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INNOVATIVE APPROACH TO MONITOR GHG EMISSIONS FROM LANDFILLS AND BROWNFIELD SITES BY COMBINING GROUND MEASUREMENTS AND SATELLITE OBSERVATIONS*

Yuri Ponzani[1], Dario Vernola[2], Veronica Villa[3], Stefano Robbiani[4], Beatrice J. Lotesoriere[3], Gabriele Viscardi[2], Christian Ratti[3], Stefano Prudenza[3], Manuel Roveri[2], Raffaele Dellacà[4], Laura Capelli[3]**

[1]Recycle2Trade Ltd, Sussex Innovation Centre, Science Park Square, Brighton BN1 9SB, UK
[2]Politecnico di Milano, Department of Electronics, Information, and Bioengineering, Via Giuseppe Ponzio 34, 20133 Milan, Italy
[3]Politecnico di Milano, Department of Chemistry, Materials and Chemical Engineering "Giulio Natta", Piazza Leonardo da Vinci 32, Milan, Italy
[4]Politecnico di Milano, Department of Electronics, Information, and Bioengineering, Via Giuseppe Colombo 40, 20133 Milan, Italy

Abstract

Landfill and brownfield sites are major sources of pollution, particularly due to methane (CH_4) emissions, which have a global warming potential 28 times greater than carbon dioxide (CO_2). Landfills contribute 11% of global anthropogenic CH_4 emissions, exacerbating extreme weather and biodiversity loss. Brownfield sites, former industrial areas, also emit volatile organic compounds (VOC), harmful to ecosystems and human health. The ESCAPE (Environmental Sites CH_4 Assessment Platform Europe) project addresses these issues by integrating satellite-based remote sensing with mobile ground sensors for real-time methane monitoring. This cost-effective system combines the wide coverage of satellites with the precision of ground-based measurements, enhanced by machine learning algorithms for improved hotspot detection. ESCAPE combines various technologies, offering a comprehensive view of CH_4 emissions, aiding in leak identification and environmental protection. This approach supports global climate change mitigation by improving the accuracy and efficiency of GHG monitoring from landfill and brownfield sites.

Keywords: CO_2, MOX sensors, pollutant, portable toolbox, soil remediation, VOCs

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** Corresponding author: e-mail: veronica.villa@polimi.it

1. Introduction

Landfills and brownfield sites pose significant environmental challenges, particularly through the emission of greenhouse gases (GHGs) and volatile organic compounds (VOCs) (Vaverková, 2019). Methane (CH_4), one of the primary GHGs emitted from landfills, is of particular concern due to its relevant impact on climate change. CH_4 has a global warming potential (GWP) approximately 28 times greater than CO_2 over a 100-year period, making it a critical target for monitoring and mitigation efforts (IPCC, 2014). The increase in CH_4 emissions contributes significantly to the acceleration of global warming, intensifying environmental challenges such as extreme weather events, rising sea levels, and loss of biodiversity (UNEP, 2020). Landfill gas (LFG) consists mainly of CH_4 and CO_2, along with smaller quantities of hydrogen sulphide (H_2S) and trace amounts of VOCs (Durmusoglu et al., 2010; Siddiqua et al., 2022). These gases are released into the atmosphere as part of the waste degradation process and can escape through poorly managed or malfunctioning landfill gas extraction and collection systems (Capaccioni et al., 2011; Kaza et al., 2018; Siddiqua et al., 2022). Landfills are currently responsible for approximately 11% of global anthropogenic CH_4 emissions, contributing significantly to GHG levels (Scheehle, E et al., 2006). As global population growth continues, the amount of waste deposited in landfills is expected to increase by 70% by 2050, further exacerbating the problem (Kaza et al., 2018). In Europe alone, landfills contribute 62% of waste-related GHG emissions (EEA, 2024), making the need for more effective monitoring and management of these emissions increasingly urgent.

Brownfield sites - previously developed land often contaminated with hazardous waste - are also significant sources of environmental pollution. These sites, which are often neglected and abandoned after industrial or commercial use, emit various pollutants, including VOCs, which pose risks to human health and the surrounding ecosystem (Cusworth et al., 2024). Revitalizing brownfield sites requires addressing their contamination issues, which are often linked to GHG emissions. As governments push for more sustainable land use practices, brownfield regeneration has become a priority, especially in urban areas where new development is limited due to the scarcity of greenfield land (NPPF, 2019). To ensure the safe redevelopment of these sites, accurate monitoring of emissions is essential, not only to prevent environmental degradation but also to safeguard public health.

