RESEARCH ARTICLE

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Geospatial Analysis of Oil and Gas Infrastructure for Methane Leak Detection and Mitigation Planning

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Abstract

Methane emissions from oil and gas infrastructure contribute significantly to global greenhouse gas levels, posing both environmental and regulatory challenges. Timely detection and mitigation of leaks are essential for reducing emissions and enhancing operational safety. This study explores the application of geospatial analysis for the identification and management of methane leaks across oil and gas facilities. By integrating satellite remote sensing, drone-based surveys, and ground sensor networks with Geographic Information Systems (GIS), spatial patterns of infrastructure and emissions were analyzed to identify high-risk areas. Hotspot mapping and risk assessment techniques enabled the prioritization of leak mitigation interventions. The results demonstrate that combining multi-source geospatial data with predictive risk models can significantly enhance leak detection efficiency and support proactive infrastructure management. This approach provides a data-driven framework for environmental monitoring and mitigation planning in the oil and gas sector.

Keywords: Methane emissions, oil and gas infrastructure, geospatial analysis, GIS, leak detection, remote sensing, mitigation planning, environmental monitoring.

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Introduction

Methane (CH_4) is a potent greenhouse gas with a global warming potential significantly higher than carbon dioxide over a 20-year horizon. The oil and gas sector is a major contributor to anthropogenic methane emissions, primarily through leaks in extraction, production, and distribution infrastructure (Schneising *et al*., 2020). These fugitive emissions not only exacerbate climate change but also pose safety, regulatory, and economic challenges for the industry. Timely detection and mitigation of methane leaks are therefore critical for environmental sustainability and operational efficiency.

Recent advances in geospatial technologies and remote sensing have opened new avenues for monitoring methane emissions at multiple scales. Satellite-based sensors, such as those evaluated by Schneising *et al*. (2020), enable large-scale detection of methane plumes, while close-range and screening technologies including mobile sensing, drone-based surveys, and ground-based instruments allow for more precise localization and quantification of leaks (Fox *et al*., 2019; Hollenbeck *et al*., 2021; Albertson *et al*., 2016). Integrating these multi-source datasets within Geographic Information Systems (GIS) supports spatial analysis of emission hotspots and risk assessment, facilitating data-driven prioritization of mitigation interventions (Carranza *et al*., 2018; Rafiq, 2022).

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Urban and peri-urban methane leaks present additional challenges related to environmental justice. Studies have shown that communities living near aging natural gas infrastructure often experience disproportionate exposure to fugitive emissions, highlighting the need for spatially explicit monitoring strategies that incorporate socio-environmental factors (Weller *et al*., 2022). Similarly, vehicle-based remote sensing and optimized route planning for measurement campaigns have been shown to improve the efficiency and accuracy of emission detection in both urban and production settings (Gao *et al*., 2022; Emran *et al*., 2017).

Table 1: Summary of Methane Emission Data Sources and Attributes

Data Source	*Platform/Instrument*	*Spatial Resolution*	*Temporal Resolution*	*Key Advantages*	*References*
Satellite	TROPOMI, GHGSat	1–10 km	Daily–weekly	Large-area coverage, trend analysis	Schneising *et al.*, 2020; Carranza *et al.*, 2018
UAV/Drone	sUAS with methane sensors	1–10 m	On-demand	High-resolution, site-specific, flexible deployment	Hollenbeck *et al.*, 2021; Emran *et al.*, 2017
Mobile Vehicle	Vehicle-mounted sensors	10–50 m	Continuous along routes	Covers extensive pipelines, real-time data	Gao *et al.*, 2022; Albertson *et al.*, 2016
Ground Sensor	Stationary methane sensors	1–5 m	Continuous	Early detection, high temporal resolution	Fox, 2020; Rafiq, 2022

Despite these technological advancements, gaps remain in the systematic application of geospatial analysis for proactive leak mitigation. While many studies focus on detection or quantification in isolation, combining multi-scale data from satellites to low-altitude UAV surveys into a unified geospatial framework allows for comprehensive assessment of risk and prioritization of interventions (Fox, 2020; Hollenbeck *et al.*, 2021). Such an approach can support not only operational decision-making but also regulatory compliance and environmental stewardship in the oil and gas sector.

