

Article

Managing Residual Methane from Abandoned Coal Mines in Urban Areas: A Post-Mining Risk Case Study from Lupeni, Romania

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Abstract

Methane emissions from abandoned coal mining operations represent a persistent environmental and safety challenge in post-mining regions undergoing urban redevelopment. As urban infrastructure expands over former underground workings, the uncontrolled migration of mine gas can compromise public safety, exacerbate greenhouse gas emissions, and undermine sustainable development goals. This study investigates the origin of methane emissions detected in an urban area of the municipality of Lupeni, Romania, following the commissioning of a new natural gas distribution pipeline installed within a historically mined perimeter. The emissions had not been previously reported and were unexpectedly discovered during technical inspections conducted after the gas network installation, highlighting the absence of historical data on gas presence in this area. This is the first documented case of an accidental discovery of methane emissions in an urban perimeter overlying historical coal mine workings in Romania, granting this study a pioneering status, both scientifically and in terms of urban risk management. The findings emphasize that administrative mine closure does not equate to risk closure, as latent methane emissions may reactivate during urban transformations (e.g., excavations, utility upgrades, drainage changes). To ensure a scientifically sound and sustainable risk assessment, an integrated diagnostic framework was applied, combining chronological field monitoring with chromatographic gas composition analysis. This methodology enabled precise attribution of the methane source to abandoned underground mine workings, excluding the public gas network as a contributor. Based on this diagnosis, a controlled drainage and methane recovery system was implemented, resulting in the elimination of detectable concentrations at all monitoring points by February 2025. The captured methane was redirected for local energy use, transforming an environmental liability into a usable resource. This intervention supports circular economy principles and aligns with EU climate and energy transition goals. The proposed methodological framework provides a replicable model for identifying and managing residual mine gas in post-industrial urban environments. Although emission fluxes were not quantified, concentration-based screening enabled risk diagnosis, prioritization, and targeted intervention. These findings are relevant to EU Regulation (2024/1785) on methane emission reduction, emphasizing the need to include post-mining methane (AMM) in urban planning and environmental monitoring strategies. Limitations of the study include the absence of baseline data and the inability to calculate total methane flux. However, the results support immediate and practical risk mitigation and highlight the need for future work focused on long-term monitoring and emission quantification.



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This case provides critical insights for other post-mining cities in Central and Eastern Europe facing similar challenges at the intersection of legacy coal infrastructure and modern urban development. This study is designed as a concentration-based diagnostic and risk-oriented case study and does not aim to quantify methane emission fluxes.

Keywords: methane emissions; abandoned coal mines; sustainable development; post-mining environmental impact; urban resilience; mine gas migration; environmental risk assessment; gas monitoring; coal mining legacy

1. Introduction

1.1. Global Context and Importance of Methane

Methane (CH₄) is widely recognized as the second most impactful anthropogenic greenhouse gas after carbon dioxide (CO₂), due to its high radiative efficiency and short atmospheric lifetime. Over a 100-year time horizon, its global warming potential (GWP) is estimated to be 28–34 times higher than that of CO₂; on a 20-year timescale, this factor may exceed 80, making methane a key lever for near-term climate action [1].

A substantial share of anthropogenic methane emissions originates from fossil fuel-related activities. According to the International Energy Agency (IEA), coal mining—encompassing both active and abandoned sites—accounts for nearly 10% of global CH₄ emissions [2]. While active mines primarily release methane via ventilation systems and extraction processes, abandoned coal mines (ACMs) continue to emit methane through residual degassing, often for decades after closure. This emission source, termed abandoned mine methane (AMM), remains under-inventoried and under-regulated despite its long-term persistence and environmental relevance.

In response to growing urgency around methane reduction, several global and regional policy initiatives have emerged. The Global Methane Pledge, launched at COP26 in 2021, commits signatory countries to reduce global methane emissions by at least 30% by 2030 compared to 2020 levels [3]. At the European level, Regulation (EU) 2024/1785 mandates enhanced monitoring, reporting, and mitigation of methane emissions across the energy sector, with particular attention to upstream oil, gas, and coal operations [4].

However, both global and EU-level policy instruments predominantly focus on emissions from operational energy infrastructure, leaving a significant regulatory gap in urban areas located above former mining zones. These urban environments are especially vulnerable due to the potential intersection between residual methane sources—such as abandoned galleries, goafs, or tectonically active fracture systems—and modern subsurface infrastructure (e.g., gas pipelines, sewers, utility vaults, or building basements).

This intersection creates dual hazards:

Unmonitored greenhouse gas leakage, with implications for national and subnational carbon inventories;

Public safety risks, including explosion hazards and indoor air contamination in confined spaces.

Despite mounting evidence of AMM persistence, urban post-mining contexts remain poorly represented in methane emission inventories and mitigation frameworks. This is particularly problematic in post-industrial regions of Central and Eastern Europe, where urbanization has often progressed over complex, poorly documented subsurface mining systems. In such settings, methane migration may go unnoticed until it is accidentally revealed during infrastructure works or crisis events.

To address this overlooked vulnerability, the present study investigates a real-world case of methane accumulation in Lupeni, Romania—a municipality situated within a historical coal basin. The study explores the interface between abandoned mine emissions and modern urban infrastructure and offers a replicable methodology for both scientific diagnosis and risk-informed decision-making in similar post-mining contexts.

1.2. Emergency Situations and Consequences, Including Methane Explosions in Confined Spaces

Cities built above abandoned mining works are exposed to significant safety risks due to the hidden presence of residual underground voids and degassing pathways. One of the most severe and immediate threats is the accumulation of methane gas (CH_4) in confined or poorly ventilated spaces, which can lead to explosive incidents if the gas reaches its lower explosive limit (LEL) in air (approximately 4.4% by volume) [1,5].

Residual emissions from abandoned mine workings—including goafs, galleries, shafts, and fracture zones—can migrate upward through natural or anthropogenic conduits such as [5,6]:

- Cracks in the ground or pavement;
- Unsealed boreholes;
- Sewer systems and utility tunnels;
- Building basements and crawl spaces.

If undetected or unmanaged, these emissions may accumulate silently over time, creating hazardous concentrations in urban environments. Unlike industrial facilities where gas concentrations are routinely monitored, residential or mixed-use urban zones often lack adequate detection systems, allowing methane to build up unnoticed [5,7].

Documented Consequences from International Case Studies:

Numerous incidents globally have highlighted the severity of the risk:

After the closure or abandonment of mining operations, residual methane (CH_4) remaining in the coal seam and in underground voids may continue to be released over long periods of time. Its migration toward the surface occurs preferentially through shafts, galleries, old boreholes, fractured zones, and tectonic structures, with the potential to accumulate in confined spaces, where it may reach concentrations hazardous to human health and pose an explosion risk. A central challenge in post-mining risk governance is that methane emissions are strongly dependent on the mine closure regime (in particular the evolution of flooding), effective permeabilities, and the connectivity of underground voids. These factors can significantly alter both emission rates and the spatial distribution of emissive zones, which is why risk analysis must be integrated into mine decommissioning and post-closure monitoring, rather than treated as an isolated or episodic event [5].

In practice, reducing uncertainty requires a combination of:

- (i) Geo-mining mapping and correlation of underground workings with urban infrastructure;
- (ii) Multi-scale monitoring (ground-based networks and remote sensing) capable of capturing temporal variability and emission clusters. For example, in the Upper Silesian Coal Basin (USCB), top-down estimates based on airborne remote sensing (MAMAP) allow the attribution of fluxes to groups of shafts and highlight variability between sources and from day to day [8,9], while a ground-based network of FTIR spectrometers in an upwind–downwind configuration can constrain emissions by integrating observations with dispersion models (WRF/FLEXPART) [9];
- (iii) Source attribution in the presence of competing sources (e.g., gas distribution infrastructure), where stable isotopes ($\delta^{13}\text{C}-\text{CH}_4$, $\delta^2\text{H}-\text{CH}_4$) are particularly useful in regions characterized by mixed thermogenic and biogenic sources and by high variability in mine gas signatures [10].

With respect to mitigation, the literature shows that controlled drainage reduces explosion risk and may enable energy recovery; however, performance is highly sensitive to system design and to geological and hydrogeological conditions. Consequently, mitigation solutions must be dimensioned on the basis of proper diagnosis and monitoring, ranging from ventilation and sealing for low-level emissions to drainage boreholes connected to degasification and recovery systems for higher emission regimes [11]. Moreover, techno-economic analyses of coal mine methane utilization (including methane from abandoned mines) indicate feasibility under specific conditions and demonstrate climate benefits through energy substitution and the reduction of uncontrolled emissions. This supports an integrated “safety–climate–resource” approach in post-mining urban planning [12] and in life-cycle assessment (LCA) studies of coal mine methane utilization [13].

Typical Emergency Outcomes:

In such events, the consequences are multifaceted [5,7]:

Human casualties and injuries due to explosions or carbon monoxide co-exposure;

Evacuation of residents and closure of buildings or public facilities;

Interruption of essential services such as electricity, water, gas, or sewer systems;

Destruction of property and increased liability for local authorities or utility operators;

Loss of public trust in urban safety management and long-term socioeconomic impacts;

Amplifying Factors in Urban Contexts [5,7,14]:

High density of underground networks (gas, water, telecom) increases the risk of unintended interactions;

Lack of baseline monitoring data limits early detection;

Legacy mining documentation is often incomplete or inaccurate;

Urban redevelopment works (excavations, utility upgrades) can trigger new gas pathways or disturb old ones.

In this context, methane emissions from abandoned mines are not only an environmental concern but also a public safety hazard of the highest order. Their unpredictable nature, combined with the potential for catastrophic outcomes, justifies the need for integrated monitoring, emergency response protocols, and the inclusion of mine gas risks in urban planning processes.

1.3. Risks Associated with Methane Emissions and Implications for Sustainable Development

Methane emissions from abandoned mine workings (commonly referred to as abandoned mine methane—AMM) pose a significant and long-lasting risk in former coal mining regions. These emissions are not only a persistent contributor to greenhouse gas inventories but also represent a multifaceted hazard for urban safety, environmental integrity, and socioeconomic stability [1–3]. Unlike controlled emissions from active industrial processes, AMM is often latent, intermittent, and spatially variable, making it difficult to monitor and manage effectively.

1.3.1. Persistence and Pathways of Emission

Following mine closure, methane may continue to escape from subsurface voids such as goafs (collapsed roof areas in mined-out zones), abandoned galleries and drifts, old boreholes or shafts, fractured overburden layers, and fault zones or tectonically induced permeability pathways [5,6].

These subsurface structures create preferential routes through which methane migrates upward, potentially reaching the surface or interacting with underground infrastructure. This migration can persist for several decades or even longer, particularly in regions with fractured geology or inadequate mine sealing practices [2,4,6].

1.3.2. Uncertainties in Quantification

Despite their importance, emissions from AMM sources are often poorly quantified:

Bottom-up inventory methods, such as applying emission factors per ton of coal, do not account for local geological conditions or mine sealing quality.

Temporal variability, including daily, seasonal, or synoptic fluctuations, can result in major underestimations when using single-day or limited sampling windows.

Many regions lack longitudinal datasets or baseline monitoring, leading to reactive rather than preventive risk management [2–4].

1.3.3. Case Study: Lupeni Incident

In Lupeni (Jiu Valley, Romania), the risk was discovered accidentally in August 2024 during gas detection tests for a newly commissioned natural gas distribution pipeline. No historical data indicated the presence of gas emissions in that urban area, which underscores the unpredictable nature of the risk and the significance of the investigation.

The discovery represents the first documented interaction in the region between residual AMM emissions and newly developed energy infrastructure. Despite the limited monitoring window (August–September 2024), the investigation was rigorous, combining:

High-resolution concentration mapping,

Gas chromatographic fingerprinting,

These methods ruled out leakage from the urban gas distribution system and confirmed the origin of emissions as residual degassing from abandoned underground mine voids. The observed spatial pattern correlated with known tectonic features and the footprint of historical underground galleries, many of which lacked comprehensive closure documentation [6,14].

