

Application of fiber optics in water distribution networks for leak detection and localization: a mixed methodology-based review

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ABSTRACT

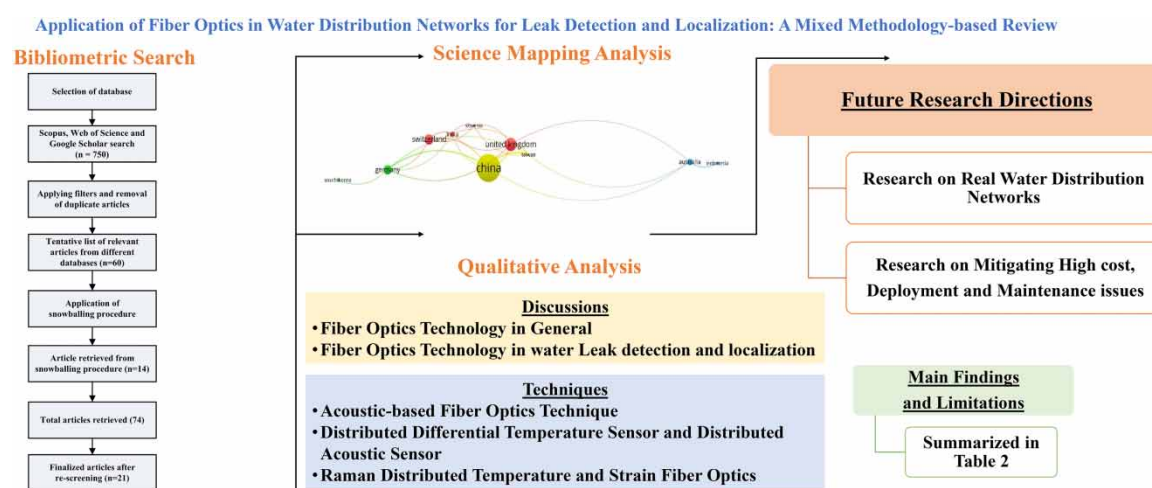
This study reviews the state-of-the-art application of fiber optics in water distribution networks for leak detection and localization. The use of fiber optics in the oil and gas sector has been well established; however, its potential in water pipelines is not evident owing to limited research. This study, therefore, presents the research developments of fiber optics in water leak detection and localization using the mixed methodology approach by integrating bibliometric and systematic analyses. A scientometric analysis is carried out to analyze the science maps of (1) journal sources, (2) contributing countries, and (3) co-occurrence of influential keywords. The systematic analysis evaluates the use of eight types of fiber optics, such as accelerometer-based fiber optics and hydrophone-based fiber optics, in water leak detection and localization. The review reveals five important directions for future research such as real network-based studies and the development of hybrid techniques.

Key words: fiber optics, leak detection, leak localization, pipelines, water distribution network, water supply

HIGHLIGHTS

- The study presents the state-of-the-art review of fiber optics application in water leak detection and localization.
- Contributing sources, influential countries, and links between keywords in this domain are discussed using scientometric analysis.
- Implementation of major fiber-optic classes including fiber Bragg grating and Raman distributed sensors are discussed.
- Limitations and future research directions are given.

GRAPHICAL ABSTRACT



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1. INTRODUCTION

The world is currently grappling with myriads of challenges, such as increasing human population and rapid urbanization, which have affected the demand for freshwater (Tariq *et al.* 2020). Not only that, 68 countries are facing extremely high to medium-high risk of water stress (WRI 2019) which depicts the need for concerted efforts to ensure the availability of freshwater for agriculture, and ecosystem use.

Freshwater is usually delivered to end-users through a system of underground and above-ground pipes (mostly underground in large metropolitans) commonly known as a water distribution network (WDN). The WDN provides an effective, fast, economical, and environmentally friendly mean for delivering water due to the (1) low requirements of physical efforts and (2) safety against weather and environmental conditions. With the passage of time, the performance of WDN is often negatively affected by factors such as old age, environment, and third-party intrusion (Zaman *et al.* 2020). These factors may cause defects such as leaks (Adedeji *et al.* 2017) which result in a diminishing/degrading performance of the WDN.

Liemberger & Wyatt (2019) reported that around 36% of the total water supplied through WDNs globally is lost, i.e. a staggering 126 billion cubic-meter a year. Water leakage is noted to be the primary cause of this water loss (Zaman *et al.* 2020) and, in some cases, may even result in 50% of the total water loss (Kanakoudis 2004; Tariq *et al.* 2020). Nevertheless, it is impossible to avoid leakages in the WDNs completely (Hu *et al.* 2021); however, the need to adopt reliable methods and techniques to detect and locate leaks immediately cannot be overstated.

Available direct/hardware-based methods and technologies for water leak detection and localization include (1) fiber optics technology, (2) listening devices such as listening sticks and electrical and mechanical geophones, (3) acoustic monitoring devices such as noise loggers, accelerometers, and hydrophones, (4) infrared thermography, (5) tracer gases, (6) leak detection robots, (7) ground penetration radar, (8) smart ball, (9) wireless-based MEMS systems, (10) visual inspections, and (11) mechanical excavation (El-Zahab & Zayed 2019; Zaman *et al.* 2020). Indirect/software-based methods include (1) transient state, (2) combined transient and steady-state, and (3) steady-state methods (Zaman *et al.* 2020). Steady-state methods are further classified into model-based and data-driven methods (Zaman *et al.* 2020). Kothandaraman *et al.* (2020a) noted the downsides of available methods and technology. For example, acoustic techniques are not appropriate for plastic pipes, whereas physical inspection and mechanical excavation require extensive human resources. With regards to the use of fiber optics technology for leak detection and localization, factors such as cost (Wong *et al.* 2018a) and application in older and existing water pipelines (Zaman *et al.* 2020) have been the major barriers in its implementation. However, fiber optics technology presents some useful advantages over other available methods and techniques such as the capability of multi-leak detection, swift response time, and concurrent transmission of feedback data (Mirzaei *et al.* 2013). Fiber optics technology also offers some special advantages such as resistance to sound and noise, flexibility, appropriateness for underwater application, suitability under aggressive environments, and immunity against electromagnetic waves (Kothandaraman *et al.* 2020b).

A critical assessment of existing literature reviews showed that none of the previously published reviews focused solely on the use of fiber optics technology for water leak detection and localization. This would have led to the emergence of new developments and ideas. Our study presents an effort to critically review past studies in an attempt to (1) reveal the salient areas of the application of fiber optics in water leak detection and localization and (2) disclose future research directions. According to Tariq *et al.* (2020), Bakhtawar & Zayed (2021), and Wang *et al.* (2021), conducting a literature review provides an avenue for understanding a research domain and facilitates identifying novel research areas. Our study, therefore, aims to fill the knowledge gap by providing a deeper understanding of the use of fiber optics technology in water leak detection and localization. This review is a mixed methodology-based review integrating both bibliometric and systematic analyses to fully disclose the state-of-the-art of this domain.

