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Comprehensive Review on Oil and Gas Pipe Leak Detection and Location

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ABSTRACT

Oil and gas pipelines play a crucial role in fuel transportation; however, leaks can result in significant loss of life and property due to the energy released. Effective and reliable leak detection and localization methods are essential for continuous monitoring and for reducing the likelihood of pipeline failure throughout their operational lifespan. Despite this, there is currently a lack of comprehensive bibliometric and systematic reviews on these techniques. To address this gap, this study performs a scientometric analysis of existing bibliographic data in the field to identify widely used methods and key challenges, along with trends in publications, institutions, and research focus areas. It also proposes a structured and comprehensive classification of leak detection techniques, summarizes relevant standards for oil and gas pipeline monitoring, and presents a flowchart to guide the selection of appropriate methods. Moreover, the paper provides an in-depth overview of various detection approaches, evaluating their advantages, limitations, and performance. It concludes by outlining potential areas for future improvement based on observed gaps and limitations in current research, offering valuable insights for both researchers and industry professionals.

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Pipelines are widely regarded as the safest and most cost-effective way to transport natural gas and crude oil from offshore locations to onshore facilities, as well as from processing plants to domestic and industrial users. However, they remain vulnerable to leaks arising from various factors, including corrosion and interference by third parties (Aalsalem *et al.,* 2018). In addition, the impact of a pipeline leak grows as its size increases, making it essential to detect and locate leaks quickly to contain the escaping product. As a result, an effective leak detection system should be implemented to monitor pipeline operations and enable preventive actions that minimize the resulting damage.

So far, researchers have carried out numerous studies on pipeline leak detection and have introduced a range of techniques, including acoustic emission (AE) (Yigit and Kadir 2018) ground penetrating radar (Sheng-Huoo et al 2010), optical fiber sensors (OFS) (Ren et al., 2018), pressure point analysis (PPA) (Rajasekaran *et al.,* 2025), negative pressure wave (NPW) (Wang *et al.,* 20216), dynamic modeling (Kim *et al.,* 2024), infrared thermography (Pan *et al.,* 2020), vapor sampling (Weber and Dennis 1991), digital signal processing (Yao *et al.,* 2023), and mass volume balance methods (Di Blasi *et al.,* 2009).

In addition, several efforts have been made to categorize these techniques using different classification approaches. These methods have commonly been grouped either as direct and indirect techniques, or as hardware-based and software-based approaches. In this study, however, the techniques are organized into three primary categories: hardware-based, non-technical, and software-based methods, drawing on existing literature. Figure 1 illustrates these three categories along with their respective

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methods, covering both leak prevention and detection strategies. In the figure, blue represents prevention methods, pink denotes detection methods, and orange indicates methods that serve both purposes. Internal (computational) leak detection methods rely on models or algorithms to monitor flow parameters in real time, while external leak detection methods depend on non-algorithmic approaches, using dedicated sensors to physically detect any escaping substance.

Leak detection classification

A wide range of pipeline leak detection techniques has been developed based on different operating principles and methodologies for identifying leaks in natural gas pipelines. These techniques range from conventional approaches, such as manual pipeline inspection and the use of trained dogs, to advanced technologies involving satellite-based hyperspectral imaging. According to Stafford and Williams 1996), the selection and application of a particular leak detection system are influenced primarily by environmental conditions, regulatory requirements, and the loss-prevention and safety policies of the operating company, rather than solely by pipeline size or configuration.

Several leak detection technologies are currently available for monitoring pipeline integrity. These include acoustic emission techniques, fibre-optic sensors, ground-penetrating radar, negative pressure wave methods, pressure point analysis, dynamic modelling, vapor sampling, infrared thermography, digital signal processing, and mass or volume balance techniques. Such methods are widely applied in the oil and gas industry to support pipeline integrity management and minimize gas losses during transportation. However, the effectiveness of a particular leak detection technique depends on its underlying detection principle, pipeline operating conditions, and the characteristics of the pipeline network (Aljameel *et al.,* 2024).

