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Review

Micro-electromechanical systems-based technologies for leak detection and localization in water supply networks: A bibliometric and systematic review

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A B S T R A C T

Leakages from water pipelines cause economic losses and environmental hazards. Despite the damages, it is challenging to avoid leaks throughout the lifetime. However, leak detection and localization, especially in real-time, minimize the damage. Owing to the recent advances, the micro-electromechanical systems (MEMS) based technologies have started to gaining recognition for water network monitoring in real-time, however, a systematic literature review to analyze the existing research trends, technological advances, and future research opportunities are largely missing. This study has based its investigation on three main MEMS-based technologies for real-time monitoring: MEMS sensors wireless networks, MEMS accelerometers, and MEMS hydrophones. Firstly, a scientometric analysis is conducted to 1) retrieve relevant research articles through Scopus, Web of Science, and Google Scholar, 2) visualize the publication trends, and 3) analyze the science mapping of influential authors, countries, organization, and top keywords occurrences. Secondly, qualitative discussions are made on research themes and sub-themes within three technologies: 1) MEMS WSNs are classified into static and mobile sensor-based wireless sensor networks. Seven sub-themes are categorized under static sensor-based wireless sensor networks such as PIPETECT, whereas three sub-themes are categorized under mobile sensor-based WSNs such as TriopusNet; 2) MEMS accelerometers are categorized into accelerometers based machine learning models and wireless systems; and 3) MEMS hydrophones are represented under one category. Thirdly, nine research opportunities including automated models, on-field real network-based experimental studies, optimal placement of sensor nodes for energy savings in wireless sensor networks, and a comparative analysis of real-time technologies are revealed. This study enhances the familiarity of early researchers with the application of MEMS-based technologies for leak detection and localization and provides seasoned researchers with a platform for future research development.

Contents

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1. Introduction

The world's population is escalating by 80 million people annually and is expected to reach a staggering 9.1 billion by 2050 (Connor, 2015). Population growth (Zhang and Tariq, 2020), urbanization (UN, 2018), industrialization (Boretti and Rosa, 2019), and resource-intensive consumption patterns (UN, 2018) have all led to accrescent demands for clean water. Global freshwater use has increased nearly six-fold since 1900 (Ritchie and Roser, 2015). In 2014, annual freshwater withdrawal in India, China, and the USA, for instance, was estimated at a massive 760 billion-m^3, 600 billion-m^3, and 450 billion-m^3, respectively (Ritchie and Roser, 2015).

The freshwater is transmitted regularly through water distribution networks (WDNs) using an extensive system of underground and above-ground pipelines. The function of WDN is to provide water at an acceptable pressure 1) safely (Al-Hawari et al., 2015), 2) economically (Barton et al., 2020), and 3) without losses (NRC, 2007). However, it is a sad fact that the WDNs, globally, are facing the dilemma of water losses (Winarni, 2009) which adversely affects the efficiency (Taha et al., 2016) and financial aspects of networks (Tariq and Zhang, 2020). Water losses typically exceed over 30% in most WDNs (Hunaidi et al., 2000; USEPA, 2010); Farley and Trow (2003) reported 35% as the global average. In older networks, these losses may exceed 50% (Kanakoudis and Muhammetoglu, 2014) and may even reach 70% in certain cases (Martini et al., 2017). Multiple causes of water losses include leakages (Hunaidi et al., 2000), metering errors (El-Zahab and Zayed, 2019), and theft (El-Abbasy et al., 2016), however, the largest part is ascribed to leakages (Kanakoudis, 2004) which sometimes represents more than 70% of the non-revenue water (Van Zyl and Clayton, 2007). Therefore, adequate approaches/techniques to detect and locate leaks in real-time are imperative to minimize the damage.

Noise loggers are the most popularly used real-time water leak and detection technologies (El-Zahab and Zayed, 2019). These acoustic-based technologies are placed in utility holes/valves without trenching and used for permanent and semi-permanent monitoring. Sophisticated algorithms are applied to distinguish leak sounds, thus leaks are detected immediately. Several loggers are typically placed throughout the network and the data is continuously delivered through a communication base. Analysis base (e.g., computer) then receives the data where pre-programmed correlation analysis is applied for faster detection and location (El-Zahab and Zayed, 2019). However, noise loggers, firstly, are prone to false alarms and, secondly, are considered to be 'not-so-effective' for plastic pipes and polyethylene pipes (Beuken et al., 2008). Secondly, the initial cost for real-time monitoring with noise loggers is high (El-Zahab and Zayed, 2019), and the exact location of leaks is not possible without the use of correlators (Hunaidi and Wang, 2006). Therefore, MEMS-based alternate technologies including wireless sensor networks (WSNs), accelerometers, and hydrophones, as alternative technologies, owing to the recent advances in MEMs, have become a 'talking point' among researchers and practitioners lately.

For example, MEMS technology has enabled the development of autonomous wireless sensor nodes, ranging in size from several mm to even as low as 1 cubic mm (Warneke and Pister, 2002), that exceed the performance of conventional sensors (Yick et al., 2008). A small-sized smart node may contain sensors for measuring pressure (Sun et al., 2011), flow (Zhang et al., 2013), temperature (Arthi et al., 2013), acoustic (Sun et al., 2011), moisture (Abbasi et al., 2014), humidity (Ganiyu et al., 2014), etc., a processor, a storage memory, a power source, a communication interface, and an actuator (Akyildiz et al., 2002). Such nodes can be deployed rapidly in-pipe (Abbas et al., 2018) or out-of-pipe (Duru and Ani, 2017) to allow effective wireless communications over the long-range of WDNs (Owojaiye and Sun, 2013; Abedeji et al., 2017). The sensors in each node collaboratively work with each other, neighboring nodes, and cluster nodes, thus forming a WSN to precisely identify and locate leaks (Warneke and Pister, 2002). For example, Sun et al. (2011) used a combination of pressure sensors, acoustic sensors, and soil property sensors for their proposed WSN. The acoustic sensor was used to complement the pressure sensor at the checkpoints. Pressure measurements were taken during transient and were sent to the remote admin center for comparison with steady-state measurements. If a threshold was exceeded, the remote control center notified the nearby pressure sensors of the suspicious area. The pressure sensors then sent out the message to the soil property sensors along that pipe segment. The data was then transferred to the processing hub which located the leak. Afterward, the results were transmitted to the admin center using wireless communications to notify the human operator. MEMS accelerometers, on the other hand, are placed on the pipe surface to measure vibrations for determining variations in pressure that occur due to pipe rupture or damage. For example, Shinozuka et al. (2010a) accurately defined the leak location using MEMS accelerometers non-invasively.

The increasing recognition of MEMS-based WSNs (Jawhar et al., 2007), accelerometers (El-Zahab et al., 2018), and hydrophones (Zhang et al., 2009) has attracted researchers worldwide and multiple studies have been carried out such as Metje et al. (2011) and Lalle et al. (2019). However, systematic literature reviews to investigate research evolution, themes, and future scholarly opportunities in this domain is missing. Sheltami et al. (2016) and Abdelhafidh et al. (2018) reviewed WSNs for pipeline monitoring. The former mostly focused on the software methods employed for leak detection in general and included some details about recent advancements in WSNs. The latter provided some critical insights but didn't specifically review from the perspective of leak detection and location in water pipelines. Besides, both these reviews didn't include database-based scientometric analysis which reduces the chances of 1) biasedness in the selection of research articles, 2) missing any important articles, and 3) inclusion of non-relevant articles for the qualitative review. No comprehensive literature review, as per the best of the authors' knowledge, was found for MEMS accelerometers and MEMS hydrophones.

This research conducted a thorough systematic literature review considering three MEMS technologies including WSNs, accelerometers, and hydrophones. The objectives include 1) analyzing the research trends and evolution in this domain, 2) disclosure of productive journal sources, researchers, countries, and research organizations, and links between them (productivity of a research entity was evaluated in six different perspectives i.e. the number of related publications, total citations, average citations, total normalized citations, average normalized citations, and average publication year), 3) classification and discussion of existing research, and 4) identifying the research directions.

2. Research methods

The research methodology for the systematic review in this study was divided into two distinct phases: 1) scientometric analysis and 2) qualitative analysis. Scientometric analysis began by validating the research idea through a preliminary search. Then, inclusion and exclusion criteria were defined for the selection of articles for review followed by developing the search strategy for retrieving articles from databases. The list of articles was narrowed down (removal of non-relevant articles) further using abstract and full screening, and the snowballing techniques were then applied for retrieving any missing relevant articles. Finally, publications trend analysis and science mapping analysis was performed. For the second phase i.e. qualitative analysis, a full-text perusal of articles was conducted to enable 1) classification of research themes within three technologies, and 2) finding future research directions. The overall research methodology is given in Fig. 1.

2.1. Scientometric analysis

The scientometric analysis was adopted to use bibliometric data to scientifically map the literature. The scientometric analysis provides a quantitative way to overcome the diagnostic limitations (Su and Lee, 2010) and the error-prone nature of manual approaches (Van Eck and Waltman, 2010). The usefulness of scientometric analysis has been demonstrated by researchers in the recent past on important topics such as sustainable megaprojects (Wang et al., 2020); green buildings (Darko et al., 2019); bikesharing (Si et al., 2019); computer vision applications in construction (Martinez et al., 2019), bridge inspection (Abdelkhalek and Zayed 2020); sustainable development (Olawumi and Chan, 2018); off-site construction (Hosseini et al., 2018); public-private partnerships (Song et al., 2016); software project management (Calderón and Ruiz, 2015); building information modeling (Zhao, 2017); and health and safety of women in construction (Mariam et al., 2020). Step by step procedure for scientometric analysis adopted in this research is given as follows.

2.1.1. Preliminary validation

Preliminary validation was carried out through a simple search in *Google Scholar* to 1) ensure the validity of review article in the global context reflecting the current science, 2) gain familiarity with existing review methodologies, 3) find any existing review article addressing a similar question, and 4) check the availability of enough articles. Besides, two online meetings were conducted with experienced public sector representatives, that were actively involved in leak and detection for local WDNs, who further confirmed the need for a review article on MEMS-based technologies for practitioners. Two related but not similar review articles, as mentioned previously, were found which helped in the better formulation of the research question.

2.1.2. Inclusion and exclusion criteria

Inclusion and exclusion criteria are typically defined to 1) describe the characteristics of relevant articles that contain necessary information regarding a research question, and 2) refrain the researchers from personal bias. The inclusion criteria for this study are as follows: 1) research articles focusing on water leak detection and localization using MEMS WSNs, MEMS accelerometers, or MEMS hydrophones, and 2) no restriction on publication year and contributing country/organization. Exclusion criteria for this study are as follows: 1) research articles focusing on leak detection and localization in a pipeline carrying fluids other than water such as oil and gas; 2) research articles focusing on water leak and detection using technologies other than MEMS WSNs, MEMS accelerometers, and MEMS hydrophones; 3) research articles from non-relevant research domains such as astronomy, molecular biology, etc.; 4) abstract only articles; 5) articles with no full-text available; and 6) non-English articles.

2.1.3. Database-based search strategy

Developing an appropriate search strategy begins with the selection of databases to retrieve articles. This selection typically depends on the popularity in a given research domain and the availability of research articles. Tawfik et al. (2019) advised choosing multiple databases to increase the accuracy and comprehensiveness of search results. Following their suggestion, *Scopus, Web of Science,* and *Google Scholar* were chosen due to their

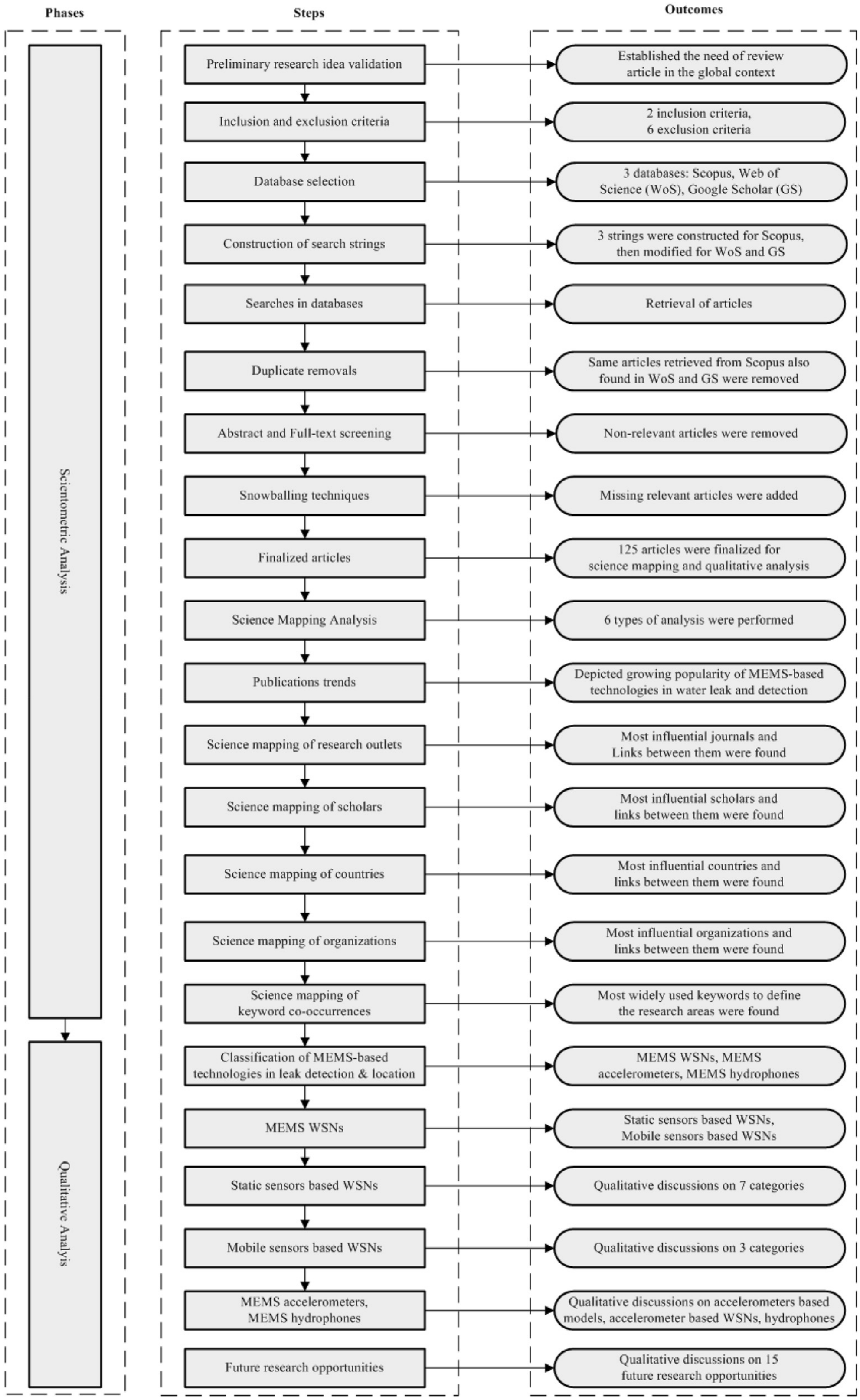

Fig. 1. Research methodology.

wide coverage of research sources (Hussein and Zayed, 2020) and popularity in the field of Engineering (Abdelmageed and Zayed, 2020). Since *Scopus* is the largest citation database of peer-reviewed research articles, a basic search using 'MEMS', 'accelerometers', 'hydrophones', 'wireless sensors', and 'water leak' as keywords were conducted and then refined based on the search results. The improvements in search terms were made through trials, and after several rounds of refinement, the following three search strings were constructed.