1.3.4. Emergency Response and Risk Management

The event exhibited the characteristics of a force majeure hazard: a sudden, unanticipated, high-risk phenomenon with immediate safety implications. Methane concentrations near or above 3% vol. were recorded in several locations, approaching the lower explosive limit (LEL) of 4.4%.

Given the explosive potential in confined spaces and the dense urban context, the decision to implement active methane drainage rather than prolong monitoring was consistent with international best practices prioritizing human safety [5,11].

By February 2025, the intervention (connection of dedicated drainage boreholes to the mine's degasification infrastructure) had completely eliminated surface anomalies and enabled safe recommissioning of the public gas system.

1.3.5. Broader Risk Dimensions

The risks associated with AMM extend across multiple domains, including safety (explosions in sewers and basements), health (air quality deterioration), environmental impacts related to methane's high global warming potential and interactions with groundwater [15], and infrastructure risks such as subsidence or collapse due to gas migration weakening underground structures [7]. Social impacts: Anxiety, community displacement, and property devaluation;

Economic costs: Emergency repairs, legal liability, or prolonged infrastructure shutdowns.

In contrast, proactive methane capture offers a dual benefit: risk mitigation and energy recovery, improving both public safety and urban sustainability metrics.

In summary, the Lupeni case demonstrates that without structured monitoring and risk governance, AMM emissions can remain undetected and unmanaged until they interact dangerously with modern infrastructure. Integrated, site-specific risk management combining geological, technical, and emergency preparedness tools is therefore essential for sustainable redevelopment in former mining regions [6,14,15].

1.4. International Methods and Approaches

A variety of mitigation strategies have been developed and implemented internationally to manage methane emissions in residential and industrial contexts, particularly in areas affected by mining activities [5,11,12]. These include:

Passive venting and surface sealing, which are relatively cost-effective but generally suitable only for sites with low and stable emission rates [5,11].

Active drainage via boreholes connected to degasification systems, offering a more robust and effective solution, although associated with higher operational and maintenance costs [11,12].

Flaring or catalytic oxidation, typically used for intermittent or low-volume emissions where energy recovery is not feasible, but where environmental compliance must still be ensured [12,13].

Permanent multi-sensor monitoring systems are integrated into early warning frameworks, providing high levels of safety and real-time data, but requiring significant upfront investment and long-term management. [8,9,16]

The overall success and efficiency of these methods strongly depend on the accurate identification and attribution of the methane emission source. Misdiagnosis—such as mistaking mine gas for leaks in public gas infrastructure—can lead to inappropriate and costly interventions, unnecessary disruptions of urban services, and a loss of public confidence in authorities and infrastructure operators [7,16,17]. In urban post-mining environments, emergency safety investigations often rely on concentration-based field measurements rather than flux quantification due to time constraints and infrastructural limitations. In this context, scientific value is derived from robust source attribution, spatial consistency analysis, and reproducible statistical treatment of measured concentrations. The present study adopts this approach and frames its contribution accordingly.

1.5. The Lupeni Case Study and Specific Contribution

In the context of increasing international attention to residual methane emissions from abandoned mining activities, the municipality of Lupeni, Romania, provides a particularly relevant and instructive case study. Located in a historic coal mining region, Lupeni exemplifies the complex interactions between legacy subsurface mining voids and modern urban infrastructure, which are increasingly recognized as a critical challenge for post-mining risk governance and sustainable urban development [2,4,5].

The investigation was initiated following the unexpected detection of methane emissions along Minerilor Street during the commissioning phase of a new natural gas distribution pipeline in mid-2024. This discovery triggered a series of systematic investigations conducted between August 2024 and February 2025, including diagnostic field campaigns in August–September 2024 and post-mitigation verification monitoring from October 2024 to February 2025, using high-precision, calibrated gas detection instruments. The absence of historical monitoring data for this urban area highlights the latent and unpredictable nature of abandoned mine methane (AMM) risks in redeveloped mining regions.

The data obtained enabled a comparative analysis of gas composition and pressure conditions, the conclusive exclusion of the public gas distribution system as the emission source, and the attribution of the observed anomalies to residual degassing from abandoned underground mine voids beneath the urban area. This diagnostic process is consistent with internationally recognized approaches for distinguishing mine gas emissions from infrastructure-related leaks [5,10].

The key scientific contribution of this study lies in the development and application of an integrated methodological framework that combines chronological monitoring of surface gas anomalies with chemical fingerprinting of gas samples. This integrated diagnostic

approach enabled the rapid identification of the methane source and supported timely, evidence-based decision-making under conditions of limited historical data, in line with best practices for post-mining methane risk management [8–11].

Based on the diagnostic results, an active mitigation strategy was implemented, consisting of methane drainage through dedicated boreholes connected to the former mine's degasification infrastructure. By February 2025, this intervention had resulted in the complete elimination of detectable surface anomalies and enabled the safe recommissioning of the urban gas distribution network. This outcome is consistent with international experience demonstrating that controlled methane drainage is an effective and reliable risk mitigation measure in post-mining urban environments [11,12].

The methodological framework developed and validated in Lupeni is highly transferable and offers a replicable model for other post-mining urban settings, particularly in Central and Eastern Europe, where similar geological conditions and legacy mining infrastructures are common. Beyond site-specific risk mitigation, this approach contributes directly to sustainable urban planning, community safety management, and the circular economy by integrating methane risk reduction with potential energy recovery pathways, in alignment with current European regulatory and policy objectives [4,13,18]. Given the complexity of post-mining urban environments and the frequent absence of baseline monitoring data, the present study adopts a structured, diagnostic-oriented methodological approach rather than an emission inventory perspective. The investigation prioritizes methane source attribution, spatial delineation of risk, and decision support for mitigation under emergency urban safety conditions. Figure 1 summarizes the integrated diagnostic framework applied in this study, illustrating the logical sequence from preliminary risk screening to mitigation decision-making.

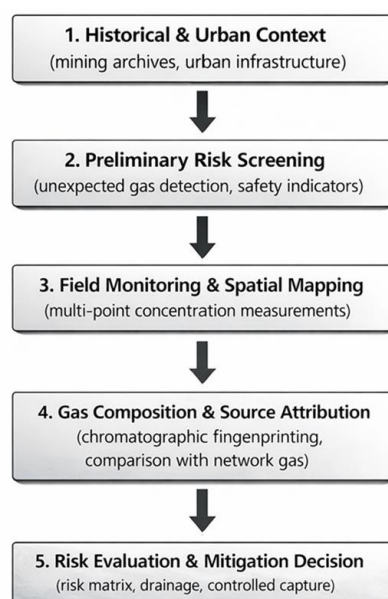


Figure 1. Integrated diagnostic framework for identifying and managing residual methane emissions in post-mining urban areas.

Figure 1 illustrates a stepwise, risk-oriented methodology designed for urban contexts where historical data and flux-based measurements are limited or unavailable. The framework integrates concentration-based field monitoring, chemical fingerprinting, and spatial correlation with legacy mining infrastructure to support robust methane source attribution and informed mitigation decisions. The approach prioritizes diagnostic accuracy and public safety rather than emission inventory quantification.

2. Situation Context

2.1. Urban Context and Mining History

Following the diagnostic framework illustrated in Figure 1, the investigation began with the analysis of the urban context and historical mining configuration of the Lupeni perimeter.

The municipality of Lupeni, located in the Jiu Valley, is characterized by a high density of subsurface technical infrastructure, resulting from a combination of modern utility networks and remnants of over a century of intense mining activity. Beginning in the late 19th century, the area experienced rapid economic development based on underground coal exploitation, which created an extensive system of galleries, shafts, and mining works. According to recent studies, the main coal seams exploited (Nos. 3, 4, 5, 8/9, 13, 14, and 15) were mined at depths between approximately 300 and 800 m, with panels in Block V particularly affected by subsidence phenomena at depths of 242–275 m. The mining system applied was the longwall top coal caving (LTCC) method, with controlled roof caving adapted to thick seams. The geological structure of the perimeter is defined by a syncline intersected by numerous faults (N–S and NNW–SSE orientations), which fragment the deposit into distinct tectonic blocks.

With the decline of the coal industry and the closure of mines starting in the final decades of the 20th century, some of these underground works remained imprecisely mapped (Figure 2), and their effects on the current urban environment are often underestimated. These decommissioned mining structures can act as reservoirs or migration channels for residual gases—particularly methane—originating either from unmined coal seams or from the surrounding rock strata. The phenomenon is exacerbated by the geographic overlap of modern infrastructure with these legacy works. In such cases, gas migration is favored by pressure differentials between the subsurface and the surface, the local permeability of geological formations, and the “chimney effect” induced by seasonal temperature variations.

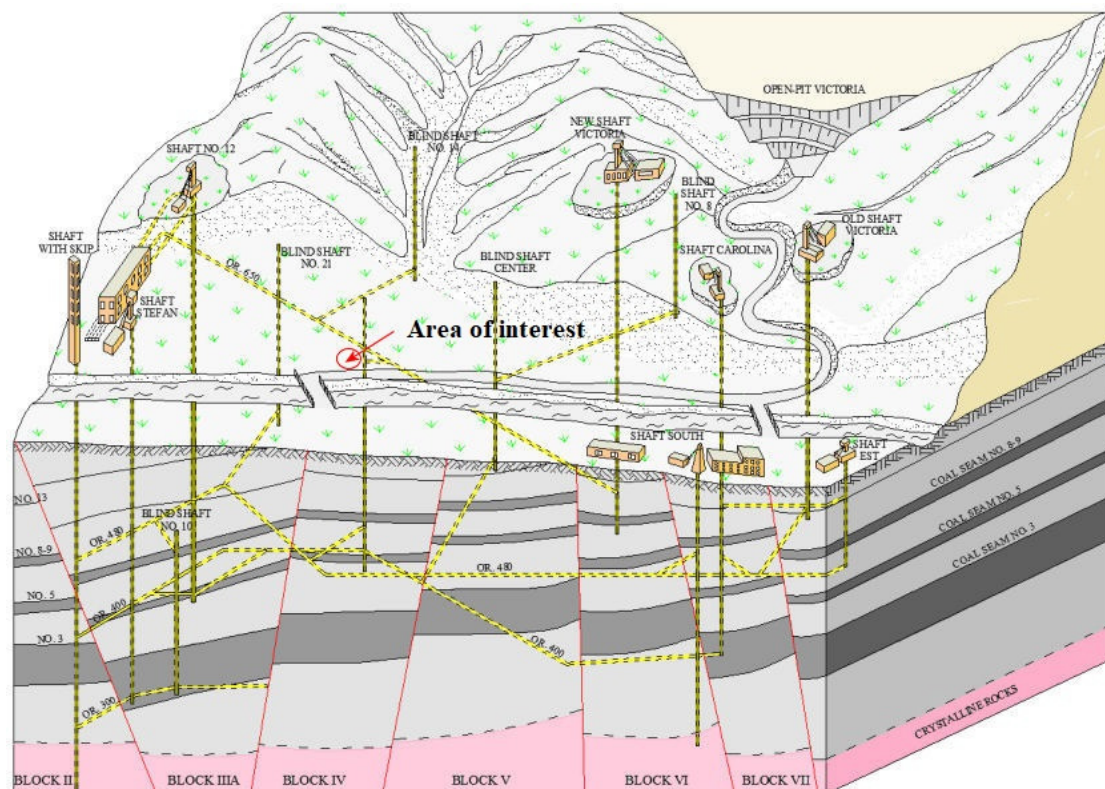


Figure 2. Diagram of mining works in the Lupeni mining perimeter. [14].

These legacy mining features, combined with limited historical documentation and incomplete subsurface mapping, significantly hinder the ability of urban planners and emergency services to predict or prevent gas-related hazards. As such, the urban context of Lupeni—characterized by the juxtaposition of modern infrastructure with a complex, faulted, and incompletely mapped mining system—creates a latent vulnerability to methane accumulation and other post-mining hazards.

2.2. Triggering Event

On 6 August 2024, as part of a major urban infrastructure modernization and expansion project, a new underground natural gas pipeline made of polyethylene PE100 SDR11, DN90 mm, was commissioned following the successful completion of all tightness tests, in accordance with current technical regulations [19]. The pipeline was installed at a depth of 0.9 m, measured from the top generatrix, along Minerilor Street (Figure 3). The main objective of the project was to increase the natural gas supply capacity of the area, supporting both residential and commercial development within the urban perimeter under study.