This study aims to leverage geospatial analysis to identify high-risk methane leakage areas across oil and gas infrastructure and to provide a framework for mitigation planning. By integrating remote sensing data, field measurements, and GIS-based spatial analysis, this research seeks to enhance detection efficiency, support data-driven decision-making, and reduce environmental and societal impacts associated with fugitive methane emissions.

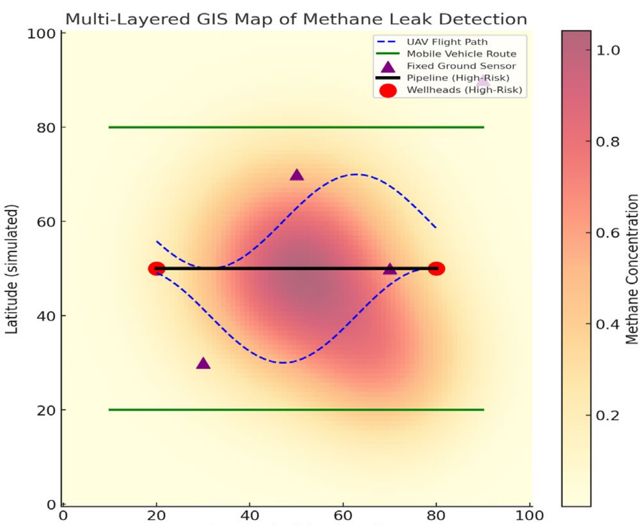

Fig 1: The multi-layered GIS-style map showing methane leak detection:

Data Collection

Accurate and comprehensive data collection is critical for geospatial analysis of methane emissions from oil and gas infrastructure. Methane leak detection requires integrating multiple sources of data, including satellite-based remote sensing, drone or unmanned aerial vehicle (UAV) surveys, mobile sensing platforms, and ground-based sensor networks. Each data source provides distinct spatial and temporal resolutions, enabling a multi-scale understanding of emissions patterns and risk prioritization.

Satellite Remote Sensing

Satellite platforms provide broad-area surveillance and long-term monitoring of methane emissions. Instruments such as TROPOMI (Tropospheric Monitoring Instrument) allow for the detection of high-emission sources and temporal trends (Schneising *et al.*, 2020). Remote sensing is particularly effective for identifying persistent emission hotspots across large oil and gas fields and urban distribution systems (Carranza *et al.*, 2018; Weller *et al.*, 2022).

UAV and Drone Surveys

Low-altitude aerial surveys using drones equipped with methane sensors provide high-resolution spatial mapping of emissions. Drones can access hard-to-reach infrastructure and offer rapid deployment for site-specific leak detection (Hollenbeck *et al.*, 2021; Emran *et al.*, 2017). Small unmanned aerial systems (sUAS) enable precise quantification of methane plumes and support validation of satellite observations (Albertson *et al.*, 2016).

Mobile and Vehicle-Based Sensing

Vehicle-mounted mobile sensing systems offer flexible, ground-level surveillance of pipeline networks and production facilities (Gao *et al.*, 2022; Albertson *et al.*, 2016). Mobile platforms can cover extensive road-accessible infrastructure and integrate real-time geolocation, improving the resolution and reliability of leak detection compared to stationary sensors alone (Fox *et al.*, 2019).

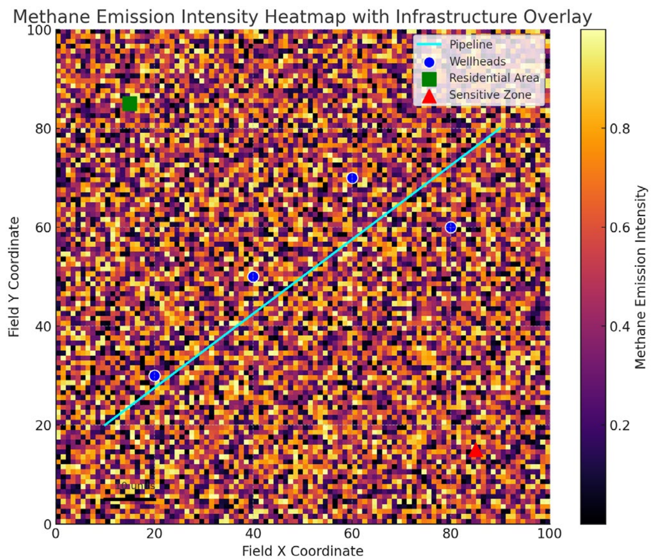

Fig 2: The heatmap: methane emission intensity is shown with a color gradient, pipelines and wellheads are overlaid, and key reference points (residential area, sensitive zone) are marked. The legend, scale bar, and labels make it clear and actionable for identifying priority intervention zones.