For a leak detection system to be considered suitable for practical or production applications, several performance requirements must be satisfied. An effective system should possess adequate sensitivity, enabling it to detect relatively small leaks within a short period. It should demonstrate high reliability by minimizing false alarms and distinguishing actual leaks from normal operating disturbances. The system should also provide sufficient accuracy to estimate the magnitude of a leak and determine its location rapidly and precisely. Furthermore, it should exhibit adequate robustness, allowing it to identify abnormal or failure conditions while maintaining operation under varying environmental and pipeline conditions.

Leak localization and accurate estimation of leakage rates are particularly important because they support early containment, maintenance, and corrective actions, thereby reducing potential environmental pollution, equipment damage, economic losses, and risks to personnel. Consequently, the identification of an effective leak detection technique for minimizing gas losses during transportation remains an important area of research (Ullah et al., 2024). Leak detection systems can broadly be classified into continuous and non-continuous monitoring systems, as illustrated in Figure 1 and further described in Table 1. Continuous monitoring systems provide ongoing surveillance of pipeline conditions and can generally be categorized into external and internal monitoring systems (Jena et al., 2023).

Continuous external monitoring systems employ locally installed sensors to identify pipeline leaks, structural abnormalities, or other physical changes. These systems typically require some form of physical interaction or contact between the sensing elements and the pipeline or monitoring environment. They generally provide high sensitivity and can offer accurate leak localization. However, their installation and maintenance costs can be relatively high, which limits their application primarily to short pipeline sections, critical facilities, or environmentally sensitive areas.

In contrast, continuous internal monitoring systems use instruments installed within the pipeline system or at measurement points to continuously monitor hydraulic and operational variables associated with fluid transportation. Typical parameters include flow

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rate, pressure, and temperature. These measurements may be evaluated directly by pipeline operators or processed automatically using mathematical algorithms, statistical techniques, and hydraulic models. A significant deviation between the measured operating parameters and their predicted or expected values may indicate the presence of a leak. One major advantage of internal monitoring systems is that they generally do not require extensive sensor installation along the entire pipeline. Examples of continuous internal leak detection techniques include Pressure Point Analysis (PPA), Mass or Volume Balance (MVB) methods, statistical-based systems, Real-Time Transient Model (RTTM) systems, and Extended Real-Time Transient Model (E-RTTM) systems.

Mascarenhas et al. (2024) non-continuous monitoring systems, on the other hand, represent more conventional approaches in which pipeline inspections or measurements are performed periodically rather than continuously.

These methods include helicopter-based inspection, intelligent pigging or smart pigging, trained-dog inspection, inspection by trained or experienced personnel, soil monitoring, remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), gas sampling, and flow monitoring devices. Although these techniques can be useful for identifying and investigating pipeline leaks, their effectiveness may be constrained by inspection frequency, accessibility, environmental conditions, response time, and the availability of specialized equipment or personnel. Leak detection was classified based on the methods of identification, which are internal-based, visual inspection methods, and external-based methods of classification, as shown in Figure 1.