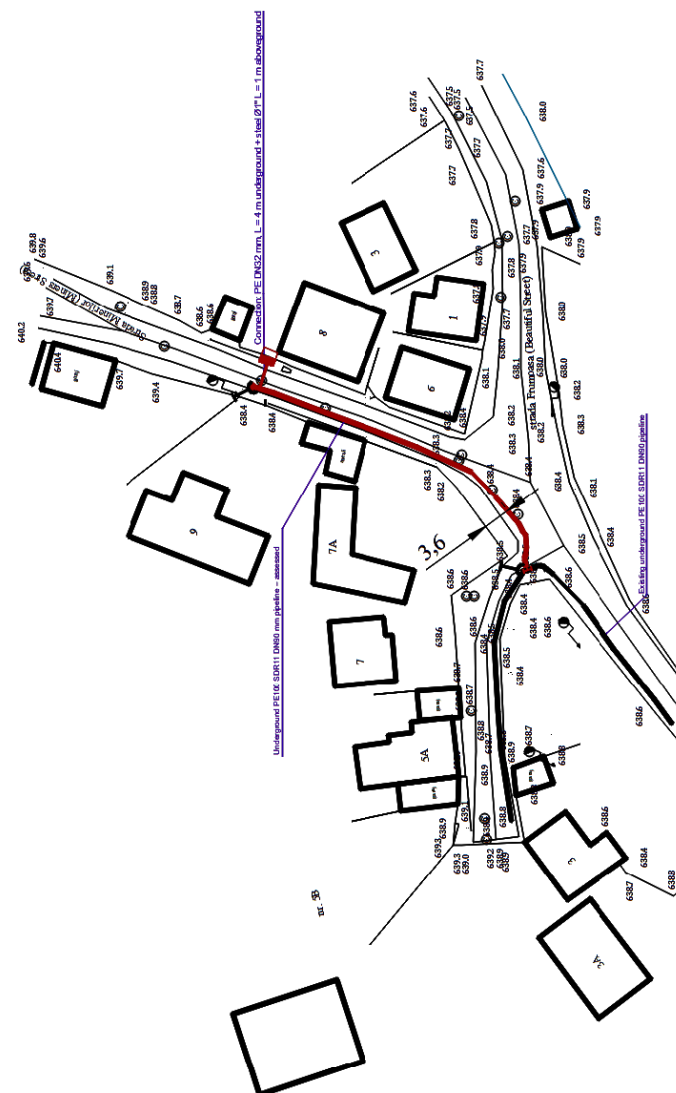


Figure 3. Layout plan. The red line highlights the alignment of the newly designed natural gas pipeline, located within the perimeter of the analyzed area. The thick black lines represent the existing distribution network, including pipelines that were in operation as well as those subsequently decommissioned at the time of the study.

The building outlines illustrate the properties located along the street, providing the built-environment context necessary for assessing the proposed alignment and its spatial relationship with the existing infrastructure.

The circles marked along the route indicate the locations of existing sewer manholes, which are relevant for infrastructure coordination and for analyzing potential interferences between utility networks.

The numerical values shown on the plan represent the coordinates of characteristic points in the national Stereographic 1970 projection system (Stereo 70), used for accurate georeferencing and spatial positioning of the depicted elements.

Just four days after the network became operational, on 10 August 2024, during scheduled gas leak inspections (as mandated by technical standards for newly installed pipelines), gas emissions were identified near the intersection of Minerilor and Frumoasa streets. The issue was initially flagged by portable detection devices and later confirmed through exploratory boreholes drilled along the pipeline route, which revealed hazardous methane concentrations. The affected surface was estimated at approximately 30 m², and the presence of gas necessitated immediate safety measures and the initiation of a multidisciplinary technical investigation into the source of the emissions.

This early-stage detection, occurring only days after pipeline commissioning, raised concerns due to the unexpected nature of the gas presence and its hazardous concentration. Given the location—within a densely populated urban area—the finding prompted immediate implementation of safety protocols and initiated a structured diagnostic process to identify the emission source and assess the risk to the population and infrastructure.

2.3. Organization of Field Investigations

Detailed investigations into the presence and migration pathways of the gas began immediately after the detection of emissions in August 2024, following the confirmation of methane presence at the aforementioned intersection and the immediate cessation of gas supply through the pipeline. Monitoring was conducted over the course of three successive field campaigns, on 14 August, 29 August, and 17 September 2024, using portable detection and sampling equipment calibrated according to international standards.

A total of 41 monitoring points were progressively established and strategically positioned to cover both the directly affected area and potential underground gas migration pathways. The measurement network included:

- Sanitary sewer manholes (CC), identified as potential gas propagation routes via utility corridors;

- Water valve chambers (CA), which may indicate interaction with subsurface voids or old mine galleries;

- Elements of the newly installed gas distribution network, monitored to rule out leakage from the infrastructure;

- Points along Minerilor Street, focusing on the area of recent construction and excavation works. The expansion of monitoring points was conducted using an adaptive strategy, where the network was gradually extended based on the emission front observed in previous campaigns. New points were added radially, beyond the initially affected area, until methane concentrations fell to zero or matched the local background levels. This approach enabled precise spatial delineation of the anomaly and provided a clear map of the affected zone. The total monitored surface for each campaign was as follows:

- 231 m² on 14 August 2024—corresponding to the initial minimum spread of emissions;

- 245 m² on 29 August 2024—indicating a slight increase in the affected area, possibly due to internal pressure fluctuations;

270 m² on 17 September 2024—representing the maximum extent reached during the plateau phase.

This phased and adaptive approach not only allowed accurate mapping of the emission zone but also enabled laboratory analysis to focus on the most diagnostically relevant sampling points. Figure 4 presents the layout of the monitoring network and includes a field photograph, offering real-world visual context of the working conditions and local urban configuration.

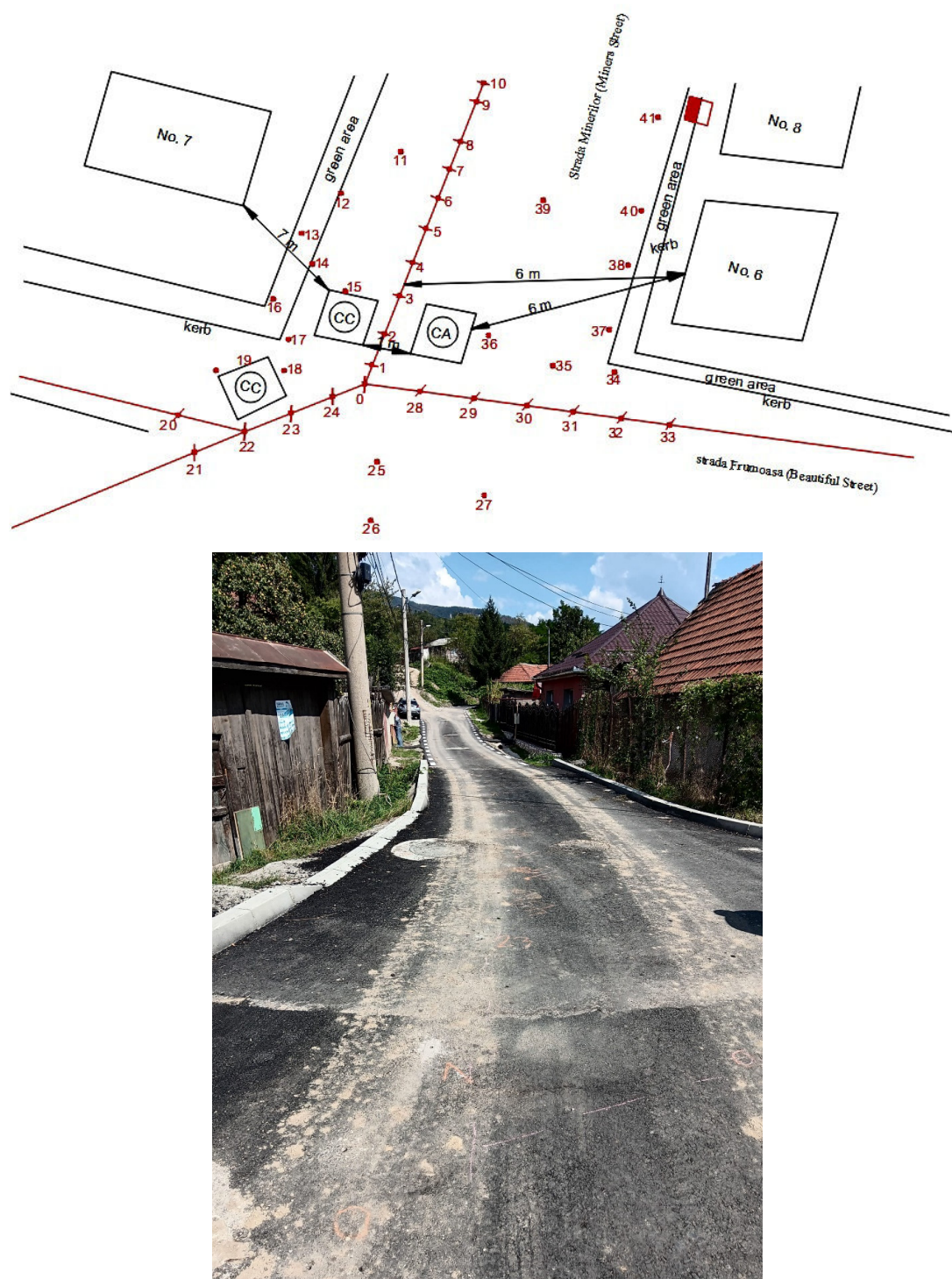


Figure 4. Selection of measurement points.

Monitoring was carried out using portable gas detectors equipped with catalytic and infrared sensors, calibrated daily in accordance with the manufacturer’s specifications and compliant with IEC 60079-29-1 [20] requirements for flammable gas detection.

The primary instrument used was the Sewerin EX-TEC HS 660 (Hermann Sewerin GmbH, Gütersloh, Germany), featuring a detection range from 0 ppm up to 0–100% LEL, enabling accurate measurement of both low methane concentrations and high anomalous values.

The implementation of daily calibration procedures, together with the certified performance of the equipment, ensured the acquisition of precise, reliable, and reproducible data throughout the monitoring network.

Sampling was performed in the early morning hours (07:00–11:00), strategically chosen to minimize the influence of diurnal atmospheric fluctuations on gas distribution. This time window was selected to reduce the effects of temperature variations, solar radiation, and convective currents, which could otherwise induce rapid dispersion or concentration fluctuations.

Meteorological Conditions During the Campaigns (Table 1)

Table 1. Meteorological conditions—Lupeni Weather Station (WMO 15296) [21].

Date and Time	Temperature (°C)	Pressure (hPa)	Humidity (%)	Wind Speed Direction (km/h)	Precipitation (mm)
14 August 2024, 12:00	23.8 °C	945.9	57.1%	4.3 km/h (NE)	0.0
29 August 2024, 12:00	20.3 °C	947.1	67.4%	6.3 km/h (E–NE)	0.0
17 September 2024, 12:00	11.4 °C	948.8	74.4%	2.6 km/h (N)	0.0

Nevertheless, it is acknowledged that even under stable meteorological conditions, gas dynamics may be influenced by the local microclimate (e.g., altitude differences, solar exposure, vegetation), which constitutes an inherent limitation in field studies. Therefore, the recorded data should be interpreted as representative of the monitoring period and not necessarily reflective of seasonal variability.

These variables significantly influence gas dynamics in both soil and air, affecting the potential for subsurface accumulation as well as detectability at the surface. Stable atmospheric conditions, low wind speeds, and the absence of precipitation minimize external dispersion effects, thus enhancing the accuracy of spatial measurements and interpretation of methane anomalies [22–24].

These relatively uniform and stable atmospheric conditions were highly favorable for the detection and comparison of methane concentrations across the 41 measurement points. They minimized the influence of external factors such as wind-driven dilution, abrupt barometric variations, or local convective effects. As a result, the spatial distribution of methane anomalies can be more confidently attributed to subsurface sources rather than short-term meteorological fluctuations.