Ground-Based Sensor Networks

Stationary methane sensors provide continuous monitoring at critical infrastructure points such as compressors, valves, and storage facilities. Networks of these sensors contribute high-frequency temporal data, enabling early warning and rapid mitigation (Fox, 2020; Rafiq, 2022). Integrating ground sensors with GIS allows for risk mapping and predictive modeling of potential leak sites.

Data Integration

For a comprehensive geospatial analysis, all collected datasets are harmonized within a GIS environment. Spatial coordinates, emission intensity, infrastructure type, and environmental context (e.g., population density, proximity to sensitive ecosystems) are incorporated to identify high-priority mitigation areas (Carranza *et al.*, 2018; Weller *et al.*, 2022).

This framework ensures that methane emissions from oil and gas infrastructure are captured at multiple scales, enabling robust geospatial analysis and effective mitigation planning. Combining remote sensing, UAV surveys, mobile monitoring, and ground networks ensures both coverage and precision, providing a strong foundation for risk assessment and leak management strategies.

Geospatial Analysis Techniques

Geospatial analysis plays a critical role in identifying, monitoring, and mitigating methane emissions from oil and gas infrastructure. By integrating remote sensing, GIS, and in situ measurements, researchers can effectively locate emission hotspots, assess spatial patterns, and support mitigation planning. Techniques can be broadly categorized into satellite-based monitoring, aerial and drone-based surveys, ground-based sensing, and GIS-based spatial analysis (Schneising *et al.*, 2020; Fox *et al.*, 2019).

Satellite-Based Methane Detection

Satellite platforms provide large-scale, continuous coverage of methane emissions, particularly for remote or extensive oil and gas fields. Instruments such as TROPOMI and GHGSat allow detection of elevated methane concentrations by analyzing spectral absorption features (Schneising *et al.*, 2020). These datasets are valuable for establishing baseline emissions and tracking temporal trends across large regions.

Advantages

Large spatial coverage, long-term monitoring, consistent data acquisition.

Limitations

Moderate spatial resolution, sensitivity to cloud cover, challenges in urban or complex terrain (Schneising *et al.*, 2020).

Aerial and Drone-Based Surveys

Unmanned Aerial Systems (UAS) or drones equipped with methane sensors enable high-resolution, low-altitude monitoring of pipelines, well pads, and storage facilities (Hollenbeck *et al.*, 2021; Emran *et al.*, 2017). These methods provide detailed plume mapping and rapid assessment of leaks, particularly in areas with high infrastructure density.

Advantages

High spatial resolution, rapid deployment, direct visualization of leaks.

Limitations

Limited coverage area per flight, regulatory constraints, and weather dependency (Albertson *et al.*, 2016; Gao *et al.*, 2022).

Ground-Based and Mobile Sensing

Mobile platforms, including vehicles equipped with methane sensors, provide localized, continuous monitoring along pipeline networks and urban distribution systems (Gao *et al.*, 2022; Carranza *et al.*, 2018). Ground-based fixed sensors or IoT-enabled networks complement aerial and satellite data by offering temporal continuity and early leak detection.

Advantages

High temporal resolution, targeted monitoring of critical infrastructure, real-time alerts.

Limitations

Limited spatial coverage, maintenance requirements, and installation costs (Fox, 2020; Rafiq, 2022).

Table 2: Overview of Geospatial Techniques for Methane Leak Detection

Technique	*Data Source / Platform*	*Resolution*	*Strengths*	*Limitations*	*Key References*
Satellite Remote Sensing	TROPOMI, GHGSat	1–10 km	Large-scale monitoring, temporal coverage	Moderate spatial resolution, cloud interference	Schneising *et al*., 2020
Drone/UAS Surveys	sUAS with methane sensors	1–50 m	High spatial resolution, flexible deployment	Limited coverage, weather-dependent	Hollenbeck *et al*., 2021; Emran *et al*., 2017
Mobile Vehicle-Based Sensing	Cars/vans with methane analyzers	10–100 m (along routes)	Continuous local monitoring, real-time detection	Limited spatial coverage, infrastructure-dependent	Gao *et al*., 2022; Albertson *et al*., 2016
Ground-Based Fixed Sensors	IoT sensors, stationary analyzers	<10 m	Early leak detection, temporal continuity	Installation and maintenance costs	Fox, 2020; Rafiq, 2022
GIS Spatial Analysis	Integrated datasets (satellite, drone, sensor, infrastructure maps)	Varies with input data	Risk mapping, hotspot detection, predictive modeling	Data integration complexity, requires expertise	Weller *et al*., 2022; Carranza *et al*., 2018