1) TITLE-ABS-KEY ("WSN" OR "WSD" OR "Wireless sensor device" OR "wireless sensor network" OR "wireless distribution network" AND "water leak" OR "pipe leak" OR "leak detection");
2) TITLE-ABS-KEY (("MEMS" OR "Micro electro mechanical system" OR "MEMS sensor") AND ("water leak" OR "pipe leak" OR "leak detection" OR "pipe monitoring" OR "water distribution system" OR "water distribution network" OR "hydrophones"));
3) TITLE-ABS-KEY ("accelerometer" AND "water leak" OR "pipe leak" OR "water distribution system" OR "water distribution network" OR "leak detection").

The search strings yielded 244 articles from *Scopus* and after applying filters through the database such as the exclusion of non-English articles, exclusion of articles published in non-relevant research areas, etc. 208 articles were retrieved. Bibliometric information regarding these articles was downloaded and listed in a *Microsoft Excel* file. Following *Scopus*, the same process of searching by constructing search strings, applying filters, and listing the bibliometric information of retrieved articles was conducted in *Web of Science* and *Google Scholar*. Duplicate articles that appeared in *Scopus,* and one of the other two databases were removed. In total, 292 articles were retrieved from all three databases.

2.1.4. Abstract and full-text screening

To minimize the handling of non-relevant articles, a further assessment of 292 retrieved articles was made through abstract screening. This screening process was carried out in two consecutive phases. In the first phase, the first author read and examined the abstracts of each of the 292 articles and omitted the articles that contained keywords but didn't concern the leak and detection in water pipelines at all. For example, Guépié et al. (2020) discussed leak detection in a heat exchanger of a sodium-cooled fast reactor. Such and other out-of-scope articles were removed. In the second phase, the doubtful articles were discussed one-by-one in weekly meetings with the principal investigator and two other researchers who were familiar with water leak and detection technologies and had a thorough understanding of the scientometric analysis. Upon reaching a unanimous decision in those meetings, the doubtful articles were discarded/included. In case of any contradiction, the final decision was made on the recommendation of the principal investigator. Abstract screening process reduced the sample size to 85 articles.

The next step was to download each research article for full-text screening. Full-text was not available for some papers, and therefore, such articles were discarded. Abstract-only articles were also discarded at this step. The articles that did not focus on real-time monitoring were omitted as well. Full-text screening followed the same set of protocol (used in abstract screening) for doubtful articles and, eventually after this step, 67 articles were left to be sent to the next phase of snowballing.

2.1.5. Snowballing

The accuracy of a database search is highly dependent on the constructed search strings. Both backward and forward snowballing techniques were applied to overcome the inaccuracies of search strings. In the backward snowballing, references of each article were checked and relevant articles were found. In the forward snowballing, the relevant cited-by articles were retrieved for each already included article. Each newly retrieved article went through the same set of consecutive scrutiny through abstract screening, full-text screening, and snowballing processes. This tedious process led to the addition of 58 new articles. 125 articles in total were finalized for further science mapping and qualitative analysis. See Fig. 2 for retrieval of articles through databases and snowballing.

2.1.6. Science mapping analysis

Science mapping is a technique that is capable of mapping out patterns and networks from a set of bibliometric data (Cobo et al., 2011). This technique was applied to show the working linkages and measurements of researchers, article sources, contributing countries, and keywords within the literature represented/visualized through graphical networks. Several software applications are popularly used for such analyses e.g., VOSviewer, Gephi, Cite explorer, Vintage point, etc. (Wuni et al., 2019). Some of the software applications are developed for general science mapping purposes and others have advanced use within the science mapping philosophy. The capacity, strength, and limitation of every application vary (Wuni et al., 2019). For this study, VOSviewer was adopted mainly due to the ease of use and its popularity in the infrastructure management literature (Abdelmageed and Zayed, 2020). In a word, VOSviewer is open-source software with sufficient capability for visualizing and analyzing bibliometric data through its text mining features, befitting the requirements of this study.

2.2. Qualitative analysis

Qualitative analysis was conducted to analyze the finalized articles to establish research themes within the existing literature and investigate how MEMS WSNs, MEMS accelerometers, and MEMS hydrophones were used for water leak and detection. Data was compiled regarding 1) research contribution, type of pipes, placement of technologies, data transfer, accuracy, parameters, software, monitoring, etc. for each article; 2) research gaps within the articles on each technology; and 3) future research directions based on the research gaps.

3. Discussions on science mapping results

Discussions on science mapping results are divided into 1) publication trends, 2) science mapping of research outlets, 3) science mapping of scholars, 4) science mapping of countries and organizations, and 5) science mapping of keywords co-occurrence.

3.1. Publication trends

Since MEMS is an emerging technology, the use of MEMS-based WSNs, accelerometers, and hydrophones in water leak detection and location started to attract researchers in the last decade. This study finalized a total of 125 articles and the search query was not constrained by the time. The first publication still appeared in 2004. Since then, except for 2005 and 2008, multiple publications have appeared each year. Years 2005 and 2008 each witnessed only one publication.

Fig. 3 demonstrates increasing interest among researchers regarding MEMS-based technologies especially after 2010. Regarding the performance of the previous year, some years saw a decrease in publication. This trend can be observed for years 2012, 2015, and 2019 in the last decade. From Fig. 3, it can be seen that 2020 also showed a declining trend relative to 2019 but that is

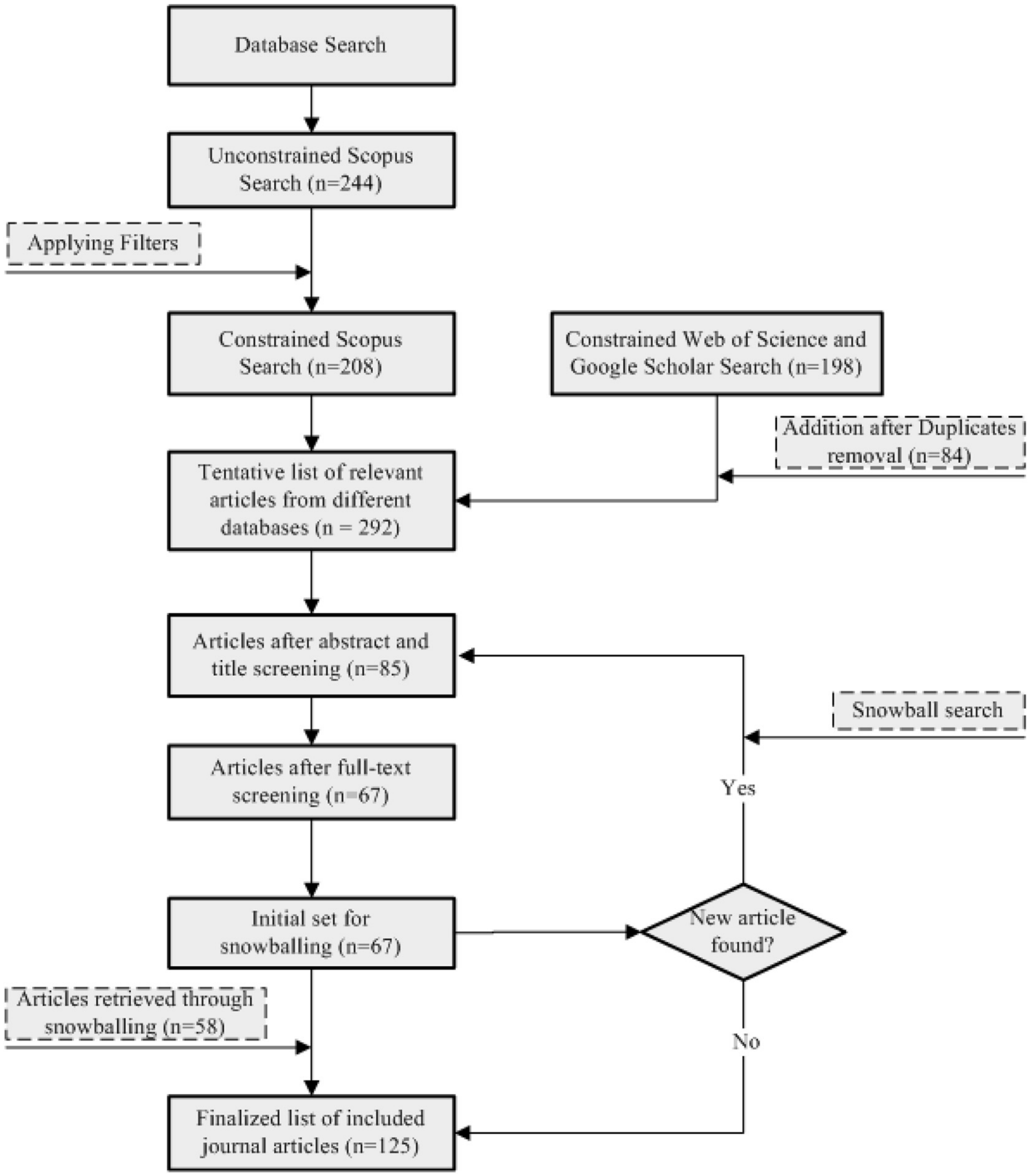

Fig. 2. Retrieval of articles from databases and snowballing search.

mainly due to the fact that the authors retrieved the bibliometric data in April 2020. More than half of the articles i.e. 63 were published in the span of four years between 2016 and 2019. The highest number of articles i.e. 18 were published in 2018, closely followed by 2017 and 2016 at 16 and 15, respectively. Although a sinusoidal pattern of publications' trend is depicted from 2010 to 2019, however, observing researchers' interest in recent years, it is safe to assume that much more research commitments are anticipated in this domain in the near future.

3.2. Science mapping of research outlets

Research outlets are the sources for disseminating information for research and innovation development. These outlets publish research material within the set of their scope (Rodríguez-Bolívar et al., 2018). Fig. 4 shows the network of research outlets in this domain. The threshold limit on the maximum number of articles published and citations was set at '1' and '30', respectively, in VOSviewer. The literature didn't set any standard rules on these restrictions for the scientometric analysis (Wuni et al., 2019). 15 research outlets met the threshold limit. The size of the nodes, in Fig. 4, represents the productivity of a research outlet in terms of total articles published. 'IEEE Access' and 'Sensors (Switzerland)' has the largest nodes, indicating that these journals were more productive than other research outlets. Other notable research outlets include 'Adhoc Networks', 'IEEE Transactions on Industrial Informatics', 'International Journal of Distributed Sensor Networks', 'Journal of Pipeline Systems Engineering and Practice', 'Procedia Computer Science', and 'Sensors'. The color and closeness of nodes depict the strong citation linkages among different outlets. For example, 'Adhoc Networks', 'IEEE Networks', and 'Journal of Pipeline Systems Engineering and Practice' are placed close together in the green cluster, showing stronger citation links between these journals.

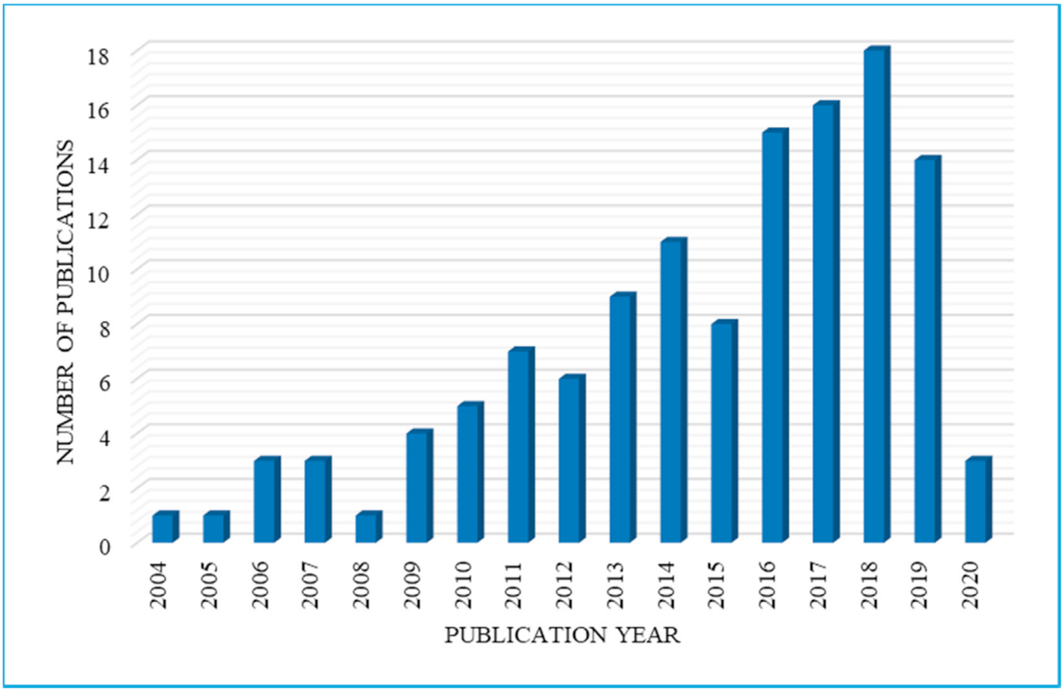

Fig. 3. Annual publication trends.