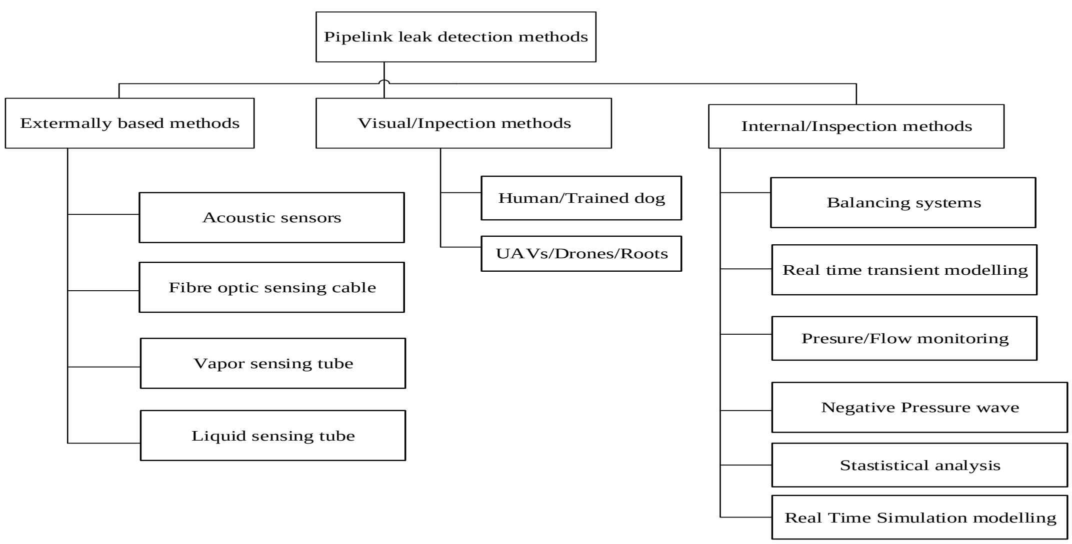

Figure 1: Classification of pipeline leak detection methods.

REVIEW OF RELATED LITERATURE

Tai et al. (2025) The review also identified several gaps in existing research and proposed future research directions, including laboratory-based investigations to characterize defect-related acoustic signals in multi-bolted flange systems under different operating conditions. Overall, the findings indicate that AET has considerable potential as an advanced condition-monitoring technique for industrial inspection and maintenance, offering improved opportunities for early defect detection, enhanced safety, and increased reliability of critical infrastructure. (Saleem et al. 2024) Proposed an advanced deep-learning framework for the real-time detection of pipeline leaks within smart city

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infrastructure. The proposed approach converts acoustic emission (AE) signals from the time domain into scalogram images using the Continuous Wavelet Transform (CWT), thereby improving the representation and extraction of leak-related characteristics. A Gaussian filtering technique is subsequently applied to suppress background noise and enhance the relevant signal features.

The effectiveness of the proposed framework was evaluated using experimental data obtained from real pipeline operations. The results demonstrated a high detection accuracy of 99.69%, indicating the strong capability of the method to distinguish between leaking and non-leaking conditions. Despite its high classification performance, further investigation may be required to assess its robustness under diverse pipeline operating conditions, environmental disturbances, different leak sizes and locations, and variations in pipeline configurations. Overall, the proposed framework demonstrates significant potential for intelligent pipeline monitoring and predictive maintenance, providing a scalable approach for improving the reliability and proactive management of smart-city infrastructure (Zhang et al., 2023)

Lee et al. (2024) The proposed system integrates an advanced ultrasonic camera with a deep-learning-based object detection algorithm trained using pipeline images collected from petrochemical plant environments. The acquired image data were used to improve the localization accuracy of gas leakage points through deep-learning techniques. The developed detection model achieved an mAP50 (mean Average Precision at an Intersection over Union threshold of 0.50) of 0.45, demonstrating its ability to identify most of the leakage points within the investigated system. To evaluate the proposed system under realistic operating conditions, the researchers studied petrochemical plant layouts and engineering drawings and subsequently established an outdoor experimental facility that replicated relevant plant conditions.

Different leakage scenarios, including flange connection failures, were simulated under medium- and low-pressure operating conditions. The developed system was then evaluated under controlled gas leakage conditions designed to represent realistic pipeline failure events.

Meng and Hu (2024) presented a comprehensive review of the operating principles of different pipeline leak detection techniques. The study examined the historical evolution of leak detection technologies, the importance of pipeline monitoring, and the relevant legal requirements and regulatory frameworks. However, the study did not identify a single optimal or most suitable leak detection technique, instead recommending further research to establish the most effective system. (Wang et al., 2023) proposed an innovative interdisciplinary approach that exploited advances in computer vision for the automatic classification of natural gas leaks.