Such consistent conditions reduced the risk of atmospheric interferences on the recorded methane concentrations, thereby enhancing the reliability of the data interpretation.

The results are presented in Figures 5–9, which graphically illustrate the spatial distribution of methane concentrations across the 41 monitoring points. Elevated values were consistently recorded near Borehole 4 and Borehole 9, while background levels remained significantly lower in areas distant from the abandoned mine galleries. This distinct spatial contrast highlights preferential pathways for methane migration associated with former underground workings.

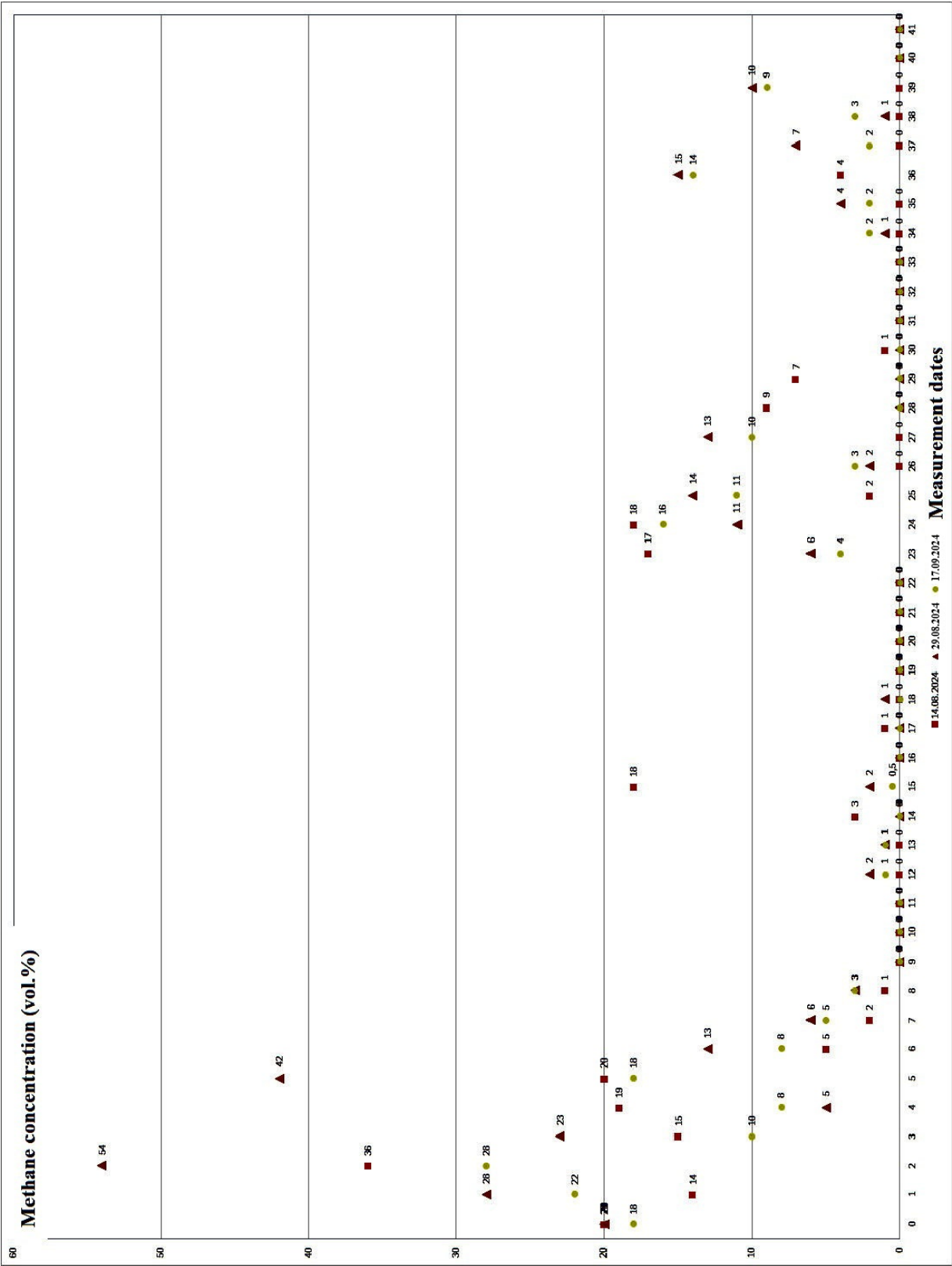


Figure 5. Field methane measurement values.

Furthermore, the temporal consistency of these anomalies across all three field campaigns provides additional evidence that the emissions originate from abandoned mining infrastructure rather than from the active public gas distribution network.

As a precautionary measure, the gas pipeline along Minerilor Street was shut down immediately after the August campaigns. Subsequent monitoring in September confirmed that the detected emissions were not linked to the distribution infrastructure but instead originated from the abandoned coal mine workings. Based on these findings, a controlled methane drainage system was implemented by the mining operator in October 2024.

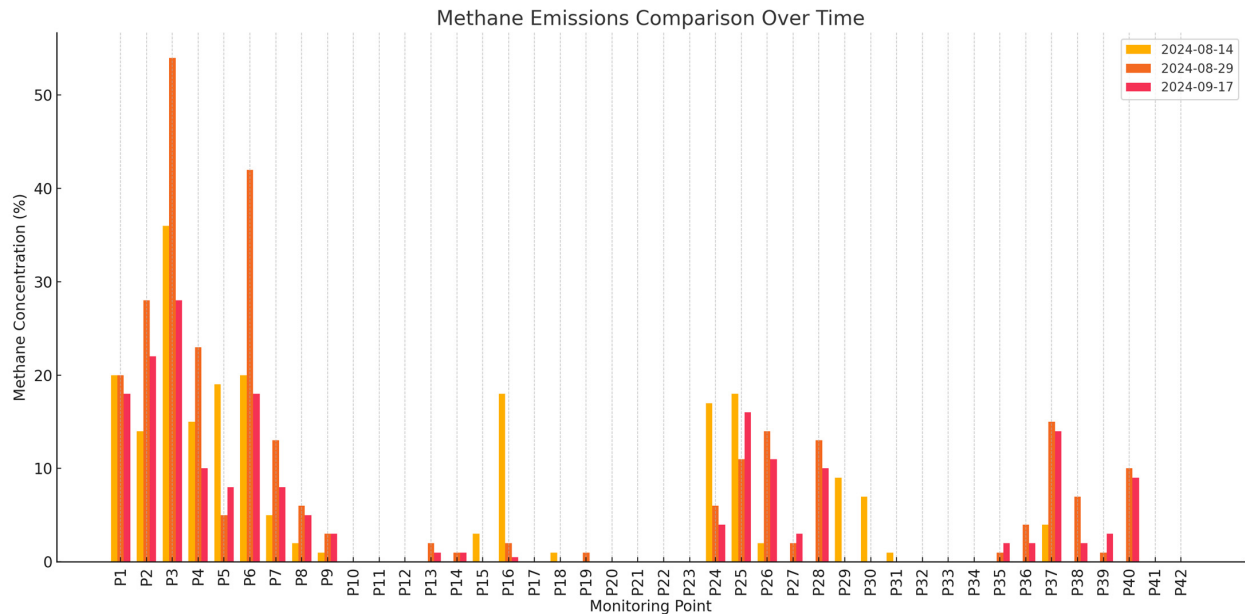


Figure 6. Methane Emission Comparison Over Time.

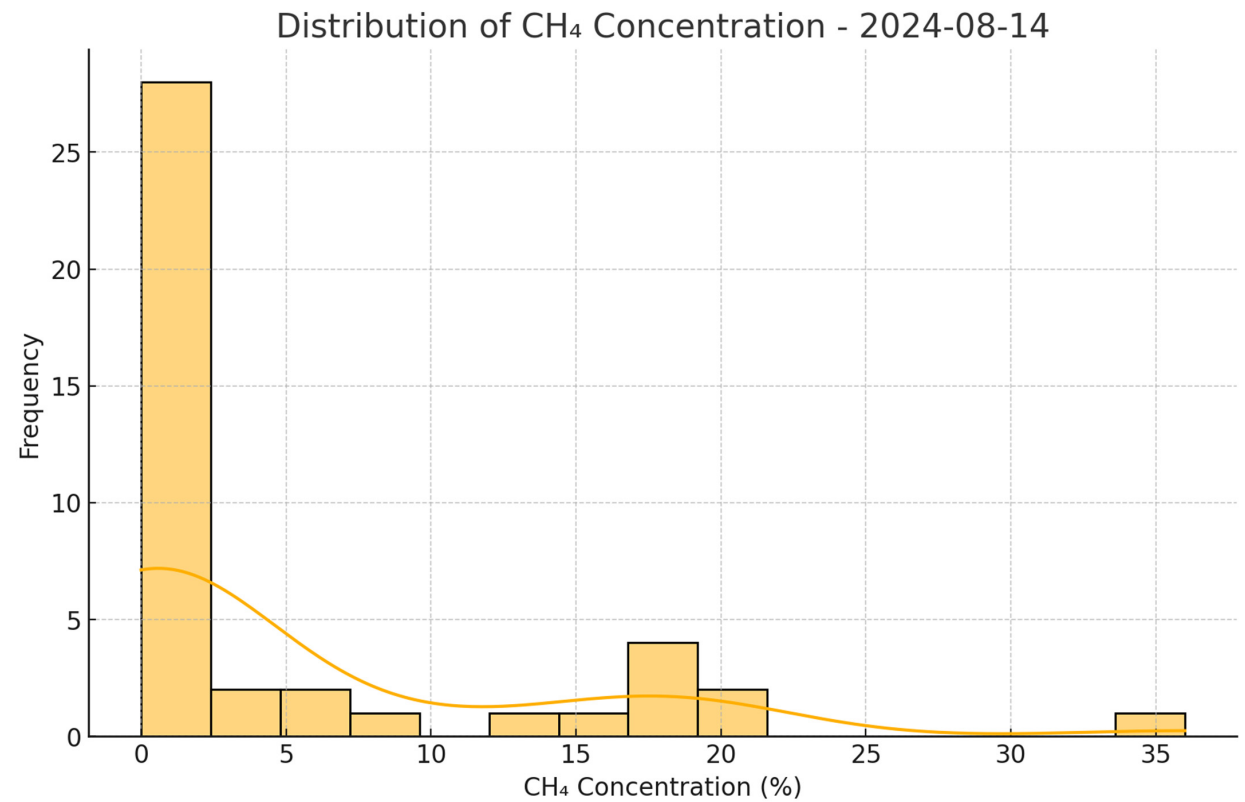


Figure 7. Distribution of CH4 Concentration 14 August 2024.