2. RESEARCH METHODOLOGY

The overall research methodology is presented in Figure 1. The research methodology was classified into two consecutive phases: (1) scientometric analysis, including bibliometric search and science mapping analysis, and (2) qualitative analysis.

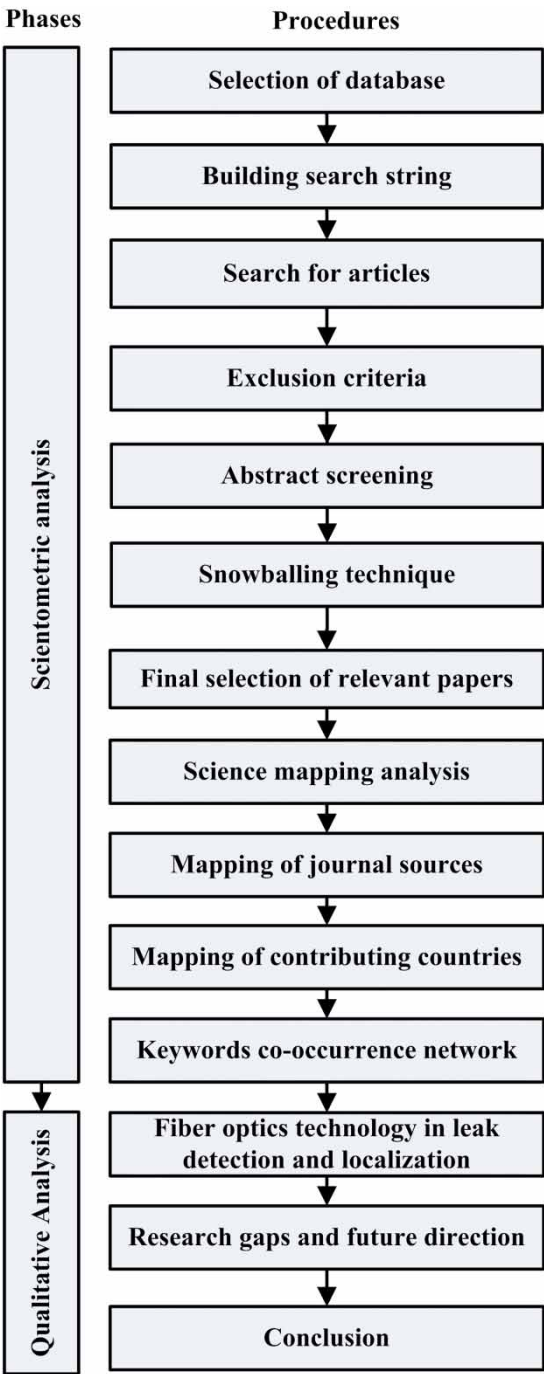


Figure 1 | Research methodology.

2.1. Scientometric analysis

2.1.1. Bibliometric search

The bibliometric analysis was initiated through searching prominent databases to find relevant published articles relating water leak detection and localization. Popular search engines, namely ‘Scopus’, ‘Web of Science’, and ‘Google scholar’, were used for that purpose. During the search, a combination of keywords including ‘fiber optics’ and ‘leak’ were used to retrieve articles. Searching through Scopus, Web of Science, and Google scholar yielded 750 articles in total, comprising of the journal and conference articles. Articles extracted from the bibliometric search were then screened out on the basis of two exclusion criteria: (1) articles written in languages other than the English language and (2) articles focusing on domains other than leaks in oil and gas pipelines and water pipelines. This process identified 60 relevant articles.

To identify more relevant articles, a snowballing technique was performed on the included articles. Backward snowballing was performed by manually screening the reference lists of the 60 included articles, and relevant articles were added to the list of included articles. Forward snowballing was conducted by using the 'cited-by function' in Google scholar, i.e. the relevant articles that cited included articles were identified. This snowballing process yielded 14 (7 from backward and 7 from forward snowballing techniques) additional relevant articles. In total, the initial literature searches and the snowballing process yielded 74 papers as shown in [Figure 2](#).

2.1.2. Science mapping analysis

Science mapping analysis aids in the analysis and visualization of patterns and networks from a set of bibliometric data. Applications such as VOSviewer ([Van Eck & Waltman 2010](#)), Gephi ([Bastian *et al.* 2009](#)), and Cite space ([Chen 2006](#)) can be used for science mapping analysis. All these applications are capable of creating and depicting basic bibliometric networks; however, VOSviewer was selected for our study due to the ease of use, easy interpretability of networks through visualization, and the popularity of the software in engineering and management research ([Tariq *et al.* 2020](#)). Science mapping analysis has already been employed in different research areas, such as construction safety ([Akinlolu *et al.* 2020](#)), megaprojects ([Wang *et al.* 2020](#)), and acoustic-based leak localization ([Hu *et al.* 2021](#)), which has yielded meaningful research outcomes including (1) working linkages and measurements between researchers, countries, and organizations and (2) preliminary

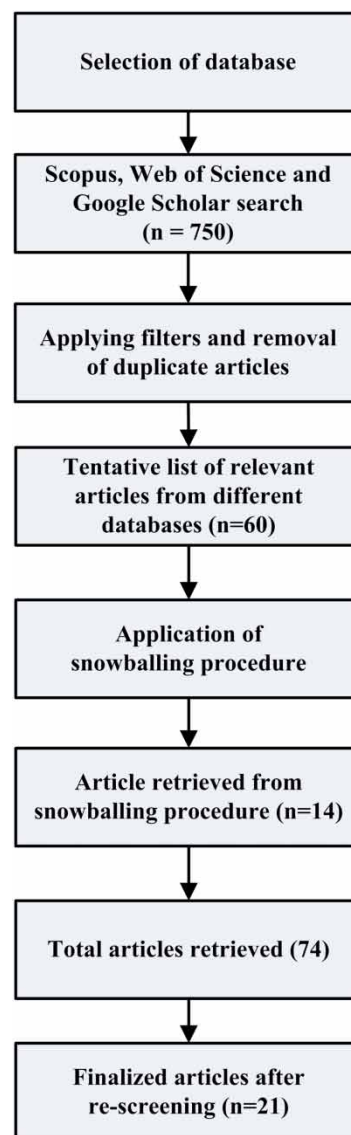


Figure 2 | Retrieval of articles from databases.

ideas on the existing research themes and future research directions (Tariq *et al.* 2020). In our study, VOSviewer was used for science mapping of journal sources, contributing countries, and popular keywords.

2.2. Qualitative analysis

To gather relevant articles for the qualitative analysis, another round of screening was performed for the entire 74 included articles. All these articles were thoroughly examined and 21 relevant articles relating water leak detection and localization were used for the qualitative analysis as given in Table 1. The reason for using articles relating water leak detection and localization was due to the lack of research on the use of fiber optics in the water leak domain and our study attempted to present the complete insight to widen readers' horizons for future avenues in this research area.