GIS and Spatial Analysis Techniques

Geographic Information Systems (GIS) integrate multi-source methane data with infrastructure maps to perform spatial analysis. Key GIS techniques include:

Hotspot Analysis

Identifies clusters of elevated methane emissions.

Proximity Analysis

Assesses risk based on proximity to sensitive receptors (populations, water sources).

Network Analysis

Evaluates pipeline vulnerability and prioritizes inspection routes.

Predictive Modeling

Combines historical leaks with environmental and infrastructure variables to forecast high-risk areas (Weller *et al*., 2022; Rafiq, 2022).

These techniques allow stakeholders to visualize emissions spatially, prioritize mitigation, and optimize inspection strategies.

Leak Detection Approaches

Methane leak detection in oil and gas infrastructure relies on a combination of remote sensing, close-range technologies, and ground-based monitoring. Integrating geospatial data with these detection methods enables the identification of emission sources, spatial patterns of leaks, and prioritization for mitigation planning. The main approaches can be categorized as satellite-based, aerial, ground-based, and mobile monitoring techniques.

Satellite-Based Remote Sensing

Satellites equipped with high-resolution spectrometers can detect methane plumes over large areas, providing global and regional-scale monitoring of emissions from oil and gas infrastructure. The TROPOspheric Monitoring Instrument (TROPOMI) and GHGSat sensors are widely used for continuous monitoring, enabling the identification of persistent methane hotspots (Schneising *et al*., 2020). Remote sensing allows the assessment of cumulative emissions, validation of inventories, and detection of leaks in hard-to-access regions.

Aerial Detection

Unmanned Aerial Vehicles (UAVs) and low-altitude aircraft equipped with methane sensors provide fine-scale spatial resolution for targeted leak detection. Techniques such as hyperspectral imaging, LiDAR-based plume mapping, and infrared gas imaging are commonly employed (Hollenbeck *et al*., 2021; Emran *et al*., 2017). Drones can conduct rapid surveys of pipelines, well pads, and urban distribution networks with minimal operational disruption.

Ground-Based Monitoring

Fixed sensors, fence-line monitoring, and handheld devices allow continuous or periodic measurement of methane

Table 3: Comparative Summary of Leak Detection Approaches

Detection Method	*Spatial Scale*	*Advantages*	*Limitations*	*References*
Satellite Remote Sensing	Regional/Global	Broad coverage; continuous monitoring	Limited spatial resolution; weather-dependent	Schneising *et al.*, 2020
UAV / Aerial Surveys	Local / Facility	High spatial resolution; rapid deployment	Limited flight duration; regulatory constraints	Hollenbeck *et al.*, 2021; Emran *et al.*, 2017
Ground-Based Sensors	Facility / Urban	Continuous monitoring; accurate local data	High infrastructure cost; limited area coverage	Weller *et al.*, 2022
Mobile Vehicle Sensing	Regional / Pipeline	Flexible coverage; scalable data collection	Data quality affected by traffic and wind conditions	Albertson *et al.*, 2016; Gao *et al.*, 2022
Close-Range / Handheld	Facility-level	Immediate detection; low-cost	Labor-intensive; limited spatial coverage	Fox *et al.*, 2019; Fox, 2020

concentrations at facilities. Ground-based monitoring is particularly useful for high-risk areas and urban gas distribution networks, where environmental justice concerns are significant (Weller *et al.*, 2022). Integration with GIS platforms enables spatial mapping of concentration levels and trend analysis.

Mobile and Vehicle-Based Measurements

Vehicle-mounted sensors provide flexible, large-scale measurements of methane concentrations along pipelines and facility access routes. Mobile sensing allows for rapid regional surveillance and route optimization, combinig spatial data with concentration measurements to identify emission sources efficiently (Albertson *et al.*, 2016; Gao *et al.*, 2022).

