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Research

Systematic literature review and bibliometric analysis of pipeline monitoring and leakage detection techniques

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Abstract
Liquids such as water, chemicals, oil, and gas are mostly transported via pipelines worldwide. It is considered one of the fastest, cheapest, and most reliable methods of transporting oil and gas. One of the major threats to this form of transportation of liquids is leakage due to vandalism or deterioration causing economic loss, environmental damages, and loss of lives and properties. To mitigate these threats, several techniques have been proposed. This systematic review analysed the various principles and approaches of pipeline leakage detection and monitoring. Furthermore, relevant standard, taxonomy of different methods of monitoring, and leakage detection of oil and gas in pipelines were discussed; their merits, performance and limitations were also discussed. Kitchenham literature search strategy was adopted to search relevant academic databases using various principles of inclusion and exclusion criteria to filter unaligned articles. It was found that integrating two or more techniques enhances the efficiency, effectiveness and accuracy of detecting and monitoring leakages in pipeline. Finally, this review concludes by outlining potential ways for future researchers based on the limitations and findings of the reviewed articles.

Keywords Pipeline · Leakage detection · Monitoring · MUSIC algorithm · Acoustic emission

1 Introduction

The increasing worldwide demand for petroleum products since the nineteenth century has led to the construction of pipeline networks to meet market needs. In the view of Valery et al. [114], the market need for oil and gas is expected to continue growing as several countries are expanding and building new industries for economic reasons. The transportation of petroleum and natural gas has always been a significant concern for both the government and industries because it requires major investments [16]. From an environmental, economic and safety view point, pipeline could be considered one of the safest, cheapest and reliable method of transportation of oil and gas [43]. Pipeline networks traverse through tens to thousands of miles, carrying oil and gas from one region to another, with such length, there are increases in the chances of damage by corrosion, vandals or industrial defects which can have disastrous effects on humans, animals, economy and environment. Aibinu et al. [5] described a pipeline as a path, medium or channel through which liquid fluids are conveyed from one point to another. Several oil- producing countries depend on oil and gas as sources of Internally

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Generated Revenue (IGR). The significance of pipelines to diverse sectors of a nation's economy cannot be overemphasized. Hence the need for an efficient, effective and automatic means of identifying leakages in a timely manner.

This study presents a bibliometric and systematic literature review of the principles, approaches and analysis of pipeline leakage detection and monitoring. Therefore, this study aims to presents the following outcomes:

I. Taxonomy of pipeline monitoring and leakage detection.
II. Analysis associated with the various principles and approaches of pipeline leakage detection and monitoring.
III. Bibliometric and comprehensive systematic literature review for pipeline leakage detection and monitoring

The subsequent parts of the paper are organized as follows: Sect. 2 outlines the analysis of existing related surveys and bibliometrics, Sect. 3 details the principles and approaches of the research methods, the taxonomy of the pipeline leakage detection and monitoring are described in Sect. 4, Sect. 5 unresolved research problems and Sect. 6 concludes the article.

2 Existing related surveys

This section presents existing relevant surveys and some literature in the field of pipeline monitoring and leakage detection research. The taxonomy, references, bibliography, and survey covered are shown in Table 1 and Fig. 2.

Sharma et al. [100] conducted a systematic literature review on the current state of pipeline leakage detection in gas pipelines using cloud technology with an Internet of Things (IoT) ecosystem. The authors explored the various non-sensor and, sensor-based, IoT techniques and systems used for leakage detection of gas content in pipeline, their relative weaknesses and strengths. The authors also review the current challenges and trends in leakage detection of gas pipelines and recommend future research directions to enhance the system efficiency, reliability and accuracy. Qurthobi et al. [93] proposed a systematic review of acoustic techniques for identifying mechanical faults in industrial machinery. The authors further classified the causes of acoustic mechanical failures by analysing the principles, approaches, and techniques, identified gaps in existing literatures and recommended the potential areas of research to work on. Korlapati et al. [63] dwelled on the review and analysis of pipeline leakage methods and suggested critical areas to consider for potential future research. Khalid et al. [58] presents comprehensive review of gas pipeline leakage detection and monitoring techniques used for identifying faults in pipelines. The authors analysed the techniques and identified the pros and cons of recently used techniques in identification of faults in pipeline and recommend areas to work on by future researchers in order to come up with lasting solutions and reform to oil and gas sector from prospective of inspection, security, surveillance and emergency response. Mutiu et al. [82] summarises cutting-edge achievements and recent advances in modern pipeline monitoring and leakage detection techniques. The authors also highlighted the weakness and strength of different technologies for monitoring and detecting leakage in pipelines; identify gaps, and open issues and recommend potential ideas for development of reliable leak detection system.

Zheng et al. [130] conducted a scientometrics' analysis of bibliographic datasets of leak detection and localization in oil and gas pipelines. The authors further identified the most current literatures techniques and their challenges. The authors also classified the techniques using a comprehensive and systematic literature review, summarized relevant standards of monitoring and detecting leaks in oil and gas pipelines, provided a flowchart for selecting leakage detection methods, identify the strength and weakness of each technique, discussed the performance of each method in detail and recommended potential directions for future research. Zaman et al. [128] submission focused on review of critical evaluation and performance-oriented of pipeline leakage detection principles conveying different types of fluids, analysed and classified an extensive array of leak detection methods with their technicalities, and recommended enhancements of various methods of leak detection techniques to achieve desired results. Al-Sabaeci et al. [8] presented a systematic literature review that focused on the novelty of using deep learning methods such as Artificial Neural Networks (ANNs), Hybrid Machine Learning (HML) algorithms and Support Vector Machines (SVMs) to predict different pipeline failures in oil and gas companies. The authors further explicit the utilization of machine learning techniques parameters as well as data reliabilities. Al-Sabaeci et al. [8] further analyse the bibliometric literature, highlighted specific machine learning techniques, and investigated faults and experimental test. In-depth details of various failures and summaries were also provided by the authors. Ali and Choi [7] in his submission reviewed existing techniques with the aim of identifying the causes of leakages in underground pipelines, and sinkholes and the effectiveness of Wireless Sensor Network (WSN) in detecting and localization of leakages as well as sink holes.

Table 1 Abbreviation and meaning

Abbreviation	Meaning
AAE	Active Acoustic Emission
ACM	Association of Computing Machinery
AE	Acoustic Emission
ANC	Adaptive Noise Cancellation
ANN	Artificial Neural Network
AUV	Autonomous Under Water Vehicle
BF	Beam Forming
CSC	Cumulative Sum Control
CSM	Capacity Sensor method
CWT	Continuous Wavelet Transform
DAC	Data Acquisition Centre
DAS	Distributed Acoustic Sensing
DBLP	Digital Bibliography and Library Project
DL	Deep Learning
DMT	Dynamic Modeling Technique
DOA	Direction of Arrival
DPW	Dynamic Pressure Wave
DTS	Distributed Temperature Sensing
DSP	Digital Signal Processing
EA	Entropy Analysis
ECDF	Empirical Cumulative Distributed Functions
EKF	Extended Kalman Filter
EMD	Empirical Mode Decomposition
EMUSIC	Enhanced Multiple Signal Classification
EWMACC	Exponential Weighted Moving Average Control Chart
FDM	Filter Diagnosis Method
FBG	Fibre Bragg Grading
FFT	Fast Fourier Transform
FT	Fourier Transform
FUT	Fibre Under Test
GCC	Generalize Cross Correlation
HAE	Hybrid Acoustic Emission
HHT	Hilbert-Huang Transform
HT	Hilbert Transform
HMM	Hidden Markov Model
HML	Hybrid Machine Learning
IEEE	Institute of Electrical and Electronics Engineers
IGR	Internally Generated Revenue
ITT	Infrared Thermography Technique
IoT	Internet of Things
KNN	K-Nearest Neighbour
KST	Kolmogorov Smirnov Test
LPCC	Linear Prediction Ceptrum Coefficient
MED	Minimum Entropy Decomposition
MUSIC	Multiple Signal Classification
MVB	Mass Volume Balance
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Technique
NN	Neural Network
PAE	Passive Acoustic Emission
PHP	Hypertext Pre-Processor

Table 1 (continued)

Abbreviation	Meaning
PIG	Pipeline Inspection Gauge
PPA	Pressure Point Analysis
RBM	Risk Based Maintenance
RTD	Resistant Temperature Detectors
RMS	Root Mean Square
ROV	Remotely Operated Vehicle
RTD	Resistant Temperature Detector
SAP	Spectral Analysis Response
SCC	Shewhart Control Chart
SFT	Short Fourier Transform
SPC	Spectral Process Control
SSMA	Steady State Mixed Approach
SVM	Support Vector Machine
TSKST	Two Sample Kolmogorov Smirnov Test
VST	Vapour Sampling Method
VIM	Visual Inspection Method
WSN	Wireless Sensor Network

Ali and Choi [7] further proposed analysing, comparing and classifying different techniques of leak detection and monitoring; advocate collocating internet of things, WSN and methods of pipeline leakage detection and monitoring to provide an everlasting solution to underground pipeline leakage and occurrence of sink holes. Ho et al. [43] reviewed some of the most subsea monitoring and inspection technologies of pipelines, methods of development and their future trends. Mehta and Kuruvilla [79] presented an in-depth review of existing techniques for detecting leakages in fluid components in a pipeline. The authors mainly focused on scrutinizing the advance and traditional techniques with applicable algorithms; analysed and identified the efficacy, parameters and limitation of each technique for detection of leakage in fluid components. The authors further presented fundamental guidelines to facilitate future research works.

Yuan et al. [126] conducted a scientometrics' analysis of bibliographic data in the detection and localization leak in oil and gas pipeline to examine existing techniques and their associated limitations. The authors further proposed comprehensive and systematic classification methods for detection, and monitoring leakages in pipelines, recommended directions of improvements to future researchers due to the drawback of existing literatures. Hu et al. [46] utilized bibliometric analysis to review existing research articles on Acoustic Emission (AE)-based leak detection and localization techniques in oil and gas pipeline networks. The authors also provided a comprehensive understanding of the current advancement, identified limitations and itemized prospective research areas for future work based on their findings. Soomr et al. [108] performed a systematic review of the literature on machine learning-based integrity assessment of deteriorated pipeline systems conveying oil and gas and provides an overview of the most frequently used evaluation for machine learning models to assess the integrity of the pipeline systems. The authors also itemized the most important model parameters and utilized them in existing literatures as inputs and projected outputs, discovered certain data sources that can be applicable to machine learning model and data preparation. Lukonge et al. [75] provided a detailed systematic review of AE-based methods for detection of leakages in gas pipeline systems. The authors further explore the principles, essential requirement for gas leak detection systems, risks involve due to natural gas pipeline failures and terminologies involved and proposed integration of surface AE wave sensor with Hilbert-Huang Transform (HHT).

The HHT is a method of decomposing signal into inherent mode function to acquire real time frequency data [75]. Behari et al. [14] conducted critical analysis of various methods of leak detection techniques applicable to undersea and subarctic conditions. The authors further summarized their findings from both field and experimental studies. The authors also stated the accuracy, requirements of resources level and risk(s) involved in each technique. The authors found that moderate- to-extensive scale leak ranging from 3 to 10 mm can be detected by Dynamic Pressure Wave (DPW) technique. Feng et al. [28] conducted a comprehensive systematic overview of the characteristics of girth welds detected in long-distance pipeline network, summarized the principles of inspections, defect sizing methods, identification of defect signal, reliability of existing girth welds defects inspection techniques and recommended new technology for inspection girth weld. Igbal et al. [49] conducted a cutting-edge assessment of oil and gas pipeline maintenance practice to examine the limitation and strength related to the challenges of implementation. The authors further explicate various methodologies of Risk-Based Maintenance (RBM) and similar issues; and concluded by recommending the most fundamental policies of uncertainties and variability to consider in pipeline maintenance. Parlak and Yavasoglu [89] conducted a comprehensive analysis of high-tech pigging system employed in steel and metal pipelines systems of oil and gas, organized each technology of the pipeline system, fault detection efficiency, approaches and principles. The authors further discussed the limitations and advantages of each technology; and concluded by recommending combination of relevant sensor-based technique in leak detection. Carlson et al. [21] conducted a comprehensive systematic literature review in oil and gas pipeline explosions in Sub-Saharan Africa and identified 28 pipeline fire disasters from different countries. The authors found that 50% of pipeline explosion were reported in academic literatures for the past ten years. The authors also found that most of the pipeline explosions originated from vandals, saboteurs and terrorist activities that maliciously damaged the pipelines. The authors conclude by recommending future researchers to supplement gaps of 50% of studies not reported in academic literature.