3. DISCUSSION OF SCIENCE MAPPING RESULTS

3.1. Mapping of sources

Analyzing publication sources can assist readers in locating the major sources of relevant information (Tariq *et al.* 2020). The mapping was carried out in VOSviewer. The threshold for the minimum number of documents of any source was set at '1', while the minimum number of citations was set at '1' in the software. Only nine sources met the set threshold. The node size depicts the level of productivity of a source as shown in Figure 3. *Sensors (Switzerland)* has the largest node size, depicting the most productive publication source in this domain. Again, other sources that made contributions are *Journal of Hydroinformatics*, *Applied Optics*, *IEEE Access*, and *Journals of Hazardous Materials*. The level of closeness between nodes and color type illustrates the degree of linkage between various publication sources. For instance, *Journals of Hazardous Materials*, *Sensors (Switzerland)*, and *IEEE Access* are located closely in the red group, which depicts that stronger citation links (i.e. included articles published in these journals actively cited each other) exist between these sources. This analysis provides the researchers an idea about where to submit their work to target dedicated researchers of this domain. Also, subscription to all publication sources is expensive and most universities, especially located in emerging economies, cannot afford the subscription to every source. The information about the top sources provides the universities necessary information about which sources to subscribe to, in the case of faculty/researchers' interest in this domain (Hussein & Zayed 2020).

3.2. Mapping of countries

The analysis of the most active countries in this domain was carried out using VOSviewer and presented in Figure 4. The threshold limit for the minimum number of publications was set at '1', while the minimum number of citations of a country was set at '2'. China has the highest number of publications (21), which corresponds to the biggest node size followed by the United Kingdom with nine publications. Countries with joint research output are grouped in Figure 4. For instance, the United Kingdom, Switzerland, India, and Slovenia are located in the same group and jointly cited each other's included articles. Similarly, Germany and South Korea are located in the same group and also jointly cited each other's included articles. The knowledge of influential countries can foster applications for the jointly funded project, collaborations among researchers, and exchange of researchers (Hussein & Zayed 2020; Tariq *et al.* 2020).

3.3. Keywords co-occurrence mapping

Keywords can depict how a research field has evolved (Tariq *et al.* 2020). Keywords assist in comprehending the main idea in a research article. Keywords co-occurrence in included articles examines the connection that exists among keywords to reveal the structure of the whole research domain (Tariq *et al.* 2020). Using VOSviewer software, a keyword co-occurrence mapping was produced. 'Authors keywords' was used as the mode of analysis and the threshold of the number of occurrences was kept at '2'. Out of the total of 173 keywords, 33 met the threshold limit as depicted in Figure 5. Keywords with the same semantic meanings such as 'leak detection' and 'leakage detection' were combined. The node size indicates the frequency at which keywords appeared in the included articles. The nodes of 'fiber optics' and 'leak detection' are much larger than the nodes of other keywords in Figure 5. The nearness of keywords reveals some gaps. For example, 'fiber optics' and 'leakage detection' are placed closer than 'distributed fiber optical sensor' and 'leakage detection'. This depicts that relatively less research is conducted on leak detection using distributed fiber optical sensors.

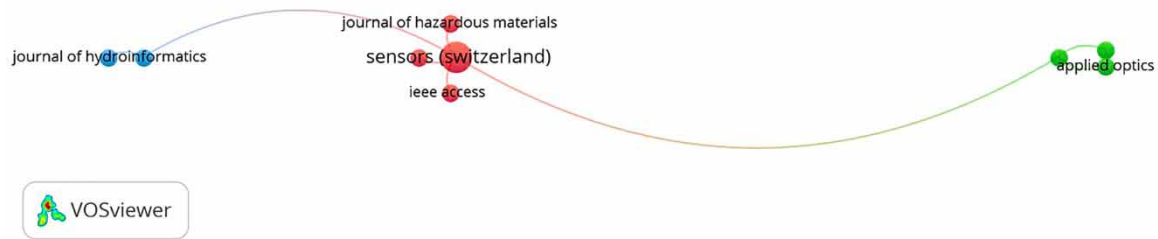
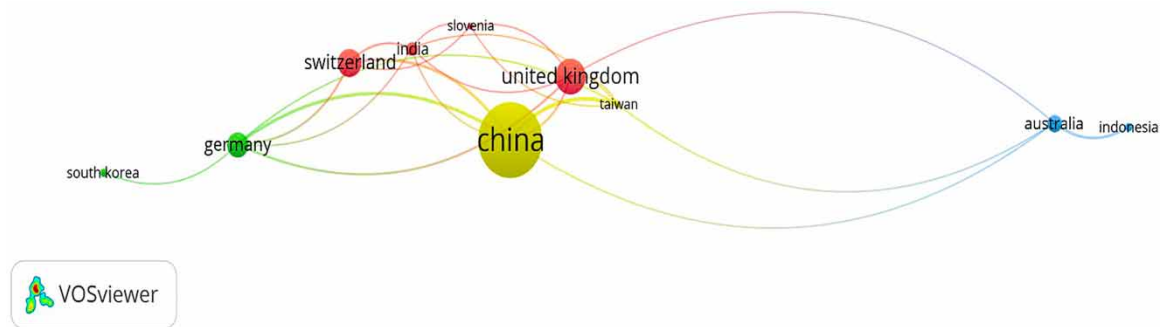
Table 1 | Included studies on fiber optics in water leak detection and localization

Titles	Authors	Laboratory scale-based study	Real network-based study	Studied leak detection	Studied leak localization
1. A hydrostatic leak test for water pipeline by using distributed optical fiber vibration sensing system	Wu <i>et al.</i> (2015)	✓		✓	
2. Distributed pH and water detection using fiber-optic sensors and hydrogels	Michie <i>et al.</i> (1995)	✓		✓	
3. Novel fiber-optic sensor probe with a pair of highly reflected connectors and a vessel of water absorption material for water leak detection	Cho <i>et al.</i> (2012)	✓		✓	
4. Experimental study on leakage monitoring of pressurized water pipeline based on fiber-optic hydrophone	Guo <i>et al.</i> (2019)	✓		✓	✓
5. Leak detection in water pipes using submersible optical optic-based pressure sensor	Wong <i>et al.</i> (2018a)	✓		✓	
6. Application of fiber laser dynamics in leak detection for operating water pipeline	Law <i>et al.</i> (2018)	✓		✓	✓
7. In-pipe fibre-optic pressure sensor array for hydraulic transient measurement with application to leak detection	Gong <i>et al.</i> (2018)	✓		✓	✓
8. Fiber-optic liquid leak detection technique with an ultrasonic actuator and a fiber Bragg grating	Lee & Tsuda (2005)	✓		✓	
9. Leak detection on water pipelines in unsaturated ground by discrete fiber-optic sensing	Jacobsz & Jahnke (2019)		✓	✓	
10. Looped back fiber mode for reduction of false alarm in leak detection using distributed optical fiber sensor	Chelliah <i>et al.</i> (2010)	✓		✓	
11. Microwave and optical monitoring of water from commercial pipelines	Malthus <i>et al.</i> (2003)	✓		✓	
12. Leak detection and quantification of leak size along water pipe using optical fiber sensors package	Wong <i>et al.</i> (2018b)	✓		✓	
13. Novel negative pressure wave-based pipeline leak detection system using fiber Bragg grating-based pressure sensors	Wang <i>et al.</i> (2016)	✓		✓	✓
14. Pipeline monitoring and leak detection using Loop Integrated Mach Zehnder Interferometer optical fiber sensor	Png <i>et al.</i> (2018)	✓		✓	
15. Wave separation and pipeline condition assessment using in-pipe fibre-optic pressure sensors	Shi <i>et al.</i> (2019)	✓		✓	
16. Reliable leak detection in pipelines using integrated DdTS temperature and DAS acoustic fiber-optic sensor	Wang <i>et al.</i> (2018)	✓		✓	✓
17. Acoustic vibration sensor based on macro-bend coated fiber for pipeline leakage detection	Ong <i>et al.</i> (2017)	✓		✓	