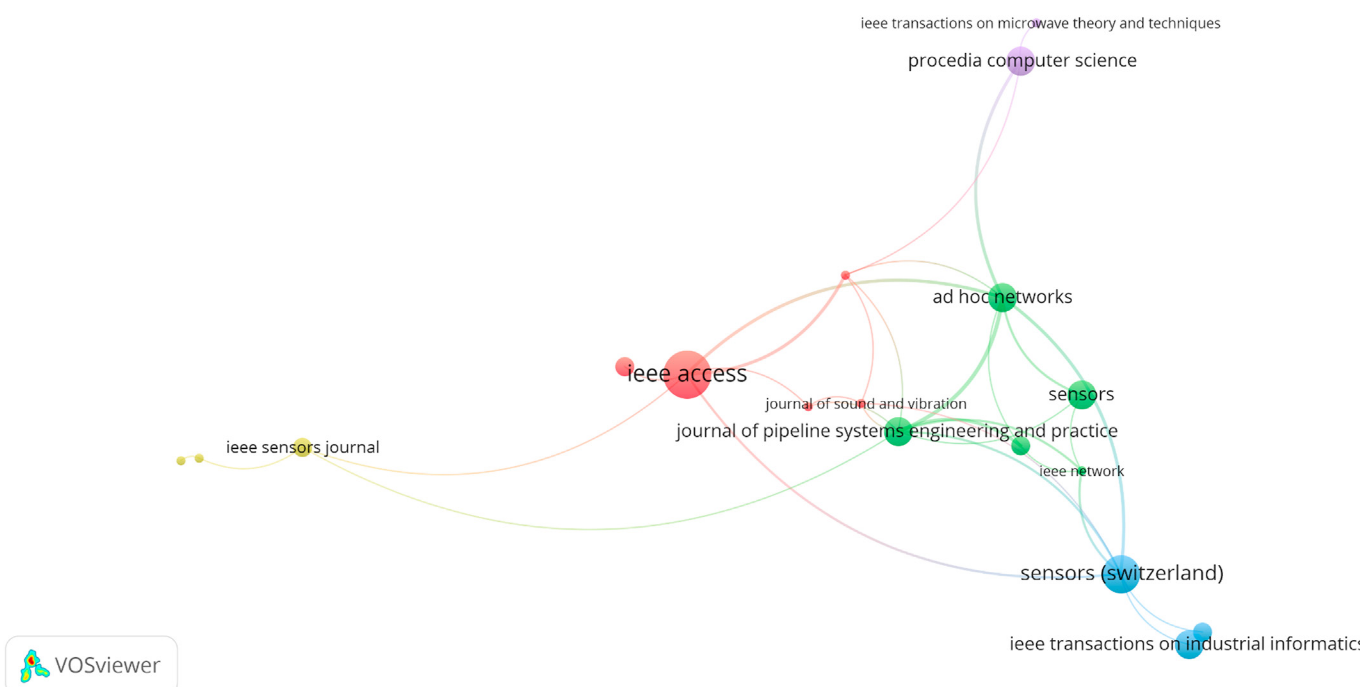

Fig. 4. Network analysis of research outlets.

Table 1 shows the qualitative measurements of the top research outlets in terms of avg. normalized citation score. 'Journal of Sensor and Actuator Networks', 'Structure and Infrastructure Engineering', and 'Applied Acoustics' are found to be the most influential research outlets in terms of avg. normalized citation. 'IEEE access' and 'Sensors (Switzerland)' which published the highest number of articles didn't appear in top research outlets as per this criterion. In terms of total citation and link strength, 'Ad Hoc Networks' was the most productive research outlet. In terms of the average citation, the most influential research outlet is found to be the 'Journal of Sound and Vibration'. The average publication year which measures the recentness of the publications in the same research outlet (Jin et al., 2019) did not vary significantly as most of the top research outlets published articles in recent years.

Table 1
Top research outlets.

Research outlets	No. of Articles	Avg. publication year	Total citations	Avg. citation	Links	Total links strength	Normalized Citation	Avg. Normalized citation
Journal of Sensor and Actuator Networks	1	2014	73	73	4	6	3.36	3.36
Structure and Infrastructure Engineering	2	2017.5	47	23.5	3	5	6.30	3.15
Applied Acoustics	2	2015	92	46	1	1	5.0	2.50
Ad Hoc Networks	2	2012	174	87	6	12	4.9	2.43
Journal of Pipeline Systems Engineering and Practice	3	2018.33	30	10	9	16	6.72	2.24
IEEE Transactions on Industrial Informatics	3	2017	88	29.33	1	1	6.54	2.18
Shock and Vibration	1	2015	38	38	3	3	2.06	2.06
Sensors (Switzerland)	4	2015.5	136	34	7	11	8.18	2.045
IEEE Transactions on Microwave Theory and Techniques	1	2009	36	36	1	1	1.57	1.57
IEEE Network	1	2011	63	63	4	6	1.48	1.48
Sensors	2	2010.5	73	36.5	3	3	2.78	1.39
IEEE Access	5	2018	43	8.6	5	9	6.90	1.39
Procedia Computer Science	3	2014.67	67	22.33	3	4	3.35	1.12
Journal of Sound and Vibration	1	2005	112	112	4	4	1.0	1.0
IEEE Sensors Journal	2	2011.5	41	20.5	2	2	1.14	0.57

3.3. Science mapping of scholars

Citation analysis of scholars was conducted using VOSviewer. The threshold limit for the number of documents was set at ‘1’ and the number of citations was set at ‘30’. 81 authors met the threshold as visualized in Fig. 5. The node size represents the number of publications of each scholar. For example, Abid, M. is found to be the most productive scholar with 9 publications. Other scholars which published 5 or more articles, as shown in Table 2, are as follows: Obeid, A.M. (7), BenSaleh, M.S. (6), Saeed, H. (5), Rashid, S. (5), and Karray, F. (5). Scholars are divided into clusters of different colors depending upon their mutual influences in Fig. 5. For example, Abid, M., Obeid A.M., and BenSaleh, M.S. appear in the same cluster depicting that they regularly cited each other’s scholarly work. The distance and links between scholars further represent the influence of scholars on each other. For example, Abid, M. and BenSaleh, M.S. are shown close together indicating a strong linkage between them.

Further qualitative measurement of top scholars based on academic influence is given in Table 3. The scholars are listed in descending order of their average normalized citation score. Anthony, C.J., Chapman, D.N., Davoudi, S., Mostafapour, A., Akyildiz, I.F., Al-Dhelaan, A.M., Al-Rodhaan, M.A., Sun, Z., Vuran, M.C., and Wang, P. are the most influential scholars in terms of average normalized citation score, however, all these scholars published one article each. Among the scholars with multiple publications, Atamturktur, S., Piratla, K.R., and Vazdekhasti, S. has the highest influence. In terms of average citations, Akyildiz, I.F., Al-Dhelaan, A.M., Al-Rodhaan, M.A., Sun, Z., Vuran, M.C., and Wang, P. has the highest academic contribution with 132 citations each. As it can be seen from the average publication year in Table 3, Atamturktur, S., Piratla, K.R., Vazdekhasti, S., and Arshad, Q. published their articles recently.

3.4. Science mapping of countries and organizations

The knowledge of the influential countries may foster collaboration for joint funded projects and the exchange of researchers

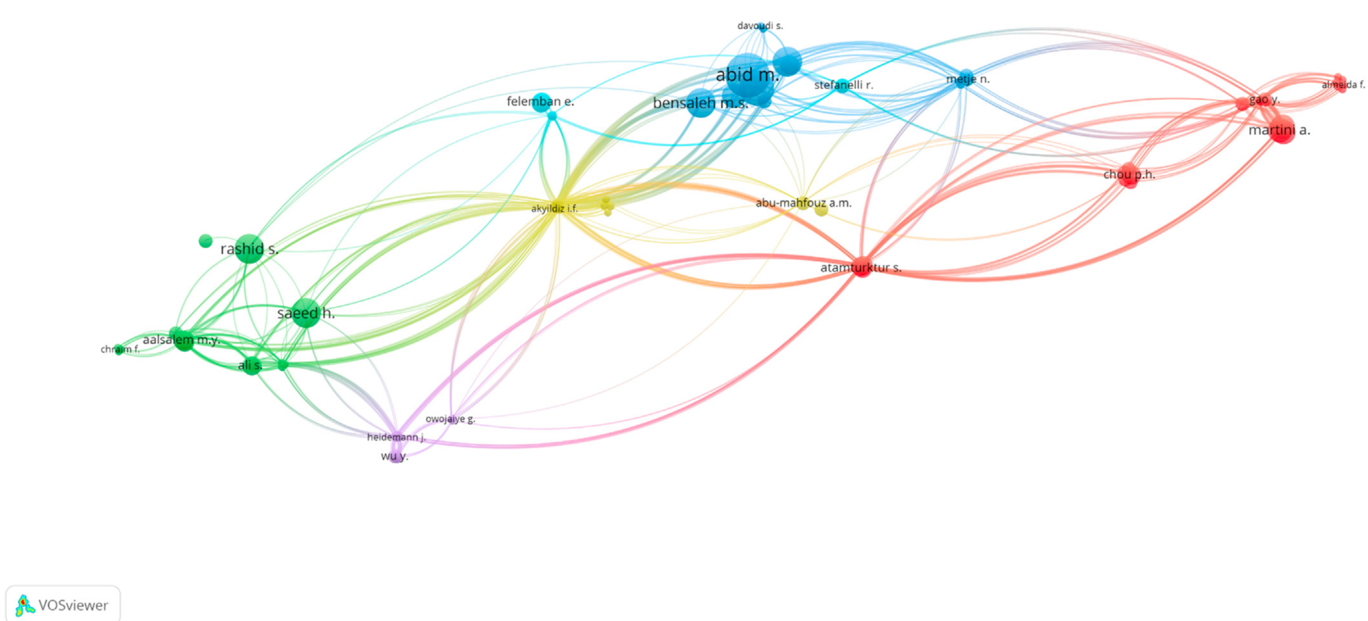

Fig. 5. Network analysis of research scholars.

Table 2
Contribution of most productive researchers.

Author	Number of publications	Articles contributed in
Abid, M.	9	Elleuchi et al. (2019, 2015); Karray et al. (2019, 2018, 2016, 2014); Obeid et al. (2016); Saida et al. (2016)
Obeid, A.M.	7	Elleuchi et al. (2015); Karray et al. (2018, 2016, 2014); Obeid et al. (2016)
BenSaleh, M.S.	6	Almazyad et al. (2014); Ayadi et al. (2017); Elleuchi et al. (2015); Karray et al. (2014); Obeid et al. (2016); Saida et al., (2016)
Karray, F.	5	Karray et al. (2019, 2018, 2016, 2014); Obeid et al. (2016)
Saeed, H.	5	Ali et al. (2015, 2016); Rashid et al. (2013, 2014); Saeed et al. (2014)
Rashid, S.	5	Ali et al. (2016); Rashid et al. (2013, 2014, 2015); Saeed et al. (2014)
Martini, A.	4	Martini et al. (2018, 2017, 2015, 2014)
Mysorewala, M. F.	4	Mysorewala et al. (2015); Mysorewala (2016, 2019); us Saqib et al. (2017)
Rivola, A.	4	Martini et al. (2018, 2017, 2015, 2014)
Troncossi, M.	4	Martini et al. (2018, 2017, 2015, 2014)

Table 3
Top research scholars.

Scholars	No. of Articles	Avg. publication year	Total citations	Avg. citation	Links	Total links strength	Normalized Citation	Avg. Normalized citation
Anthony, C.J.	1	2014	73	73	18	22	3.36	3.36
Chapman, D.N.	1	2014	73	73	18	22	3.36	3.36
Davoudi, S.	1	2013	77	77	6	6	3.21	3.21
Mostafapour, A.	1	2013	77	77	6	6	3.21	3.21
Akyildiz, I.F.	1	2011	132	132	30	46	3.11	3.11
Al-Dhelaan, A.M.	1	2011	132	132	30	46	3.11	3.11
Al-Rodhaan, M.A.	1	2011	132	132	30	46	3.11	3.11
Sun, Z.	1	2011	132	132	30	46	3.11	3.11
Vuran, M.C.	1	2011	132	132	30	46	3.11	3.11
Wang, P.	1	2011	132	132	30	46	3.11	3.11
Atamturktur, S.	3	2018.33	48	16	28	60	9.30	3.10
Piratla, K.R.	3	2018.33	48	16	28	60	9.30	3.10
Vazdekhasti, S.	3	2018.33	48	16	28	60	9.30	3.10
Anpalagan, A.	1	2015	55	55	19	22	2.99	2.99
Khan, M.F.	1	2015	55	55	19	22	2.99	2.99
Naeem, M.	1	2015	55	55	19	22	2.99	2.99
Chraim, F.	1	2016	44	44	4	4	2.54	2.54
Erol, Y.B.	1	2016	44	44	4	4	2.54	2.54
Pister, K.	1	2016	44	44	4	4	2.54	2.54
Qaisar, S.B.	2	2016.5	69	34.5	21	30	5.02	2.51
Arshad, Q.	2	2017.5	33	16.5	16	20	4.54	2.27
Metje, N.	2	2016	80	40	19	24	4.38	2.19
Sadeghioon, A.M.	2	2016	80	40	19	24	4.38	2.19
Ali, S.	3	2015.67	93	31	21	30	6.12	2.04
Martini, A.	4	2016	94	23.5	10	36	8.02	2.05
Rivola, A.	4	2016	94	23.5	10	36	8.02	2.05
Troncossi, M.	4	2016	94	23.5	10	36	8.02	2.05
Al-Nasheri, A.Y.	1	2014	42	42	7	7	1.93	1.93
Almazyad, A.S.	1	2014	42	42	7	7	1.93	1.93

(Abdelmageed and Zayed, 2020). Fig. 6 illustrates the network analysis of contributing countries using VOSviewer. The threshold limit for the number of citations was set at 30 and the minimum number of documents was set at 3.12 countries met the threshold limit. Saudi Arabia has the highest node size and is found to be the most productive country with 26 articles closely followed by the United States at 25 articles. Countries having mutual research influence are placed in clusters. For example, Saudi Arabia, Tunisia, and South Africa are in the same cluster and mutually cited each other work. Also, the countries that are placed closed together such as Saudi Arabia and Tunisia cited each other's work frequently.

Further qualitative measurements are given in Table 4. Countries are listed with reference to their average normalized citation scores. In terms of the average normalized citation, major changes can be observed in comparison with the countries' network. Italy and Singapore are the most influential countries in regard to the average normalized citation. Saudi Arabia, which is the most productive country in terms of the number of articles published, has lesser influence in terms of this criterion. In terms of total citations, the United States is the leading country. The United Kingdom tops the scoreboard in terms of the average citation. Most recent publications appeared from Tunisia as its average publication year is 2017.