Liu et al. [72] conducted a systematic analysis of industry 4.0 in the oil and gas sector. The authors became the first to introduce the core concepts of industry 4.0 in the oil and gas sector using technologies such as IOTs, and big data and analysed the application scenario of core leak detection technologies. The authors also recommended the adoption of industry 4.0 in the oil and gas sector as a data-driven analytic system of optimized digitization with the aim of exploring the technology to train personnel of petroleum industry. Alireza et al. [1] presented bibliometric and comprehensive literature review of petroleum products failures and consequences analysis. The author evaluated the existing research patterns, identified the number of top cited journals, and mapped out occurrence examination of authors keywords and contributions from each country. The authors conclude by recommending future researchers to narrow their researches based on cluster analysis and keywords from existing literatures in order to uncover future research directions. Abdulshaheed et al. [2] reviewed various leak detection method analyses based on pressure; the authors itemized the advantages and disadvantages of each method and recommended the best technique that is suitable to both oil and water pipelines. Colombo et al. [27] conducted a comprehensive review of literature on transient-based pipeline leakage detection techniques with the aim of summarizing the existing and current methods with their respective state-of-the-art research areas. Onuoha et al. [86] presented a systematic review based on the implementation of industry 4.0 technologies for cathodic protection and off-site monitoring of petroleum and gas pipelines. It was found that monitoring and modeling of the cathodic protection in real-time gave the same functionality when one visit research field (site). Coramik and Ege [28] presented an overview in pipeline leakage detection and monitoring based on the Non-Destructive Evaluation (NDE) technique and Pipeline Inspection Guage (PIG) by examining the purpose of applying the PIGs and NDE techniques. Lu et al. [74] reviewed the progress of carbon dioxide transportation via pipelines from four perspectives; safety, specifications, processes and design. The authors also examined the four perspectives in detail and summarized the technical challenges with development directions. The authors found that there are numerous similarities between gas pipelines and carbon dioxides pipeline but due to the difference in contents, composition and transport destination, the design, construction and transport process differ substantially, especially with respect of management.

Wasiu and Djukic [122] reviewed the various factors responsible for the surface-level corrosion of pipelines conveying petroleum products. The authors analysed the various forms of surface-level corrosion in pipeline and their respective fault detection mechanisms. The authors conclude by recommending predictive measures as a means of preventing external corrosion in petroleum and natural gas pipeline systems. Ghazali et al. [39] conducted a comparative reviewed of instantaneous frequency techniques of pressure-based transient methods in pipeline networks. The authors analysed these techniques to demonstrate the efficiency of the instantaneous frequency in detecting leakages in pipelines. Sharma et al. [100] conducted a systematic literature review on cloud technology and current state leak detection using the principles and approaches of the Internet of Things (IoT). The authors explored different non-sensor and sensor-based IoT techniques used for the detection of leakages in gas pipelines, summarized their advantages, disadvantages, current trends and challenges. The authors further recommend future research directions to enhance the reliability and accuracy of these techniques. Yang et al. [124] proposed transient flow basic equations, and outline the problem-solving approach based on the characteristics line method and finite difference method. The authors further illustrate the proposed method using handling of friction term which is a new technique of leakage point boundary constrain. The authors found out that the variations of flow rate and pressure in the end node and start node are obtained when leak occur, which provided a fundamental theoretical basic for recognizing anomalies such as leakage.

Woldesellasse and Tesfamariam [123] conducted a comprehensive literature review and bibliometric assessments of an onshore pipeline system for conveying oil and gas. The authors conclude by recommending directions for future researchers in areas risks assessment management in pipeline system conveying petroleum products. Kyew [65] comprehensively review on subsea oil and gas pipeline competency and quality. The author found that various techniques have been developed from existing literature to provide solutions to underwater pipeline leakages that occur due to deterioration and other factors. The authors further identified various gaps and challenges and recommended directions that future researchers can improve on. Wanasinghe et al. [121] conducted a systematic review and assessment of the impact, role, current status, strength and weakness of IoT application in petroleum and natural gas industries.

The existing articles identified gaps and recommended techniques for monitoring and detecting leakages in pipeline systems. The identified gaps can help advance the field of pipeline monitoring and leakage detection to develop sustainable and effective solutions. The following summarizes the gaps identified in the reviewed articles:

I. Most of the previous study focused on the techniques and principles of pipeline leakage detection and monitoring techniques rather than the datasets used to conduct the experiments. Even with the most effective and efficient technique, the improper datasets used to test the experiment matters a lot.
II. Some analyses only overviewed articles on specific techniques of pipeline leak detection rather than over viewing two or more techniques and identifying ways of integrating the two identified techniques to achieve a desired goal.
III. Some articles highlighted standard methodologies utilized for performance evaluation of leakage detection systems. However, the overview did not consider the weaknesses of these methodologies by comparing the results across other studies to assess their effectiveness.
IV. There is also limited focus on environmental impact assessment and effectiveness of leakage detection and monitoring systems for mitigating damage to the environment leading to a lack of long-term effect and consequences of leakages in habitats and ecosystem.
V. There are also limited overviews on integration of two or more techniques for real-time leakage detection monitoring of pipeline networks, including challenges related to communication protocols, data fusion and scalability in sensor networks.
VI. Fewer reviews focused on the cost-benefits analysis on cost effectiveness of different techniques for pipeline leakage detection and monitoring. This will however make it difficult for decision makers and investors to prioritize investments in pipeline infrastructure.
VII. Many articles focus on particular geographical search coverage, such as offshore or onshore pipeline networks, leading to limited research in comparing and identifying challenges related to other geographical areas.
VIII. A few overviews have focus on identifying gaps in the accessibility and availability of datasets for research purposes. This leads to a gap in obtaining and evaluating the performance of detection models and algorithms. Table 1 presents an overview of lists of acronyms used frequently throughout the manuscript along with their corresponding meanings, which is essential for clarification of technical terms to ensure a consistent understanding of the technologies being used in pipeline leakage detection and monitoring.

Table 2 presents a comprehensive overview of existing surveys in research areas of pipeline leakage detection and monitoring, mainly focusing on the number of references covered, the primary focus of each survey, and the taxonomy adopted in the research, which is crucial for better understanding of the depth and scope of previous work in the domain, as well as identifying gaps for future research.

Table 3 provides a comprehensive bibliometric analysis detailing key elements, such as authors with their respective number of citations, organizations, countries, references and journals in which the research is published. This analysis serves as a crucial indicator of the impact and reach of the publications by highlighting the most prolific authors with respective numbers of citations reflecting the influence of the work within the academic community. Colombo et al. [27] received 608 citations showcasing their significant contributions to the field of pipeline leakage detection and monitoring. On the other hand, Mutiu et al. [82], Wasiu and Djuvic [122] follow closely with 383 and 221citations, respectively demonstrating the competitive nature of research in the field of pipeline leakage detection and monitoring. Table 3 also categorizes the institutions and organizations associated with the authors. Institutions such as University of Toronto and Aberden University emerge as key contributors, suggesting that their researchers are leading voices in this domain. This provides more insight into how organizational resources and academic environments may influence scholarly output. In terms of geographical distribution, the countries represented include Canada, the United Kingdom (UK), the United State

Table 2 Related survey on pipeline leakage detection

S/N	References	References covered	Primary focus of the survey	Taxonomy
1	Qurtobi et al. [93]	52	Review Acoustic method for detection of mechanical fault	Yes
2	Korlapati et al. [63]	88	Analysis of Pipeline leak detection	Yes
3	Mutiu et al. [82]		Achievements, strengths, and weaknesses of leakage detection techniques	Yes
4	Zaman et al. [128]	93	Review performance evaluation of leak detection technique	Yes
5	Al-Sabaeei et al. [8]	65	Systematic review of machine learning techniques	No
6	Ali and Choi [7]	62	Reviewed underground pipelines and sinkhole leak detection and monitoring methods	No
7	Ho et al. [43]	48	Review of subsea pipeline leak detection	No
8	Mehta and Karuvilla [79]	78	Reviewed on traditional and advanced detection techniques on pipeline	Yes
9	Yuan et al. [125]	54	Systematic analysis of bibliographic of pipeline leak detection	Yes
10	Hu et al. [46]	72	Systematically examined acoustic base leak detection technique	Yes
11	Soomro et al. [108]	61	Systematically reviewed on machine learning-based integrity assessment	No
12	Lukonge et al. [75]	51	Systematic review of AE techniques	No
13	Behari et al. [14]	67	Critical analysis and review of leak detection techniques	No
14	Feng et al. [35]	78	Systematic review of girth weld defects in pipelines	No
15	Iqbal et al. [49]	65	Review on maintenance policies of oil and gas pipeline	No
16	Parlak and Yavasaglu [89]	88	Comprehensive analysis of smart pig technique in petroleum and natural gas pipeline system	No
17	Carlson et al. [21]	89	Systematic overview of petroleum and natural gas pipeline system leakages and explosion	No
18	Liu et al. [72]	78	Systematic analysis of petroleum natural gas 4.0 era	NO
19	Aalirezaei et al. [1]	68	Bibiometric and comprehensive review of petroleum and natural gaspipeline system failures and consequences analysis	NO
20	Abdulshaheed et al. [2]	51	Review and analysis based on pressure technique	Yes
21	Columbo et al. [27]	75	Comprehensive review of transient based technique of leak detection	Yes
22	Onuoha et al. [85]	64	Systematic review based on implementation of 4.0 technology	No
23	Coramik and Ege [28]	54	Overview of leakage detection technique based on NDE and PIG	Yes
24	Lu et al. [74]	84	Review of leak detection on carbon dioxide pipeline	No
25	Wasin and Djukic [122]	63	Reviewed various potential measures of leakages based on corrosion of metal pipelines	Yes
26	Ghazali et al. [39]	68	Comprehensive review on pipeline leakages based on pressure transient methods	Yes
27	Sharma et al. [100]	42	Systematic review on cloud and IoT techniques of leak detection	No
28	Woldesellasse and Tespamariam [122]	75	Bibliometric review of onshore pipeline system	Yes
29	Kyew [65]	75	Comprehensive review of subsea pipeline leak detection technique	Yes
30	Wanasinghe et al. [121]	87	Systematic review on IoT techniques of leak detection in oil and gas industries	No