(continued)

Table 1 | continued

Titles	Authors	Laboratory scale-based study	Real network-based study	Studied leak detection	Studied leak localization
18. Adaptive independent component analysis-based cross-correlation techniques along with empirical mode decomposition for water pipeline leakage localization utilizing acousto-optic sensors	Kothandaraman <i>et al.</i> (2020a)	✓		✓	✓
19. An adaptive ICA based cross-correlation techniques for water pipeline leakage localization utilizing acousto-optic sensors	Kothandaraman <i>et al.</i> (2020b)	✓		✓	✓
20. Fiber Bragg grating accelerometer-based nonintrusive flow rate measurements and leak detection	Jiang <i>et al.</i> (2020)	✓		✓	✓
21. Leak detection for pipelines using in-pipe optical fiber pressure sensors and a paired-IRF technique	Zeng <i>et al.</i> (2020)	✓		✓	

**Figure 3** | A network analysis of journal sources.**Figure 4** | A network analysis of countries.

4. QUALITATIVE ANALYSIS

A qualitative discussion regarding fiber optics technology based on its application, output analysis, and other parameters measured is presented below. Figure 6 shows the classification of various themes and subthemes considered in analyzing the selected 21 articles for qualitative analysis.

4.1. Fiber optics technology

A fiber optic-based sensing system operates on reflection and transmission principle, in which the fiber optic acts as a sensing component to changes in the external environment (Krohn *et al.* 2014), thus, revealing useful

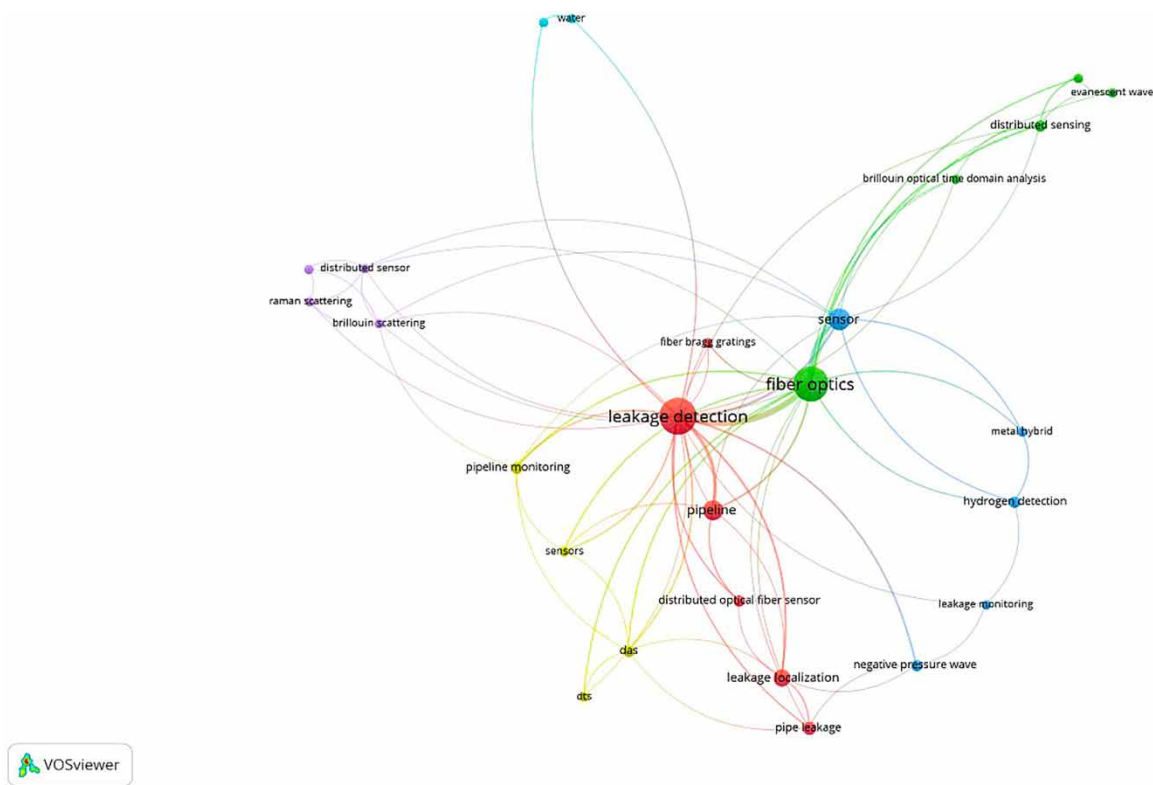


Figure 5 | A network analysis of the top keywords.

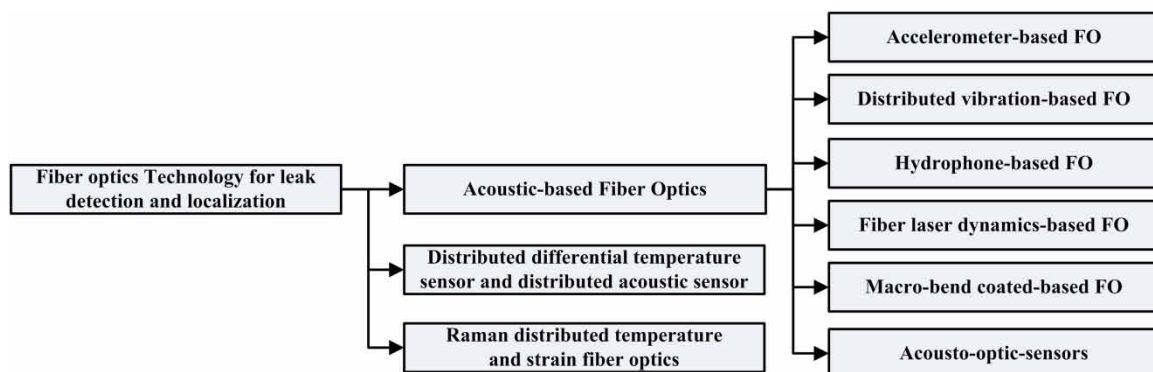


Figure 6 | Fiber optics technology for leak localization and detection.

information about the collected signal such as intensity, wavelength, phase, and spectral content. This information is impressed upon the fiber optic which acts like a ‘black box’ and transmits the information back to an electronic processor (Yin *et al.* 2017). The fiber-optic sensing systems have various classes and subclasses depending upon the internal geometry, assembly design, and modulation schemes of the system (Gupta 2006).