The qualitative measurement of top organizations is given in Table 5. Similar to Table 4, organizations are also listed in descending order of their normalized citation score. In terms of average normalized citation, 'University of Birmingham, UK', 'University of Tabriz, Iran', 'Clemson University, USA', 'Georgia Institute of Technology, USA', and 'King Saud University, Saudi Arabia' are the top five research organizations. The last two organizations from the top five are leading in terms of total and average citations. With reference to average publication years, 'Clemson University, USA' has the most active researchers.

3.5. Science mapping of keywords Co-occurrence

Keywords provide an easy way to describe the main research theme of an article (Sun and Lee, 2010) and give an idea of the knowledge domain a particular article belongs to (He et al., 2017). Keywords establish a form of indexation in databases for convenient search (Wuni et al., 2019). Keywords mapping not only shows the interconnection between them but also defines the research

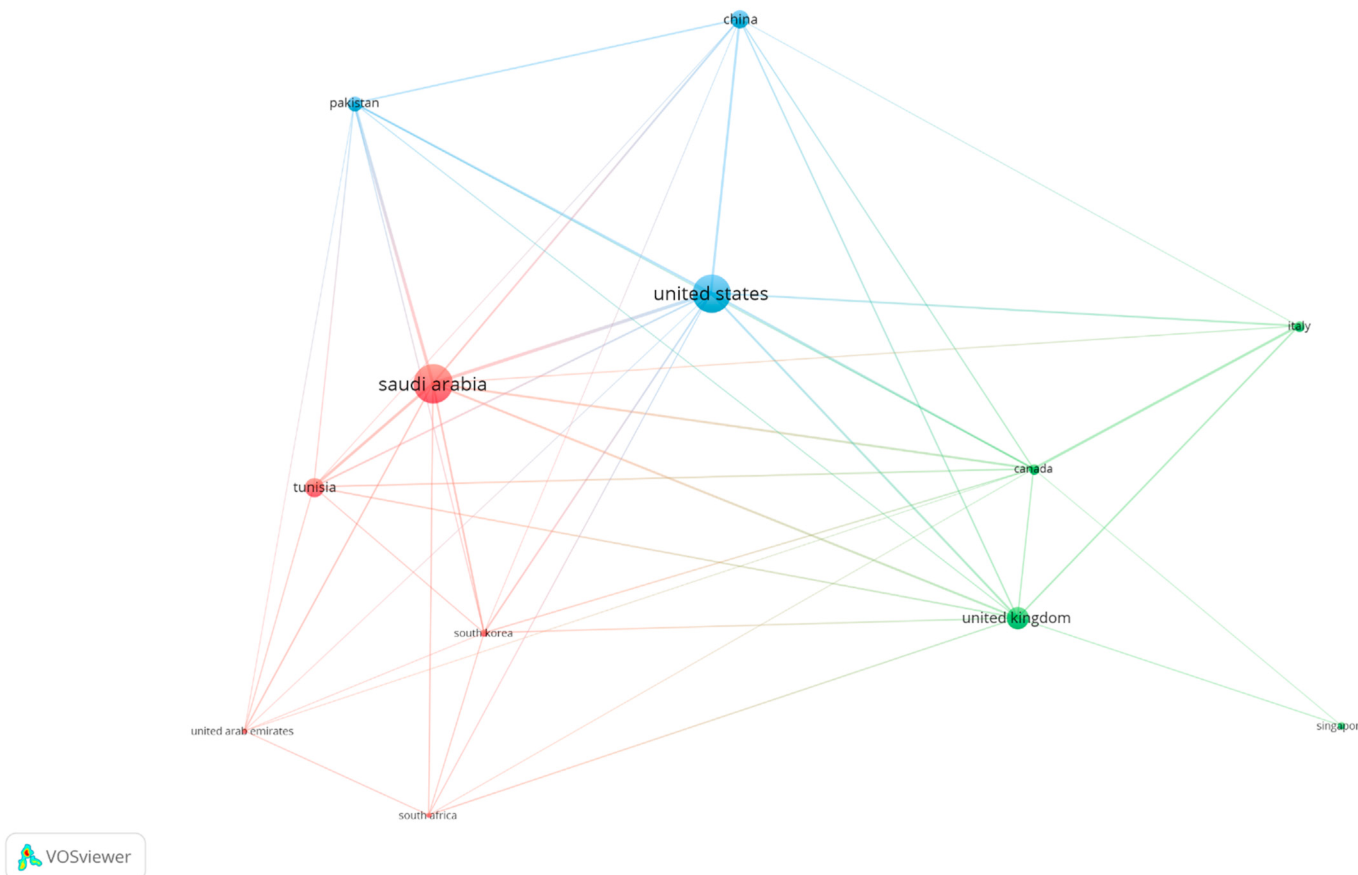

Fig. 6. Network analysis of countries.

Table 4
Top countries.

Scholars	No. of Articles	Avg. publication year	Total citations	Avg. citation	Links	Total links strength	Normalized Citation	Avg. Normalized citation
Italy	7	2015	134	19.14	5	25	9.77	1.40
Singapore	5	2014	93	18.60	2	3	6.74	1.35
United Kingdom	15	2013	463	30.87	10	42	20.14	1.34
United States	25	2014	585	23.40	10	72	31.89	1.28
Canada	7	2014	231	33.00	11	45	8.89	1.27
United Arab Emirates	3	2011	126	42.00	7	12	3.35	1.12
Saudi Arabia	26	2016	526	20.23	10	85	28.60	1.10
South Korea	5	2012	77	15.40	9	25	5.19	1.04
Pakistan	10	2016	151	15.10	8	38	9.90	0.99
South Africa	4	2016	42	10.50	6	13	3.59	0.90
China	12	2014	178	14.83	8	31	9.38	0.78
Tunisia	13	2017	122	9.39	8	33	8.31	0.64

Table 5
Top research organizations.

Scholars	No. of Articles	Avg. publication year	Total citations	Avg. citation	Links	Total links strength	Normalized Citation	Avg. Normalized citation
University of Birmingham, UK	1	2014	73	73	10	11	3.36	3.36
University of Tabriz, Iran	1	2013	77	77	3	3	3.21	3.21
Clemson University, USA	2	2017.5	47	23.5	19	19	6.30	3.15
Georgia Institute of Technology, USA	1	2011	132	132	28	29	3.11	3.11
King Saud University, Saudi Arabia	1	2011	132	132	28	29	3.11	3.11

areas within a domain. Following Jin et al. (2019), a map of 'authors keywords' was constructed in VOSviewer using 'fractional counting' as the method of analysis. The threshold limit for the minimum number of occurrences was kept at '2'. Out of a total of 315 keywords in 125 articles, 66 met the threshold as shown in Fig. 7. Occurrences of the top keywords and link strengths are also generated. Some keywords were found to have the same semantic meanings such as 'leaks' and 'leakage'. These types of individual keywords, shown in Fig. 7, were combined and the total occurrences and total link strengths were calculated by summation of occurrences and link strengths of individual keywords, respectively, as shown in Table 6.

From Fig. 7, it can be observed that the keywords which occurred frequently have larger node sizes. For example, 'leak detection' and 'wireless sensor network' have larger node size. However, the node size of the 'wireless sensor network' is smaller than 'leak detection'. But in reality, the former keyword occurred more frequently than the latter as shown in Table 6. That's because researchers used different keywords for 'wireless sensor network', all had the same semantic meanings such as 'WSN' or plural form 'Wireless sensor networks'. The keywords links and nearness, in Fig. 7, show their interrelatedness. For example, 'wireless sensor network' is placed near 'node design' shows several articles that focused on 'wireless sensor network' concerned 'node design' as well. The keywords that frequently co-occurred are placed in the same clusters. For example, 'MEMS sensors', 'wireless sensor network', 'node design', and 'water pipeline monitoring' are placed in the same cluster.

The network also reveals useful information regarding research gaps. For example, in Fig. 7, 'leak detection' is placed much closer to 'pipeline monitoring' than 'leak localization' which means that 'leak localization' considering MEMS-based WSNs, accelerometers, and hydrophones is a research gap. Similarly, 'routing', 'energy harvesting', and 'energy efficiency' are emerging topics in WSNs that need further research. From Table 6, it can be observed that the top ten keywords co-occurred, with the other 65 keywords in Fig. 7, for at least four times. 'Wireless sensor network' and 'leak detection' co-occurred with other keywords 57 and 42 times, respectively. The knowledge of the keywords can also help future researchers to use them in their articles to reach a wider audience.

Table 6
Top keywords.

Keywords	Occurrences	Total link strength
Wireless Sensor Network	57	48
Leak Detection	42	36
Pipeline Monitoring	10	10
Pipeline	8	8
Water Pipeline Monitoring	6	6
Zigbee	6	6
Sensors	6	5
Water Distribution Network	6	6
Localization	4	4
Leaks	4	4

4. Discussion on qualitative analysis

Qualitative discussions on MEMS-based WSNs, accelerometers, and hydrophones are given as under. Fig. 8 shows the hierarchical distribution of themes and sub-themes within these three MEMS technologies for qualitative discussions.

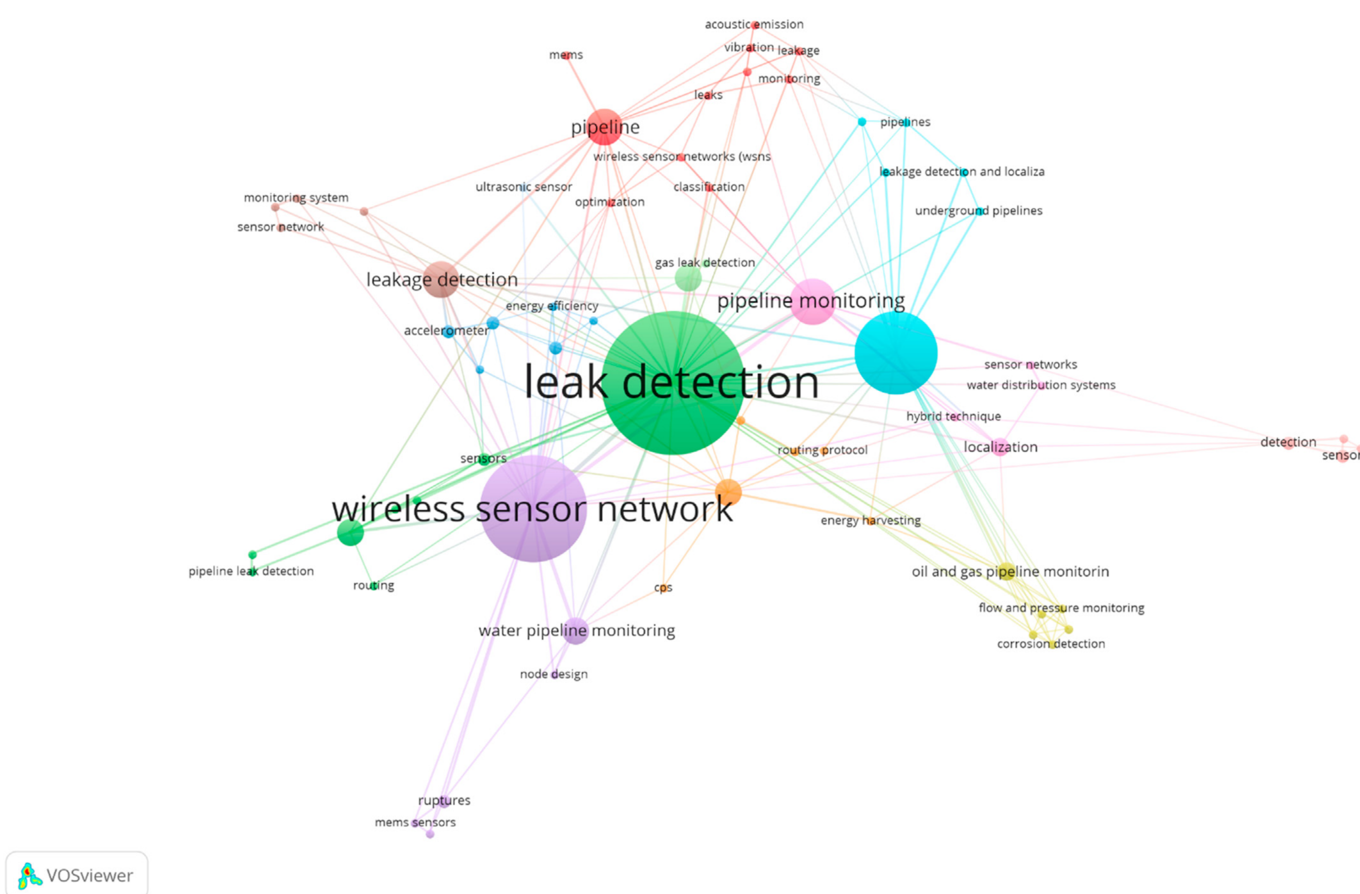

Fig. 7. Network analysis of countries.