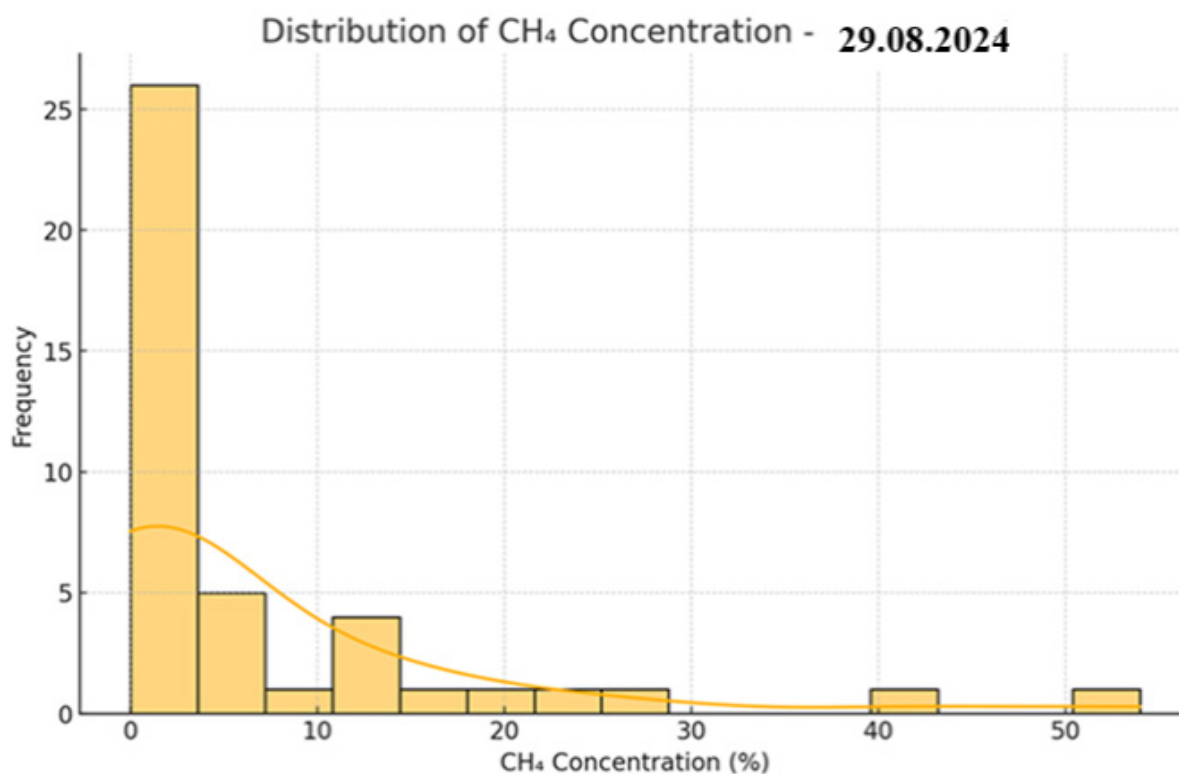


Figure 8. Distribution of CH₄ Concentration 29 August 2024.

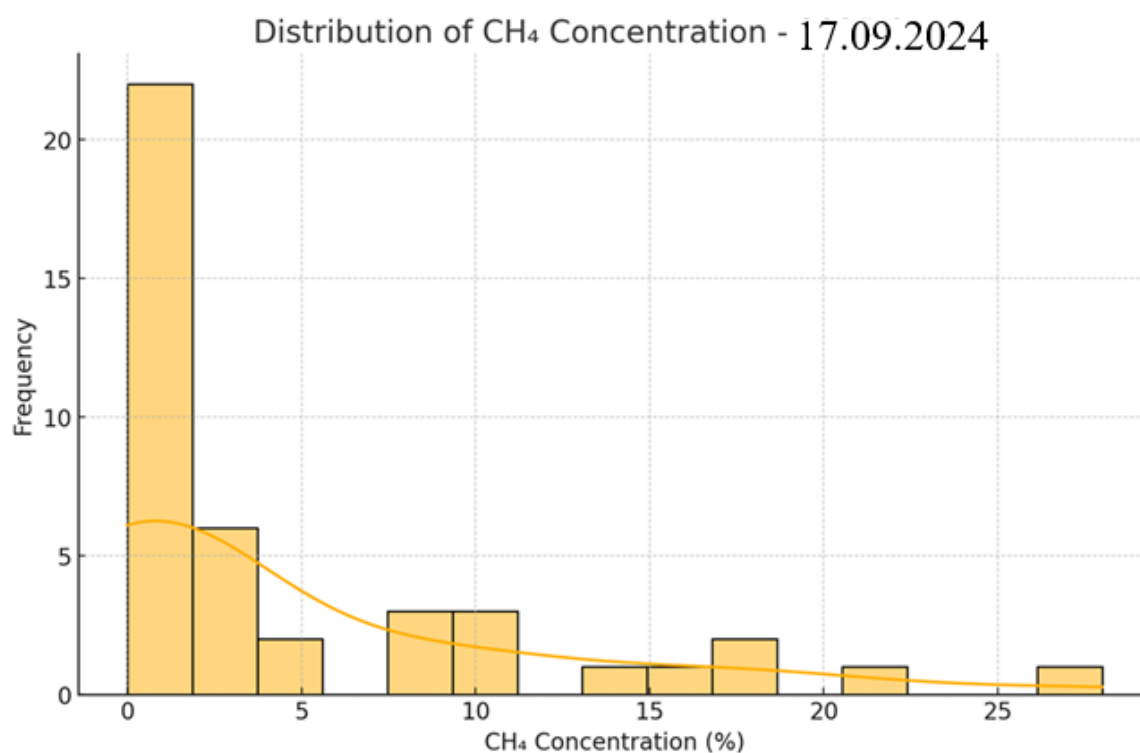


Figure 9. Distribution of CH₄ Concentration 17 September 2024.

Follow-up monitoring campaigns conducted in November, December, and January showed a progressive decline in methane concentrations, with complete disappearance of the emissions by February 2025. Once the situation stabilized, the affected area was rehabilitated, and the street surface was restored. In July 2025, public gas supply was

safely reinstated, following comprehensive integrity and safety testing that confirmed the effectiveness of the implemented solution.

Measured methane concentrations (% vol. and % LEL) were treated as quantitative variables. Statistical analyses were performed to assess spatial consistency and temporal persistence across the three monitoring campaigns. Pearson correlation coefficients were computed between campaigns, and one-way ANOVA was applied to evaluate variance between monitoring periods. Statistical significance was assessed at $p < 0.001$. This approach ensures reproducibility and objective comparison of concentration-based datasets.

3. Technical and Analytical Investigation

3.1. Context and Objectives

In accordance with the integrated diagnostic framework (Figure 1), the technical investigation focused on field monitoring, gas composition analysis, and comparative source attribution.

The primary objective of the investigation was to identify the actual source of the gas detected in the Minerilor Street area, since initial suspicions pointed to a possible leak from the newly installed natural gas network. Given the location within a historic mining perimeter, there were reasonable grounds to suspect the migration of residual mine gases.

The specific objectives of the study were:

- To determine the chemical composition of the gas from the emission zones;
- To compare the composition with gas from the public distribution network (reference sample);
- To identify chemical markers capable of distinguishing mine gas from commercial gas;
- To correlate the results with historical geotechnical and topographic data;
- To propose long-term remediation and monitoring solutions.

3.2. Sampling Procedure

3.2.1. Selection of Measurement Points

The initial monitoring campaigns covered 41 measurement points distributed along Minerilor Street and its surroundings, including sewer manholes, water manholes, utility elements, and intersections with high subsurface connectivity. From this extended grid, two representative points were selected for detailed chromatographic analysis:

Borehole 4—located near a sewer manhole and a major road intersection, consistently showing the highest and most persistent methane concentrations across campaigns;

Borehole 9—located in an area with moderate concentrations but intermittent anomalies, suggesting episodic migration linked to localized underground voids or fissures.

This targeted selection was guided by the need to focus on the most relevant anomalies, where the probability of distinguishing the emission source was greatest.

The monitoring network consisted of 41 points strategically positioned to capture potential methane migration pathways. These included: (i) sewer manholes (CC), as potential gas propagation conduits; (ii) water manholes (CA), representing connectivity with subsurface voids; (iii) elements of the gas distribution network, to exclude possible leaks; and (iv) points along Minerilor Street, where recent pipeline works had been carried out. From this extended grid, two representative points (Boreholes 4 and 9) were selected for chromatographic analyses, as they consistently showed the most relevant anomalies. This focused approach ensured that laboratory investigations targeted areas with the highest diagnostic value.

3.2.2. Sampling Methodology

Gas samples were collected in strict accordance with ISO 10715:1997 [25]—Natural Gas Sampling Guidelines, ensuring reliability and reproducibility of results. The procedure included:

Use of stainless-steel containers equipped with airtight valves to prevent leakage or contamination;

Purging of the sampling system with local gas prior to collection, to eliminate residual air and ensure representative samples;

Collection of a comparative reference sample directly from the public distribution network, serving as a baseline for chemical composition analysis.

Figure 10 provides a comprehensive visualization of the statistical distribution of methane concentrations (CH_4 , expressed in %) recorded during three field measurement campaigns conducted on:

- 14 August 2024
- 29 August 2024
- 17 September 2024

A violin plot combines elements of a boxplot with a kernel density estimation, allowing for simultaneous interpretation of central tendency, variability, and distribution shape.

Interpretation

- The central dashed line within each violin indicates the median concentration, while the upper and lower dashed lines represent the first and third quartiles (interquartile range).
- The width of each violin at different concentration levels represents the density of observations—wider sections correspond to a higher frequency of values.
- The vertical extension of each violin reflects the range and spread of the data, including potential outliers.

Campaign Comparison

- 14 August 2024:

The distribution is moderately skewed, with a concentration of values near 0–2% CH_4 , and a long upper tail reaching above 30%, indicative of localized high-emission points (e.g., Borehole 4).

Most measurement points recorded low concentrations, but significant anomalies were present.

- 29 August 2024:

This campaign exhibits the greatest dispersion in CH_4 values, with several outliers reaching up to ~60%. The broader shape indicates elevated variability, possibly related to transient increases in subsurface pressure or enhanced gas migration dynamics.

- 17 September 2024:

The distribution is more compact, with most values clustering between 0% and 5%, and fewer extreme outliers. This suggests a stabilization of emissions, likely as a result of effective mitigation actions (e.g., active drainage implemented after August).

Implications

The violin plots demonstrate the heterogeneous spatial behavior of methane emissions across the monitoring area, with persistent anomalies suggesting direct connections to abandoned mining voids. Although median values remained low, the presence of extreme concentrations indicates high-risk emission points. The progressive narrowing of the distributions over time reflects the effectiveness of implemented countermeasures and

supports the hypothesis of a localized, non-distributed source (i.e., legacy mine workings rather than diffuse surface leaks).

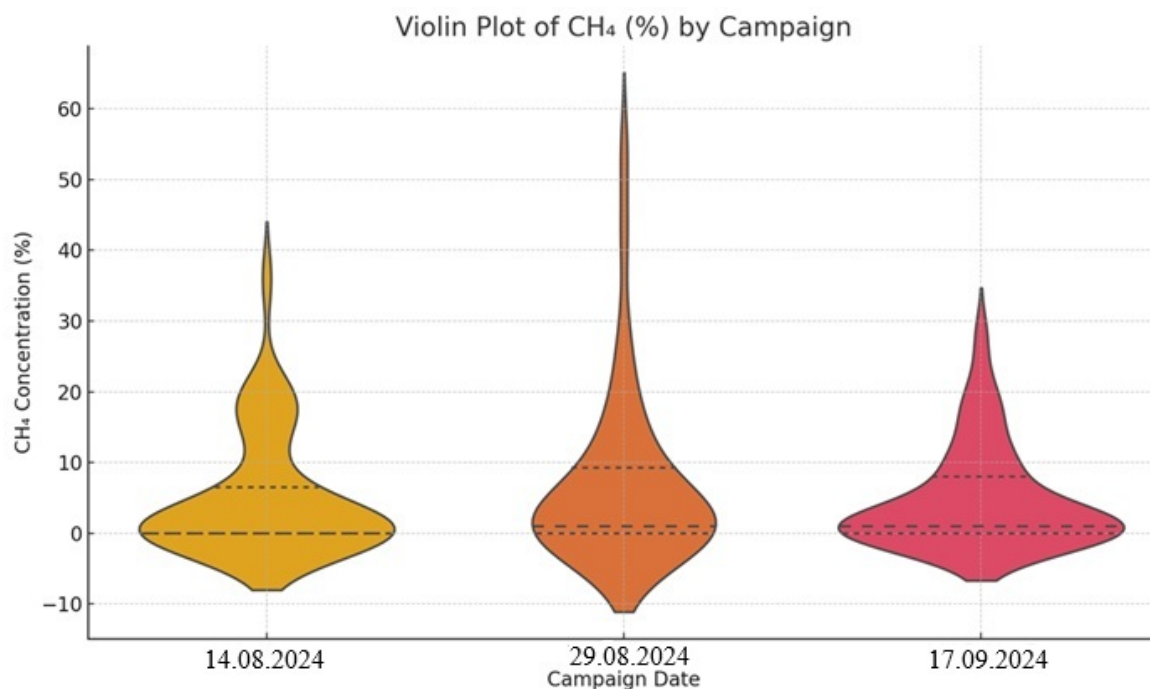


Figure 10. Violin plot illustrating the distribution of CH₄ concentrations (%) across 41 monitoring points during three field campaigns. The width of each violin reflects the density of data points at different concentration levels, while the dashed lines indicate quartiles and the median. The plot highlights persistent spatial anomalies and a general trend toward stabilization over time, likely due to mitigation measures.

