changes are expected, and reporting through the PRTR system will continue unchanged.

The aforementioned Methane Regulation 2024/1787, adopted by the European Parliament and the Council of the EU on 13 June 2024, concerns the accuracy of measurements, quantification, monitoring, reporting, and verification of methane emissions exclusively in the energy sector within the European Union. This regulation applies to:

- The exploration and production of crude oil and natural gas, as well as the collection and processing of natural gas;
- Inactive wells, temporarily plugged wells, and permanently plugged and abandoned wells;
- The transmission and distribution of natural gas;
- Active underground coal mines and open-pit coal mines, closed underground coal mines, and abandoned underground coal mines.

Therefore, it cannot be applied to diffuse methane emissions from landfill surfaces.

It is difficult to imagine that the current economic conditions, particularly the present fee level paid by landfill operators, could cover the costs resulting from global warming, public health damage, and the declining yields in agricultural and forest ecosystems. In this situation, systemic changes are necessary to strengthen and make the system more transparent, especially in determining the actual amount of methane emissions from landfills and in clearly defining when the emission threshold is exceeded [105].

The key aspect remains the economic issue of adjusting the environmental fee system so that it reflects the real social costs and financial burdens caused by methane emissions. Given the multifaceted nature of the problem, it is particularly important in the future to continue research into technological, economic, and social solutions aimed at reducing methane emissions from landfills [106].

5. Conclusions

Methane generated at municipal solid waste landfills is—after carbon dioxide—the second most significant greenhouse gas produced by human activity, substantially contributing to global warming and ecosystem degradation. Therefore, methane emissions from landfills represent a serious environmental and climate challenge. The conducted research showed that emissions of this gas from Polish landfills in the years 2019–2023 exhibited a clear upward trend, reaching their highest levels in 2023 within the analyzed period, while also showing substantial regional disparities. Despite the obligation to report emissions exceeding 100 Mg of CH_4 per year (in accordance with the requirements of the National Pollutant Release and Transfer Register), no such emissions were reported in several voivodeships, which suggests either the absence of emissions of that magnitude or deficiencies in the monitoring system. Since the authors do not have information on how individual landfill operators collect data (measurements, calculations, estimates), it is possible that the data in the reports are underestimated. Underestimates may result from the use of an incorrect method or errors in its application, resulting in the emission threshold not being exceeded and, consequently, a failure to report. Effective management of this issue therefore requires ensuring a reliable and uniform system of measurement and reporting—only credible and comparable data will enable the implementation of adequate measures aimed at reducing the negative impact of methane on the environment.

The study results confirm correlations between methane emissions from landfills into the air and measurable social and economic impacts. This situation requires systemic changes. This applies in particular to the need to ensure reliable control of the reporting system, transparent verification of methane emissions reported by operators, and oversight of cases where emission thresholds are exceeded. The research should also spark a discussion on adjusting environmental fees to reflect the actual social costs of methane emissions.

Another important conclusion from the analysis is that the current economic mechanisms do not compensate for the real environmental and social costs associated with methane emissions. The current environmental usage fee for methane emissions (approximately EUR 0.1 per Mg of CH_4) is symbolic and several orders of magnitude lower than the estimated external costs of such emissions (ranging from several hundred to even several thousand euros per Mg). This disparity indicates a lack of internalization of environmental impacts within the existing system and therefore insufficient incentives to reduce emissions. The research results thus point to the need for systemic changes—in particular, adjusting environmental fee policies so that they better reflect the actual social costs of emissions and motivate operators to reduce them.

Such an integrated approach combines environmental benefits (lower emissions and reduced climate impact), economic benefits (cost savings), and social benefits (reduction in external costs affecting public health and the economy). From a technological perspective, further development and improvement of emission reduction methods and methane recovery efficiency are essential. From an economic perspective, in-depth analyses are needed to evaluate the effectiveness of market-based and regulatory instruments that encourage operators to reduce emissions. Future research should assess, among other issues, the effects of raising methane emission fees to levels corresponding to social costs, the feasibility of including methane emissions in an emissions trading system (similar to the EU ETS), and the cost-effectiveness of investments in energy recovery installations for landfill biogas.

From a social perspective, it is crucial to consider the level of public awareness and acceptance of actions aimed at reducing emissions at landfills. It is worth conducting research on education and the involvement of local communities in emission monitoring, as well as analyzing the extent to which emission reductions translate into improved public health and quality of life for residents living near landfills.

An interdisciplinary research approach combining the above aspects will make it possible to develop more effective strategies for reducing methane emissions and fully utilizing its potential as a renewable energy source, thus supporting the achievement of climate and sustainable development goals.

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Abbreviations

The following abbreviations are used in this manuscript:

CAS	Chemical Abstracts Service
CSO	Central Statistical Office
EC	European Commission
EEA	European Environment Agency
E-PRTR	European Pollutant Release and Transfer Register
EPA	Environmental Protection Agency
ESG	Environmental, Social and Governance
EU	European Union
EU ETS	European Union Emissions Trading System
GHG	Greenhouse Gas
GIS	Geographic Information System
GWP	Global Warming Potential
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquefied Natural Gas
NCEM	National Centre for Emissions Management
NPRTR	National Pollutant Release and Transfer Register
PRTR	Pollutant Release and Transfer Register
SCM	Social Cost of Methane
SD	Sustainable Development
TLA	Three-Letter Acronym
UN	United Nations
WHO	World Health Organization

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