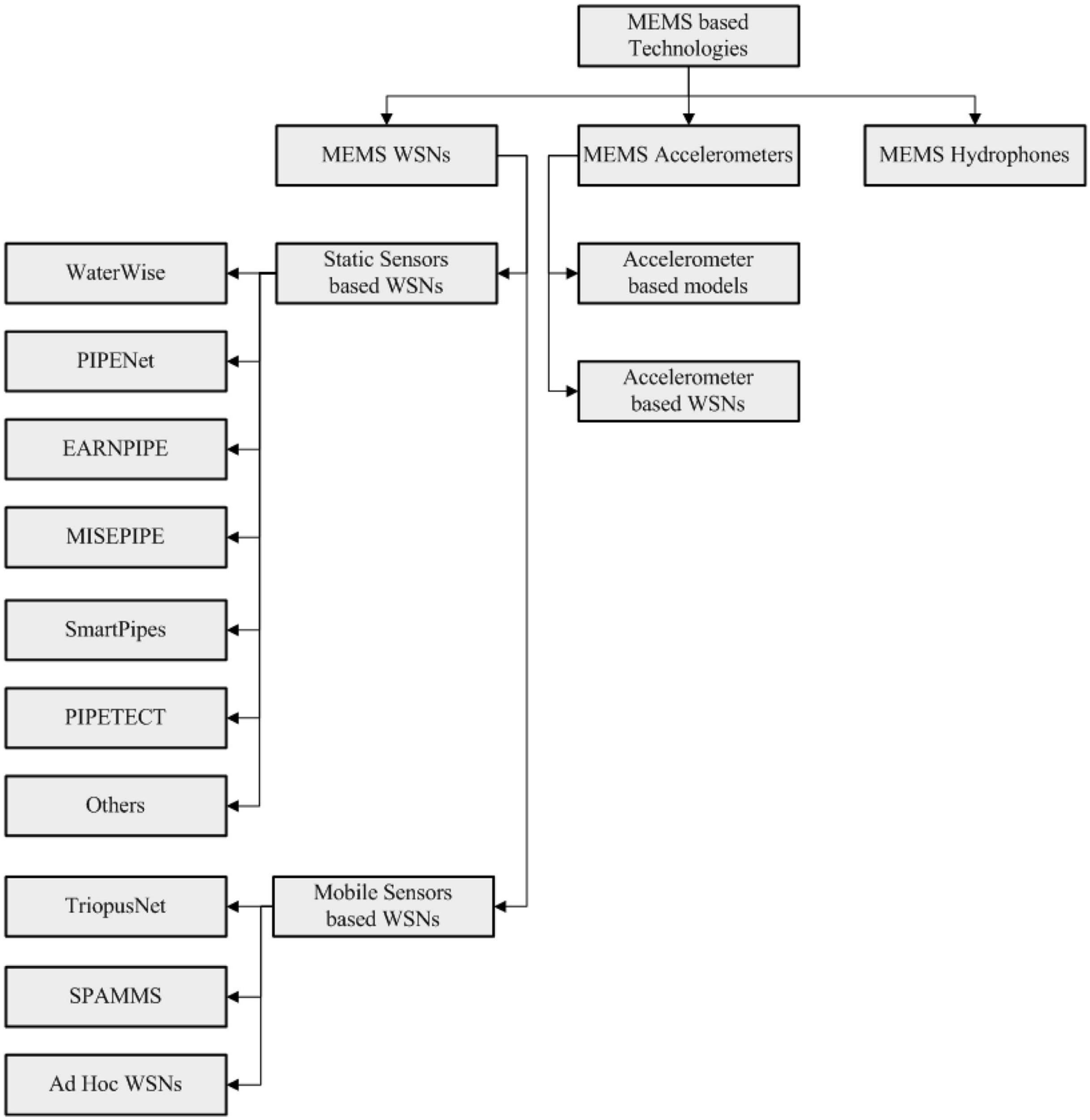

Fig. 8. Organization of qualitative discussion on MEMS technologies.

4.1. Wireless sensor networks (WSNs)

WSN can be defined as a network of scattered and dedicated sensors that are employed to monitor the physical conditions of a system (Akkaya and Younis, 2005; Cheng et al., 2011). The sensors may be allocated to monitor temperature, vibration, pressure, PH, etc. (Matin and Islam, 2012) and the collaborative information is passed on to the sink/base station for further analysis, observation, and results (Heinzelman et al., 2000). The base station acts as an interface between humans and the network (Sen, 2010). A typical WSN is given in Fig. 9. A WSN is typically composed of several (even hundreds) sensors that are equipped with a sensing unit, processing unit, transceiver unit, and power unit, however, they have limited processing speed, communication bandwidth, and storage capacity (Akyildiz et al., 2002). After the deployment of sensors, they self-organize an appropriate network infrastructure (Al-Karaki and Kamal, 2004) often with multi-hop communication, and start collecting information (Van Hoesel and Havinga, 2004). The sensors communicate with one another or the base station through radio signals depending on the type of communication topology adopted (Matin and Islam, 2012) i.e. star network, mesh network, and hybrid star-mesh network (Wilson, 2005). Please refer to Labrador and Wightman (2009) for communication topology, and Sharma and Jena (2011) and Kulik et al. (2002) for different types of routing protocols in WSNs. WSN based devices are designed to respond to queries from the control center (Fabbri et al., 2009) and collect and disseminate 'as specified', 'event-driven', or 'continuous' information (Intanagonwiwat et al., 2000; Matin and Islam, 2012). Since minimizing energy consumption is the key aspect of WSNs (Matin and Rahman, 2011), and communications require the largest amount of power (Paul and Matin, 2011), usually 'as specified' and 'event-driven' information is sent over the network (Lindsey and

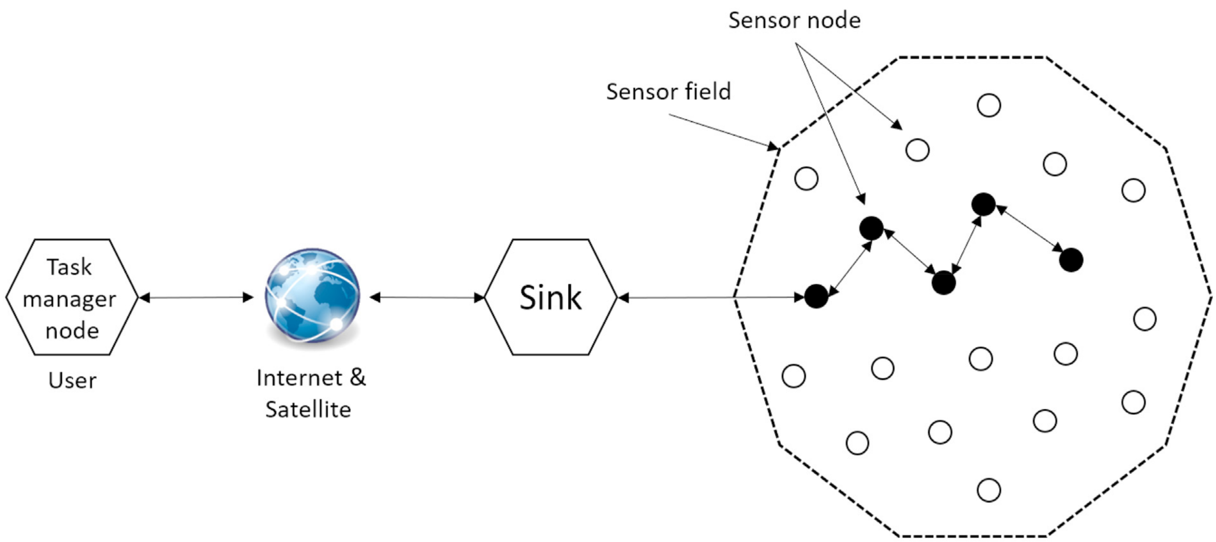

Fig. 9. A typical WSN.

Raghavendra, 2002). Global and local positioning algorithms are used to acquire positioning information of nodes (Matin and Islam, 2012). WSNs have been used to solve problems in several fields (Sohraby et al., 2007) such as surveillance (Yick et al., 2008), reconnaissance (Bharathidasan and Ponduru, 2002), area monitoring (Popescu et al., 2018), real-time traffic information (Boukerche, 2008), air pollution monitoring (Boubrima et al., 2017), landslide prediction (Giri et al., 2018), structural health monitoring (Verdone et al., 2010), machinery condition (Hou and Bergmann, 2012), automated irrigation (Gutiérrez et al., 2013), agricultural monitoring (Buratti et al., 2009), etc. The use of WSNs in leak detection has also gained researchers' interest recently (Jayalakshami and Gomathi, 2015).

Conventional leak detection methods require huge involvement of maintenance personnel and the response to leakage is generally slow (Gong et al., 2016). Due to the recent advancement in MEMS, inexpensive low power sensors have been developed which are equipped with a processor, memory, power source, and actuator (Mustafa and Chou, 2012). These sensors use radio communication to the admin center for real-time leak detection (Van Hieu et al., 2011). Common with WSNs in general, power consumption is usually the main issue in the deployment of such sensors in leak detection as well (Zabasta et al., 2014). The sensors for leak detection can be broadly divided into static sensors and mobile sensors. Mobile sensors flow on water and always keep in contact with the transported water. The static sensors are placed either in contact with the flowing water in the pipelines or otherwise. Static sensors which are placed in contact with the water are termed as invasive sensors, and the sensors which are not placed in contact with water are termed as non-invasive sensors (Sheltami et al., 2016).

Based on the sensor types, WSNs in this study were categorized into static sensors based WSNs and mobile sensors-based WSNs. The working architecture of different classifications of static sensors based WSNs is given in Fig. 10. The working architecture of different classifications of mobile sensors based WSNs is illustrated in Fig. 11. Table 7 provides the comparison of WSNs in terms of the type of sensors used, the mode of communication adopted for data collection, placements of nodes in or out of pipe, and types of pipes on which tests were performed.

4.1.1. *Static sensors-based WSNs*

As shown in Fig. 8, static sensors-based WSNs are divided into seven categories: 1) WaterWise, 2) PipeNet, 3) EARNPIPE, 4) MISEPIPE, 5) SmartPipes, 6) PIPETECT, and 7) others. Detailed discussions on the working, contributions, and limitations of each category are given as follows.

4.1.1.1. WaterWise. WaterWise, a research-based WSN project was deployed in Singapore with the support of the Public Utilities Board that enabled real-time monitoring of water networks in Singapore (Whittle et al., 2010). The principal aims of the project included the development and application of an inexpensive WSN for 1) online monitoring of hydraulic parameters such as pressure and flow measurements which were incorporated in hydraulic models to estimate and improve the state of a large urban WDS; 2) enabling remote leak detection and predict pipe burst events; and 3) integrated monitoring of water quality parameters (Whittle et al., 2010). The WaterWise platform comprised of three main components: 1) online-WSN that provided data; 2) IDEAS that processed raw data for leak detection and other water quality-related events such as contamination; and 3) DSTM that provided a decision support tool (Allen et al., 2013).

The system was implemented in three phases. In the first phase, a small network of WSN was deployed to 1) collect hydraulic data to validate the software and hardware components of the system and 2) test processing techniques to detect and localize leak and to inform the system for optimal placement of sensors. In the second phase, twenty-five nodes were placed at optimal locations. In this phase, the collaborative processing and measurements of water quality monitoring parameters were also incorporated into the system. In the third phase, the network was extended to one hundred nodes while optimizing the placement of nodes for minimum power consumption (Whittle et al., 2010).

The working architecture and system workflow of WaterWise is given in Figs. 9a and Figure 12, respectively. A single WaterWise sensor node was composed of a pressure sensor, a hydrophone, a flow meter, 2 GB storage, GPS, a USB 3G modem (for primary communication), and a USB Wifi radio (for short term communication when necessary). The sensors were highly time-synchronized which allowed high accuracy of the leak location.

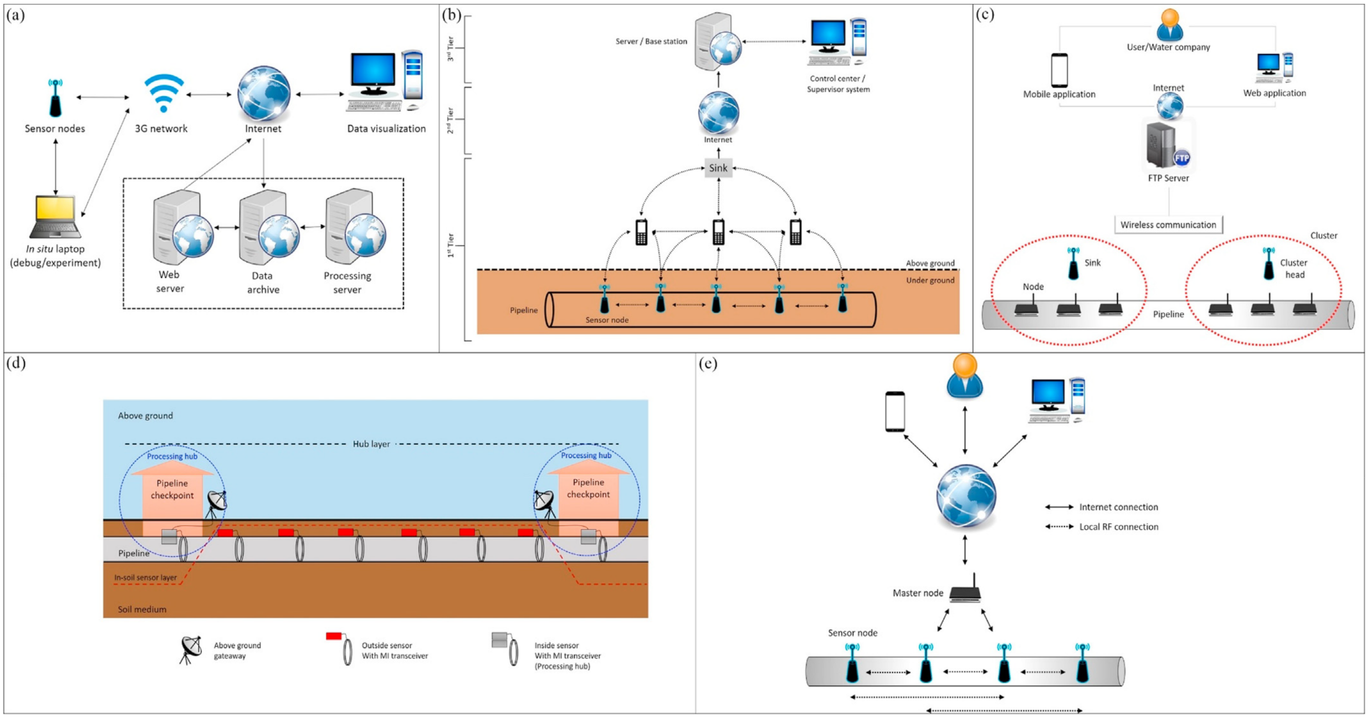

Fig. 10. Static sensors based WSNs (a) WaterWise (b) PipeNet (c) EARNPIPE (d) MISEPIPE (e)SmartPipes.

Such synchronization is not possible in noise loggers. At the first level, the sensor nodes, enclosed in water-resistant packing, gathered data at a high rate and transmit it to the group of servers in real-time through the internet using a 3G connection. (Whittle et al., 2010). Of the group of servers, the data server stored raw data; the processing server facilitated hydraulic modeling and leak detection using raw data; and the web-server formed an interface between WaterWise and the user and also facilitated historical and real-time data visualization. Through the visualization tool, the utility engineers were able to see water consumption data in demand zones, water pressure at junctions, and flow rates in pipes (Fig. 12).

The system used a wavelet detection algorithm to determine any irregularities for further investigation by engineers. Firstly, the algorithm decomposed the pressure signals into several coefficients. Analyzing the coefficients and picking up the most consistent signal determined the abnormal event. Secondly, the time arrival of pressure fronts at different sensors was used in the leak localization algorithm. The localization algorithm employed a graph search procedure to find the physical location of the potential leak event. Low-pressure/potential-leak points were then allocated on a Google map for the exact identification of the points of interest (Whittle et al., 2010). An SMS alert through DSTM was then sent to the maintenance engineers which deployed field teams based on the location generated by the IDEAS. Over a few hours, the leaking pipe was isolated by closing valves and repaired. An online EPAnet model was used for predicting system response by closing certain valves. The results of the model helped the engineers in determining the minimum and maximum pressure during maintenance operations. The repaired location was monitored on IDEAS for a few days ensuring that the repair was fixed as anticipated (Allen et al., 2013).