Table 3 Bibliometric analysis on pipeline leakage detection

S/N	Authors	No. of citation	Organization & country	No. of references	Name of journal
1	Qurtobi et al. [93]	12	Kaunas Lithonia	52	Sensor Journal
2	Korlapati et al. [63]	78	Texas, USA	88	Journal of Pipeline Science and Engineering
3	Mutiu et al. [82]	383	Aberden, Uk	204	Sensor Journal
4	Zaman et al. [128]	102	Kharaspur, Indian	93	Engineering Journal of Failure Analysis
5	Al-Sabaeei et al. [8]	10	Perak, Malaysia	119	Journal of Energy Report
6	Ali and Choi [7]	80	Saha-Gu, Korea	124	Journal of Sustainability
7	Ho et al. [33]	112	Texas, USA	227	Journal of structural health Monitoring
8	Mehta and Karuvilla [59]	–	Indian	66	Journal of Engineering Failure Analysis
9	Yuan et al. [100]	27	Beijing, China	164	Journal of Engineering Failure Analysis
10	Hu et al. [46]	84	Hong Kong Polytechnic University	104	Journal of Mechanical System and Signal Processing
11	Soomro et al. [108]	60	Universiti Technologi Perak Darul Ridzuan, Malaysia	113	Journal of Engineering Failure Analysis
12	Lukonge et al. [75]	31	Indian	77	Transition of Indian Institute
13	Behari et al. [14]	50	Netherland	107	Journal of Natural Gas Pipeline and Engineering
14	Feng et al. [35]	106	University of Petroleum, Beijing, China	113	Sensor Journal
15	Iqbal et al. [49]	76		95	Journal of Structure and Infrasture Engineering
16	Parlak and Yavasaglu [89]	13	Technical Universities, Istanbul, Turkey	225	Journal of Sustainability
17	Carlson et al. [21]	24	Baltimore, USA	88	Journal of Publik Medicine
18	Liu et al. [72]	188	Louisiana Technical University	120	Journal of Computer in Industries
19	Aalirezaei et al. [1]	11	University of Regina, Canada	54	Journal of Innovation and Infrastural Solution
20	Abdushaheed et al. [2]	115	University of Pultra, Malaysia	58	Journal of reneweble and Sustable Energy Reviews
21	Colombo et al. [27]	608	University of Toronto, Toronto	79	Journal of Hydro-Environment Reserch
22	Onuoha et al. [66]	3	Nnamdi Azikiwe University, Awka, Nigeria	53	Internationa Journal of Industrial and Production Engineering
23	Coramik and Ege [28]	110	Balikesir University, Turkey	53	Measurement Journal
24	Lu et al. [74]	104	Southwest Petroleum University, Chengdu, China	13	Journal of Cleaner Production
25	Wasin and Djukic [122]	221	University of Melbourne, Parkville, Autralia	132	Journal of Natural gas Science and Engineering
26	Sharma et al. [100]	3	Chaitanya Bharati Institutes Technology, Hyderabad, India	30	E3S Web of Conferences
27	Ghazali et al. [39]	157	University of Sheffield, UK	34	Journal of Mechanical System and Signal Processing
28	Woldesellasse and Tes-pamariam [123]	1	University of British Columbia,Kelowna, Canada	89	Journal of Infrastructure Intelligence
29	Kyew [48]	3	–	–	Collaborate Engineering Daily Book Series
30	Wanasinghe et al. [121]	79	Memorial University, New foundland, Canada	166	IEEE Internet of Things Journal

of America (USA) and China, demonstrating a global interest in this area of research. The presence of authors from various parts of the world suggests the research field broad appeal and relevance across different regions. Furthermore, Table 3 also provides a count to the number of references used by each author to help understand the depth of the literature review covered and engagement with existing research. Authors with higher reference counts such as Ho et al. [43] with 225 references may indicate a more comprehensive analysis where as those with few references might focus on novel contributions. Finally, the inclusion of the names of journals in which these reviews were published adds another layer of analysis. Most of the listed journals are prominently featured for their ability to publish quality and prestigious research.

3 Research methodology

This section outlines the steps taken to examine the extant literature on pipeline monitoring and leakage detection systems. These reviews also explained the selection of existing studies using set of exclusion and inclusion metrics.

3.1 Search criteria

Multiple databases were explored to acquire literature related to pipeline monitoring and leakage detection techniques. The queried articles were carefully scrutinized to identify primary techniques used aside from other techniques. This article adopted procedures to search across relevant academic databases, including ScienceDirect, Springer, Google scholar, Wiley online, Web of science, IEEE explore, ACM digital library, DBLP, Taylor and Francis, and Scopus as shown in Table 4 and Fig. 1.

Table 4 summarizes the database sources and the respective numbers of articles retrieved. Google scholar has 86 scores, Science Direct 94, Springer, 49, Willey Online Library 8, Web of Science 12, IEEE explore 38, ACM Digital Library 28, DBLP 48, Tailor and Francis 16 and Scopus 98.

3.2 Search terms (keywords)

The literature search strategy employed was based on the approach used by Kitchenham et al. [62]. Key search terms were identified and prioritized to determine the most relevant keywords for the search. The following keywords were used to conduct a comprehensive search of the academic literature in various databases: "pipeline", leakage detection", "pipeline + leakage detection", "pipeline leakage + monitoring".

3.3 Selection and rejection criteria

To ensure a precise and targeted approach to the article subject matter, this study utilized various principles of inclusion/exclusion criteria as enumerated in Table 5; articles that review pipeline leakage detection and monitoring, articles that developed pipeline leakage detection and monitoring technique, articles that are in English languages and articles that are peer reviewed as shown in Table 5.

Table 4 Database sources

S/N	Sources	Uniform resources locator	Total articles
1	Google Scholar	http://scholar.google.com/	86
2	Science Direct	http://www.sciencedirect.com/	94
3	Springer	http://www.springer.com/	49
4	Wiley Online Library	http://onlinelibrary.wiley.com/	8
5	Web of Science	http://webofknowledge.com/	12
6	*IEEE explore*	http://ieeexplre.ieee.org	38
7	ACM Digital Library	http://dl.acm.org/	28
8	DBLP	http://dblp.org	48
9	Taylor and Francis	https://taylorandfrancis.com/	16
10	Scopus	http://www.scopus.com	98
Total			477

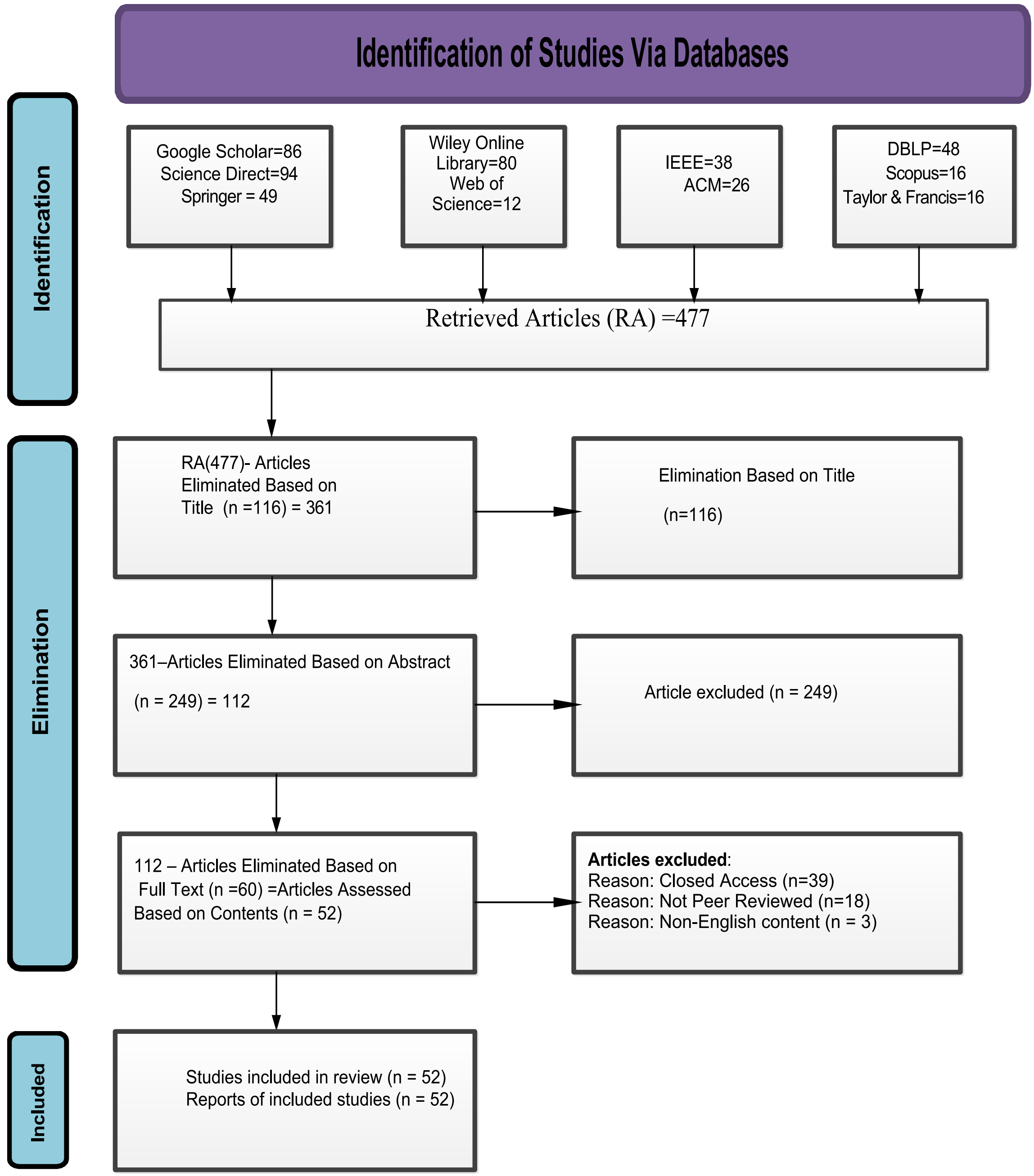


Fig. 1 Literature search processes

3.4 Data collection

The reviewed articles were relevant and consistent with the reality of growing impacts of pipeline leakage detection vis-a-vis human, economic, and environmental point of view. The increase in pipeline leakages and vandalism has led to huge losses across the world and sort of nightmares for oil gas industries stakeholders. The causes of pipeline leakages include terrestrial disruption such as earthquake, landslides, climatic effects leading to corrosion and arson.

Table 5 Selection and rejection criteria

S/N	Selection criteria	Rejection criteria
1	The research concentrates on the detection and monitoring of leaks in petroleum and natural gas pipelines	The study did not focus on water or other liquid transportation leakage detection and monitoring
2	The articles were either research papers or peer- reviewed journals	The study did not focus on articles that are neither research papers nor peer reviewed journal
3	The articles were published in reputable conference papers and journals	The study excluded articles in journals and conferences which were not considered reputable
4	The articles were written in English Languages	The articles that were written in language other than English

3.5 Study selection and filtration

The study reviewed articles beginning with key term definitions relevant to pipeline monitoring and leakage detection utilizing the relevant search terms aforementioned in Sect. 3.2 which facilitates to filtering articles that are not aligned to the study under consideration. This article focuses on research work and surveys whose subject matters are relevant to monitoring and detection of leaks in petroleum and natural gas pipelines, presented in the English language. The selection and filtration criteria utilized are illustrated in Fig. 1 and the percentage of articles counted per journal database is illustrated in Fig. 2. The entire review processes were conducted with no hitches as articles were selected and pruned based on titles from 477 to 361, 361 selections were screened and elimination were made based on abstracts from 361 to 112 and 112 were screened based on contents and directions of research for final evaluation to 52 articles as shown in Fig. 1.

4 Taxonomy of pipeline monitoring and leak detection

The taxonomy of pipeline monitoring and leakage detection techniques discussed in this review is summarized in Figs. 3, 4 and 5. The taxonomy categorizes the techniques into three primary categories; these are based on internal, external and visual inspection methods. The external method is divided into acoustic emission, fibre optic, vapour sampling, infrared thermography, ground penetration radar, fluorescence and capacitive sensing techniques. The visual inspection method is divided into robotics drones such as Autonomous Underwater Vehicle (AUV), and train dog or human. The internal method is divided into mass volume, negative pressure and pressure point.