On the basis of the fiber-optic function in the system, they can be categorized as intrinsic or extrinsic. In the extrinsic fiber-optic sensors, the optical fiber plays a passive role in the sensing process and help to transmit signal from the source of light to be received at the other end with a suitable detector. In the intrinsic fiber-optic system, on the other hand, the fiber optic plays an active role in the sensing process. The changes along the length of the fiber when light propagates through it reveal information about the phenomena under study.

On the basis of the monitoring scheme, the fiber-optic sensors can be classified as discrete and distributed. A discrete scheme allows measurement at a single point and mainly uses fiber Bragg grating as the sensing material whose center wavelength changes with temperature or strain variation (Li *et al.* 2021). A number of fiber Bragg gratings are inscribed on various distances over the same fiber for long-distance sensing. The distributed scheme,

on the other hand, allows for simultaneous measurements over multiple locations and uses different scattering phenomena for the sensing scheme. As light propagates through the fiber, it interacts with the fiber constituent material and gets backscattered. The backscattered signal has unique spectral properties depending upon the kind of external stimuli the fiber is being exposed to. Some of the scattering phenomena used in this scheme are Spontaneous Raman Scattering, Rayleigh Scattering, Spontaneous Brillouin Scattering, and Stimulated Brillouin Scattering (Muanenda *et al.* 2019).

Furthermore, optical fibers come in two variants, namely multimode fiber and single-mode fiber. The multimode fiber can transmit multiple rays of light traveling simultaneously through the core of the fiber. The core of the multimode fiber is wider than the single-mode fiber, which allows multiple rays of light to pass. Every beam of light follows a different path and reaches the other end of the fiber at different times. This phenomenon called modal dispersion increases over distance and limits the use of a multi-fiber system over long distances. However, the single-mode fiber has a very thin core for the light to pass through limiting the dispersion of light in the core and creating a sharp resolution signal (Krohn *et al.* 2014). The single-mode fiber has a greater wavelength dependence, whereas the multimode fiber is comparatively insensitive to wavelength variations.

The fiber optics technology can be allocated to accurately monitor qualities such as strain and stress. When an abnormality is sensed by a fiber optics sensor, a signal is instantly sent to the receiver notifying the presence of abnormality. The analysis of the signal determines the location of the abnormality (Thodi *et al.* 2014).

The methods for fiber optics deployment can be classified into internal and external methods of deployment. The externally deployed fiber optics sensor is either placed in contact with the pipe or attached to the pipe, while the internal method of deployment entails the deployment of the fiber optics sensor internally into the pipe through an opening. The internal method of fiber optics deployment can be suitable for monitoring old and existing pipelines.

4.2. Fiber optics technique in leak detection and localization

Recent studies indicate that fiber optics technology has been used to provide solutions in long-term pipeline monitoring, geo-hydrological monitoring, railway imbalance, corrosion monitoring in reinforced concrete, and leak detection in water detection networks (Fan & Bao 2021; Tangudu & Sahu 2021; Yao *et al.* 2021). In the water leak domain, fiber optics usage has some advantages over other technologies for water leak detection due to its small size, lightweight, great immunity to electromagnetic fields (Kim & Kim 2015). However, a drawback with the use of fiber-optic technology in the water leak domain is the cost of deployment and challenges in monitoring existing or old pipes (Wong *et al.* 2018c). The current section presents various fiber optic-based systems for water leak detection and localization.

4.2.1. Acoustic-based fiber optics technique

As depicted in Figure 6, acoustic-based fiber optics techniques are grouped into three (3) categories, namely acoustic-based fiber optics, distributed differential temperature sensor (DdTS) and distributed acoustic sensor (DAS), and Raman distributed temperature and strain fiber optics. Acoustic-based fiber optics is further categorized into (1) accelerometer-based fiber optics, (2) distributed vibration-based fiber optics, (3) hydrophone-based fiber optics, (4) fiber laser dynamics-based fiber optics, (5) macro-bend coated fiber optics, and (6) acousto-optic fibers. Discussions are provided below.

4.2.1.1. Accelerometer-based fiber optics. A fiber-optic-based accelerometer sensor is used for single-point vibration sensing in an inaccessible area (Rong *et al.* 2017). Fiber-optic-based accelerometers have received attention owing to their inherent immunity to electromagnetic interference, sensitivity, and stability under harsh environments. Recently, fiber Bragg grating-based sensors have undergone huge development for vibration measurement which made them the leaders over other fiber-based technologies due to their multiplexing capabilities (the ability to encode multiple signals from multiple sources to transmit over a single communication channel), good linearity (depicting good performance for their consistency of measurements, thus better representing the reality), and simple wavelength demodulation (Feng *et al.* 2015).

The fiber-optic-based accelerometers have found their way into water leak detection and localization. For instance, Jiang *et al.* (2020) manufactured a reliable and convenient fiber-optics accelerometer to detect leaks in water pipes. The accelerometer was designed considering high sensitivity, fast response time, compact size, and the capability of long-distance reach and long-term monitoring. The accelerometer was composed of a

base, a flexible hinge, a mass block, a fiber Bragg grating sensor, and a protective metal shell. The study provided research-based evidence that could improve the relationship between the velocity of flow and vibration (Jiang *et al.* 2020).

Using an accelerometer attached to the test pipe, monitoring index efficiency or MIE (calculated from the standard deviation of the data obtained using simulated experiments) was estimated to identify the leak. To detect leaks accurately, the support vector machine (SVM) was adopted. The MIE and flow rate were the input data features selected for the training of the SVM classifier. The study showed the potentials of the fiber-optics accelerometer in leak detection, where the proposed model achieved a high level of accuracy of 99.00% in differentiating the leak state from the non-leak state. The drawback of this system is that the precision of flow measurement and distance-setting of the sensor is needed to be ascertained. This study was based on the experimental setting in the laboratory; however, the applicability of their model needs to be validated on real networks due to the fact that many variables such as background noise from vehicles may distort the vibration data and the obtained MIE values might be very different from laboratory settings.