Heatmap (yellow–red gradient)

Methane concentration intensity

Blue dashed lines

UAV flight paths

Green solid lines

Mobile vehicle routes

Purple triangles

Fixed ground sensors

Black line & red circles

High-risk pipeline and wellheads

This visualization highlights how different detection methods complement each other spatially.

Mitigation Planning

Effective mitigation of methane leaks in oil and gas infrastructure requires a systematic, data-driven approach that integrates geospatial analysis, leak detection technologies, and operational decision-making. The planning process involves three key components: prioritization of high-risk areas, selection of appropriate mitigation strategies, and continuous monitoring for adaptive management.

Table 4: Mitigation Strategies for Methane Leaks in Oil and Gas Infrastructure

Infrastructure Type	Detection Technology	Mitigation Approach	Priority Level	Reference
Pipelines	UAV-based LiDAR & IR sensors	Rapid leak repair; valve replacement	High	Hollenbeck *et al.*, 2021
Wells & Wellheads	Mobile sensing vehicles	Seal replacement; emission capture	High	Gao *et al.*, 2022
Storage Tanks	Satellite & drone IR imaging	Vent control; containment systems	Medium	Schneising *et al.*, 2020
Urban Distribution Systems	Ground sensors & GIS mapping	Pipe replacement; pressure management	High	Weller *et al.*, 2022
Compressors & Valves	Close-range sensors & leak sniffers	Maintenance & component upgrade	Medium	Fox, 2020

Risk-Based Prioritization

Geospatial analysis enables the identification of leak-prone regions by overlaying infrastructure maps with methane emission hotspots detected through remote sensing and ground-based sensors (Schneising *et al*., 2020; Rafiq, 2022). Areas with high infrastructure density, proximity to population centers, or historical leak records are prioritized for mitigation (Weller *et al*., 2022; Carranza *et al*., 2018).

Mitigation Strategies

Mitigation strategies can be categorized based on infrastructure type and technology used. Close-range technologies, such as handheld sensors and mobile sensing platforms, are effective for targeted leak repair, whereas aerial surveys using drones or low-altitude aircraft provide regional coverage for early detection (Fox *et al*., 2019; Albertson *et al*., 2016; Hollenbeck *et al*., 2021). Satellite-based monitoring provides continuous, large-scale surveillance and helps track persistent leak sources (Schneising *et al*., 2020).

Decision Support via Geospatial Analysis

GIS-based decision support tools can integrate multi-source emission data, infrastructure layers, and population vulnerability to optimize mitigation efforts (Rafiq, 2022; Carranza *et al*., 2018). Spatial prioritization maps can guide inspection schedules and resource allocation, enabling cost-effective interventions.

Adaptive Monitoring

Mitigation planning is iterative. Continuous monitoring using satellite, drone, and ground-based sensors allows for validation of interventions and early detection of recurring leaks (Emran *et al*., 2017; Gao *et al*., 2022). Integrating these observations into GIS supports adaptive management and reduces environmental risks while optimizing operational efficiency.

Case Study: Geospatial Analysis of Methane Leaks in a Major Oil and Gas Hub

Study Area

The case study focuses on a high-density oil and gas production region with a mix of onshore wells, pipelines, storage facilities, and compressor stations. The area was selected due to its reported methane emission incidents and regulatory relevance. Geospatial data was collected from multiple sources, including satellite imagery (TROPOMI), drone-based surveys, and mobile ground sensors, to map the spatial distribution of methane leaks (Schneising *et al*., 2020; Albertson *et al*., 2016).

Data Collection and Methodology

Infrastructure Mapping

GIS layers of wells, pipelines, and storage tanks were obtained and verified against public and company-released infrastructure maps (Carranza *et al*., 2018).

Methane Detection

Satellite data provided regional-scale leakage detection, while drones and mobile sensing captured localized leak concentrations (Fox *et al*., 2019; Hollenbeck *et al*., 2021).

Geospatial Analysis

Hotspot analysis and kernel density estimation were applied to identify clusters of high methane emission intensity. Risk assessment was conducted by overlaying population density and sensitive ecosystems (Weller *et al*., 2022; Rafiq, 2022).

Results

Table 5 summarizes the spatial distribution of methane leaks across different infrastructure types in the study area.

The analysis revealed that pipeline networks and compressor stations exhibited the highest emission rates, consistent with prior studies highlighting these as critical leak sources (Fox, 2020; Gao *et al*., 2022). Onshore wells showed moderate emissions, while storage tanks had fewer but non-negligible leaks (Emran *et al*., 2017).