4.1 Synthesis of external-based leakage detection techniques

The Non-Destructive Testing (NDT) also known as external-based leak detection method evaluates the internal flaw condition of the pipeline without causing or interfering with the permanent integrity of the pipeline and the suitability of the service by utilizing an automated man-made sensing device placed along a pipeline to monitor the external part of the pipeline [82]. This is achieved by determining the abnormalities in the pipeline surroundings and detecting leakages. Irrespective of the principles and approaches of the NDT sensing devices, they require physical contact between the pipes and a sensors.

Fig. 2 Articles count per journal database

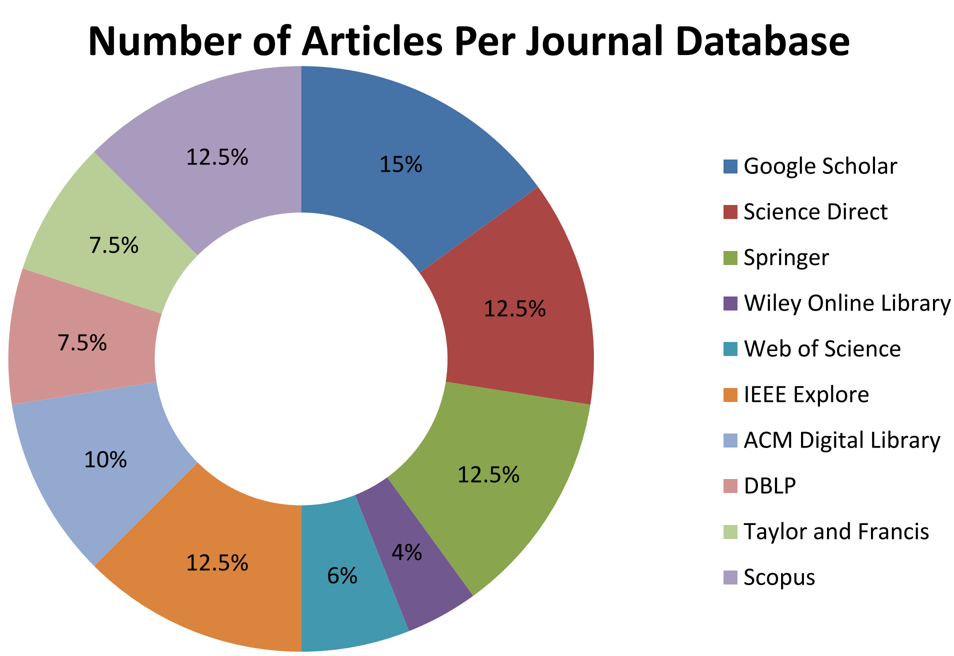
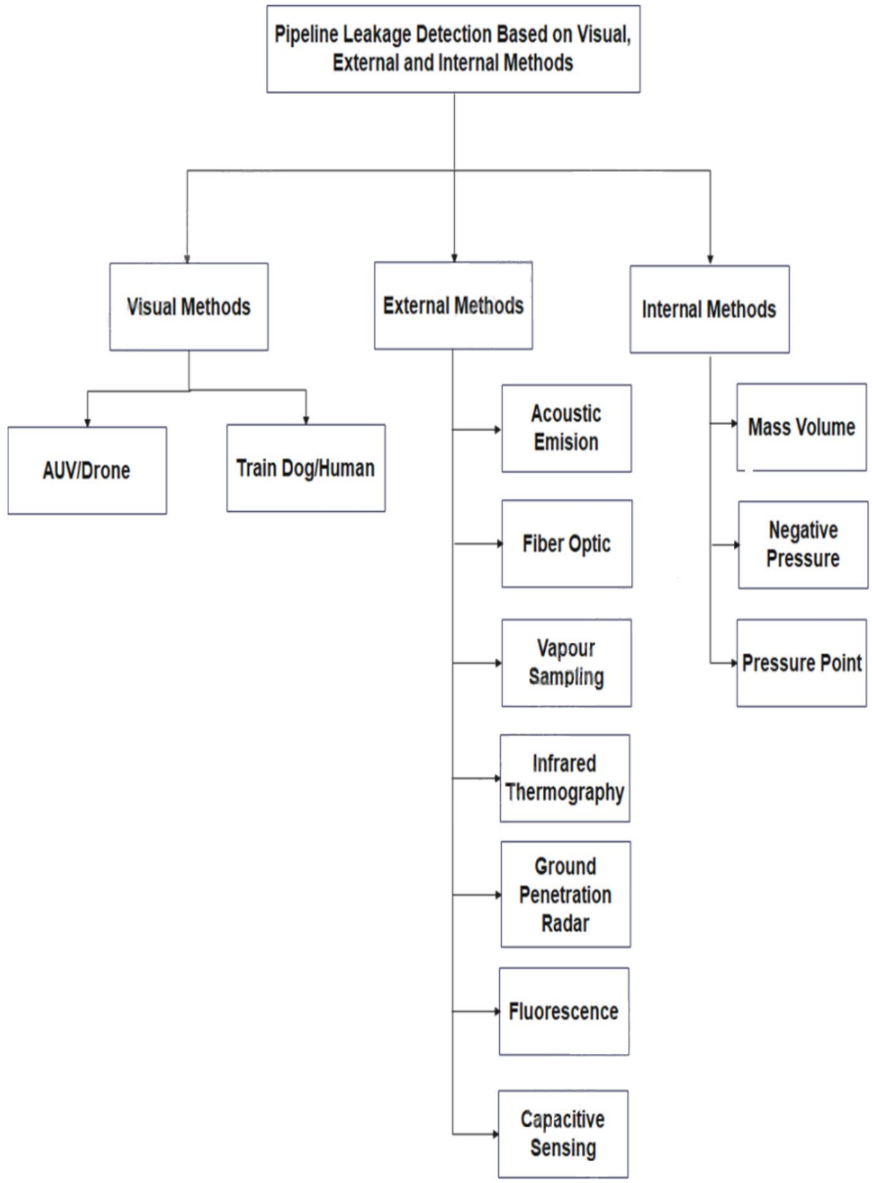


Fig. 3 Taxonomy of pipeline leakage detection -base on internal, external and visual inspection technique



The Acoustic Emission (AE) technique is one of NDTs most promising passive leakage detection methods; other techniques of the NDT include magnetic, ultrasonic, vapour sampling, fibre optic, ground penetration radar and infrared thermography techniques.

4.1.1 Acoustic emission technique

The AE is the most efficient, effective and promising NDT method in leakage detection and monitoring than the magnetic, ultrasonic, vapour sampling, fibre optic, ground penetration radar and infrared thermography techniques [82].

The AE technique uses AE sensors that have capability to:

I. Record acoustic event in real time, at the moment of initiation.
II. Monitor acoustic event in real time
III. Acquire analogue signals, convert them into digital signals and forward it to the Data Acquisition Centre (DAC)
IV. Perform automated and efficient service
V. Maintain the integrity or permanent properties of the pipeline during and after leakage detection and monitoring.
VI. Connect to wireless protocols and

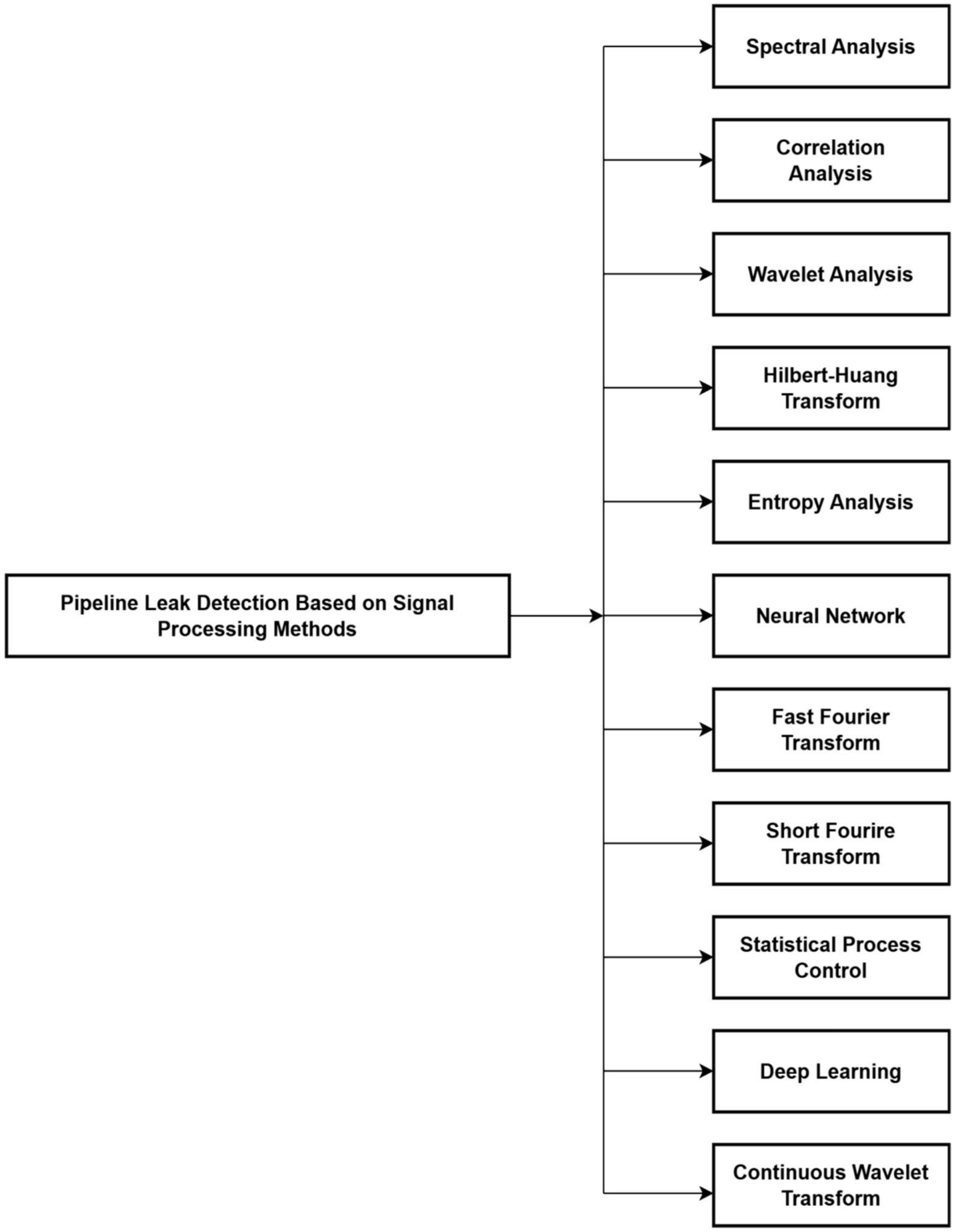


Fig. 4 Pipeline leak detection based on DSP techniques

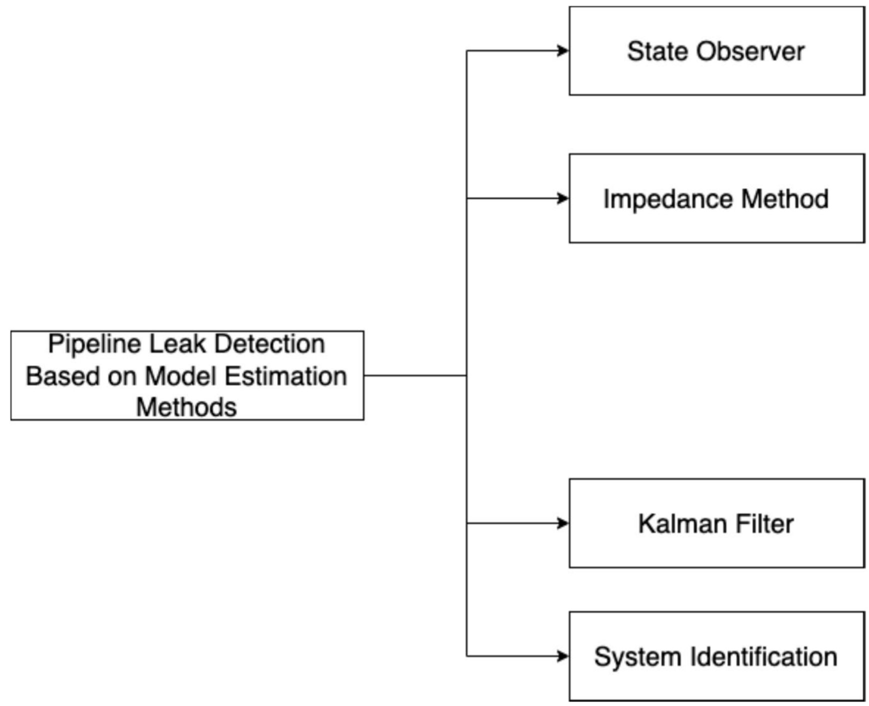
VII. Integrate with wireless devices

When leak occurs, it generates an intrinsic leak signal by the fluid escaping at a very high pressure at the perforated point, which can be sensed by the Acoustic Emission (AE) sensor to determine the presence of leakage using the information in the elastic wave signal from the leak source. The AE sensor converts the sound generated from the leak into a digital signal, which is then transmitted to the Data Acquisition Centre (DAC) for processing. To achieve the desired system to justify the objectives of this research, this study re-examined the characteristics of two types of AE sensors; the active AE and the passive AE sensor [60]

The Active AE (AAE) Sensor emits sound signals into the environment and receives the reflection or echoes of the signal for further analysis. The AAE directly interacts with the source of the signal being emitted for further classification.