Given the scale and complexity of landfill and brownfield sites, monitoring GHG emissions presents several challenges. Traditional methods for detecting methane emissions, such as flux chambers and infrared gas analysers, provide detailed measurements but are often labour-intensive, costly, and limited in spatial coverage (Mønster et al., 2019).These methods are also prone to underestimating emissions due to the high spatial and temporal variability of emissions across landfill surfaces (Huang et al., 2022; Mønster et al., 2019). Advanced techniques like Differential Absorption Lidar (DIAL) and tracer correlation methods offer greater precision but are too expensive for widespread use (EEA, 2024). As a result, there is a growing need for low-cost, scalable monitoring solutions that can provide real-time, comprehensive data across large areas.

The ESCAPE (Environmental Sites CH_4 Assessment Platform Europe) project, funded by the Eureka Eurostars Funding Framework, addresses these challenges by integrating satellite-based remote sensing with mobile ground-based sensors. This innovative approach aims to develop a low-cost, portable sensor toolbox that can be used to monitor methane emissions in real-time, providing valuable data to landfill operators, developers, and environmental authorities. The combination of satellite data with ground measurements offers a comprehensive view of emissions, allowing for better detection of hotspots and operational anomalies. Furthermore, the use of machine learning algorithms to analyse the collected data will enhance the accuracy of predictions over time, ultimately improving the management of landfills and brownfield sites. By providing a cost-effective, scalable, and accurate method for monitoring GHG emissions, the ESCAPE project represents a significant advancement in environmental monitoring technologies.

2. Available technology for methane emission detection

CH_4 emission detection technologies can be broadly categorised into three types: satellite-based remote sensing, ground-based measurements, and unmanned aerial vehicles (UAVs). Each method offers unique advantages, and combining these approaches can provide a more comprehensive picture of emissions. A schematic summary of these technologies is available at Table 1.

2.1. Satellite data

Satellite-based remote sensing provides a powerful tool for monitoring CH_4 emissions over large areas. Satellites equipped with sensors designed to detect CH_4 can provide near-global coverage, enabling the detection of emission hotspots and trends. Several satellite missions are specifically designed to monitor greenhouse gases, including methane.

Key satellites involved in methane monitoring include:

- GHGSat: This satellite is designed to detect methane emissions with a spatial resolution of 25x25 meters, allowing for detailed monitoring of individual sites like landfills. It can detect small CH_4 leaks with a minimum detection threshold of 100 kg/hr (CEOS, 2024).
- MethaneSat: launched in 2024, MethaneSat will offer a resolution of 100x400 meters and can detect CH_4 emissions as low as 500 kg/hr (EO Portal, 2024).
- Sentinel-5P: Part of the European Space Agency’s Sentinel series, Sentinel-5P focuses on monitoring air quality and CH_4. Its broad spatial coverage (5500x7000 meters) is useful for identifying regional CH_4 emissions (EO Portal, 2024).

Satellite data offers several advantages, including wide-area coverage and the ability to monitor remote or inaccessible locations. Satellites can continuously track CH_4 levels over time, providing insights into long-term trends and helping identify emission sources that may otherwise go undetected. However, satellite remote sensing monitoring has limitations (Table 1). The temporal revisit time of satellites varies and the near real-time data might not always be available. Weather conditions such as cloud cover can also obstruct satellite payloads, reducing the frequency and accuracy of CH_4 detection. A recent study highlights that satellite data is most effective when used in conjunction with ground-based measurements, offering a more comprehensive approach to CH_4 emission monitoring (Cusworth et al., 2024)

2.2. Ground-based measurements

While satellites provide a broad view of CH_4 emissions, ground-based measurements offer more detailed, site-specific data. These methods are essential for accurately identifying methane leaks and understanding the localised dynamics of emissions at landfill sites.

Key ground-based measurement techniques include:

- *Flux Chambers:* flux chambers are placed over a section of the landfill surface to capture CH_4 emissions. They provide accurate, localised measurements, but their small coverage area means they cannot capture emissions across the entire landfill, leading to underestimation of total emissions (Mønster et al., 2019)

- *Flame Ionisation Detectors (FIDs):* FIDs are commonly used in walkover surveys of landfill sites, providing immediate feedback on CH_4 levels. However, they are labour-intensive and limited in spatial coverage (Babilotte et al., 2010; Cusworth et al., 2024)
- *Differential Absorption Lidar (DIAL):* DIAL uses laser technology to measure CH_4 concentrations over large areas. It provides high-precision, real-time data, but the equipment is expensive and complex to operate, making it less accessible for routine monitoring (Innocenti et al., 2017)

Ground-based sensors are increasingly being integrated with IoT technology, enabling continuous, real-time monitoring of CH_4 emissions. Low-cost sensors connected to a cloud-based system can provide valuable, localised data on emissions, complementing the broader view provided by satellite observations. These sensors are placed at multiple points across a landfill, allowing for continuous monitoring of methane concentrations and enabling operators to detect anomalies or sudden spikes in emissions.