Waterwise attempted to provide a complete WSN solution for the water supply network. The system was not only capable of real-time leak detection but also provided online water quality and hydraulic parametric modeling. Power consumption for Waterwise was a big challenge; nodes were charged using solar panels attached to the top of poles. In the case of obstruction, lamp posts with a wired system were used to recharge nodes. Research work on the tradeoff between the system's power requirements and processing capabilities is required to justify the cost-effectiveness of Waterwise.

4.1.1.2. PipeNet. PipeNet was deployed at the Boston Water and Sewer Commission in 2004 for gathering and processing real-time hydraulic and water quality data (Stoianov et al., 2008). The remote system had distinct functionalities such as a high sampling rate (up to 1000 samples/second) and highly accurate time synchronization (up to 1 ms). With these features, PipeNet aimed at capturing fast pressure transient events; detecting, localizing, quantifying leaks and bursts; and monitoring water quality (Stoianov et al., 2007).

The main challenges for developing such an integrated system was bandwidth, local data processing, power requirements, and to create a balance between wireless communication in the long run. A hierarchy-based tier system was developed to address these challenges. The schematic diagram for three tiers of the monitoring system namely sensor nodes (tier-1), data gathering and gateway (tier-2), and middleware and back-end (tier 3) is given in Fig. 10b. The first tier consisted of sensor nodes, with a transmission range within 10–100 m, to transmit the data to the local data-gatherer in tier two. For intensive real-time data processing in the nodes, an advanced microprocessor architecture was required to maintain low power consumption which was solved by using novel Intel mote. Each mote in the first tier was equipped with a data acquisition board and several sensors. The primary function of motes was to gather data, process data locally, and transfer to the second tier via Bluetooth (Stoianov et al., 2008). Tier two consisted of a single board computer (Intel Stargate) which acted as a cluster head and gateway. Second-tier managed long-term communication with the third tier using GPRS and also transmitted time beacons for time synchronization. The mote in the first tier was programmed to periodically turn on, discover the gateway, collect the samples,

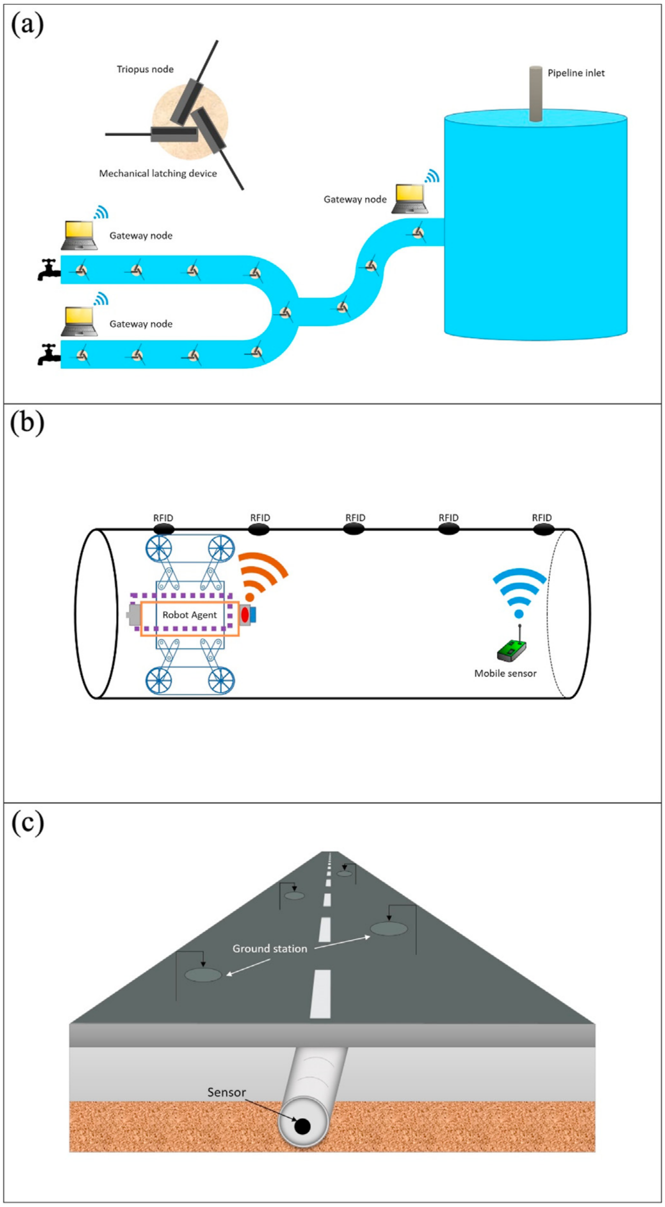

Fig. 11. Mobile sensors based WSNs (a) TriopusNet (b) SPAMMS (c) Ad Hoc WSN.

transmit the data, and go back to sleep for a configurable period of time. The sampling regime in the first tier was classified into a continuous mode and a burst mode. In the case of a burst mode, the sampling rate reached 1000 samples per second for 15 min. The data acquired was compressed locally, before transmission, to reduce battery depletion. In the second tier, a watchdog feature was added to the gateway nodes to reboot the gateway after 24 h or on halting of the system (Stoianov et al., 2008). Sophisticated algorithms at tier three (middleware and back-end) detected ruptures in the pipeline (Stoianov et al., 2008).

Data from pressure and flow sensors were used for detecting large leaks whereas smaller leaks were detected using data from acoustic/vibration sensors. For large leaks, a relatively lower number of sensors were required since large leaks generate pressure pulses which could be detected over a long distance. For continuous sampling, such sensors were placed near pumping stations where solar charging systems were available. The data was communicated with the gateway, where the Haar wavelet transform was used to detect pressure pulses that confirmed the presence of a leak. For small leaks, acoustic/vibration data was gathered through closely spaced (600 m apart) hydrophones. Since data for small leaks was not time-sensitive, therefore, data was only collected during low noise periods (2–4 am) for a short period (3–5 min). Cross-correlation analysis was then applied which used the time delay between the signals and distance between them to localize leak (Stoianov et al., 2007). Equation (1) defined the cross-correlation function (Gao et al., 2006).

$$R_{s_1 s_2}(\tau) = E[s_1(t)s_2(t+\tau)] \tag{1}$$

Where τ = time lag; E = expectation operator; $s_1(t)$ *and* $s_2(t)$ = stationary random signals with zero mean. The value of τ that maximized equation (1) provided the estimate of τ_{peak}. τ_{peak} was then used in equation (2) that defined the relationship between time delay τ_{peak}, wave propagation speed c, and distance between sensors at access points d.

$$d_1 = \frac{d - c\tau_{peak}}{2} \tag{2}$$

PipeNet provided several trustworthy properties such as automatic leak and burst detection, low false alarm rates, high-frequency data sampling, applicability on different pipe materials, and inexpensive to use/install. Some of the limitations of PipeNet are as follows. Firstly, due to the high data sampling and insufficient data storage in sensor nodes, the data were directly communicated with the cluster head which created problems in case a connection was lost. Secondly, crude time synchronization was used by having a gateway periodically transmitting a time bean through the cluster head. A refined time synchronization mechanism within/across cluster heads is required to enhance the accuracy of leak localization.

4.1.1.3. EARNPIPE. EARNPIPE was developed to provide a low power solution for accurate leak detection and localization in above-ground long-distance pipes. An in-node algorithm was used to process, filter, compress, and detect the leak. As shown in Fig. 10c, EARNPIPE was a clustering-based WSN since clustering routing forms an efficient way to minimize the power consumption of the network (Karray et al., 2016). The nodes were designed on system-on-chip architecture consisted of the ARM processor, timer, Kalman filter accelerator, wireless transceiver, rechargeable battery, energy harvester, and sensors. The nodes collected data every hour for 5 min at 1000 samples/second. A Predictive Kalman Filter 'PKL' algorithm was then run locally which filtered out the noise and detected anomalies. PKL, then, further detected pressure variations caused by anomalies. The difference between the measured pressure and estimate pressure gave an idea of the occurrence of a leak.

$$R_k = z_k - Hx_k \tag{3}$$

Where z_k = measurement pressure; H = measurement matrix; and x_k = estimated pressure.

When the difference in equation (3) exceeded a certain value, a flag was updated. The flag and the processed data were then transferred to the cluster head where the Earnloca algorithm computed the position of the leak, in case the anomaly was a leak. Earnloca algorithm was based on the time difference of pressure signal arrival between two nodes studied through cross-correlating the signals. The information was afterward transferred to the control center where various statistics were carried out and an interactive interface was used to visualize the database. The database allowed the user to access historical graphs, maps, pipeline

Table 7
Comparison of different WSNs.

WSN	Type	Sensors	Communications	Placement	Type of pipes	Attractive features	Challenges	Algorithms/models used
WaterWise	Static Sensors based WSN	Pressure, flow, acoustic	USB 3G modem, radio WIFI	In-pipe/ out-of-pipe	–	Very high time synchronization, Complete system for WDS monitoring	Power consumption	Wavelet detection algorithm, leak localization algorithms, EPAnet prediction model
PipeNet	Static Sensors based WSN	Pressure, flow, acoustic	Bluetooth, GPRS	In-pipe/ out-of-pipe	Cast Iron/ PVC	Low power consumption, low false alarm rate, inexpensive	Time synchronization, communication	Haar wavelet transform, leak detection, and localization algorithm
EARNPIPE	Static Sensors based WSN	Pressure	Bluetooth	Out-of-pipe	Polyethylene	Low power consumption, low communication cost	Implementation in the field, implementation in underground pipes	Predictive Kalman filter, Earnloca Algorithm
MISEPIPE	Static Sensors based WSN	Pressure, acoustic, soil property	Magnetic induction	In-pipe/ out-of-pipe	–	MI communication, integration of soil property sensors for leak detection	Implementation in the field, cost concern	Leak detection and localization algorithm
SmartPipes	Static Sensors based WSN	Pressure, temperature, FSR	RF signals	Out-of-pipe	High-density polyethylene	Long life, the effectiveness of temperature sensors for leak detection	Communication	Leak detection and localization algorithm
PIPETECT	Static Sensors based WSN	Acceleration	Xbee, Xtream, WIFI, CAN	Out-of-pipe	Polyvinyl chloride	Triple axis vibration analysis	Implementation in the field	Hammer code simulation
Others	Static Sensors based WSN	Pressure sensors	Zigbee, radio	In-pipe/ out-of-pipe	–	Machine learning-based decision making	Implementation in the field	Artificial intelligence
TriopusNet	Mobile Sensors based WSN	Pressure, gyroscope	Radio	In-pipe	–	Autonomous system	Communication	Pipe probe system, sensor deployment algorithm, sensor localization algorithm
SPAMMS	Mobile Sensors based WSN	Pressure, flow	RF signals, RFID	In-pipe	Any type	Cost-effectiveness, autonomous system	Communication	Tag-reading algorithm, an algorithm for measuring mobile sensors characteristics
Ad hoc WSNs	Mobile Sensors based WSN	Acoustic, pressure	RF, microwave frequency	In-pipe	–	Low power consumption	Communication range, implementation in the field	Iterative algorithm

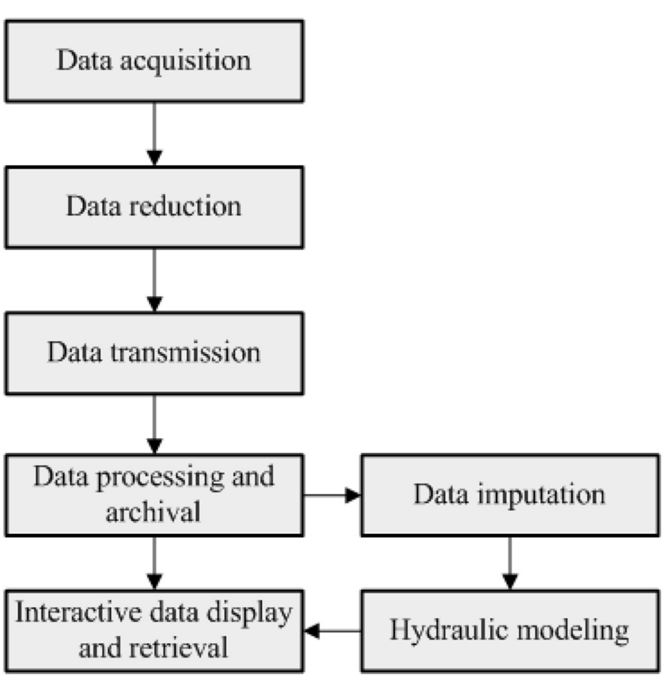

Fig. 12. System workflow of WaterWise.

location, and network state. Karray et al. (2016) validated the proposed system at the lab scale using 25 m polyethylene pipes and found good accuracy for leak detection and location. The average error for leak position using 3 tests was 1.93 cm.

The main contribution of this system was 1) the use of system-on-chip design, characterized by its small size and low power consumption, and 2) exploration of PKL algorithm in WSN. PKL algorithm was combined with the Kalman filter to preprocess all the useless information which reduced the communication cost in WSN. This system was the first one to employ such a combination of PKL and filter in WSN. However, EARNPIPE was developed only for above-ground pipes and its application in the underground pipes was not investigated. Also, the accuracy of leak detection and localization was only validated for lab-scale experiments.

4.1.1.4. MISEPIPE. MISEPIPE, a magnetic induction (MI) based WSN, was developed for providing real-time and low-cost leak detection and localization in underground pipelines (Sun et al., 2011). Sensors were located both inside and outside of the pipe; the measurements of which were transmitted to the control center in real-time. In-pipe sensors measured the pressure, flowrate, and acoustic vibrations. Whereas, the out-of-pipe (in-soil) sensors measured the temperature, humidity, and other properties of the soil. The measurements of both types of sensors complemented each other and provided accurate leak detection and location at a low cost and minimum energy consumption.

The system architecture of MISEPIPE is given in Fig. 10d. MISEPIPE had a clustered architecture with two layers: 1) hub layer consisting of in-pipe sensors that were deployed at the checkpoints and pump station, and 2) in-soil sensor layer consisting of various sensors to measure soil properties. The in-pipe sensors also acted as cluster heads which were equipped with MI transceivers to collect data from sensors located at the in-soil layer. The cluster heads were high power devices with rich processing abilities. These cluster heads preprocessed data at the in-network level and transmitted it to the control center located somewhere in the city.