Figure 11 presents a Pearson correlation matrix illustrating the relationships between methane concentrations (% CH₄) measured at 41 monitoring points during three field campaigns conducted on:

14 August 2024

29 August 2024

17 September 2024

Pearson Correlation Coefficient (r)

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \cdot \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}}$$

Explanation:

- x_i, y_i : Methane concentrations measured at the i -th point for two different sampling campaigns.
- $\bar{x}, \bar{y}$: Mean concentrations across all 41 monitoring points for each respective campaign.
- $n = 41$: Number of monitoring points (i.e., paired observations).
- This formula evaluates the strength and direction of the linear relationship between two datasets.

Each matrix cell displays the Pearson correlation coefficient (r), which quantifies the strength and direction of the linear relationship between two datasets. The coefficient is interpreted as follows:

$r = +1.0 \rightarrow$ perfect positive correlation (both variables increase together)

$r = 0 \rightarrow$ no correlation

$r = -1.0 \rightarrow$ perfect negative correlation (one variable increases as the other decreases)
Results: (Table 2)

Table 2. Pearson correlation coefficients (r) and associated p -values for methane concentrations measured during the three field campaigns ($n = 41$ monitoring points).

Comparison	Pearson r	p -Value
14 August 2024 vs. 29 August 2024	0.76	5.91×10^{-9}
14 August 2024 vs. 17 September 2024	0.75	1.23×10^{-8}
29 August 2024 vs. 17 September 2024	0.92	2.69×10^{-18}

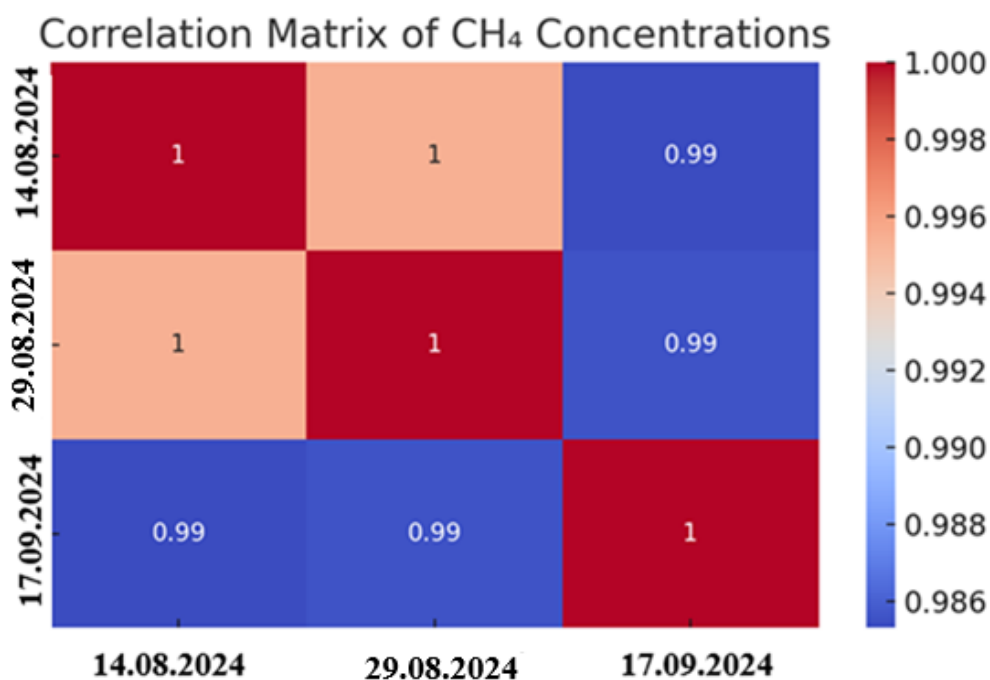


Figure 11. Correlation matrix of CH₄ concentrations (% vol) measured at 41 monitoring points during three campaigns (14 August 2024, 29 August 2024, 17 September 2024). Pearson correlation coefficients (r) show extremely strong and statistically significant correlations between all datasets, indicating consistent spatial distribution of methane emissions. The data confirm a persistent and localized underground source rather than variability caused by surface or atmospheric factors.

All correlations are strong, positive, and statistically highly significant ($p < 0.001$), indicating that the spatial distribution of methane emissions remained consistent across the three campaigns (August–September 2024). This consistency strongly supports the hypothesis that the emissions originate from a localized and persistent subsurface source, rather than from random or weather-dependent surface processes.

To determine whether the mean methane concentrations differed significantly across the three campaigns, a one-way analysis of variance (ANOVA) was performed. The ANOVA test evaluates whether there are statistically significant differences between the group means. The F-statistic is calculated as:

$$F = \frac{MS_{\text{between}}}{MS_{\text{within}}} = \frac{SS_{\text{between}} / (k - 1)}{SS_{\text{within}} / (n - k)}$$

Explanation:

SS: Sum of Squares

SS_{between} : Variation due to differences between group means (i.e., variation across campaigns).

SS_{within} : Variation within each campaign (i.e., random or measurement error).

MS: Mean Squares

Calculated by dividing each SS by its degrees of freedom.

$k = 3$: Number of groups (sampling campaigns)

$n = 123$: Total number of observations (41 points $\times$ 3 campaigns)

F-value: Represents the ratio of between-group variance to within-group variance.

Interpretation:

$F > 1$ with low p -value indicates significant differences between groups.

If $p > 0.05$, no statistically significant difference exists between the groups.

Scientific Interpretation and Implications

Spatial Persistence of Emissions

The strong, consistent correlations across datasets confirm that high-methane zones were stable in both space and time. These zones correlate with the mapped positions of abandoned mining infrastructure, suggesting preferential pathways of gas migration through old galleries, voids, or faults.

Methodological Robustness

The high reproducibility across campaigns highlights the reliability of the sampling design and analytical protocol. Measurement error, atmospheric variability, and instrument drift are unlikely to account for the observed CH_4 distributions.

Geological Significance

The emission consistency suggests that methane follows stable geological structures, such as faulted zones or connected collapse galleries. These pathways can allow methane to migrate for extended periods after mine closure, as supported by literature on abandoned mine methane (AMM).

Conclusion

This correlation and variance analysis supports the following key conclusions:

Methane emissions are geographically and temporally stable

The emissions are not linked to the gas distribution network, but rather to residual gases from abandoned mine workings

The observed pattern is diagnostic of a post-mining emission regime and requires targeted, long-term mitigation

These findings underscore the critical importance of integrated monitoring in urban areas overlying former mining operations and provide a quantitative foundation for risk-informed planning and intervention.

3.2.3. Measured Variables and Inferred Outcomes

Measured variables (primary data). This study reports direct field and laboratory measurements recorded per monitoring point and campaign: (i) methane concentration in air reported as %vol and/or %LEL from portable gas detectors; (ii) chromatographic gas composition (CH_4 , C_2H_6 , C_3H_8 , CO_2 , CO , C_2H_2) reported in mol% or ppmv depending on calibration; (iii) spatial coordinates (WGS84) and timestamp for each reading/sample; and (iv) meteorological parameters (temperature, pressure, humidity, wind) measured for each campaign.

Inferred outcomes (derived results). The following outcomes are not direct measurements; they are derived from the measured dataset through explicit decision rules and data integration: (i) source attribution (abandoned mine methane vs. distribution network gas); (ii) delineation of anomaly footprint (area and persistence); (iii) risk classi-

fication (probability–consequence matrix); and (iv) operational recommendations (shut-down/monitoring/mitigation), contingent on attribution and risk level.

3.3. Chromatographic Analysis

Laboratory analyses were conducted in accordance with the internal procedure PI-13 “Determination of saturated and unsaturated aliphatic hydrocarbons, hydrogen, and carbon monoxide”, specifically designed for the identification of combustible gases and associated compounds in industrial and mining contexts.

For this purpose, a Clarus 500/650 gas chromatograph (model N8022108, PerkinElmer, Inc., Waltham, MA, USA) was used, equipped with FID (Flame Ionization Detector) and TCD (Thermal Conductivity Detector) systems. The instrument was periodically calibrated in accordance with the manufacturer’s specifications using certified reference gas mixtures. Analytical details included:

Chromatographic column: Capillary, 30 m length, 0.53 mm internal diameter, low-polarity siloxane-based stationary phase, optimized for the separation of C1–C5 hydrocarbons;

Carrier gas: Helium, with $\geq 99.999\%$ purity, controlled via constant flow mode;

Temperature program: Initial temperature at 50 °C (held for 2 min), ramped at 10 °C/min up to 180 °C, held for 5 min—optimized for efficient separation of saturated and unsaturated hydrocarbons;

Injector/Detector temperatures: 200 °C/250 °C;

Retention times (average, subject to slight variation under operational conditions):

CH₄ ~2.3 min

C₂H₆ ~3.8 min

C₃H₈ ~5.2 min

CO₂ ~6.1 min

Methodological justification:

This method was selected for its ability to accurately characterize the compositional profile of gas samples, including tracer compounds such as ethane, propane, and carbon monoxide, which are critical in differentiating between pipeline gas and residual gas from abandoned mining sources. Furthermore, the presence of unsaturated hydrocarbons and acetylene was specifically monitored as diagnostic indicators of potential subsurface thermal or oxidative processes.

3.4. Analysis Results

3.4.1. Composition of Network Gas

Laboratory analyses of the reference sample indicated the following composition for the commercial gas:

Methane (CH₄): $98.31 \pm 0.05\%$ mol/mol

Ethane (C₂H₆): $0.68 \pm 0.02\%$ mol/mol

Propane (C₃H₈): $0.23 \pm 0.01\%$ mol/mol

CO₂: $0.78 \pm 0.05\%$ mol/mol

Unsaturated hydrocarbons (C₂H₄, C₃H₆): absent

Carbon monoxide (CO): absent

3.4.2. Composition of Emission Gas

The results of the gas composition analysis from the two borehole sampling points reveal significant differences between the detected emissions and the composition of gas from the public distribution network. Borehole 4, located in the area with the most persistent anomalies, indicated a high concentration of methane (CH₄ = 16.63%), accompanied by ethane (C₂H₆ = 0.0755%), carbon dioxide (CO₂ = 0.95%), and traces of carbon monoxide

(CO = 0.00024%). Additionally, reactive species such as acetylene (C_2H_2) and unsaturated hydrocarbons were detected, confirming the presence of oxidative and/or thermal processes at the emission source.

In contrast, Borehole 9 showed a markedly different composition, with methane concentrations at very low levels ($CH_4 = 0.0113\%$), ethane ($C_2H_6 = 0.000049\%$), and carbon dioxide ($CO_2 = 0.517\%$), while carbon monoxide (CO) was detected qualitatively but not quantitatively. These values suggest a more diluted character of the emissions, possibly resulting from secondary migration through underground pathways that are weakly connected to the primary source.

3.5. Analysis of Differences

Major differences were revealed between emission gas and network gas:

- Methane/Ethane ratio—in Borehole 4, the ratio was much lower than that of network gas, indicating a mixture with other hydrocarbons and residual gases;
- Carbon monoxide (CO)—detected in Borehole 9, absent in commercial gas, but common in mine gases due to coal oxidation;
- Acetylene and unsaturated hydrocarbons—unstable compounds resulting from underground thermal reactions;

High spatial variability—Borehole 4 exhibited significant methane content, while Borehole 9 showed very low concentrations, suggesting different sources and migration pathways.

3.6. Comparative Conclusions

The compositional analysis unequivocally confirms that the gas detected in the field does not originate from the public distribution network but rather from residual accumulations related to abandoned mining operations at the Lupeni coal mine. This conclusion is supported by:

The presence of compounds absent in commercial gas (e.g., carbon monoxide—CO, acetylene— C_2H_2);

Abnormal CH_4/C_2H_6 and CH_4/CO_2 ratios, deviating from typical pipeline gas profiles;

Spatial correlation between elevated concentrations and the known geological positions of historical underground mine workings.