The advantage of ground-based sensors lies in their ability to provide detailed insights into specific sources of methane emissions, helping operators identify leaks or failures in gas management systems. However, their main drawback is that they are labour-intensive and provide data from limited areas, necessitating multiple installations across a landfill site to achieve comprehensive coverage (Mønster et al., 2019) (Table 1).

2.3. Unmanned Aerial Vehicles (UAVs)

Unmanned Aerial Vehicles (UAVs), or drones, offer a flexible and efficient means of monitoring CH_4 emissions by covering large area and providing real-time CH_4 concentrations. Their ability to hover over specific areas allows for targeted monitoring, which is useful for identifying emissions from difficult-to-reach areas like slopes or closed sections of landfills.

The advantages of UAVs include:

- *Rapid deployment:* Drones can be deployed on short notice, allowing operators to quickly investigate suspected CH_4 leaks or high-emission areas (Mønster et al., 2019).
- *Safety and efficiency:* Drones reduce the need for manual inspections. By using drones, operators can collect data without putting personnel at risk of exposure to harmful gases or hazardous terrain.
- *Detailed data collection:* Drones can capture high-resolution CH_4 data over large areas, providing more comprehensive coverage than ground-based methods. UAVs can also perform repeated surveys, tracking changes in CH_4 emissions and identifying trends (Cusworth et al., 2024).
- However, drones also have limitations (Table 1). Their operations are weather-dependent, with strong winds or rain potentially grounding UAVs or affecting the accuracy of the data collected. Additionally, while drones provide excellent localised data, they require extensive post-processing and analysis, which can be time-consuming (Mønster et al., 2019).

3. The ESCAPE project: Integrating satellite and ground data

3.1. ESCAPE key components

The ESCAPE project offers an innovative approach to overcome the limitations of current methods, providing a cost-effective and scalable solution for real-time monitoring of

CH_4 emissions from landfills and brownfield sites. By combining data from satellites, ground-based sensors, and artificial intelligence (AI)-driven analytics (**Fig. 1**), ESCAPE enables more accurate and timely detection of CH_4 leaks, supporting efforts to mitigate environmental harm caused by GHG emissions.

Table 1. General summary of available solution for emission data collection

Solution type	***Data granularity***	***Temporal frequency***	***Spatial coverage***	***Limitations***
Drones, Aircraft, Plume Mappers Satellite Missions	High (Granular data)	Low (On demand)	Limited	Continuous monitoring not possible
Mobile detection sensors (FID and Flux Box)	Low	Low	Limited	Less detail, snapshots limited in time
Global Mappers Satellite Missions	Coarse	High	High	Limited spatial resolution
IoT fixed Sensors	High (Fixed points)	High	Restricted to a few sections within landfill areas	Does not detect emissions across entire sites