Pressure sensors identified large leakages based on transient methods. Acoustic sensors were used to complement pressure sensors in identifying small leaks. Since pressure/acoustic sensors were placed only at the checkpoint, they did not provide data for accurate detection and localization. Soil property sensors that were placed along the underground pipes gave continuous measurements such as moisture level of soil in case of a leak suspicion. This solved the low accuracy problem of pressure sensors and low range problem of acoustic sensors and facilitated in accurately detecting and locating leaks. Soil sensors remained in sleep mode to save energy until received commands from in-pipe sensors. After collaboratively identifying the occurrence of a leak event and its location, information was shared with the control center to notify maintenance personnel (Sun et al., 2011).

The unique contribution of MISEPIPE was the use of MI communication for WSNs in underground pipes. Tradition electromagnetic waves suffer from path loss in underground communication. MI is a promising signal propagation method that reduced the path loss issue as signals do not attenuate at a higher rate. MISEPIPE also introduced the employability of soil sensors in addition to pressure and acoustic sensors which showed the potential to enhance the accuracy of leak detection and localization. However, for accurate leak detection, these in-soil sensors cannot be placed far apart which may increase the cost. The optimal location of these sensors for long-distance pipes without sacrificing the accuracy is a challenge that needs to be addressed for this system. The practical applicability of MISEPIPE is yet to be revealed as lab experiments were only conducted at a small-scale testbed.

4.1.1.5. SmartPipes. Sadeghioon et al. (2014) presented a smart long-life WSN for leak detection in underground plastic pipes. Leaks were detected through the measurement of relative changes in pressure profiles. Power consumption was reduced by adopted several methods such as taking one measurement every 6 h, using long-life batteries and applying other energy harvesting techniques.

Fig. 10e provides the proposed SmartPipes WSN. In SmartPipes, the nodes were attached to the pipeline. For each set of four-five nodes, there was a master node that communicated with nodes and also received data from nodes through RF transmission. Each node had three basic units: data gathering and processing unit, transmission unit, and power management unit. Since power consumption was a big challenge in WSN and there was no need for high-frequency sampling, the nodes remained at sleep for most periods of time. To save energy, sensor nodes cut power to all components during sleep time which enabled a lifetime of 100 years. The master node transferred the data to the cloud which was excessed by control devices with internet connectivity.

Pressure sensors were used for detecting large leaks or burst by measuring the internal pressure of the pipe based on force-sensitive resistors (FSR). These sensors were clamped to the pipe surface with a clip, as shown in Fig. 13, whose young's modulus was greater than that of the pipe. Pressure in pipes caused a contact force between the pipe and the clip which was measured by the FSR sensor. Using the contact force, internal pipe pressure changes were calculated using equations (4) and (5).

$$F_c = K.A_s.\,P_c \tag{4}$$

$$\frac{P.r_p^2.E_j.T_j}{\left(r_p^2.E_j.T_j\right) + \left(r_j^2.E_p.T_p\right)} \tag{5}$$

Where F_c = contact force on the sensor; K = constant that values between 0 and 1; P_c = contact pressure between pipe and clip; A_s = sensor area; P = internal pipe pressure; r_p = pipe radius; r_j = clip radius; E_j = young's modulus of the clip; E_p = young's modulus of the pipe; T_j = clip thickness; and T_p = pipe thickness.

For small/slow leakages, temperature sensors were used to detect leaks. These sensors were also clipped to the pipe surface and used to draw changes in the temperature profile of the pipe walls in case of a leak. Experimental and field trials using PVC pipes showed the potential of SmartPipes in leak detection and location (Sadeghioon et al., 2014). Pressure profiles were studied before and after the leak and differences were used to determine the approximate location. The experiments also showed the potential of temperature sensors in leak detection as the temperature at the pipe wall dropped quickly with the drop in pressure. The experiments confirmed that pressure sensors can be used in conjunction with temperature sensors for more accurate leak detection and localization.

Similar to MISEPIPE, SmartPipes also validated the effectiveness of temperature sensors in water leak detection and localization. The system showed another advantage that the sensors can be retrofitted with the existing pipes eliminating the damage to the structural integrity of pipes and the need for costly continuous trenching. The main drawback of this system includes limited communication between the nodes due to the low transmission range of RF signals in soil.

4.1.1.6. PIPETECT. PIPETECT consisted of long-distance wireless communication units and highly precise sensor nodes. The nodes sampled and transmitted data in real-time for analysis in a nearby data aggregation unit (Shinozuka et al., 2010a). To identify leak location, a numerical simulation based code called HAMMER was developed that used transient hydrodynamic analysis. The analysis was based on the fact that the pressure change near the source of the transient is larger and decays in both directions with distance. As a result, a leak can be located by computing the maximum water head gradient (MWHG) between two adjacent joints. PIPETECT used the maximum pipe acceleration method (MPAG) instead of MWHG which was based on the principle that a sharp pressure change causes a sharp acceleration change on the surface of the pipe. Therefore, the whole process of observing MWHG was replaced by observing MPAG using less expensive and high precision triple accelerometer-based sensor nodes rather than expensive pressure gauges. The leak identification was done in three basic steps: 1) observing and analyzing the acceleration-based changes using the non-invasive technique, 2) developing contour maps of acceleration changes, and 3) identifying leaks between two adjacent joints on the basis of maximum acceleration change (Shinozuka et al., 2010a).

To monitor the water pipe network, sensor nodes were placed underground at two end joints of every link. Wired Controller Area Network (CAN) was used for underground communication between sensor nodes and aggregation units. The aggregation units were equipped with several radio transceivers for control and communication with sensor nodes (Shinozuka et al., 2010a). The communication between the aggregation unit and the cloud server was carried through WIFI. To initiate the transmission through

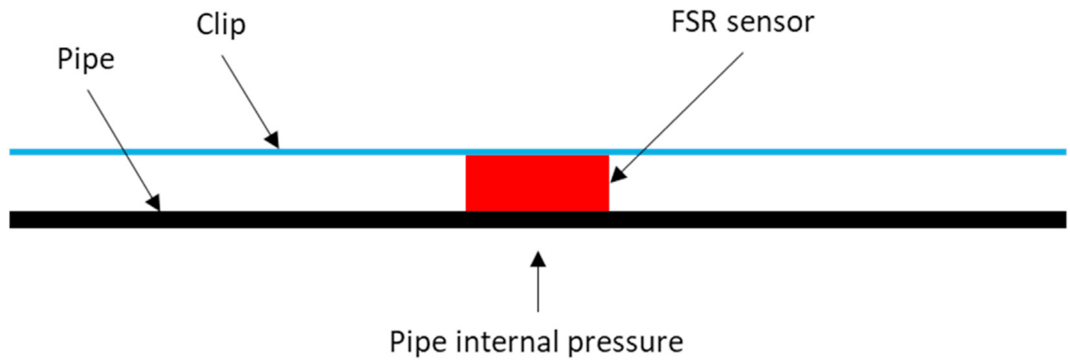

Fig. 13. Schematic diagram of FSR clipped to a pipeline.

sensor nodes, the cloud server gave the command to the aggregation units which then set the reference time and broadcasted the command to the sensor nodes for data transmission. Sensor nodes transferred the acceleration data to aggregation units which stored data locally in sequential order of time and went to sleep mode. Through contour mapping (details in the later section), the leak was located and detected at the cloud server (Shinozuka et al., 2010a).

The unique contribution of PIPETECT was the use of acceleration data in three axes which allowed the cloud server three options to analyze the data i.e. if vibration data in one axis was not able to detect the leak, the data in one or both of the other two axes might well do so. The utilization of three axes in a real network needs further exploration as accelerometers are to be placed on valves and the usefulness of vibration data in the x and y axes requires thorough examination. Leak analysis considering the properties of real-life networks such as bends, T-joints, and ambient conditions also needs further investigation.

4.1.1.7. Others. Nasir et al. (2010) developed a cyber-physical wireless PipeSense system to detect the leak. PipeSense used artificial intelligence for initial decision-making but the system was human-centric as a human was taken as the final decision maker, not the system. It consisted of six tiers including the sensing tier, processing tier, modeling tier, decision tier, human tier, and actuator tier. In the Sensing tier, nodes captured and sent the information regarding pressure and other parameters. Some level of data cleansing was done at the node level and then data was sent to the processing tier for further cleansing in real-time. The data was also stored for future reference here. The processed data was then passed on to the modeling tier which contained hidden Markov models for demand pattern predictions. Next, the decision was made through the decision tier system which was made up of artificial intelligence. However, the decision was not imposed on the system rather it was sent to the human tier system for the final decision. Humans were given the authority to overrule the system and declare it a false alarm. The decision tier was programmed to learn from such decisions. Finally, there was an actuator tier which consisted of valves, pumps, etc. Humans/automatic systems repaired/closed the actuator tier in case of a leak.

Rashid et al. (2015) proposed a WML-WSN for leak detection and size estimation. This system used machine learning algorithms for learning, decision-making, and reporting leak events. The system was based on the principle of negative pressure. The basic idea was that the leak events reflect a negative pressure wave which can be sensed using pressure transducers. The sensor nodes in the data collection and communication module sent the data through the Zigbee network to the learning and inference module for further processing. The noise was removed using wavelet analysis. The machine learning techniques i.e. support vector machines, K-Nearest Neighbor, Gaussian mixture model, and Navis Bayes were used to detect leak and size of the leak. Navis Bayes had the highest accuracy in terms of leak detection i.e. 94.8% closely followed by support vector machines at 93.73%. K-nearest neighbor had the highest accuracy in terms of estimating leak size.

Santos and Younis (2011) designed a non-invasive WSN system for leak detection and early warning in long-distance pipes that used ultrasonic transducers. Leaks were detected by monitoring fluid volume at the entry and exit points in a pipeline. Since fluid volume is proportional to fluid velocity for known diameter pipe, ultrasonic transducers were used to calculate fluid velocity. The ultrasonic transducers were wrapped around the pipe and the accurate fluid velocity was continually measured. Any drop in fluid velocity was considered as an indication of a crack in the pipe. The information from individual sensors were immediately corresponded to the base station. The base station did a further temporal and spatial analysis to detect trends and confirmed leaks pointed out by the individual sensors.

4.1.2. Mobile sensors based WSNs

As illustrated in Fig. 8, mobile sensors based WSNs are classified into three categories: 1) TriopusNet, 2) SPAMMS, and 3) Ad-hoc WSNs. Detailed descriptions of the working, contributions, and limitations of each category are given as under.

4.1.2.1. TriopusNet. Lai et al. (2012) presented a mobile WSN for the autonomous deployment of mobile sensor nodes for pipeline monitoring. TriopusNet worked by releasing sensor nodes at a centralized repository located at the source of the pipeline. The human effort was only needed to deposit mobile nodes at the source of water in a pipeline. Mobile nodes, equipped with gyroscope and pressure sensors to detect bends in the pipe, were deployed in sequence, with the deployment of downstream sensors first. Placing nodes closer to the source might hinder the movement of other nodes. Therefore, prior to releasing the sensor nodes, TriopusNet ran a deployment algorithm that considered pipeline as a virtual tree. The nodes at the source were considered as the root node, the nodes at the endpoints as the leaf nodes, and the other nodes as the intermediate nodes. The algorithm subsequently placed the nodes in the transversal sequence of their deployment order. Each mobile node was equipped with three mechanical arms that latched to the inner pipe surface upon reaching the deployment position. Each node then gradually built its connectivity with other nodes depending upon its sensing coverage radius i.e. the distance between two consecutive nodes was set at less than 2 times the sensing coverage radius of each node so that the entire pipeline can be covered. Upon low-battery level, the nodes detached themselves from the pipe's inner surface and flew to the pipe outlet. TriopusNet replaced the battery depleted nodes with the fresh ones to repair the WSN (Lai et al., 2012).

To communicate with nodes inside the pipeline, gateway nodes were installed prior to the deployment of mobile sensors. Gateway nodes were installed out of the pipe and connected with at least one of the mobile sensors for data collection. Gateway nodes were connected with a computer for data logging, remote control, and running deployment and replacement algorithms (Lai et al., 2012). An overview of TriopusNet is given in Fig. 11a. A testbed was prepared, consisting of 6 pipes, 2 valves, and bends for checking the accuracy of the system. Experimental results showed that the positional accuracy of nodes was very high, with a median error of less than 7.14 cm, which helped in accurately locating or pinpointing a leak (Lai et al., 2012).

This system provided an alternate WSN that scaled down the human effort and the accuracy was proven through a real testbed. However, the system had several limitations. Firstly, the sensor prototype was too big to be used for smaller diameter pipes. Due to the bigger size, the battery depleted sensors in an effort to reach the outlet might clog the pipeline with the downstream sensors. Secondly, the nodes prototype used radio communication which is not ideal for water; light and sonar communications are better. Better communication is a must for this kind of system as with bad connectivity the mobile sensors would not be able to form a virtual tree without which the whole pipeline system cannot be covered.

4.1.2.2. SPAMMS. SPAMMS, a novel method that integrated RFID systems based-fixed sensors with mobile sensors and autonomous robot agents for 1) identification, reporting, and effective localization of events and 2) repair of pipelines in case of damages from such events (Kim et al., 2010). The set of powerless fixed sensors was implemented through inexpensive RFID (Radio Frequency Identification) system for providing location information to the mobile sensors within the pipeline topology. These sensors were uniformly distributed and the distance between them was controlled by an acceptable level of the localization error. Due to the low price of RFID, these sensors were separated by 50 cm or so.

Mobile sensors were placed at strategic locations by analyzing the available information provided by GPS and the inspection needs. These mobile sensors were equipped with several functions including pressure sensing. The selection of function was decided before deployment as per the requirement for a particular sensing feature. Mobile sensors were equipped with RFID writer and reader for communicating with fixed sensors and reaching their location. Mobile sensors also communicated with other mobile sensors and the controlling system. Upon receiving the leak information, the control system commanded the fully autonomous robot to travel inside the pipeline for repair. An RFID reader and writer were incorporated into the robot. The robot upon reaching the location, with the help of RFID and mobile sensors, repaired the damaged part (Kim et al., 2010). The corrective monitoring scenario through SPAMMS is shown in Fig. 11b.