While these findings are specific to the Lupeni case study, they underscore the broader need for a structured and reproducible diagnostic framework applicable in other urban contexts affected by post-mining subsurface conditions.

The detection of carbon monoxide (CO) and acetylene (C_2H_2) in gas samples collected from surface emissions serves as a relevant diagnostic indicator of oxidative and/or thermal processes associated with mining environments (e.g., goafs, abandoned galleries, and areas with intermittent air ingress). These species are typically linked to:

- the generation and migration of CO in underground voids influenced by air infiltration and oxidation reactions involving coal and/or carbonaceous material;
- the formation of acetylene under thermal treatment/pyrolysis (cracking) conditions, indicating a more energy-intensive regime than biogenic or residual methane release alone.

Regarding CO, the literature explicitly notes that mine goafs may host mechanisms of CO generation, migration, and accumulation, strongly influenced by air leakage dynamics and the configuration of underground fractures and voids. Consequently, the presence of CO in emitted gas samples—especially when absent in the reference sample from the gas distribution network—reinforces the attribution of emissions to underground mining sources, rather than to the commercial gas infrastructure [26].

As for acetylene, it is widely recognized as a characteristic product of thermal processes acting on coal. Pyrolysis experiments have shown that both C₂H₂ and CO can emerge as major gaseous products under high-temperature conditions, alongside other light hydrocarbons [27]. Even if local thermal regimes within abandoned mines may be heterogeneous and often below the threshold of intense pyrolysis, the detection of C₂H₂ nonetheless indicates the presence of micro-environments with sufficient energy to generate unsaturated hydrocarbons, consistent with thermal/oxidative transformations in carbonaceous materials.

Moreover, from a chemical fingerprinting perspective, CO and C₂H₂ are widely employed in atmospheric studies as tracers of combustion and thermal alteration, precisely because they co-occur with other hydrocarbons in mixtures originating from oxidation and burning processes [28]. By analogy, their identification in a methane-dominated gas mixture, but with distinct signals of combustion/thermal species, supports a more nuanced source attribution than a simple CH₄ vs. network gas comparison.

In conclusion, the presence of CO and C₂H₂ in emitted gas samples holds high diagnostic value for interpreting the origin and underlying processes of the emissions. CO is typically associated with the oxidation of carbonaceous matter and the dynamics of infiltrated air in underground voids or goafs [1], while C₂H₂ is a distinctive product of thermal transformations (e.g., pyrolysis/cracking) of coal, often appearing concurrently with CO under elevated thermal regimes [2]. The use of CO and C₂H₂ as tracer species aligns with the specialized literature, which documents their co-emission in gaseous mixtures produced by thermal and oxidative processes [3]. Multi-point measurements, corroborated by chromatographic data and the exclusion of alternative sources, strongly support the conclusion that the emissions originate from residual underground mining networks.

3.7. Generalized Methodological Framework

To move from case-specific diagnostics to a generalizable approach, the investigation was synthesized into a five-step framework integrating risk assessment, monitoring, chemical fingerprinting, data correlation, and remediation, as summarized in Table 3.

Table 3. Operationalization of the diagnostic framework illustrated in Figure 1.

Stage	Key Actions	Expected Outputs
1. Preliminary risk assessment	Collect historical data on mining operations, closure plans, and urban expansion; identify areas where current infrastructure overlaps with abandoned galleries	Risk map and delineation of priority monitoring zones
2. Field monitoring and detection	Conduct periodic campaigns with portable detectors and fixed monitoring stations to measure methane concentrations	Chronological dataset of spatial and temporal emission variations
3. Comparative sampling and laboratory analysis	Collect gas samples from emission zones and from the public network; conduct chromatographic and isotopic analyses to differentiate sources	Chemical fingerprint of gas origin (mine methane vs. distribution network)
4. Data integration and correlation	Overlay monitoring results with mining maps, geological structures, and urban technical networks	Accurate diagnosis of emission sources and migration pathways
5. Remediation and management measures	Implement active drainage, controlled venting, sealing, or energetic valorization; establish continuous monitoring protocols	Reduced urban risk, public safety protection, and sustainable resource utilization

Table 3 translates the conceptual diagnostic framework presented in Figure 1 into operational steps, expected outputs, and decision-support elements applicable in post-mining urban environments.

4. Mitigation of Methane Emissions and Reactivation of the Gas Network

As a precautionary measure, the natural gas distribution network along Minerilor Street had already been shut down in August 2024, immediately after the first monitoring campaigns confirmed the presence of uncontrolled emissions. This ensured public safety during the entire diagnostic and remediation process and explains why recommissioning of the pipeline was carried out only in July 2025, after all risks had been eliminated.

Multi-point measurements conducted between August and September 2024 indicated persistent concentration anomalies, which led to the initiation of drainage works in October. Subsequent monitoring between October 2024 and February 2025 revealed a progressive decrease in methane concentrations, culminating in the complete disappearance of emissions by February.

In February 2025, after an intensive monitoring period of the affected area, measurements at all points of interest indicated zero methane concentrations in the soil. This complete reduction resulted from the implementation of a controlled mine gas drainage plan by the Lupeni mining operation. Figure 12 illustrates the area where the drainage pipelines were installed, capturing the proximity of these interventions immediately after their completion and highlighting the direct link between the technical works and the elimination of emissions.



Figure 12. Area where mine gas drainage works were carried out.

The adopted technical solution consisted of installing methane drainage pipelines directly connected to the existing degassing network. Through this measure, residual gas was captured and redirected into a controlled utilization circuit, thereby eliminating the risk of urban accumulation and associated hazards. The collected gas was subsequently used to produce hot water for ongoing mining activities at Lupeni.

This intervention, which transformed a potentially catastrophic risk into an opportunity, generated multiple benefits:

- Increased public safety through the elimination of uncontrolled emissions;
- Reduced environmental impact by capturing and utilizing methane, a significant greenhouse gas;

Economic efficiency through the partial substitution of other energy sources required for hot water production.

Figure 13 shows the rehabilitated area and the recommissioning of the natural gas pipeline along Minerilor Street. The image illustrates the return to a safe and normal situation, confirmed by integrity tests conducted prior to putting the public network back into operation. Thus, the photograph provides visual evidence of the effectiveness of the applied solution and of the stability achieved following the implementation of the drainage works.



Figure 13. Rehabilitated area and pipeline back in operation.

4.1. Economic and Social Implications

The economic and social implications discussed below derive directly from the diagnostic results presented in Sections 3.4–3.6, particularly the chromatographic exclusion of the gas distribution network as the emission source. This diagnostic outcome guided decision-making and mitigation priorities.

The investigation demonstrated that correctly identifying the source of methane emissions has a direct impact on costs and public confidence. In the absence of accurate diagnostics, there is a risk of:

Erroneous allocation of resources for repairs to the distribution network, even when it is unaffected;

Prolonged shutdown of gas supply to residential areas, with economic and social consequences for residents and commercial operators;

Additional costs for unnecessary works or compensation claims;

Damage to the reputation of the network operator and local authorities due to public perception of poor crisis management.

In the Lupeni case, rapid intervention and confirmation of the mining origin of the gas avoided significant economic losses, maintained the functionality of other segments of the urban network, and prevented temporary relocation of the population.

4.2. Risk Scenarios in the Absence of Intervention

The monitoring campaigns conducted in August and September 2024 provided not only quantitative data on methane concentrations but also enabled the delineation of the

spatial footprint of the anomaly. On 14 August 2024, elevated methane concentrations were confined to an area of approximately 6×45 m. By 29 August, the anomaly expanded slightly to 7×35 m, and on 17 September it persisted over a 7×33 m area. These consistent observations indicate that the anomaly footprint remained relatively stable in size, without exponential growth, confirming the persistence and localization of the emission and justifying the decision to implement active drainage measures.

If these methane emissions had not been drained and neutralized, several critical risks would likely have materialized:

- **Explosion hazard:** Methane concentrations accumulating in confined spaces such as sewer systems, utility chambers, or building foundations could have exceeded the Lower Explosive Limit (LEL), posing a high risk of explosion with potential human casualties and severe structural damage [5,29–31].
- **Public health impacts:** Infiltration of methane into basements and poorly ventilated indoor spaces could have degraded indoor air quality, leading to acute safety hazards (oxygen displacement) and longer-term health concerns for exposed residents [5,7,15].
- **Disruption of urban services:** To ensure public safety, authorities would likely have been forced to evacuate residents and temporarily shut down essential urban utilities (water supply, sewerage, electricity, and gas distribution), resulting in significant social and economic disruption.
- **Infrastructure deterioration:** Persistent gas pressure and migration through fractured media may have exerted stress on underground structures, potentially exacerbating subsurface instability and fracture development in Lupeni's faulted geological context [6,14,32].

This spatial and temporal risk assessment highlighted the urgency of remedial action. The subsequent implementation of a controlled methane drainage system successfully eliminated detectable surface concentrations by February 2025, mitigating all four identified risk categories and restoring safe operational conditions for both the urban gas network and the surrounding infrastructure.

In response to the need for a structured and reproducible evaluation of risks associated with residual methane emissions, this study adopted a semi-quantitative risk assessment framework, which enables the prioritization of hazard scenarios based on combined estimates of probability and consequence [5,33]. The total risk score (R) is defined as:

$$R = P \times C$$

where

- R: Total risk score (dimensionless)
- P: Probability of occurrence, rated on a scale from 1 (rare) to 5 (frequent)
- C: Severity of consequences, rated on a scale from 1 (minor) to 5 (catastrophic)

This approach enables the comparison of various hazard scenarios even in the absence of exact frequencies or cost data, by providing relative prioritization based on field observations and expert judgment.

4.2.1. Risk Matrix

The combined risk score R was classified using a 5×5 probability–consequence matrix, as shown in Table 4, Figure 14.

Table 4. Probability–consequence classification for the risk score ($R = P \times C$).

Risk Score (R)	Risk Level	Description	Recommended Action
1–4	Low	Tolerable risk; minor impacts	Routine monitoring
5–9	Moderate	Noticeable but manageable	Increased monitoring and planning
10–16	High	Significant hazard potential	Mitigation planning required
17–25	Critical	Unacceptable risk; major hazard	Immediate action and remediation

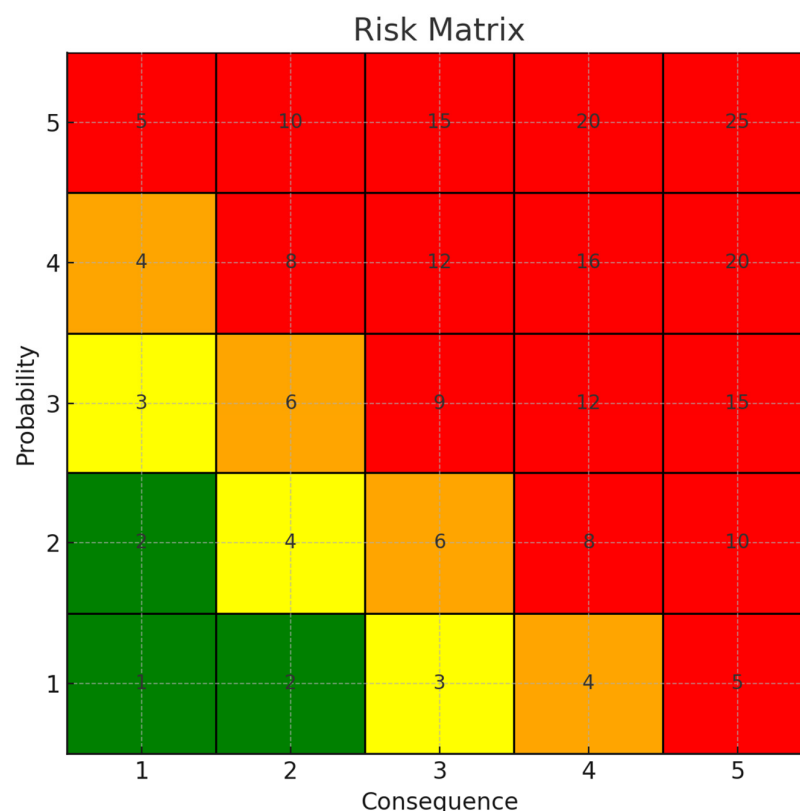


Figure 14. Semi-quantitative risk matrix used to assess methane emission scenarios. Each cell represents the risk level determined by the combination of probability (vertical axis) and consequence (horizontal axis). The color coding illustrates the severity of risk from “Low” (green) to “Critical” (red), guiding prioritization of mitigation actions.