Passive AE (PAE) Sensors detect and analyze sound signals without emitting any signal to the environment but convert the analogue signals received record and transmit to data acquisition centre for further processing [60]. PAE

Fig. 5 Pipeline leak detection based on model estimation techniques



relies on reception of signals in real time from sources, and has the capability to detect, locate and monitor sounds without interfering with the natural acoustic environment [60]

When leak occurs in a pipeline, it generates intrinsic leak signal by the fluid escaping at a very high pressure at the perforated point which can be detected by the PAE sensor to determine the presence of leakage using. The PAE sensor then employ the sound generated from the leak and converts it into digital signal for onward transmission to the Data Acquisition Centre (DAC) for further processing. The PAE also have the ability to maintain the integrity or permanent properties of a pipeline during and after leakage detection and monitoring without causing any permanent damage to the pipeline [60]. Table 6 highlights the key differences between active and passive acoustic emission with the AAE is relying on artificial induction and the PAE leveraging natural occurrences of signals. technique.

Table 6 highlights the key differences between Active Acoustic Emission (AAE) and Passive Acoustic Emission (PAE) with the AAE is relying on artificial induction and the PAE leverages natural occurrences of signals. The fundamental distinction impacts the application, signal analysis and sensibility requirements of each technique.

There are literatures on pipeline leakage detection and monitoring using the principle and working approaches of AE techniques. The AE technique in pipeline leakage detection, localization and monitoring has been reported in several literatures; Li et al. [69] presented a research-based investigation for detecting and monitoring leaks in a pipeline that was subject to failure of the socket joint using pattern recognition and AE technology to investigate pipeline leakage experimentally. The study found that the dominant frequency of environmental acoustic signals is concentrated at 0–10 kHz in range and the dominant frequency of environmental noise is less than 2 kHz. A set of agents were trained using Artificial Neural Network (ANN) to obtain a highly accurate estimate of 96.9%, which indicates that an AE based technique can exhibit high sensitivity across extended distance. However, enhanced sensitivity such as amplification of the pressure is required to increase the leak noise. Ai et al. [6] devised combination of Linear Prediction Cepstrum Coefficient (LPCC) with Hidden Markov Model (HMM) to examine deteriorated acoustic signals. The LPCC denotes a short-term AE pulse and was utilized for the parameter of the signal attributes where as the HMM was adopted for identification of corrupted signals. The results obtained revealed a significant improvement of the acoustic signal with a value rate of up to 97%.

Jia et al. [55] carried out a pipeline leakage detection experiment with a network of sensors strategically placed at various points along 3.3 km length of the pipeline. The experiment was conducted by measuring real-time acoustic wave monitoring along the gas pipeline using a set of sensors and it was found that AE emitted as a result of leakages from the damaged points to different sections of the pipeline corresponding to the velocity of gas flow. As a result of this, the AE signal with high-frequency components exhibits rapid attenuation, where as the low-frequency components decay

Table 6 Comparison between active acoustic emission and passive acoustic emission

S/N		Active acoustic emission	Passive acoustic emission
1	Sound Source	Artificially generated sound waves	Natural sound emissions from the pipeline
2	Purpose	Detect and locate leaks in real-time	Detect, locate leaks real time and continuous monitoring
3	Detection Capability	Can detect leaks even in noisy environments	Relies on identifying distinct acoustic signatures emitted by the leakage
4	Sensitivity to Leak Size	Relatively lower sensitivity to small leaks	High sensitivity to small leaks
5	Leak Detection Speed	Real-time detection and immediate results	Real time detection, immediate results and continuous monitoring
6	Required Pipeline Shutdown	Shutdown not required during detection	Shutdown not required during detection
7	Cost	Equipment costs can be relatively high	Equipment costs can be relatively low
8	Suitability to Length of Pipeline	Not suitable for long-distance pipelines	Applicable to both short and long-distance pipelines network

more slowly. The authors found that low-frequency signals are adequate for detecting leaks in gas pipelines. The effect of background noise was noted as it readily obscures the AE signal.

Ozevin and Yalcinkaya [87] developed a gas leakage detection and monitoring system in a gas pipeline using AE technique. The system works perfectly provided the escape liquid passes through the defect part of the pipeline and the AE signal flow through the pipeline, which in turn is detected by the AE sensor attached along the pipeline. This technique has the advantage of detecting leak accurately in real time; however external sources such as background noise affect the signal and cannot be applicable to a network of pipeline covering long distance. Scott and Barrufet [107] applied an acoustic emission technique for detection and localization of leakage in gas pipeline networks. The system detects early leaks, estimates leak size and localization. However, the effect of background noise was noted as it easily masks the actual sound of leakage.

Ullah et al. [113] developed a leak detection and monitoring system using AE acoustic and machine learning algorithm. The study was carried out by extracting certain statistical parameters like skewness, mean square, root mean square, standard deviation, peak value, frequency spectrum attributes and entropy obtained from acoustic emission signals as a set feature in training the machine learning model. The authors further utilized adaptive threshold sliding window to preserve both the burst emission and continuous characteristics of the AE signal. Three AE sensor datasets were collected for the experiments; the authors also extracted 14 frequency domain and 11-time domain features for each of the sensor categories which were further transformed into features vectors for the purpose of training and evaluating the machine learning-based monitoring and leak detection model of various pin-size holes. The proposed system found that the system provides effective and reliable leak detection with 99% classification accuracy. However, the model can not simultaneously predict the leak status of the transportation medium and pressure.

Nawal et al. [83] developed a pipeline leakage detection system that uses a passive AE technique. The authors investigated different flow rates of leakages in pipelines using passive AE techniques and metrics attributed to rise time, count, frequency, threshold, duration, amplitude and AE count by localizing or identifying the damage. The authors found that the AE features could be utilized in the localization of leakages in the pipelines and could distinguish between minor and major leakage by qualitatively assessing the leak velocity. The results are constrained to a short section of pipeline under controlled laboratory settings and are applicable to single leak only. Additional research is therefore required to establish whether these findings can be applied for real-world service on prototype pipeline network systems.

Quy and Kim [94] combined features derived from AE signals and K-NN classifier for monitoring and detecting pipeline leakages. The authors embedded a set of leak detection algorithms in a microcontroller unit for real-time leakage detection in the pipelines. The embedded system continuously receives signals from sensors mounted on the surface of gas pipelines. To determine the accuracy of the developed system, the authors adopt a trained K-NN classifier with normalized features derived from the AE signals.

Thang et al. [112] segmented AE signals into overlapping frames of fix length using a Hanning window function with a 50% overlap ratio. Intermediate AE parameters that embody the signal characteristics of leaks with their complete properties were obtained and calculated. A k-nearest neighbor was trained from the extracted features of the signal to detect pipeline leakage. The process was repeated experimentally in various laboratory conditions to measure the accuracy of the proposed technique and it was found that the proposed technique offers enhanced reliability and accuracy as an alternative to intrinsic features extracted directly to train the k-nearest neighbor classifier. Only a few training data are required to train the classifier compared to the other techniques that requires much data. In addition, data transformation is more robust and reliable.

Claudiu-Ionel et al. [25] developed a pipeline leakage identification system using cross-correlation location-based principles, a cross-correlation method, a data acquisition system and AE sensors. Although the developed system works accurately, however, there are needs for further research to expand the system to a sensor array wireless network for detection of leak in sections of intertwine pipelines.

Rai et al. [95] proposed a pipeline leakage detection technique based on Kolmogorov–Smirnov Test (KST) and AE event features to solve the drawback of ineffective mean value, Root Mean Square (RMS), standard deviation, entropy and peak value features. The authors first extracted AE event features from the AE signal and used an adaptive threshold sliding window to retain the characteristics of continuous type emission and bursts. The authors further utilized Two Sample Kolmogorov–Smirnov Test (TSKST) to distinguish between the datasets obtained through comparison with their Empirical Cumulative Distribution Functions (ECDFs), as adopted by Wang and Makis [116]. The hypothesis of the TSKST states that if two datasets samples share the same ECDFs; it implies that they originate from same population else they fall into separate population.

Ahmad et al. [4] developed leakage detection method by acquiring an acoustic image over time of an AE signal applying continuous wavelet to visualize time–frequency scales of an AE signal as an image. The generated images were then used as an input data for a convolutional neural network and convolutional autoencoder for further processing.

Hou et al. [45] proposed to address the drawback of single leak detection in valves by improving the existing MUSIC algorithm to accurately detect multiple leakages in safety valves. To de-noise the traditional MUSIC algorithm, the authors adopted the principles and approach of Yoo and Owhadi [125]. The authors further utilized windowed Fast Fourier Transform (FFT) with frequency division to extract narrow band signals. Results obtained shows that when pressure was 0.80, 0.75 and 0.70 mpa, the relative error is within 3.5%. Although the proposed method could detect multiple leakages with 96.5% accuracy, it is however limited to safety valve as no experiment has been carried out on pipelines using same principles, approach and parameters.

Gao et al. [38] proposed a hybrid AE technique for detecting of leakages in pipelines. The authors utilize minimal entropy deconvolution techniques that leverages the maximization of kurtosis of the AE signal to effectively de-noise and extract significant features from the desired signals for further processing. To denoise the source signal, the authors first utilize Minimum Entropy Deconvolution (MED) to extract periodic signals from the multiple source data. The authors also extracted significant energy information using damping frequency energy and further utilized the Minimum Entropy Deconvolution (MED) to apply frequency filtering and damping to de-noise the acoustic wave noise with the aim of accurately locating leakages in pipelines. It was observed that the proposed system provides efficient accuracy than the conventional Generalize Cross Correlation (GCC) and EMD-GCC methods. Due to internal flaws in the pipelines, additional parameters and additional experiments are required to obtain accurate leak localization in pipelines.

4.1.2 Fibre optic leak detection technique

The fibre optic leak detection technique entails the placement of fibre-optic sensors parallel to a pipeline. The sensors can be installed at point-to-point or in a distributed fashion to extensively detect changes in chemical or physical properties along the pipelines. One of the operational principles of fibre optic technique of leak detection is the change in the cable temperature when leakage occurs along the pipeline as a result of oil or gas fluid engrossing into the coated cable. The variations in the temperature of the fibre optic cable determine the presence or absence of leak along the pipeline [24].