4.2.1.2. Distributed vibration-based fiber optics. The distributed vibration-based fiber optics provide some unique advantages over other conventional fiber optics such as smaller size, lighter weight, higher sensitivity, and better electrical passive operation (Kots & Paritsky 1999). It can reliably measure pressure or acceleration in water (Watanabe *et al.* 2010). The distributed vibration-based fiber optics can be used in monitoring leakages in buried pipelines (Jin *et al.* 2016). Png *et al.* (2018) proposed a simple and handy acoustic vibration sensing device to monitor water pipelines. The sensor was cased with a polyvinyl chloride base for protection and handy use. The Loop Integrated Mach Zehnder Interferometer (LMZI) sensor was proposed. Frequency characterization was devised to ensure that the protective base between the optical fiber and measured surface does not interfere with the reading (Png *et al.* 2018). The test result showed that the LMZI sensor was able to detect a leak-induced peak at 100 Hz with 2 bar water pressure. It also detected a leak-induced peak at 288 Hz during leak when water pressure was increased to 3 bar. In their study, a fiber loop was embedded between tapers to intensify the vibrational sensitivity of the sensor. To prevent over-attenuation of the signal, a 15 mm diameter loop was introduced in the sensor. Exposure of the sensor to a varying degree of vibration was carried out to allow the fiber loop to apply torsion intermittently. The results obtained from the experiments were compared with the values from a commercial accelerometer which indicated good agreement with only 0.4% error at 2 bar pressure and 2.64% error at 3 bar pressure. The outcome of the experiment showed that the capability of the developed technique for detecting the water leak in a pipeline, however, reliable detection in water pipelines is to be determined in the field. The results are merely a promise in that regard. The main limitation of their system is that the experiments were conducted on small pipes. Results might not be reliable for long-distance pipes as signals attenuation increase with an increase in pipe length.

Wu *et al.* (2015) proposed a hydrostatic leak test for water pipelines and used the distributed optical fiber vibration sensing (DOVS) method. In their study, a pulse was generated through the acoustic-optical modulator (AOM) and amplified using an erbium-doped fiber amplifier (EDFA). The fiber optics sensor was laid internally in the pipeline for the experiment. When leakage occurred, water released through the pipe's opening induced vibrations in the pipe close to the leakage point. The study demonstrated that the DOVS technique can sense leaks as small as 4 mm in diameter. The developed sensor was cheap, required less effort to set up, and showed reliability regarding vibration sensing. The study claimed that DOVS is an effective method to detect multi-leaks under laboratory conditions; however, their study was based on steel pipes only and there is a need for experimentations on real-life networks to validate the study outcomes as detection of small leaks depends on, among other factors, the water pressure.

4.2.1.3. Hydrophone-based fiber optics. The hydrophone-based fiber optics are characterized by direct intensity demodulation which makes it easy for the interrogation for anomaly detection with greater accuracy (Wang *et al.* 2014). In a typical hydrophone-based fiber optics sensor, acoustic pressure is encoded into its grating reflection wavelength which enables wavelength division multiplexing and thereby enhancing its detection capabilities and sensitivity (Guan *et al.* 2005).

Hydrophone-based fiber optics has been deployed in many applications due to its small size and high sensitivity (Guan *et al.* 2005). It has also been used in the water leak domain. For instance, Guo *et al.* (2019) adopted a fiber

optics hydrophone sensor (FOH) for water leak detection. The operation of the FOH is based on underwater acoustic transducer technology. The FOH analyzer was deployed for the demodulation of a signal of the interferometric FOH to increase the accuracy of the result and reduce the background noise. The system was implemented in three phases. The first phase entailed the conversion of a sound signal into an optical phase information signal. In the second phase, phase information through fiber optics was conveyed to a machine that acquired signal information. In the third phase, the collected information was restored into a sound signal with the aid of an optical phase modulator. When water leakage occurs in a pipeline, vibration is induced around the leakage point due to the difference in pressure between the internal and external surface of the pipeline resulting in an overall vibration of the pipeline. In their study, key activities such as (1) delay calibration, (2) parameter dispatch, (3) demodulation, and (4) contrast were all carried out to ensure the reliability of the result. To prevent the impact of the water inlet and outlet from affecting the research outcome, the fiber optics hydrophone was not placed at both ends of the pipe.

Their proposed system has two main limitations that require further work. Firstly, the system did not validate the identification of the leakage location and accuracy on different types of pipes. Secondly, the study ignored some vital conditions such as (1) water pressure, (2) pipe diameter, (3) leak size, (4) sensor combination, and (5) sensor distance.

4.2.1.4. Fiber laser dynamics-based fiber optics. The fiber laser dynamics-based fiber optics has demonstrated its capability regarding real-time monitoring. It has shown among other optical fiber-based sensors, its high degree of miniaturization (Caucheteur *et al.* 2016). The fiber laser dynamics-based fiber optics is found to be sensitive to acoustic waves (Pua *et al.* 2013). These capabilities have attracted interest in many sectors such as the water distribution sector. For instance, Law *et al.* (2018) demonstrate the ability of a laser dynamics-based fiber sensor in point-to-point sensing and compare its performance with acoustic emission sensors commonly used to localize leaks in the water pipeline. The fiber-optic sensors were constructed based on the principle of the Fabry–Perot lasing system. The basic idea was that the system was powered by a laser diode that excites electrons in an erbium-doped fiber to emit photons. The photons traveled to the sensing arm with a clean cleaved end. The photons reflected by the sensing arm were then guided by the wavelength division multiplexer to the photodetector that separated photons of different wavelengths. In their study, two fiber-optic sensors were used for leak localization, where one sensor was placed 1 m from the point of water leakage and the second sensor was placed 3 m away from the leak on the other end. The study localized the point at which water leaked in the pipeline by less than 10 cm. Leak localization was carried out using the following equations.

$$K_1 = \frac{K_{12} - w\Delta u}{2} \quad (1)$$

$$K_2 = \frac{K_{12} + w\Delta u}{2} \quad (2)$$

where K_1 and K_2 are the location from the sensors to leakage location, u is the estimated velocity of leakage signal, K_{12} is the distance between the sensors, and Δu is the time delay measured.

When the proposed sensors were tested, they performed better than mainstream acoustic sensors due to their higher sensitivity and immunity against electromagnetic interference. The cross-correlation method localized the position of the leak in the pipeline with an accuracy of about $\pm 5\%$ or less than 10 cm. The real-life applicability of the fiber laser dynamics-based fiber optics is still not known as the research outcome is based on an experiment conducted on a small scale in a laboratory.