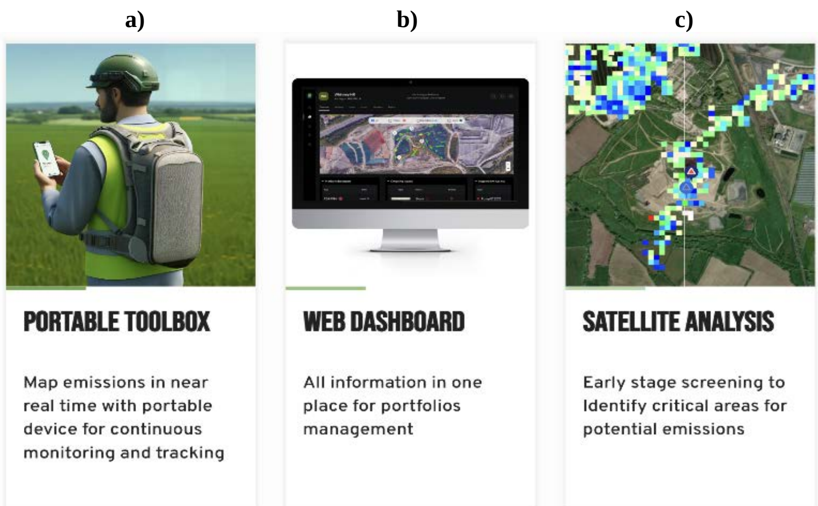

Fig. 1. a) Portable toolbox; b) Web Dashboard; c) Satellite Analysis

3.1.1. Satellite data

Satellite remote sensing plays a key role to monitor large areas and several solutions are available (Table 2). Satellites such as GHGSat and Sentinel-5P are equipped with shortwave infrared (SWIR) sensors designed to detect CH_4 emissions from space. GHGSat offers a spatial resolution of 25x25 meters, allowing to detect CH_4 plumes from specific facilities, while MethaneSat, launched in 2024, will offer alternative detection capabilities (GHGSat, 2022; Maasakkers et al., 2022).

Earth Observation Satellites provide broad-scale coverage, allowing for continuous monitoring of CH_4 emissions over time. This is especially useful for detecting large-scale emission trends or identifying hotspots in remote or inaccessible areas. However, satellite data can be affected by weather conditions like cloud cover, and its revisit times may delay real-time responses. Thus, ESCAPE complements satellite observations with ground-based measurements for more immediate and localized data (Cusworth et al., 2024).

Table 2. Summary of satellite remote sensing solutions, derived from a variety of sources

Sensor	*Launch Date*	*Spatial Resolution (m)*	*Revisit Time (days)*	*Min. Detection Threshold (kg/hr)*
GOSAT	2009	10,500 x 10,500	3	7,000
GOSAT-2	2018	9,700 x 9,700	3	4,000
Sentinel 5-P	2017	5,500 x 7,000	1	4,000
MethaneSat	2024	100 x 400	3 to 4	500
GHGSat-D	2016	50 x 50	14	1,000
GHGSat Constellation	2019	25 x 25	1	100

(Bel Hadj Ali et al., 2020; CEOS Database; EO Portal, 2024; International Energy Agency (IEA), 2024; Jacob et al., 2022).

3.1.2. Ground-based sensors

Ground-based monitoring provides granular, site-specific data. ESCAPE employs an array of low-cost, portable sensors to monitor CH_4 concentrations in real-time. The portable sensor toolbox developed allows operators to conduct walkover surveys of landfill sites, identifying areas of high CH_4 concentration quickly and efficiently. This mobility ensures that the system can adapt to changes in emission patterns and respond to emerging hotspots in real-time. The integration of IoT-enabled sensors also facilitates continuous monitoring, complementing satellite data with real-time, ground-based insights.

3.1.3. Data integration platform

The data collected by satellites and ground-based sensors is integrated into a cloud-based platform for analysis and visualisation. This platform provides a comprehensive overview of CH_4 emissions, enabling operators to track emissions trends over time, detect anomalies, and make informed decisions on emission mitigation strategies. The platform incorporates machine learning algorithms that analyse data to improve prediction accuracy over time. These algorithms can identify patterns in methane concentrations and predict future emissions, providing operators with early warnings of potential leaks or operational failures (Cusworth et al., 2024). The integration of satellite data with ground-based sensor readings offers a complete, real-time picture of CH_4 emissions, improving both the accuracy and efficiency of monitoring efforts.

3.2 Benefit of the integrated approach

The integration of satellite data, ground-based sensors, and AI analytics offers several key advantages over traditional CH_4 monitoring methods:

- Comprehensive Coverage: Satellite observations provide broad-scale monitoring, while ground sensors offer detailed, localised data. This combination ensures that both regional and site-specific CH_4 emissions are effectively tracked (GHGSat, 2022).

- Real-Time Monitoring: Ground-based sensors allow for continuous, real-time data collection, enabling operators to detect and respond to CH_4 emissions immediately. This is critical for preventing large-scale emissions from going unnoticed (Cusworth et al., 2024).
- Cost-Effectiveness: ESCAPE's use of low-cost sensors makes it an affordable solution for landfill operators, especially in regions in which traditional, high-cost monitoring systems may not be viable.
- Scalability: The ESCAPE system can be scaled to monitor CH_4 emissions across multiple sites, from landfills to broader regional areas, making it suitable for both small operators and large government monitoring programs.
- Predictive Capabilities: Machine learning algorithms enhance the system's predictive capabilities, allowing it to detect potential leaks or operational failures before they become serious environmental hazards.