Walker [115] proposed a leak detection technique that employs Distributed Temperature Sensing (DTS) technology to detect leakage in a buried anhydrous gaseous ammonia pipeline. It was observed that the accuracy of the developed system increased over time. When the pressure of the leakage increases, the temperature to decreases. The use of Brillouin fibre optic approach was proposed by Tennyson et al. [110] to monitor the strain measurement resulting in any external anomaly in pipelines. Wang et al. [118] proposed a differential temperature sensor based on fibre optic leakage detection with an accurate level of sensitivity of 0.0005 C. The authors also asserted that the distributed differential temperature sensor sensitivity of the study is higher in magnitude than that of Brillouin and Raman-based sensors.

Zhang [129] proposed a Fibre Bragg Grading (FBG) sensor to overcome the drawback of uncertainty in interferometric fibre optic sensor phase measurements to improve the accuracy and sensitivity of positioning the FBG based fibre sensor by increasing the strain response sensitivity. Wang et al. [119] proposed a pipeline leak localization and detection technique integrated with compressed sensing theory and FBG pipe-fixture sensor array to determine the accurate leak point in a pipeline without estimating the differences in time of arrival with a minimal number of sensors, with standard localization accuracy and stability.

Pavol et al. [90] proposed Distributed Acoustic Sensing (DAS) for detecting small leaks that is less than 1% in a gas pipeline by wrapping ta fibre sensor parallel to the pipeline to increase the accuracy of detecting a leak in the pipeline system. The DAS technique facilitates measurements, interpretation and analysis of the recorded signal. The findings reveal that the DAS technique which was helically wrapped directly around the pipeline was effective in detecting signals from the intrinsic vibration of the pipeline. The authors also found that the proposed system could detect small leak rates with less than 0.1% emitted from the artificial perforated leak hole but the experiment was only applicable to short and medium length of pipelines.

Shangran, et al. [103] proposed a coupling and multi-physics propagation process with Fibre Under Test (FUT) across soil layers using fibre optic principle and approach. The results show that the principle of the fibre optic method of leakage is dependent on soil type. It was also discovered that soil with higher viscous resistance tends to be highly favourable than soil with lower viscous resistance; hence the installation of the method over a long-distance pipeline network is directly dependent on the type of soil.

The advantage of using fibre optic technique is its ability to detect small leaks and its potentials in monitoring pipelines over a long distance coupled with capabilities to function both at surface pipeline networks at subsea level. However, a drawback is its inability to estimate the number of leakages; the technique has shorter life spam. The fibre optic method of leakage detection is very sensitive and must be setup adjacent to the pipe. In addition, the installation of fibre optic cable along a pipeline network over long distance is challenging and expensive. There is also a lack of sensor redundancy; if one part of the cable fails or deteriorates, the whole system stops functioning. Also, fibre optic cables are generally known to be fragile [110].

4.1.3 Vapour sampling technique

Vapour Sampling Technique (VST) is mostly applicable to determine the discharge of gas in pipelines and storage tanks into the surrounding environment along the pipeline by using a pressure-reliant tube containing air at atmospheric conditions. Leakage is detected by measuring the concentration of gas with respect to the pumping time. The VST technique uses a gas sensor and a pressure dependent tube. When leaks occur, vapour diffused into the tube to indicate the presence of leakage. Golmohamad [40] asserted that the oil spillage can be detected by assessing the level gas concentration in relation to the pumping time and the rate of absorption. If a leak occurs in a pipeline system, the vaporized gas diffuses into the tube chamber due to the gradient of its concentration for a certain period at the end of which it generates signal indicating the presence of gas concentration in the surrounding. In the VST, the leakage rate was directly proportional to the surrounding gas concentration.

Cosham and Hopkins [29] proposed a gas-permeable cylinder-based sniffer tube for detecting leakage in pipeline systems. It was observed that gas diffused into the sniffer tube, indicating leakages in the pipeline and surrounding. The benefits of using vapour sampling include its ability to detect small leaks in pipelines, independent pressure or flow balance and the ability to detect multiple leakages. However, a major drawback to vapour sampling is the response time, which takes several days before reporting leakages and has limited effectiveness for subsea pipelines.

4.1.4 Infrared thermography technique

The Infrared Thermography Technique (ITT) employs infrared imaging technology that uses thermographic means to determine the temperature change in a pipeline environment with the aid of infrared camera which displays infrared spanning 900–1400 nm [77]. The image captured by an infrared thermography camera is called a thermogram [82]. The thermal camera is one of the most effective devices for capturing objects with varying shapes from any angle made of distinct properties. The captured object can be analyzed to identify pipeline anomalies and, in their environments, using the change in temperature by analyzing the cooler and warmer areas, displaying the results in the form of thermal images with different color signifying the presence of leakages in the pipeline and the surrounding environment.

Unlike other technique like thermocouples and Resistant Temperature Detectors (RTDs) used in measuring temperature changes, ITT is one of the most non-contact and non-intrusive pipeline conditions detection and monitoring techniques, which has gained widespread acceptance for its real-time temperature monitoring capabilities and continuous distributed temperature measurements across a region [102]. ITT enables remote temperature mapping of an object, which presents results in visual format, signifying the accuracy of the measured data with specific colours in the areas of interest (region). The common indication of gas discharge from the pipeline is the change in temperature in the ITT and the gas leaks usually caused abnormal temperature to the pipeline, and its environment. The use of ITT for pipeline leakage detection and monitoring gains widespread acceptance due to its real-time and contactless temperature measurement capability [11].

The ITT has undergone significant improvements over the past few decades. The principles and approaches of ITT have been widely applied to pipeline leakage detection and monitoring (Flores-Bolarin and Royo-Pastor, [36]; Jadin and Ghazali, [50]). Kroll et al., [64]; Manekiya and Arulmozhivarman [77]) proposed a method of detecting gas at high pressure using passive ITT to differentiate different abnormalities in gas pipelines. The authors utilized fundamental image segmentation methods to differentiate between the target area and defect section in thermal images. The result shows that the condition of clogging piping, cavitation erosion and metal-steel reservoir, such as leakages can be detected using an infrared camera. Jadin and Ghazali [50] proposed a technique for detecting gas leakages in the pipeline using thermal imaging by inspecting the surrounding area of the pipeline with the aid of an infrared camera and filtering processes to enhance the target areas of interest. The authors extracted suitable features from the captured segmented thermal images to identify the rupture parts of the pipelines. The results demonstrate the significance of ITT in distinguishing between abnormal and normal conditions for gas pipelines.

[48] analyzed and evaluated two contactless techniques for quantifying compressed air leaks using ultrasound and infrared thermography. The authors analyzed the accuracy and reliability of the results. It was observed that thermography offered better results for leakage quantification when orifices (an opening in pipeline) are greater than 1.0 mm and could only be applied to small leaks. The study also found that ultrasound can detect all leaks with respect to the dimension of orifices.

Cadelano et al. [20] proposed a system detecting corrosion in pipelines using ITT. The authors applied infrared thermography to a sectioforn of the pipeline under laboratory conditions while the liquid was heated to approximately 90 degrees through the pipeline to analyse the thermal effect of the pipeline due to the presence of water. The principle is applicable under laboratory condition.

Furthermore, ITT offers the advantage of efficient scanning, detecting, acquiring and transmission of object inform of image to display unit for further analysis in fast response time (Meola et al. [80]; Jadin and Taib [51]). ITT is easy to use and can be operated by not necessarily experience or trained personnel. ITT also has the capability to detect and transmit scanned objects within a short period of time [51]. Despite the benefits and wide spread acceptance of ITT, its application is very challenging due to the exorbitant cost of a high-resolution infrared cameras. Furthermore, measuring leak orifices less than 1.0 mm using ITT is challenging. Several authors have attempted to resolve the aforementioned drawback of ITT; the combination of ITT and ultrasound quantification mechanism to quantify leak orifices lesser than 1.0 mm was proposed by Dudic et al. [33]. The authors found that ITT can quantify pipeline orifices larger than 1 mm and ultrasound can quantify orifices of all dimensions. Similarly, Adefila et al. [3] combined platinum-resistant temperature detectors and thermograms using a flow rig with an internal diameter of 50 mm for experiments with the aim of determining accurate spot temperature measurements. A Numerical computation was used to calculate the volume rate of leakage.

4.1.5 Ground penetration radar

Ground Penetration Radar (GPR) is an environmental tool used for identifying and detecting structures such as buried pipelines [82]. The GPR is a non-intrusive high-precision technique which uses electromagnetic scattering and wave propagation technique to detect changes in the electrical and magnetic properties of soil surrounding the pipeline, allowing for the identification of potential anomalies or defects in the underground pipelines. The GPR is very accurate and has the ability of providing detailed information about the subsurface object [82].

Sevket et al. [101] formulated a back-projection algorithm for ground-penetration radar leak detection. The authors measured the medium at various instants and reconstructed the B-scan images and then assessed the signature of the leak region using the direct interpretation and change in the procedure, and it was found that GPR has the capability to detect leaks accurately but the signals can be distorted in clay soil.

Moreover, GPR can detect leakages before getting to advance stage. GPR is suitable to various types of pipeline system for the detection of leakages because it has shown great capability in both metal and non-metal pipelines [133]. The signals in GPR can be corrupted by environmental noise and it is not applicable to pipeline networks covering a long distance, in addition, it cannot be applied in a clay soil environment.

4.1.6 Fluorescence method

The fluorescence method employed a light source of a certain wavelength for excitation molecules in a target substance of higher energy level to detect leakages in the pipeline. Leakage detection relies on the correlation between light emission rates and gas emission quantities at various wavelengths [53]. The fluorescence method has the capability of detecting leakages in respective of the direction of the tidal flow. Furthermore, for optimal performance, the visibility of the pipeline must be high to achieve an accurate response and the medium must be naturally fluorescent before it can be detected.

4.1.7 Capacitive sensor method

The Capacitive Sensor Method (CSM) is employed to cover the local coverage in subsea pipelines. The CSM utilizes dielectric constant variations spanning across gas and sea water to identify the presence of gas that causes the disparity between them. The sensitivity of the sensor to leakage size is subject to the length or distance of the drift medium and leak position [30]. Although capacitive sensor relatively works better in capacitive sensing, there are however, several false alarm reporting and it requires physical contact with the pipeline medium [82].

4.2 Synthesis of internal-based leakage detection techniques

The internal method known as computational method is the use of fluid measurements tools to monitor variations of some parameters associated with the level of fluid flow rate in a pipeline. The computational method is used for continuous monitoring of the status of petroleum and natural gas in the pipeline systems. The following are the various types of internal-based leakage detections methods:

4.2.1 Mass-volume balance

The Mass-Volume Balance (MVB) utilizes the concept of mass conservation operation. The principle asserts that liquid that flows to a section of a pipeline remains inside the pipe except if it exits the section of the pipeline [82]. The assumption is that the outflow measured and the inflow at the both ends section of the pipeline must be balanced. The variation in the measured volume flows measured at end of the pipeline indicates present of leakage. Arnold [10] presented the basic theory, prerequisites and techniques of an online pipeline leakage detection system using mass volume balance.

4.2.2 Negative pressure wave technique

In the negative pressure wave technique, when leakage occurs, the change in pressure and the flow speed of oil and gas decrease which result in sudden pressure change and deviation in speed along the pipeline. The sudden drop in pressure creates a negative pressure pulse at the point of leakage which travels as a wave at a specific velocity towards both the downstream and upstream ends of the pipeline. The pressure pulse containing information on the leak can be computed via signal analysis and visual inspection to ascertain localization of leakage by analysing the time difference in which the pressure waves arrive the end of the pipeline [98].