4.2.1.5. Macro-bend coated fiber optics. Macro-bend coated fiber optics sensor relies on the bending loss to sense abnormality (Ong *et al.* 2017). Bending loss can be attributed to the random change in the radius of bending fiber due to the application of force (Murakami & Tsuchiya 1978). Macro-bend coated fiber optics sensors are compatible with arrays of technology and are cheaper than other fiber optics sensors. Ong *et al.* (2017) adopted a macro-bend coated single-mode fiber (SMF-28) for water leak detection. The study leveraged on bending loss of the fiber optics sensor induced by acoustic vibration. A 5 mm bend-coated fiber optics sensor

was placed near the predetermined leak point close to the pipe in the field experiment. The experiment results demonstrated that when the optical fiber bend is less than or equal to 8 mm, optical power loss increases progressively from -2.82 to -22.44 dB.

In analyzing the data, fast Fourier transform (FFT) was conducted. The vibration was detected at frequencies between 20 and 2500 Hz. The main drawbacks of the study are (1) more research is required in establishing the location of the leak using correlation and standard deviation methods and (2) results were based on the use of low-pressure pipes.

4.2.1.6. Acousto-optic fibers. Kothandaraman *et al.* (2020b) proposed the adaptive independent component analysis (ICA) approach for leak detection and localization using acousto-optic sensors. The study was based on the cross-correlation technique aided with an empirical mode decomposition (EMD) to detect and locate leaks in water pipelines. The technique for localizing leaks in a water pipeline was premised on evaluating the difference in time between two sensor signals using the cross-correlation technique. The experiments were conducted on galvanized iron using single wavelength, laser source, wavelength division multiplex, erbium-doped fiber, single-side fiber Bragg grating, and a photodetector. In evaluating the time delay, two acousto-optic sensors were placed on both sides of the pipeline's predetermined leak positions. Water was released to circulate the system. Reading was taken concurrently from the two sensors installed for a minute. The distance between the sensors was recorded for data analysis, pinpointing the position leak position, and comparing the results obtained. To confirm the leak distance, the sensor positions were adjusted several times. Data obtained were passed through a filter at a frequency of 256 kHz. Results indicated that the proposed method reliably localized leaks with a 95% level of accuracy. However, a drawback of the study is that accurate leak localization in long distance pipes without foregoing accuracy is an area that needs attention.

Kothandaraman *et al.* (2020a) extended their study in Kothandaraman *et al.* (2020b) and used a non-Gaussianity adaptive algorithm to separate leak vibration waves from the convoluted impulse response of the pipe with the noise. The study explored a new time delay estimation method to locate water leaks in a real-time distribution system. To locate the leak, the acousto-optics sensor was positioned at a predetermined leak position along the pipeline to assess acoustic vibration. In this study, various correlator techniques were used to determine the difference in time of the various signals received. The method developed can be used for a real-time environment. Furthermore, the newly developed adaptive ICA technique simplifies the computational difficulty of the ICA algorithm. Data analysis was conducted using Matlab R2018a. The result revealed that the proposed method is reliable regarding leak localization in the water pipeline. The bottom line is that Kothandaraman *et al.* (2020b) created an improved version of ICA that renders better results. The major drawbacks of the study include that (1) leak simulation was limited to only one hole and (2) placement of the two-fiber optics sensor was randomly carried around the leak point.

4.2.2. Distributed differential temperature sensor and distributed acoustic sensor

A distributed fiber optics sensor monitors strain, temperature, and vibration along an entire fiber optics length using a prearranged spatial resolution. It offers some advantages over other sensors such as reliability, lightweight, and compactness (Wang *et al.* 2018). The distributed fiber optics is compatible with arrays of techniques and principles. Wang *et al.* (2018) presented a combination of two highly sensitivity fiber-optic sensing techniques (DdTS temperature and DAS acoustic fiber-optic sensor) for water leak detection in buried water pipes. The two techniques were combined to complement the shortcomings of either of the two, such as false alarm (false positives) and leak detection accuracy. DdTS has the capability of detecting leaks within a few seconds, whereas the DAS can detect leaks within minutes.

The experiment was conducted in two ways, one method involved burying the sensor directly in the soil, and the other method involved burying the sensor in a conduit. The results showed that DdTS fiber sensor detected water leaks when placed directly in the soil and a conduit. However, DAS acoustic fiber-optic sensor only detected water leakage when buried directly under the soil. This finding confirmed the need to combine two techniques for an accurate leak detection system in water pipelines.

Validation for the DdTS and DAS techniques confirmed that a combination of the two techniques provides some advantages such as suitability for long-range monitoring, detection of small leaks, rapid leak detection

time, the low probability of false alarm, real-time monitoring, low operating cost, and third-party intrusion detection. Again, the deployment DdTS and DAS techniques in a real-life network requires detailed investigation.

4.2.3. Raman distributed temperature and strain fiber optics

Signals generated by the Raman distributed temperature and strain fiber optics are sensitive to strain and temperature. Raman distributed temperature and strain fiber optics have been established as the primary means for long-range temperature and strain measurement due to their high sensitivity level, simplicity, and long sensing range (Masoudi & Newson 2016). The comparison between the stoke and anti-stoke relays information about the temperature in Raman distributed sensors (Niklès *et al.* 1996). Chelliah *et al.* (2010) showed that the Raman distributed temperature sensor (RDTS) can be used to detect water leaks. The study was premised on the combined benefit of the optical time-domain reflectometer (OTDR) and the temperature dependence of Raman scattering. The unique feature of RDTS is that it is possible to collect relevant measurements along the whole length of the sensor. The fiber optics sensor was laid below and above the pipe in the experiment. A laser pulse was introduced into the fiber, which scattered across the fiber's length. The backscatter stokes and anti-stokes were separated using filters. A thermocouple was introduced in the experiment to measure the water temperature.

A threshold was determined to detect leaks individually and when the temperature reading exceeded the pre-determined threshold, the leak was detected. The mean and the standard deviation were regularly amended to have a new threshold. The unique contribution of the study is the ability of the RDTS to detect water leaks and reduce false alarms simultaneously. The utilization of the RDTS in a real-life setting needs further comprehensive inquiry.

5. RESEARCH GAPS AND FUTURE DIRECTIONS

This section discusses the research gaps emerging from the qualitative review carried out.

5.1. Research on real WDNs

The majority of the past studies were conducted in the laboratory, where water leaks were already known even before the trials were conducted. The main challenge for real-life deployment of fiber optics technology is to identify and overcome practical and economic issues in its implementation. As it is still in the testing phase for the water sector, there is less experience for practitioners available in the area about the possible field issues. The technology is more expensive than several other already-in-use technologies; therefore, it is only favorable for a long-term and long-range deployment preferably an entire network. Moreover, deployment in an urban environment involves the risk of signal interference from urban activities such as traffic and damage to optical fiber for which repair or replacement can then pose a huge challenge to practitioners. However, Meribout & Khezzar (2020) review the possibility of an optical fiber system being a more robust leak detection system for oil and gas pipelines. Thus, the potential can be similarly explored through further research for the case of water pipelines as well.