The study conducted sensitivity analyses to evaluate the influence of feature selection, the sizes of the training and testing datasets, the noise threshold used in optical flow computation, and the number of frames required for histogram-of-oriented-gradients analysis. Despite these contributions, the study emphasized the need for sufficiently large and representative datasets to develop more robust algorithms for detecting gas plumes. Further improvement was also required in estimating leak magnitude through regression-based models and convolutional neural network techniques.

Aljameel et al. (2024) reviewed several pipeline leak detection technologies, focusing on their respective advantages, limitations, and potential applications in deep water, subsea, and Arctic oil and gas developments. The authors further examined the applicability of existing leak detection techniques to emerging oil and gas development strategies. Nevertheless, they identified several areas requiring further investigation. These included the need for large-scale experimental studies on multiphase leak detection, the application of distributed pressure and temperature sensor arrays to improve the capabilities of pressure-loss-based detection methods, and the investigation of combined continuous and batch sampling techniques to reduce leak detection time.

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Wang et al. (2001) conducted an extensive review of pipeline leak detection techniques, outlining the advantages and limitations associated with each method and emphasizing the importance of selecting an appropriate detection technique according to the characteristics of a particular pipeline system. The authors also examined recent developments in inverse transient-based leak detection, with particular emphasis on the inverse transient method. However, they recommended extending research to other transient-based techniques, including transient reflection, transient damping, and transient frequency analysis, to improve detection speed and accuracy and facilitate their implementation in practical pipeline networks.

El-Shiekh (2010) developed a methodological framework for facilitating the selection of appropriate pipeline leak detection systems. The study considered both external detection techniques and internal methods based primarily on pipeline flow and pressure measurements. However, the research did not establish a definitive best-performing technique and recommended more detailed investigations into leak detection and localization, particularly for transmission pipelines. Similarly, (Sivathanu 1991) reviewed the state of the art in natural gas pipeline leak detection and discussed several techniques used for identifying gas leaks. Particular attention was given to optical-based detection methods because of their potential for natural gas leak identification. Nevertheless, the study concluded that no single technique could be regarded as an industry-wide standard because each method exhibited specific operational limitations and challenges.

Appah et al. (2021) conducted a comprehensive evaluation of existing methods for detecting and quantifying gas leaks in natural gas infrastructure. Their assessment considered the quantity of gas leaked relative to the total volume of gas produced from the facilities. The authors observed that uncertainties associated with the accurate quantification of natural gas leak rates highlight the need for innovative techniques and improved procedures for identifying and estimating leak rates from gas infrastructure. They therefore emphasized the need for urgent action and further technological development. However, the study did not identify a universally superior leak detection method, noting that the selection of an appropriate technique depends on the specific application, desired performance, installation cost, operational and maintenance requirements, and site conditions.

Adegboye et al. (2019) reviewed various pipeline leak detection technologies and summarized recent state-of-the-art developments, including the strengths and limitations of the available methods. The study also provided a comparative performance analysis intended to guide the selection of suitable leak detection techniques for different pipeline operating conditions. Nevertheless, the study did not address the development and implementation of a real-time intelligent system for simultaneous leak detection and localization in subsea pipeline networks. In addition, the effects of environmental factors, particularly hydrodynamic forces resulting from oblique waves and current-induced loading on subsea pipelines, were not considered, thereby creating an area requiring further investigation.

The Canadian Association of Petroleum Producers (CAPP 2018) developed best management practices to guide upstream pipeline operators in the selection, operation, and maintenance of leak detection programs. These practices were designed to support pipeline integrity management and enhance the overall performance of upstream pipeline operations. Their implementation contributed to faster leak identification, reduced environmental consequences of pipeline leaks, and improved pipeline performance, particularly in high-risk locations.

However, the report emphasized that whenever modifications are made to pipeline systems or operating conditions, their potential effects on existing leak detection management programs should be carefully evaluated, and the leak detection system should be appropriately adjusted where necessary. (Baroudi et al., 2019) provided an extensive review of different leak detection systems and data fusion techniques applicable to pipeline monitoring. The study

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presented a detailed classification, analysis, and comparison of the available approaches.