4. Sensor selection and testing

The selection and testing of sensors for the ESCAPE project are critical to develop an effective CH_4 monitoring system for landfills and brownfield sites. The primary aim is to create a low-cost, portable sensor toolbox that can provide real-time, accurate CH_4 detection under variable environmental conditions.

4.1. Sensor selection criteria

The ESCAPE project identified several key criteria for selecting CH_4 sensors:

- Sensitivity to CH_4: Sensors must accurately detect CH_4 at various concentrations, from low parts per million (ppm) to higher levels indicative of significant emissions
- Cost-Effectiveness: Since the project aims to deploy sensors across multiple sites, the chosen sensors must be affordable while maintaining adequate performance
- Durability: Sensors must withstand harsh landfill environments with fluctuating temperatures, humidity, and the presence of other gases (Mønster et al., 2019)
- Selectivity: Methane-selective sensors are essential to avoid interference from other gases, such as CO_2 and VOCs, which are also common at landfill sites
- Integration: The sensors need to seamlessly integrate with the ESCAPE platform, enabling real-time data transmission and analysis

4.2. Sensors evaluated

Several sensor types were considered based on their cost, sensitivity, and performance under landfill conditions:

- Metal-Oxide Sensors (MOX): MOX sensors are widely used due to their affordability and wide detection range. However, they tend to suffer from cross-sensitivity to other gases like CO_2 and VOCs, which can complicate CH_4 detection (Mønster et al., 2019)

- Infrared (IR) Sensors: IR sensors offer high accuracy and selectivity by detecting CH_4 absorption of infrared light. Although effective, IR sensors are more expensive than MOX sensors, limiting their feasibility for large-scale deployment (GHGSat, 2022).

4.3. Selected sensors for preliminary screening

After evaluating different sensor types, the ESCAPE project selected a set of sensors to the following sensors to be preliminary tested:

- TGS2611: A MOX sensor, known for its reliability and ability to detect CH_4 concentrations as low as 500 ppm according to manufactury. In literature it's reported to be able to detect up to 10 ppm of CH4, reason for which it's been selected to be tested in this study. It strikes a balance between cost and performance making it suitable for landfill applications.
- SGP40: Primarily a VOC sensor, the SGP40 digital sensor can detect CH_4 while offering valuable data on other gases. Its multi-gas detection capability helps in identifying cross-sensitivities that may affect CH_4 readings.
- ENS160: Digital MOX sensor for VOCs detection. It has an on-chip RH compensation. Its multi-gas detection capability helps in identifying cross-sensitivities that may affect CH_4 readings.
- BME688: This sensor can detect CH_4, CO_2, and VOCs, and is equipped with built-in compensation for temperature and humidity fluctuations, ensuring stability under varying environmental conditions.
- MH-441D: While less sensitive at lower CH_4 concentrations, this optical (IR) sensor is highly selective for CH_4, minimizing interference from other gases like CO_2. It is included in the sensor toolbox to reduce false positives.

4.4. Laboratory testing

The selected sensors were subjected to rigorous laboratory testing to simulate landfill conditions and assess their performance. Testing procedures included:

- Controlled Gas Mixtures: Sensors were exposed to different concentrations of CH_4 and CO_2 (from 10 to 10,000 ppm) to evaluate their sensitivity and selectivity.
- Environmental Simulation: The sensors were tested with a setup to control humidity to simulate real-world landfill conditions (Mønster et al., 2019)
- Real-World Gas Samples: Biogas samples from a decommissioned landfill were analysed to test the sensors' performance in a mixed-gas environment, providing more practical insights into their capabilities.

4.5. Preliminary results

Laboratory testing results are reported in Fig. 2.