Delgado et al. [31] proposed a scheme for diagnosing multiple leaks by employing an extended Kalma filter and modelling strategy which utilized nonlinear modelling derived from water hammer equation. To identify multiple leakages, the authors design a state estimator to estimate the position and magnitude of every leak. Boxiang et al. [18] applied negative pressure wave mode decomposition using variational methods to detect leakage in the pipeline. The authors used permutation entropy and correlation coefficient for effective intrinsic mode function for parameters optimization and component selection. The authors found that the system can effectively conserve mutating characteristics of leakage and the system can suppress noise interference.

Lin et al. [73] proposed a reverse pressure signal using the principles of cross-correlation time delay, estimation algorithm and theoretical analysis. The leak localization of the signal indicating the negative pressure and the time delay estimation were monitored by a sensor. The authors found that using a negative pressure wave yielded high leakage detection accuracy.

Olubukola et al. [85] formulated a first order differential equation that when employ could accurately detect leakages in a pipeline. The authors utilize kinetic energy model and turbulent kinetic energy transport equation and found that pressure measurement is highly sensitive for the detection of leakages than velocity measurement.

Liu et al. [71] developed model for locating and detecting gas leaks using dynamic pressure wave amplitude attenuation. The authors evaluated the developed model with the conventional method with respect to the time difference and signal velocity as measured by the wave pattern of the downstream and upstream signals. Furthermore, the study concludes that the impact of gas flow effects cannot be disregarded by both approach and the developed model can be utilized for gas monitoring in pipelines.

Khalid et al. [58] used the concept of negative pressure technique to monitor and detect leakage by employing a typical setup of materials comprising two pairs of sensors, with one pair installed at one end and the other pair installed at the other end. Leakages were identified and quantified by detecting the negative waterfront associated with the pressure wave generated by the leak event. The authors found that the developed technique could identify and localize leaks in a timely manner. The pros of this technique are overall low cost, while the cons are its resistance due to moving contact, sensitivity to vibration and its high hysteresis.

4.2.3 Pressure point analysis technique

This leakage detection technique utilizes the concept of Pressure Point Analysis (PPA) in detecting leaks in the pipeline and relies on the statistical analysis of pressure measurements taken at various locations along the pipeline. To determine the presence of leakage, the measured value is compared with statistical pattern of pre-existing measurement [15]. The presence of leakage is indicated whenever the statistical pressure of received data is below the predetermine threshold [82]. The pressure points analysis exhibits exceptional speed in detecting leaks in pipeline, immediate drop in pressure indicates the existence of a leak [9]. In addition to that, the PPA method works in cold climate, deep sea and sufficiently functions under different water flow conditions. The PPA also has advantage of detecting small leak and it has low cost of implementation. However, it is difficult to determine the localization of leakage using PPA method [120].

4.3 Pipeline leakage detection based on digital signal processing techniques

Digital Signal Processing (DSP) processes signals collected from sensors in pipelines to detect anomalies, such as leaks. This is achieved by measuring in flow rate or pressure, pre-processed signal, extracted features, extracted patterns and pipeline vibration to detect leaks in the pipeline system [57]. The working principles and approach in digital signal processing for pipeline leak detection typically involve five steps; these are:

I. Initialization of the sensors to measure the source signal from the pipeline and acquisition of data.
II. Pre-processing of the acquired data to remove ambient noise.
III. Extraction of relevant features using statistical, spectral and various signal transformation techniques to evaluate the state of the transported fluid in the pipeline.
IV. The extracted features pattern is compared with verified initial signal values for analysis.
V. Leakage is detected by comparing the pattern to a predetermined threshold.

Various principles and approaches of signal processing have been applied in the pipeline leakage detection and monitoring field of study. The existing approaches comprise cross-correlation [37], impedance method [66], Haar wavelet transform [91] and wavelet transform [81] as shown in Fig. 4. [68] proposed spectral-based analysis for pipeline leakage detection using the Filter Diagonalisation Method (FDM) with the aim of utilizing FDM to improve the limitation of FFT correcting error in constrained pipeline networks. Santos_Ruiz et al. [99] developed an online leakage detection system which diagnoses the condition of pipelines for leakage using an Extended Kalman Filter (EKF) and Steady State Mixed Approach (SSMA). The authors evaluated the efficiency of the proposed online leakage detection system using localization and measurement of non-simultaneous leaks at various positions in pipelines. The findings show that the method could efficiently detect and locate leakages with an average accuracy of 99% and a maximum error margin of 3% for localization of leaks.

Shibata et al. [104] proposed a leak detection system with Fourier Fast Transform. The system demonstrated the ability to identify and report leakage in the pipeline by analyzing the data obtained at certain points of leakage. The discrimination and classification of the acquired data rely on the extracted signal pattern. DSP is easy to implement as a pipeline leakage detection technique using sophisticated algorithms. However, DSP has problems of attenuation, and contamination by noise and requires several sensors to cover the network of pipeline. Figure 4 shows classification of pipeline leak detection based on DSP methods.

4.3.1 Spectral analysis response technique

The Spectral Analysis Response (SAP) technique for pipeline leakage detection and monitoring utilizes the spectrum of frequency and related quantities, such as eigenvalues and energies, to estimate the strength of various frequency components of time-domain signals [67]. The spectral analysis response is generally based on mathematical tools like the Fast Fourier Transform (FFT). The FFT is one of the most widely used methods for converting time-domain signals into frequency domains [19]. In the case of leaks in pipelines, the Fourier Transform (FT) works by identifying specific signals associated with leak pressure fluctuations or vibrations. A detailed discussion of the spectral analysis response technique can be found in [109] and [117].

4.3.2 Correlation analysis technique

Correlation analysis is an effective technique for localizing and detecting leaks in pipelines by analyzing the acoustic signals generated by leaks. When a leak occurs in a pipeline, it generates an intrinsic signal that travels along the pipeline and surrounding medium, detectable with the aid of sensors. A detailed description of correlation analysis can be found in [12, 13], and [59].

4.3.3 Wavelet analysis

The wavelet analysis technique for monitoring and detecting leaks in pipelines utilizes mathematical concepts to analyze and decompose signals into distinct frequency components, allowing for the extraction of patterns and features in signals. This technique can examine signals undetectable by conventional digital signal processing techniques [32]. For an in-depth overview of wavelet analysis, refer to [81] and [98].

4.3.4 Hilbert-Huang transform

The Hilbert-Huang Transform (HHT) is a frequency technique for analyzing signals in both frequency and time domains, operating by combining the Hilbert Transform (HT) and the Empirical Mode Decomposition (EMD). The HHT is specifically useful in analyzing non-stationary and non-linear signals [44]. An extensive discussion of HHT is available in [44].

4.3.5 Entropy analysis

The Entropy Analysis (EA) technique is suitable for measuring uncertainty or complexity of signals to identify changes in patterns and ascertain if there is a leak in the pipeline [47]. EA works by collecting signals from sensor arrays, filtering acquired signals, normalizing signals, calculating entropy, and detecting leaks. Some merits of EA include high sensitivity, real-time monitoring, and low false alarms. However, EA requires high-quality signals and optimal threshold value selection [132].

4.3.6 Neural network

The Neural Network (NN) consists of multiple simple and highly interconnected units for processing signals [41]. In the context of Digital Signal Processing (DSP), NN utilizes mathematical computing to detect and analyze signals [44]. NN works by acquiring signals, extracting features, computing extracted features, training NN, and detecting anomalies [88].

4.3.7 Fast Fourier transform

The Fast Fourier Transform (FFT) is a vital signal processing technique that efficiently calculates the Discrete Fourier Transform (DFT) of a sequence by transforming signals from time or space domains to frequency domains [76]. FFT determines leaks by acquiring signals, processing signals, applying FFT, and detecting anomalies [42]. FFT is effective in analyzing signals, identifying patterns, and detecting complex changes. However, FFT has limitations, including stationary assumptions, sensitivity to background noise, and requiring expertise for analysis [42].

4.3.8 Short Fourier transform

The Short Fourier Transform (SFT) is a fundamental digital signal processing technique used to analyze dynamic signals whose frequency content changes over time [97]. SFT represents signals in both frequency and time domains simultaneously. SFT works by dividing signals into overlapping windows, applying Fourier Transform, and producing a spectrogram [54].

4.3.9 Statistical process control

The Statistical Process Control (SPC) is a technique for monitoring and controlling processes using statistical concepts, such as Cumulative Sum Control (CSC) and Shewhart Control Chart (SCC) [56]. SPC collects data, analyzes, takes corrective action, and maintains process stability. For more information on SPC, refer to [26].

4.3.10 Deep learning

Deep Learning (DL) is a powerful DSP tool for solving complex signal processing problems in pipeline leakage detection and monitoring [127]. DL is a subset of machine learning that automatically learns features from raw data. DL models have transformed the field of DSP, offering unprecedented performance in pipeline monitoring and leakage detection. However, DL has limitations, including requiring extensive label training data, being computationally demanding, and being prone to adversarial attacks [111]. Further readings on DL can be found in [92].

4.3.11 Continuous wavelet transform

The Continuous Wavelet Transform (CWT) is a mathematical tool used in DSP to analyze and represent signals in both frequency and time domains simultaneously [106]. CWT decomposes signals into sets of coefficients to represent frequency content at various time scales [11]. The CWT works by utilizing a wavelet function (mathematical function which oscillates at a particular frequency and decays over a period of time) to scale and shift in order to match the signal characteristics.

4.4 Model estimation based techniques

Model estimation-based leakage detection and monitoring technique rely on computational or mathematical models' behaviour to detect anomalies in pipeline. The model estimation-based techniques of pipeline leakage detection and monitoring includes state observer, impedance, Kalman filter and system identification technique as sown in Fig. 5:

4.4.1 State observer technique

The state observer-based pipeline leakage detection and monitoring technique involves utilizing mathematical models and input–output data to estimate the internal state variables of pipeline system. The state observer works by continuously estimating the state variables such as flow rate, pressure and, temperature of the pipeline system and compares the estimated variables with the actual measured values. The differences between the estimated variables and real measurements indicate the presence of leak in the pipeline. Additional details on state observer technique can be found in (Ole et al., [84]; Martin and Jan, [78].

4.4.2 Impedance technique

The impedance is a technique of pipeline leakage detection and monitoring that utilizes electrical impedance to detect leaks in pipeline system. The impedance technique uses electrical tomography, acoustic and pressure-flow measurement to measure a change in a system. The electrical tomography works by combining the reactance and resistance which affects the flow of alternating current in a circuit and a change in the impedance can be used to detect anomalies in a system. The acoustic impedance analyses sound wave reflections and pressure impedance measures flow rate pressure to detect leaks in pipelines system respectively. For a detailed discussion on impedance, refer to Chi et al., [22] and Kim [61].

4.4.3 Kalman filter

The Kalman filter is a technique of estimating leak in pipeline system which uses real-time data collected from sensors to predict the system state and correct the predicted data using the observed data. The process of prediction is repeated continuously by updating and estimating the system state, an anomaly is detected when the difference between the observed and predicted state exceeds a certain threshold. Further discussion on Kalman filter is found in Jafari et al., [52].

4.4.4 System identification technique

System identification technique of pipeline leakage detection and monitoring entails building an accurate mathematical dynamic model based on observed input–output data. The system identification technique utilizes the following steps to detect leak on a pipeline system:

- The normal state or operating behaviour of the pipeline system is identified and modelled.

- The identified and modelled state of the pipeline system is continuously monitored; any deviation identified from the normal state of the modelled signifies the presence of leak.

More discussion on system identification model estimation-based technique can be found in Christina and Lizeth, [23]; Zheng and Yehuda, [131].