The authors concluded that no single leak detection system suits all pipeline applications, as each system is typically designed around the characteristics and requirements of a particular pipeline. Consequently, selecting a leak detection method should follow a fit-for-purpose approach based on relevant operational parameters, such as pipeline diameter, length, and instrumentation configuration. However, the authors recommended a more comprehensive analysis of historical pipeline performance and failure data to provide deeper insights into system behavior and failure mechanisms. They also highlighted the need to improve detection accuracy to reduce the occurrence of false alarms

Software-Based and IoT-Based Gas Leak Detection Techniques

This section reviews software-based and intelligent gas leak detection techniques that utilize internal fluid measurements to monitor operational parameters associated with oil and gas transportation through pipelines. Parameters such as pressure, temperature, density, flow characteristics, acoustic signals, and gas concentration can provide useful indications of pipeline leakage. Among the techniques reported in the literature are negative pressure wave (NPW) methods, Internet of Things (IoT)-based monitoring systems, and machine-learning approaches.

Ye et al. (2025) developed an improved negative pressure wave-based system for detecting leaks in natural gas pipelines. Their approach combined Fiber Bragg Grating (FBG) strain sensors with wavelet analysis to improve leak detection and localization. The proposed method incorporated natural gas velocity and variations in the negative pressure wave into the conventional leak-location formulation. The modified mathematical model was solved using the compound Simpson method and dichotomy-based identification techniques. An FBG strain sensor was employed to acquire negative pressure wave signals, thereby overcoming some of the installation difficulties associated with conventional pressure sensors. The technique offers several advantages, including relatively simple installation, good insulation characteristics, and low cost. In addition, wavelet transform analysis was applied to identify pressure-drop points within the FBG signals. Experimental results demonstrated that the proposed approach could accurately determine the location of a natural gas pipeline leak, with an absolute localization error of approximately **0.38 m**. However, further validation under different pipeline operating and environmental conditions would be necessary to establish its robustness in practical applications.

Ayamga et al. (2024) proposed an anti-damage and early-warning monitoring system for natural gas pipelines by integrating sound and vibration sensing with IoT technology. The system was designed to continuously monitor abnormal pipeline conditions and transmit warning information through a centralized data-analysis platform. Acoustic sensing was used to identify abnormal pipeline noise, while IoT-enabled sensors transmitted detected vibration information to the monitoring platform. The frequency and amplitude characteristics associated with pipeline leakage were analyzed to determine whether a leak had occurred.

Once an abnormal condition was identified, the system transmitted the corresponding warning information to maintenance personnel. The proposed architecture was therefore intended to provide real-time pipeline monitoring and early warning. Nevertheless, the effectiveness of the system may depend on its ability to distinguish leak-induced acoustic and vibration signals from environmental and operational noise. (Aljameel et al., 2024) developed a gas leakage detection and safety system based on embedded electronics and IoT technology. The primary objective was to reduce the risk of gas-related accidents by providing automated leakage detection and immediate warning capabilities.

In addition to detecting gas leakage, the system incorporated an automatic gas shut-off mechanism intended to limit the consequences of a detected leak. Users were alerted through

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audible alarms and IoT-enabled messages. Temperature measurements were also incorporated to monitor the condition of the gas cylinder. The communication architecture was enhanced using Android and GSM technologies to facilitate remote notifications, including email-based alerts. Light-emitting diodes (LEDs) were incorporated as visual indicators to improve the reliability of the warning mechanism. The developed system successfully performed the intended functions, demonstrating its potential as a practical safety device for gas leakage detection. However, its application is more suitable for localized or household gas monitoring than for large-scale pipeline networks.

Ralevski and Stojkoska (2024) investigated an IoT-based system for detecting gas leakage in residential environments. The proposed architecture consisted of a laptop and two Raspberry Pi devices equipped with appropriate sensing units. The system was designed to operate in potentially hazardous environments and collect environmental measurements for subsequent analysis. Gas leakage was identified using measurements of gas concentration and temperature. To reduce energy consumption, a Moving Average (MA) algorithm was integrated into the distributed IoT architecture. The system operated according to predefined rules that controlled communication among the connected devices and facilitated the identification of abnormal conditions.