5.2. Research on mitigating high cost, deployment and maintenance issues

The literature review revealed that most of the studies adopted distributed optical fibre sensors (DOFS) sensing mechanism for leak detection and localization (Nikles *et al.* 2004; Li *et al.* 2021; Yao *et al.* 2021). Research demonstrating other available fiber optics sensing systems for leak detection is limited and their potential of higher efficiency and cost-effectiveness is less explored. For example, Guo *et al.* (2019) used a fiber-optic-based hydrophone for successful leak detection and early alarm, but the study did not cover any solution for practical implementation and financial limitations. Overall, the cost of procurement has been the major barrier limiting the utilization of fiber optics technology in the WDN for long-term monitoring.

Additionally, fiber optics technology is expensive to install due to the requirement for specialized equipment and specialized skilled workers, and maintain due to the vulnerability to physical damage. They are mostly deployed within conduits close to the pipeline and may damage during repairs because challenges such as horizontal directional drilling (HDD) often occurs in this process which has a high operating cost due to the need to use specialized equipment (Yan *et al.* 2018). Most of the times as-built drawings of underground utilities are not very accurate. Thus, problems can arise and special care must be taken during cable deployment to prevent damage.

Table 2 | Comparison of main findings

Prevalent fiber-optic based systems	Distinguishing characteristics	Limitations	References
Optical fiber-based accelerometer	<ul style="list-style-type: none"> Discrete fiber-optic system High leak detection accuracy High sensitivity and quick response time Better linearity and wavelength modulation 	<ul style="list-style-type: none"> Experimentation limited to laboratory scale Limited understanding of distance-setting and flow measurement precision for the experiments 	Jiang <i>et al.</i> (2020)
Distributed vibration optical fiber	<ul style="list-style-type: none"> Small size, lightweight, and high sensitivity Multiple leak detection possible 	<ul style="list-style-type: none"> Prone to high attenuation over a longer distance Demonstrated for small diameter and steel pipes only 	Wu <i>et al.</i> (2015) and Png <i>et al.</i> (2018)
Optical fiber-based hydrophone	<ul style="list-style-type: none"> Useful for real-life monitoring 	<ul style="list-style-type: none"> Experimentation limited to laboratory scale testing Further study required to develop technology for leak localization 	Guo <i>et al.</i> (2019)
Fiber laser dynamics-based fiber optics	<ul style="list-style-type: none"> Effective for both leak detection and localization 	<ul style="list-style-type: none"> Small scale adoption carried out only 	Law <i>et al.</i> (2018)
Macro-bend coated-based fiber optics	<ul style="list-style-type: none"> Bending loss-based detection Cheaper than other fiber sensors 	<ul style="list-style-type: none"> Only demonstrated for low-pressure pipelines only Technique developed for leak detection only 	Ong <i>et al.</i> (2017)
Acousto-optic sensors	<ul style="list-style-type: none"> Applicable to both leak detection and localization 	<ul style="list-style-type: none"> Leak localization limited over long distance 	Kothandaraman <i>et al.</i> (2020a)
Distributed differential temperature sensor (DdTS) and distributed acoustic sensor (DAS)	<ul style="list-style-type: none"> Long-range monitoring Detection of small leaks Rapid leak detection time Low false alarms Real-time monitoring Low operating cost and third-party intrusion detection 	<ul style="list-style-type: none"> Leak detection, sensing, and intruder notification are limited to 40 km 	Wang <i>et al.</i> (2018)
Raman distributed temperature and strain fiber optics	<ul style="list-style-type: none"> Long-range temperature and strain measurement Reduced false positive rate Simple design 	<ul style="list-style-type: none"> Real-life application requires a comprehensive study 	Masoudi & Newson (2016)

Besides, the fiber optics sensors are deployed into an existing water pipeline through an opening made on the pipe. Water contamination may occur when the fiber optics sensor is introduced into a pipeline. Therefore, more research should be conducted on the deployment of fiber optics in existing pipelines. Moreover, it is very challenging to troubleshoot glitches such as insufficient power transmission, excessive signal loss, faulty connections, in a fiber optics monitored system. Currently, little information is available regarding repairing a damaged fiber optics sensor on a WDN. More researches should be directed toward troubleshooting and the maintenance of installations using fiber optics technology.

To explore more cost-effective and safer solutions, cheaper fiber optics sensors and cables need to be developed by exploring alternative fabrication technologies and easy deployment strategies. For real-time monitoring, researchers in the fiber optics water leak detection and localization domain can explore other traditional sensing methods, such as vibrational sensors (MEMS accelerometers) due to their low cost and high sensitivity ability (Tariq *et al.* 2020), to investigate if the combination of fiber optics and accelerometers can reduce the cost.

6. CONCLUSION

This study cast a lens on fiber optics technology application for water leak detection and localization by carrying out a systematic review of relevant papers on water leak detection in two phases: scientometric (including bibliometric search and scientometric analysis) and qualitative analyses. Science mapping analysis revealed *Sensors* (Switzerland) as the most productive publication source and Wang Q as the most influential research author. Among the influential countries, China is noted to be the country with the highest number of publications. Lastly, 'Leakage detection' and 'Fiber optics sensors' are the top keywords with the highest occurrence in the included articles depicting authors' interest in leakage detection using fiber optics sensors.

The qualitative analysis showed that when compared with the other types of techniques, the acoustic-based technique has attracted more research interest, which was further grouped into six types: (1) accelerometer-based fiber optics, (2) distributed vibration-based fiber optics, (3) hydrophone-based fiber optics, (4) fiber laser dynamics-based fiber optics, (5) macro-bend coated-based fiber optics, and (6) acoustic-based fiber optics. Our research revealed that there are limited studies available on the application of temperature and strain techniques for water leak detection and localization. The results further show that studies using hybrid fiber optics are also limited. For example, only one article focused on the combination of temperature, strain, and acoustic fiber-based techniques. A comparison summary of the main findings for the prevalent optical fiber-based leak detection and localization systems is presented in Table 2.

In light of identified limitations and gaps, our research identified five future directions: (1) research on real WDNs, (2) cost reduction of fiber optics technology, (3) deployment of fiber-optic sensors cable, (4) use of hybrid techniques for leak detection and localization in a WDN, and (5) repair issues of fiber optics sensor.

Our study showed that there is a limited understanding of the application of fiber-optic sensing technology for water leak detection and location. Through the detailed review, the study filled this gap by guiding practitioners about the past work, the current state of its application, and issues in implementation. Thus, practitioners and researchers can use the findings of the current study to further their experiments on the use of fiber optics in WDN applications.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support from the Innovation and Technology Fund (Innovation and Technology Support Programme (ITSP)), Hong Kong, and the Water Supplies Department, Hong Kong, under grant number ITS/067/19FP. The authors would also like to thank the two anonymous reviewers for their useful comments.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 27 May 2021; accepted in revised form 9 September 2021. Available online 24 September 2021