4.5 Visual inspection method

The Visual Inspection Method (VIM) of pipeline leakage involves walking across, flying or driving across the pipeline to inspect or look for signs of defect or leak in the pipeline. In many cases local residents residing within the pipeline passage who are familiar with the terrain are being employed to physically inspect or monitor for signs of defect or leak on the pipeline and report in the case of leakage. A major drawback to VIM in detecting and monitoring leakages in pipeline system include the untimely detection which requires human to physically inspect the pipeline by scanning over the whole pipeline network. VIM is perhaps the oldest, obsolete and unsystematic leak detection system which involves physical observation of abnormalities such as an indication of ponding across the ground surface Colombo et al. [27]. VIM has low reliability in leak detection, requires a significant amount of time, labour intensive and dependent on experienced personnel for accurate leak detection.

4.5.1 Robotics and autonomous technique

Robotics and autonomous technique entail the use of smart devices such as drones to inspect and detect leakages in pipeline. Drones can be equipped with data acquisition device with sensors, fluorescent and visual camera sensor equipped with high sensitivity. Similarly, Remotely Operated Vehicle (ROV) can also be utilized for monitoring and reporting of pipeline leakage in deep water that cannot be accessible by other leakage detection methods. ROV operates on principles of teleoperation which involved a slave-master system. The slave is a robot which operates by interacting with a very dangerous deep-sea environment. The human operator acts as the master and remotely operates the movement of the slave (robot) from a safe environment using joystick and other haptic devices. All commands are transmitted to the slave (robot) with the aid of harness cord or cable linking the vessel to the ROV [105]. Another autonomous method is the use of Autonomous Underwater Vehicle (AUV) at deepwater and subsea levels to monitor and report pipeline leakages. Though the operational principles and approach of teleoperation in ROV is related AUV operation, only basic skills are necessary to operate the AUV. Both AUV and ROV have the benefits of being control remotely and suitably used for observation and monitoring of dangerous environments. In addition to that, it is very safe and has lower cost of maintenance. However, the cost of hiring or purchasing ROV and AUV is extremely high. Additionally, wind and clouds affect the efficient operation of ROVs and AUVs.

Table 7 provides a comprehensive synthesis of pipeline leakage detection and monitoring highlighting the methodology adopted by various researchers as well as the strength and weakness of each method.

4.6 Multiple signal classification algorithms (MUSIC)

The MUSIC technique is suitable for unknown parameter estimation and noisy environments. The MUSIC technique has been applied in several array signal processing research and localization of signal sources [96]. The MUSIC technique has also been applied for localization of harsh sound in underwater environment. The MUSIC-like algorithm has also been proposed by Borijindargoon et al. [17] for the localization of source in electrical impedance tomography. The fundamental concept of the MUSIC algorithm the estimation of the Direction of Arrival (DOA) of signals by computing the eigenvectors and eigenvalues of the signal correlation matrix. In the case of pipeline leakage detection, the signals of interest are usually acoustic signals generated by the leaking fluid or gas. By estimating the DOA of these signals, the position of the acoustic signal can be estimated.

The MUSIC algorithm has shown promising results in pipeline leakage detection, particularly in detecting small leaks or leaks in challenging environments such as underwater pipelines. However, its performance can be impacted by the number and spacing of the sensors, the frequency of the leaking signal, and the presence of interfering sources. Therefore, careful system design and optimization are essential to achieve reliable and accurate leakage detection using the MUSIC algorithm. The strength and weakness of the MUSIC algorithm is shown in Table 8.

Table 7 Synthesis of pipeline leakage detection and monitoring

Detection method	Title/author/year	Methodology	Strength	Weakness
Acoustic-Based	Leak detection of water distribution pipeline subject to failure of socket joint based on acoustic emission and pattern recognition, Measurement. Li et al. [69]	The authors subject socket joint failure using pattern recognition and AE technology to investigate pipeline leakage experimentally	Leakage estimation accuracy of 96.9% was obtained which signify that an AE- driven technique show remarkable sensitivity across long range	.a. Too many parameters to handle b. Susceptible to ambient noise
Acoustic-Based	Pipe Line Leakage Detection and Monitoring using AE and ML Algorithms. Ullah et al. [113]	The authors compute certain statistics metrics from AE signals utilizing them as input variables in machine learning model development	The system provides effective and reliable leak detection with 99% classification accuracy	a. Only applicable to short length of pipeline under laboratory condition b. can detect single leak at a time
Acoustic-Based	A Reliable Acoustic Emission Based Technique for Detection of Small Leak in a Pipeline System. Thang et al. [112]	Segments AE signal into short frames based on Hanning Window, trained a k-nearest neighbour (KNN) utilizing features derived from the converted signal investigates pipeline leakages	Requires less training data and the transformation method are highly accurate. The results also shows that the method works accurate even with limited data, the classifier learn effectively	a. Only applicable to short length of pipeline under laboratory condition b. limited to single leak only
Fibre Optic	A Reliable Acoustic Emission Based Technique for Detection of Small Leak in a Pipeline System. Thang et al. [112]	Distributed Temperature Sensing (DTS) technology for detection of leakage in a buried anhydrous gaseous ammonia pipeline	The reliability and accuracy of the developed system increases with time, as the leakages increase in quantity and also caused the temperature to decrease	Requires complex data interpretation and analysis
Fibre Optic	A Novel Pipeline Leak Detection and Localization Method Based on FBG Pipe Fixture Sensor Array and Compressed sensing Theory. Wang et al. [119]	Developed leak localization and detection system integrated with compressed sensing theory and FBG pipe-fixture sensor array to calculate the accurate leak position	Capable of estimating the arrival time difference with minimal number of sensors, with standard localizations accuracy and stability	Inability to estimate number of leakage and the technique has shorter life spam
Vapour Sampling	The pipeline Defect Assessment Manual. Cosham and Hopkins [29]	Proposed concept of gas-permeable cylinder-based sniffer tube for detecting leakage in pipeline system	Ability to detect small leak in pipeline, independent pressure or flow balance and ability to detect multiple leakages	Not suitable for subsea pipeline. Takes longer time to report leakage
Infrared Thermography	Leakage Quantification of Compressed Air Using Ultrasound and Infrared Thermography. Ivana et al. [48]	Analyzed and evaluate two different contactless techniques for quantifying compressed air leaks using ultrasound and infrared thermography	Offers better results for leakage quantification when an orifice is greater than 1.0 mm and can only be applicable to small leaks	Can not quantify leakage when the orifices are less than 1.0 mm
Ground Penetration Radar	Recent Advances in Pipeline Monitoring and Oil Leakage Detection Technologies. Mutiu et al. [82]	Comparative analysis of recent techniques for leak detection	Suitable techniques of detecting leakage in underground pipeline Ability of providing detailed information of the subsurface object	Signal can be distorted in environment with clay soil
Fluorescence-Based	–	Relationship between fluid flow rate and spectral light emission across various wavelengths	The fluorescence method has the capability of detecting leakages regardless of the tidal flow direction	Can only be applicable to medium that is naturally fluorescent

Table 7 (continued)

Detection method	Title/author/year	Methodology	Strength	Weakness
Capacitive Sensor	A Method to Obtain Precise Determination of Relative Humidity Using Thin film capacitive sensors Under Normal or Extreme Humidity Conditions. Dario [30]	Utilizes dielectric constant variations spanning across gas and sea water to identify the presence of gas which causes the disparity between them	Can be employed to cover local coverage in subsea pipeline	Require Direct contact with the pipeline
Visual Inspection	–	Walking across, flying or driving across the pipeline or using AUVs and ROVs	Less expensive and has ability to inspect unreachable terrain by human by using The ROV AUV	Has low response time as it takes several minutes before reporting leakages
Mass-Volume	–	Using concept of mass conservation operation A pressure wave is generated in pipeline by closing a valve or pump. When leak occur, the reflected wave is detected by sensors	System can effectively conserve mutating characteristics of leakage and the system has the ability to suppress noise interference	Issue of false alarm due to environmental factors, limited sensitivity and location uncertainty
Negative Pressure Wave	–	Utilizes statistics metrics to evaluate pressure change at various points across the pipeline	Highly sensitive for detection of leakages than velocity measurement	The leak detection model was derived and simulated in only one dimension, cannot applied to multiple leak detection
Pressure Point Analysis	–	–	Works in cold climate, deep sea and also has advantage of detecting small leak and it. Additionally, it has low cost of implementation	Extremely difficult to determine the localization of leakage
Dynamic Modeling	Mathematical modeling and simulation of leak detection system in crude oil pipeline. Olubukola et al. [85]	Formulated mathematical model to define the operations of pipeline system centered around the principles of physics	Able to produce realistic long-range estimate for leakage detection	Most complex and sensitive technique in pipeline leakage detection that depends on mathematical formulation of fluid dynamics

The use of Multiple Signal Classification (MUSIC) and AE technique for pipeline detection of leakages and monitoring were proposed in few studies; Wang et al. [117] developed a spectral-based system for the identification of leakage based on one dimensional search. It was found that two or more close leakages on pipeline surfaces cannot be separately detected and can only detect single leak at a time. Li et al. [70] developed a transient-based leakage detection system to overcome the drawback of Wang et al. [91]. The authors proposed a transient model using matrix analysis to detect two separate leakages at a time. Though the model developed by Li et al. [53] could overcome the limitation of Wang et al. [117] a spectral-based system, but it is only applicable to short length of pipeline under laboratory condition.

Elandalibe et al. [34] use a cross-correlation technique to investigate multiple leakages on a buried pipeline. The authors found that measuring AE signals with two leakage detectors positioned at both side of the pipeline efficiently increase the accuracy of the signal.

5 Future research directions and unresolved research problems

Pipeline monitoring and leakage detection are rapidly evolving with many unresolved research problems to attend to such as simultaneous multiple leakage detection in pipeline. The survey and research articles analysed in this systematic review showed that significant research on pipeline leakage detection and monitoring have been carried out with only few in the areas of Multiple Signal Classification (MUSIC) algorithms as most of the studies were based on single leak detection. Furthermore, future researchers can premise their research on interdisciplinary research efforts for the enhancement in combining innovations on computational models, data analytic and sensor technologies.

An accurate and effective leakage detection and monitoring technique must have the capability to simultaneously detect, locate and monitor multiple leaks in real-time. Addressing these future research directions and unresolved research problems will enhance pipeline leakage detection and monitoring techniques to attain efficient and safer pipeline operations.

6 Conclusion

This study presents a systematic review of oil and gas pipeline leakage detection and monitoring. Articles were reviewed, analysed, while different principles and approaches of pipeline leakage detection and monitoring were considered. The viewed articles dwelled much into external, internal, visual inspection and the MUSIC principles and approaches, analysed their strength and limitations. The review also shows growing interest in this research area; however, challenges such as early detection and localization of small leaks, accuracy in leak detection and localization, and cost-effective remote technique for large scale pipeline system monitoring remain unresolved. Further research is increasingly dwelling into solution in addressing these challenges with development of more sensitive and resilient leak detection system.

Table 8 Strength and weakness of multiple signal classification (MUSIC) algorithms

Strength	Weakness
Efficient in localizing multiple leak positions	Requires accurate knowledge of the acoustic signal propagation environment
Suitable for both liquid and gas pipelines	Challenging in complex environments with multiple sources of noise
Real-time monitoring capability	Limited accuracy in leak localization
Non-intrusive and non-destructive testing	Signal attenuation in long pipelines
Can handle various pipeline sizes and materials	Requires proper sensor placement and calibration
Suitable for continuous monitoring of pipelines	Equipment and installation costs can be relatively high
Real-time monitoring capability	Limited spatial resolution in complex pipeline geometries
Can handle multiple leak sources	Complex implementation to handle multiple leaks and parameter tuning
Robust against frequency variations	Limited effectiveness in detecting slow or small leaks
Can operate with a small number of sensors	Performance dependent on signal-to-sensor sensibility

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