A time-series forecasting technique was also employed to reduce the number of data packets transmitted by measurement nodes and improve communication efficiency. When a leak was detected, an alert was transmitted to the end user's mobile device. The researchers evaluated the MA algorithm by comparing its performance with other prediction techniques and found that it provided accurate predictions of indoor temperature measurements. They suggested that future research could incorporate statistical analysis of the recorded temperature data to further improve prediction performance. However, the study primarily focused on indoor environments and did not address the complexities associated with long-distance oil and gas pipeline monitoring.

Debnath et al. (2025) proposed a low-cost IoT-based gas leakage detection and warning system capable of detecting gas leakage and temperature increases and subsequently notifying users. In emergency situations, the system could initiate a telephone call, generate an alarm, and transmit location information to a web server. The proposed architecture combined several hardware and software components, while machine-learning algorithms were used to evaluate the performance and prediction accuracy of the system. The hardware consisted of an MQ-2 gas and smoke sensor, infrared (IR) sensor, GSM communication module, NodeMCU microcontroller, buzzer, and DHT11 temperature sensor.

The integrated system was capable of detecting gas leakage, fire, and elevated temperature conditions. The software component was implemented using Arduino-based programming. To assess the detection performance, several machine-learning algorithms, including Multilayer Perceptron (MLP), Support Vector Machine (SVM), and Naïve Bayes (NB), were evaluated. The system achieved an average prediction accuracy of approximately 92.63%. However, a major limitation was that the emergency notification mechanism could contact only a single user. Consequently, further development is required to support simultaneous alerts to multiple users, particularly in large-scale or industrial applications. (Alshammari and Chughtai 2026) similarly developed an IoT-based gas leakage monitoring system using an MQ-5 gas sensor.

Sensor measurements were transmitted to a cloud platform for monitoring and analysis, allowing gas leakage to be detected under different atmospheric conditions. An Arduino UNO was employed as the central processing unit responsible for coordinating the different components of the system. When the gas concentration exceeded the predefined threshold, an audible buzzer was activated to warn users. An LCD interface was also incorporated to provide information concerning the detected leakage,

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while an exhaust fan could be automatically activated to remove accumulated gas from the affected area.

Experimental implementation demonstrated that the system could successfully detect gas leakage and transmit warning messages to users. A printed circuit board (PCB)-based gas leakage detector was subsequently used to obtain practical results, with the high-accuracy sensor capable of detecting concentrations of up to approximately 10,000 ppm, accompanied by a red LED warning indication. Although the system demonstrated satisfactory performance, the authors indicated that modifications would be necessary to optimize its application for domestic environments.

Overall, the reviewed studies demonstrate the increasing application of IoT, sensing technologies, signal processing, and machine learning in gas leak detection and warning systems. However, many of the existing approaches are designed for localized or indoor applications and rely on threshold-based sensing, limited sensor configurations, or relatively small datasets. Their applicability to long-distance oil and gas pipelines can therefore be constrained by environmental noise, changing operating conditions, communication limitations, sensor deployment requirements, and the difficulty of accurately determining leak location and magnitude. These limitations provide motivation for the development of more robust intelligent leak detection and localization systems, particularly those capable of integrating multiple sensor measurements with advanced machine-learning or optimization techniques for real-time pipeline monitoring.

CONCLUSION

This study reviewed extensive research works on oil and gas pipeline leak detection, which were broadly categorized into hardware-based, software-based, and intelligence-based techniques. The review revealed several important limitations in the existing literature. One major limitation is that a considerable number of studies did not utilize real-world pipeline datasets. Instead, they relied on hypothetical or artificially generated datasets derived from sensor measurements and other simulated parameters. The use of relatively small and synthetic datasets may limit the generalizability and reliability of the reported results. Therefore, improving the size, diversity, and quality of datasets, as well as incorporating additional relevant features, could significantly enhance the performance and robustness of existing leak detection models.

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