Spatial Patterns and Hotspots

Using kernel density estimation, high-emission clusters were predominantly located along pipeline corridors and near compressor stations, suggesting operational or maintenance deficiencies. These spatial insights allow targeted inspections

Table 5: Methane Leak Incidence by Infrastructure Type

Infrastructure Type	*Number of Sites Surveyed*	*Leaks Detected*	*Average Emission Rate (kg CH_4/h)*	*Risk Level (Low/Medium/High)*
Onshore Wells	120	18	3.5	Medium
Pipelines	85	12	5.2	High
Storage Tanks	40	5	2.1	Medium
Compressor Stations	25	7	6.0	High
Total	270	42	4.2	–

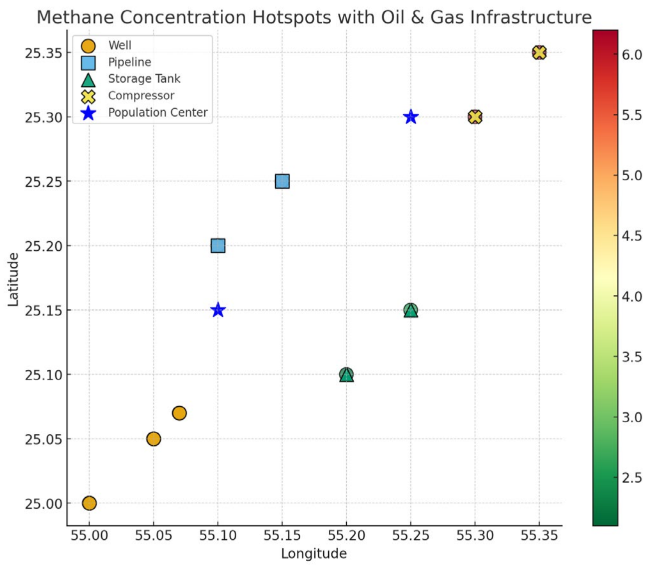

Fig 4: The heatmap visualization of methane concentration hotspots across the study area.

and mitigation planning.

Discussion

The case study demonstrates the utility of integrating multi-source geospatial data for methane leak detection and mitigation prioritization. Satellite data captures broad trends (Schneising *et al.*, 2020), drones provide site-level resolution (Hollenbeck *et al.*, 2021; Emran *et al.*, 2017), and mobile sensing ensures real-time monitoring (Albertson *et al.*, 2016; Gao *et al.*, 2022). Risk-based mapping enables operators to allocate resources efficiently and reduce emissions in high-priority areas, aligning with environmental and regulatory goals.

The geospatial analytical approach successfully identified leak hotspots, quantified emission rates, and informed mitigation strategies. This methodology can be scaled for regional or national monitoring programs to minimize environmental and public health impacts from fugitive methane emissions.

Conclusion

This study demonstrates that geospatial analysis provides a robust framework for the detection and mitigation of methane leaks from oil and gas infrastructure. By integrating multi-source datasets, including satellite remote sensing, drone-based surveys, and ground sensor networks, high-risk areas and emission hotspots can be effectively identified and prioritized for intervention (Schneising *et al.*, 2020; Fox *et al.*, 2019). The application of GIS-based spatial analysis enables the visualization of infrastructure vulnerabilities and supports data-driven decision-making for maintenance and mitigation planning (Carranza *et al.*, 2018; Rafiq, 2022). Mobile and low-altitude sensing approaches further enhance the resolution and accuracy of leak detection, allowing for real-time monitoring and localized interventions (Albertson *et al.*, 2016; Hollenbeck *et al.*, 2021; Emran *et al.*, 2017).

The findings highlight the potential of geospatial tools to address environmental injustices associated with methane leaks, particularly in urban areas where vulnerable populations may be disproportionately affected (Weller *et al.*, 2022). Moreover, route optimization and predictive modeling techniques improve operational efficiency and reduce costs associated with inspection and repair (Gao *et al.*, 2022). Overall, integrating geospatial analysis with emerging sensing technologies establishes a proactive approach for mitigating methane emissions, aligning operational practices with environmental and regulatory objectives (Fox, 2020; Rafiq, 2022).

Future research should focus on enhancing the temporal resolution of monitoring, integrating machine learning for predictive leak detection, and expanding the approach to diverse geographic contexts to ensure broader applicability and sustainability in methane management.

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