Given the confirmed persistence and underground origin of methane emissions, a semi-quantitative risk analysis was conducted to evaluate potential hazards posed to public safety and infrastructure. This approach integrates expert judgment with measured field data in a structured framework and follows standard probability–consequence risk modeling principles commonly applied in environmental and industrial hazard assessments [5,33].

4.2.2. Scenario Application: Methane Accumulation in Confined Spaces

A relevant scenario was identified in this study: the accumulation of methane in underground utility chambers, including sewer and water access points (e.g., CC17, CA9). Field measurements revealed methane concentrations exceeding 3% vol. in certain locations—well approaching the lower explosive limit (LEL) of 4.4% in air. Combined with stagnant airflow and proximity to populated areas, this poses a critical hazard [5,30,31].

Based on field data and risk scoring:

- Probability (P): 4 (Likely)
- Consequence (C): 5 (Catastrophic)

$$R = P \times C = 4 \times 5 = 20 \Rightarrow \text{Critical Risk}$$

This result justified the immediate implementation of active methane drainage and the temporary shutdown of the gas distribution network. It further supports the post-monitoring decision to permanently connect the emission points to the mine's degassing infrastructure.

4.2.3. Scientific Implications and Transferability

The applied semi-quantitative risk model ensures transparency, consistency, and reproducibility in decision-making and can be readily adapted to other urban post-mining environments. While it does not replace fully probabilistic approaches (e.g., fault-tree analysis or Monte Carlo simulations), it is particularly valuable in data-limited contexts, where rapid risk prioritization is required [5,33].

By explicitly linking gas monitoring results to structured risk scores, this framework bridges the gap between technical diagnostics and risk-informed urban planning, offering a scalable methodology for managing hazards associated with abandoned mine methane (AMM).

4.3. Benefits Achieved After Remediation

The connection of new drainage pipelines to the Lupeni mine's degassing network produced a set of tangible, multi-dimensional benefits:

Economic benefits: Direct savings were achieved by reducing dependence on external fuel purchases. The captured methane replaced a portion of the fossil fuels otherwise required for hot water production, lowering operational costs and contributing to local energy security [18].

Climate benefits: By capturing methane and utilizing it for energy purposes instead of allowing uncontrolled atmospheric release, the intervention significantly reduced greenhouse gas emissions. Given methane's global warming potential—28 to 34 times higher than that of carbon dioxide over a 100-year horizon [1]—its controlled management has a measurable contribution to climate change mitigation [16].

Safety benefits: The risk of conflux between residual mine gas and the public urban network was eliminated, removing the threat of explosions, infrastructure damage, or health hazards for the local population [5,6,8].

These benefits, while concrete in terms of technical performance, also directly align with the broader objectives of sustainable development:

Greenhouse gas mitigation: The project directly contributes to national and EU-level strategies on emission reduction, including the objectives of the Global Methane Pledge [3] and Regulation (EU) 2024/1785 on methane emissions reduction [4].

Sustainable urban planning and resilience: By integrating post-mining risk assessment into infrastructure rehabilitation, the case of Lupeni illustrates how urban growth in post-industrial regions can be managed safely, ensuring the resilience of communities located above abandoned mining works [14,31,32].

Circular resource use and energy transition: The transformation of methane from a latent hazard into a usable energy resource exemplifies circular economy principles. What was previously a risk stream was revalorized to provide utility, reduce environmental burdens, and support the transition to more sustainable energy practices [18,34,35].

These results confirm that remediation measures not only solved a local safety issue but also provided a transferable model for similar post-mining urban areas. Overall, the Lupeni remediation demonstrates that urban safety, environmental protection, and energy efficiency are mutually reinforcing goals. When addressed through integrated diagnostic

and management frameworks, post-mining risks can be converted into opportunities that simultaneously enhance public safety, mitigate climate change, and support sustainable development [7,16,23,24]

5. Conclusions

The case documented in Lupeni municipality provides rigorous confirmation that residual methane emissions from abandoned mining works can persist long after official mine closure, sometimes manifesting under unexpected circumstances—such as during the commissioning tests of a new gas pipeline. This scenario is not isolated: international studies indicate that abandoned mines may remain active methane sources for decades, with spatially and temporally variable dynamics.

From this perspective, administrative mine closure does not automatically imply risk elimination. On the contrary, data support the idea that risk can become active or visible during urban reorganizations (e.g., infrastructure upgrades, excavations, pressure changes, new drainage systems). In this context, abandoned mine methane (AMM) emissions should be regarded as latent hazards—invisible under normal conditions but potentially triggered by unintentional interactions.

5.1. Scientific Contribution of the Study

The primary scientific contribution of this study lies in the application of a multidisciplinary methodology that enabled:

- Precise identification and characterization of the detected gas source through multi-point monitoring, chemical composition analysis, spatial correlation, and verification of gas network integrity;
- Exclusion of a leak from the distribution network, thereby avoiding unjustified, costly, or even dangerous interventions on urban infrastructure;
- Attribution of the emissions to residual underground mine gas based on the convergence of three indicators: (a) stable and repeatable spatial distribution; (b) distinct chemical signature from commercial gas; (c) correlation with old mining galleries and local tectonics.

This attribution logic may serve as a model for other cases involving suspected subsurface emissions from unclear sources.

5.2. Practical Operational Outcome

On a practical level, the rapid intervention involving active drainage and connection to Lupeni mine's degassing system led to:

- Complete elimination of detectable concentrations at all monitored points by February 2025;
- Reduced risk of gas accumulation/explosion in underground urban infrastructure (e.g., manholes, sewers, basements);
- The possibility of energy valorization of captured methane, turning a passive risk into a functional opportunity, aligned with EU policies on energy transition and circular economy.

Thus, the Lupeni case represents not only accurate risk diagnosis but also a replicable technical intervention model with integrated safety, climate, and economic benefits.

5.3. Study Limitations (Impact on Interpretation)

To ensure scientific rigor, the study's conclusions should be interpreted in light of several limitations:

- Absence of methane flux measurements (e.g., accumulation chambers or real-time flow sensors) limits the ability to quantify emissions in mass units (kg CH₄/day). The study offers valuable point concentration data for detection and localization but is insufficient for climate inventories.
- Lack of a pre-installation monitoring baseline prevents clear separation between a pre-existing latent phenomenon and any potential activation caused by recent works.
- Incomplete geological and mining data (classified as confidential) reduced the capacity to model subsurface pathways and permeability. This limits deep causal analysis and generalization to other areas.

In addition, detailed technical data regarding the methane drainage system (e.g., number of drainage points, pipe layout, or flow rates) were unavailable to the authors, as the intervention was carried out independently by the mining operator. Consequently, the analysis of the system’s technical performance could not be included in this study.

To ensure transparency and to avoid overinterpretation of the results, the main limitations of the present study and the explicit boundaries of its scientific scope are summarized below. These limitations are inherent to emergency-driven investigations in dense urban environments and do not invalidate the diagnostic and risk-oriented objectives of the study. Table 5.

Table 5. Study limitations and explicit scope delimitation.

Identified limitation	Description	What the Study Explicitly Does Not Claim
Absence of methane flux measurements	Methane emissions were characterized using concentration-based field measurements due to emergency safety conditions and urban constraints that prevented the deployment of flux chambers or continuous flow monitoring systems.	The study does not claim to quantify total methane emissions (e.g., kg CH ₄ /day or annual emission factors) nor to contribute directly to national or regional methane emission inventories.
Lack of long-term baseline data	No historical methane monitoring data were available for the investigated urban area prior to August 2024, limiting the assessment of long-term temporal variability.	The study does not claim to reconstruct historical emission trends or to evaluate long-term post-closure methane evolution.
Limited subsurface characterization	Detailed geological, hydrogeological, and mining documentation was incomplete or partially inaccessible, restricting the ability to model subsurface permeability and precise gas migration pathways.	The study does not claim to provide a comprehensive geomechanical or hydrogeological model of methane migration.
Concentration-based diagnostic approach	Field investigations focused on methane concentration (% vol., % LEL) and spatial distribution rather than direct mass flow rates.	The study does not aim to replace flux-based or inventory-oriented methane emission studies, but to support source attribution, spatial delineation, and risk prioritization.
Emergency-driven intervention	Rapid mitigation measures were implemented immediately after diagnosis to ensure public safety, limiting prolonged experimental observation under unmanaged conditions.	The study does not aim to observe natural system evolution without intervention, but to document a risk-informed decision-making process.

These limitations define the scope of the present work as a diagnostic and risk-oriented case study rather than an emission inventory study. Within this clearly defined scope, the applied methodology provides scientifically robust evidence for methane source attribution and supports timely decision-making in post-mining urban environments.

The diagnostic framework presented in Figure 1 should be interpreted in conjunction with the limitations summarized in Table 5, which explicitly delimit the scope of the study as a risk-oriented, concentration-based case analysis.

5.4. Implications for Urban Planning and Public Policy

The results clearly support integrating AMM-related risks into urban planning, especially in cities located above former coal basins: (Table 6)

Table 6. Policy and urban planning recommendations for managing AMM-related risks in post-mining urban areas.

Domain	Specific Recommendations
Urban Mapping	Systematic overlay of mining archives (even incomplete) with utility networks.
Preventive Monitoring	Periodic screening in critical zones: manholes, utility intersections, subsidence-prone areas.
Risk Management	Use of semi-quantitative matrices (probability–consequence), FTA/ETA protocols, and rapid source attribution methods.
Technical Intervention	Selecting optimal response (ventilation, drainage, capture) based on risk, urban context, and feasibility.
Energy Valorization	Evaluating the potential for local energy use (heating, electricity) based on captured flow rates and exploitation conditions.

Incorporating these elements into institutional frameworks (e.g., national technical norms, ANRM procedures, or municipal urban plans) would enable broader replication of the proposed methodology across post-mining zones with latent methane risks.

5.5. Transferability and Broader Applicability

The proposed method—structured in clear steps: detection → compositional analysis → geological correlation → infrastructure verification → intervention—is transferable to any context where

- Historical mining works overlap with current urban infrastructure;
- Technical documentation is incomplete or fragmented;
- Suspicion arises of underground gas accumulations.

In post-mining regions across Central and Eastern Europe (e.g., Romania, Poland, Czechia, Slovakia), where such conditions are common, the study offers a fast, evidence-based intervention model.

5.6. Final Conclusions

The operational closure of the intervention was completed in late February 2025, when methane concentrations at all monitoring points dropped to undetectable levels. Subsequently, in July 2025, the public gas distribution network was safely recommissioned following integrity testing and validation of the drainage system’s effectiveness. Thus, the timeline from August 2024 to July 2025 represents a full cycle of detection → analysis → mitigation → remediation → safe reintegration.

The Lupeni case study demonstrates that:

- Post-mining risks are real, persistent, and often undetectable without proactive monitoring;
- Even short-term integrated methodologies can yield robust, practically and scientifically relevant results;
- Methane management from abandoned mines is not just a safety issue but an opportunity—energetic, ecological, and urbanistic.

The approach proposed here can be expanded into public policies, technical guidelines, and planning tools for post-industrial territories.

The Lupeni case study demonstrates not only that post-mining risks are real and persistent but also that these risks can be transformed into opportunities through proper

diagnosis, intervention, and resource valorization. Methane, often perceived solely as a hazard, can become a usable energy asset when managed proactively.

In this respect, the study offers more than a successful technical solution—it outlines a scalable and policy-relevant framework for addressing abandoned mine methane in post-industrial urban regions. It shows that urban safety, climate mitigation, and energy transition are not mutually exclusive but can be synergistically achieved when guided by integrated, science-based strategies.

Future work should integrate flux-based measurements and long-term monitoring to complement the diagnostic framework presented here, particularly once emergency safety conditions are resolved.

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