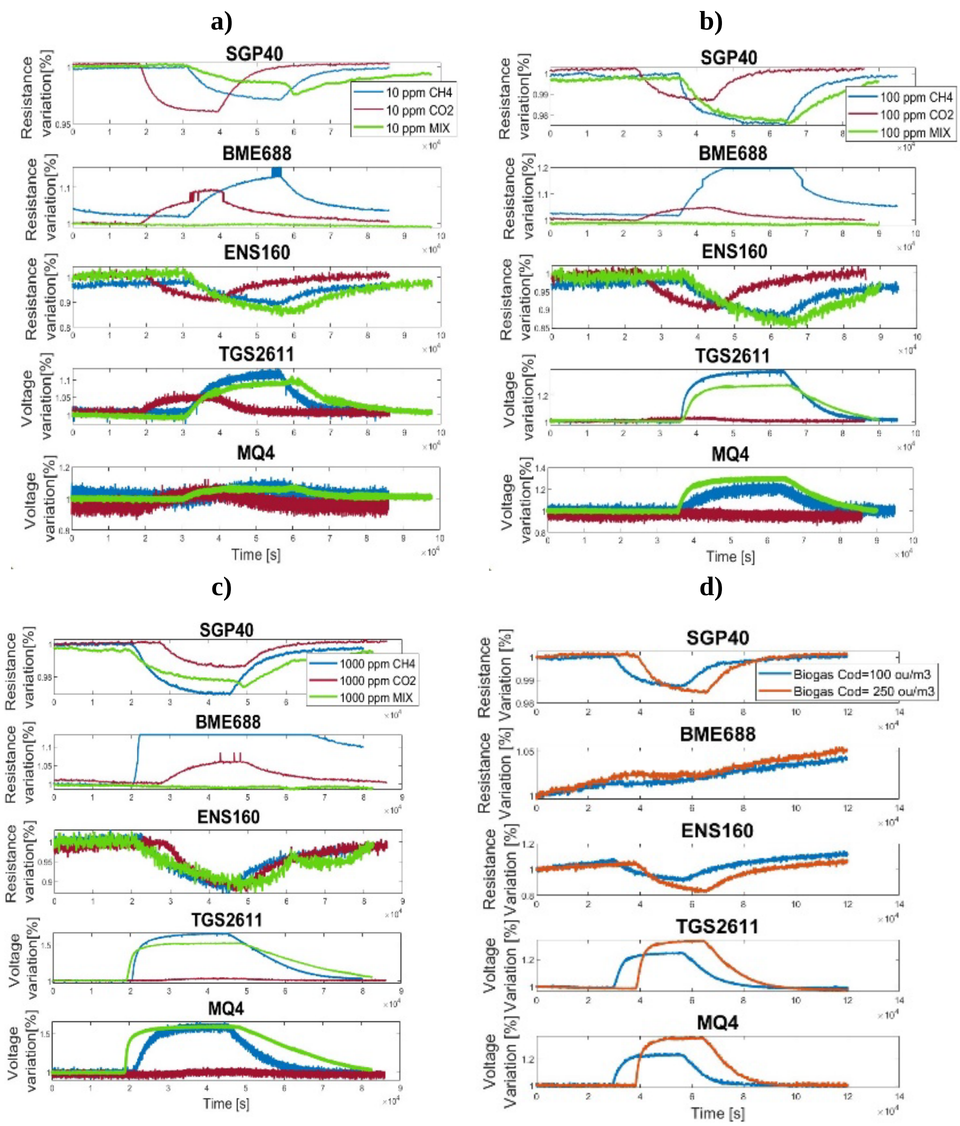

Fig. 2. Example of response curves of the 5 MOX sensors to CH_4, CO_2 and a mixture of the two at a) 10, b) 100 and c) 1’000 ppm, respectively and response curves of 2 real-world biogas samples at different dilutions d)

The testing produced the following key findings:

- Sensitivity: The TGS2611 and BME688 sensors demonstrated good sensitivity to CH_4 at concentrations as low as 10 ppm, making them well-suited for detecting small leaks.
- Cross-Sensitivity: The SGP40 and BME688 showed some cross-sensitivity to CO_2 and VOCs, but the MH-441D’s strong selectivity for CH_4 minimised the risk of false positives.

- Environmental Performance: The BME688's ability to compensate for changes in humidity and temperature helped maintain consistent performance under fluctuating conditions.

5. Concluding remarks

The ESCAPE project represents a significant advancement in methane emission monitoring by integrating satellite data, affordable ground-based sensors, and AI-driven analytics into a unified, cost-effective system. This comprehensive approach addresses the inherent limitations of traditional methods by offering real-time, precise data collection and analysis of methane emissions from landfills and brownfield sites. The combination of satellite coverage, capable of detecting regional emission trends, with detailed ground-level monitoring ensures a holistic solution for tracking and mitigating CH_4 emissions.

The project's findings highlight that accurate methane detection, improved hotspot identification, and mitigation strategies are crucial for reducing greenhouse gas emissions. The system's scalability and adaptability, demonstrated through pilot implementations, suggest that it can play a pivotal role in global methane management efforts.

Furthermore, enhancing eco-efficiency in waste management and developing advanced solutions for methane reduction are critical steps in mitigating climate change. Future work will focus on refining sensor calibration, advancing machine learning algorithms for predictive capabilities, and expanding real-world applications to ensure robust and reliable environmental monitoring solutions.

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