The unique contribution of SPAMMS is the cost-effectiveness as the system used an inexpensive RFID system and the number of mobile sensors and robot agents were limited. The deployment of mobile sensors was dependent on the inspection demand and the number of robot agents was dependent on the maintenance request. Another advantage of SPAMMS was that the sensors could be only be attached to the new pipe during the construction or in the latter stages with the help of robotic agents. Similar to TriopusNet, SPAMMS also assumed that just by controlling the water flow the mobile sensors' path can be made deterministic without disrupting the connectivity issues in WSNs, which is impractical in real-life networks. The effect of fluid speed, as a result, on the movement of mobile sensors and robot agents and the connection in WSNs remains to be future work.

4.1.2.3. Ad-hoc WSNs. Trinchero and Stefanelli (2009) and Trinchero et al. (2010) presented mobile sensors-based WSN to detect and localize leak (Fig. 11c). The mobile sensors could flow inside the pipeline without any interruption and they were able to detect anomalies and monitor the pressure profile of the water flow inside a pipe. Before the deployment of mobile sensors, the ground stations were installed in the proximity of pipe crossing positions. The ground stations were equipped with directive antennas to communicate with the mobile sensors. Each mobile sensor had two units: hydrophone that acted as a sensing unit and radio/microwave frequency as a transmitting unit. When any mobile sensor was intercepted by the ground station, its position was identified and the acquired spectrum data was correlated to leak locations. The ground station after processing the data transmitted it to the central unit where further advanced signal processing techniques were applied to provide accurate leak location (Trinchero and Stefanelli, 2009). The system was validated through experiments in the lab which showed easy maintenance and low power consumption but the communication range was limited.

4.2. MEMS accelerometers

A considerable amount of past research has been conducted on acoustic-based noise-logger for real-time monitoring. However, noise-loggers give rise to several challenges such as placing the noise-loggers at the right location and difficulty in detecting quiet leaks. Besides, the noise sound from the leak gets absorbed by the plastic pipes due to their viscoelastic nature and noise sound waves become weak. It is due to these disadvantages, vibration-based leak detection using sensitive accelerometers has caught researchers' interest (Ismail et al., 2019). Accelerometers are sensing devices that can detect and measure acceleration/vibration (El-Zahab et al., 2016).

Ismail et al. (2019) compared 6 break-out accelerometer sensors that are used in plastic pipes based on the number of axes, sensitivity, price, and power consumption. They found that the accelerometers with a higher number of axis have higher accuracy which means that if X-axis is unable to identify the pipe condition, the other two axes will. Among the accelerometers with triple-axis, they found MPU6050 to be cheaper, accurate, and sensitive. The sensitivity of MPU6050 is $\pm$ 16 g was much higher than the other three triple-axis accelerometers ADXL335, Hitachi-Metal H34C, and MMA7361. The comparison of the triple-axis accelerometer is given in Table 8. Ismail et al. (2015) checked the accuracy of MPU6050 for leak detection in high-pressure ABS pipes. The pressure was varied between 58.84 and 117.8 kPa at three states namely 'no leakage', '1 mm leak hole', and '3 mm leak hole'. It was found that leak size was difficult to identify at a high pressure of 117.8 KPa, however, up till 98.1 KPa, there was no problem in identifying leak size.

4.2.1. MEMS accelerometer-based linear regression model

Linear regression is a statistical method to predict a dependent variable based on the relationships with independent variables. El-Zahab et al. (2016) presented a linear regression model for the location of a single leak event in a pressurized pipe. The experiments were conducted on PVC and cast iron pipes and the accelerometers were placed on the connecting valves within the testing pipes. Monitoring indexes for the non-leak state were developed based on the vibrations measured by the accelerometers for several hours. 'Monitoring efficiency index' was then formulated by dividing the current state monitoring index and the lowest non-leak state monitoring index for every 100 s. A leak was detected

Table 8
Comparison of triple-axis accelerometer (source: Ismail et al., 2019).

Triple axis accelerometer	Price	Accuracy	Sensitivity	Power consumption
MPU6050	Low	High	±16 g	500μA/3 V
ADXL335	Low	Low	±3 g	180μA/1.8 V
Hitachi-Metal H34C	Medium	Low	±3 g	360μA/3 V
MMA7361	Low	Low	±3 g	47μA/1.71 V

when the threshold values of the non-leak monitoring efficiency index were exceeded. The monitoring efficiency indexes of two sensors on the left and right side of the leak along with the distance between the sensors allowed the regression model to locate the leak within ±25 cm. The developed model is given as follows.

$$X_L = -2.05 + \left(0.1718\frac{L}{R}\right) + \left(3.5\frac{L}{T}\right) - (0.295D) + \left(0.01985D^2\right) - \left(0.3351\frac{L}{T}D\right) \tag{6}$$

$$X_R = -2.766 - \left(6.88\frac{R}{R}\right) + \left(2.251\left(\frac{R}{T}\right)^2\right) + (0.4178D) + \left(0.0248D^2\right) - \left(0.3187\frac{L}{T}D\right) \tag{7}$$

Where, X_L = the distance from the left sensor to the suspected leak; X_R = the distance from the right sensor to the suspected leak; L = monitoring index efficiency at the left sensor; R = monitoring index efficiency at the right sensor; T = total monitoring index; and D = total distance between sensors. R^2 value of the developed models $X_L$and X_R came out to be 92.84% and 98.08%, respectively.

Although the linear regression-based models rarely exist for MEMS-based technologies but the implementation and development of such a model for real-life networks is highly questionable. Firstly, the field conditions vary considerably with every site such as the distance between two valves is not always the same as assumed in the lab-scale experiments. The pipe diameters, materials, ground conditions, and water table may also vary. The accuracy of non-leak monitoring indexes based on measurements on pipes without considering these factors is debatable and so does the linear regression model. Secondly, the water pipes are typically buried under the ground, the given regression model was made for above-ground short distance pipes. Thirdly, the model didn't take the effect of leak size into the account.

4.2.2. MEMS accelerometer-based advanced models

El-Zahab et al. (2016) extended their study in El-Zahab et al. (2018) and used three machine learning-based techniques including support vector machines, decision trees, and Naïve-Bayes for leak detection and localization in real-time. The study compared the accuracy of three techniques. The models were also capable of identifying the size of the leak. Experiments were performed on ductile iron and PVC pipes. A hose pump was utilized to provide water at a steady flow of 30 L per minute. Triple-axis accelerometers (model AX3D from brand Beanair) were used. The sensitivity of accelerometers was ±2 g with a maximum sampling rate of 1000 samples per second if all three axes were used and 3000 samples per second if the only axis was used. Monitoring index efficiency (MIE) was established for all three models using 8 h of vibration data and the models detected leaks based on the threshold value (equations (8)–(10)). Leaks were also classified as 'no leak, small leak, and big leak'. The discharge rate for small leaks was assumed between 10% and 25% of the overall flow rate whereas the discharge rate for big leaks was assumed between 26% and 50%.

$$\text{Vector machine state} = \begin{cases} \text{No leak, if } MIE \leq 1.018 \\ \text{Small leak, if } MIE \in [1.018,\ 2.24] \\ \text{Big leak, if } MIE > 2.24 \end{cases} \tag{8}$$

$$\text{Decision tree state} = \begin{cases} \text{No leak, if } MIE \leq 1.052 \\ \text{Small leak, if } MIE \in [1.052,\ 1.595] \\ \text{Big leak, if } MIE > 1.595 \end{cases} \tag{9}$$

$$\text{Naïve} - \text{Bayes} = \begin{cases} \text{No leak, if } MIE \leq 1.07 \\ \text{Small leak, if } MIE \in [1.07,\ 1.88] \\ \text{Big leak, if } MIE > 1.88 \end{cases} \tag{10}$$

In terms of leak detection, the decision tree provided the highest accuracy. Whereas, Naïve-Bayes provided the highest accuracy in terms of leak size. This is an important lab-scale work that provided an accuracy of over 80% for leak detection which is very high in comparison to traditional leak detection methods used in the field. Similar to the regression model, these machine learning models were developed only for above-ground pipes which is not a typical case in real-life networks. A further extension of their proposed models using on-field experiments, taking different site conditions into accounts, would be valuable.

4.2.3. Accelerometer-based WSNs

Shinozuka et al. (2010a) proposed non-destructive monitoring of water pipelines through accelerometers-based WSN. It was composed of several inexpensive sensors equipped with MEMS accelerometers to measure vibration on the pipe surface. The sensors were daisy-chained underground to a wireless board for transmitting data. The data were transmitted in real-time for leak assessment by a nearby aggregation unit. As per their methodology, the sensors were placed typically on the network joints and at least two joints of every link in the network were monitored. In case of a leak, a change in pressure caused a change in acceleration. The measure acceleration was then computed and analyzed by constructing contour maps for acceleration changes. The damage and location of the leak were identified from the locally maximum acceleration changes. The leak location was then found at the innermost and smallest polygon in the contour map, please refer to Shinozuka et al. (2010b).

Another study on accelerometer-based WSN was conducted by Nwalozie et al. (2015) for leak detection and localization in real-time. They made an experimental investigation on the relation between flow-induced vibration and pressure fluctuation which indicated a positive linear correlation. The studies also showed that a non-linear but proportional relation exists between water flow rate and flow-induced vibrations.

4.3. MEMS hydrophones

Among water leak detection techniques, the acoustic correlator method has gained popularity. It requires two hydrophones to detect the leak and then the time lag between the received signals confirms the location of the leak. Existing piezo-ceramics-based hydrophones are expensive, large-sized, and consume high power. For real-time leak detection, hydrophones are needed to be installed in-pipe to reduce the external noise. Some researchers such as Xu et al. (2016) and Xu et al. (2019) attempted to overcome the limitations of traditional hydrophones. For example, Xu et al. (2019) proposed a MEMS-based hydrophone that was small-sized, cheap, and consumed low power. The fabricated 10×10 element size was a tiny 3.5×3.5 mm^2 hydrophone device. Overall size after packaging and assembly was Φ 1.2×3.5 cm.

They demonstrated the capability of these hydrophones for detecting leaks both in existing and new pipelines. The devices were sensitive and recorded both leak and external noises caused difficulty in decoupling the signals. They conducted experiments for detection by installing hydrophones both and outside of the pipeline and found that the inside approach was better. Leak location was calculated using correlation analysis by placing two hydrophones on the same side of the leak. The time delay was observed which demonstrated the feasibility of leak location with MEMS-based hydrophones. Comparison with commercial hydrophones established the decent performance of these cheaper devices in real-time that can be installed permanently. Research gaps regarding MEMS-based hydrophones include 1) testing on plastic pipes, 2) use of different configurations of hydrophones for leak location, 3) use of artificial intelligence to analyze and separate leak signals from external signals, and 4) testing in the field.

5. Future research opportunities

The research in MEMS-based leak detection and localization technologies are still in the primitive stage. Therefore, opportunities for future research are vast. This study suggests some of the opportunities that might be of interest to future researchers.

5.1. On-field real networks based experimental studies

Most of the previous studies are based on lab-based experiments. Leaks are artificially generated and the location of the leaks is sometimes already known to the investigators even before starting the experiments which are not the case on-field. Lab studies usually fail to incorporate real-life aspects such as topography, complexities of pipes, conditions of valves, background noise, etc. Field experiments would serve as references for understanding the efficient use and placements of sensors. The results obtained and any difficulties encountered during 1) network deployment such as connection issues and time of experiments, and 2) data interpretation especially procedures for selecting threshold limits for leak and non-leak states should also be reported.

5.2. Multi-leaks

Past studies typically focused on single leak/rupture events. In actual practice, there can be more than one leak in a single pipeline which may result in faulty results in both leak detection and localization. Although some studies were conducted based on transient pressure, acoustic-based methods have not been well developed for multiple leaks' situation. More studies on multi-leaks are needed. This might require modification in existing methodologies, especially for leak localization.

5.3. Optimal placement of sensor nodes and other strategies for energy-savings in WSNs

Energy savings in WSNs is a big challenge. The sensors are battery-operated and, for continuous monitoring over long networks, require high power consumption. This leads to expenses incurred in replacing the batteries as well as maneuvering the resources. Different researchers have come up with strategies for low power consumption such as the introduction of sleep/wake cycles of nodes. More research is required for optimal placement of nodes, communications with cluster nodes, and other strategies for low power consumption. The development of algorithms for the optimal placement of sensors can also minimize human efforts and network costs.

5.4. Automated models

Excepts for a few studies, common software-based methods such as cross-correlation, pressure transient methods, etc. are used for leak detection and localization. AI-based neural networks and other machine learning algorithms can be established for automatic leak detection and localization. Web-based or mobile-based apps can further be developed for easy communication between site personnel and engineers at the back end. A human component can be added at the end for a final decision. Such a component would furnish the engineer with an authority to accept or reject the leak detected by the algorithms considering actual field conditions which might suggest otherwise. AI algorithms will learn from such decisions and experiences. Some researchers, such as El-Zahab et al. (2018), as mentioned previously, used machine learning techniques for leak detection and localization but again only lab-scale experiments were conducted and the results were not validated using real network data. Automated AI-based models are especially required for ameliorating the leak detection situation on the field.

5.5. Robot-based WSNs for small diameter pipes

Existing literature has developed mobile-based WSNs which not only detect and localize leaks but can also repair the damage. Such robot-based WSNs are restricted by size and are not suitable for small pipe diameters. Further research can be carried out for small diameter pipes.

5.6. Overall network coverage

Network coverage parameters including sensors range and direction flow of data play a significant role in WSNs. More research is required to establish the linear connection between the nodes and also with the cluster nodes. The best applicable communication technologies in different typologies also need to be established. Furthermore, all of the existing studies used a central control system that is adequate for a small network, but for a larger network covering thousands of kilometers of pipes, such a system may affect overall network performance. A single central control system can be replaced with distributed control systems.

5.7. Comparative analysis of real-time technologies

Experiments on the comparative analysis of MEMS-based WSNs and other real-time technologies such as the Noise loggers are limited. Such analysis can provide comparisons on the accuracy of leak detection and localization using different technologies. Both lab-scale and field experiments can be conducted. Similarly, further investigation is required to enhance the feasibility of using MEMS hydrophones as only a few pieces of literature were found. Comparative analysis with noise loggers and normal hydrophones can be conducted.

5.8. Integration of sewers and water supply monitoring

Since sewer pipes and water supply pipes are often buried close to each other. Any leak in sewer pipes may cause seepage of hazardous wastewater to the water supply lines. WSNs present a unique opportunity to use integrated solutions for both sewers and water supply monitoring. PH sensors nodes can also be installed for water quality monitoring in-pipe.

5.9. Feasibility and challenges to the implementation from the policy perspective

Survey and interview-based studies on the challenges to the implementation of MEMS-based technologies can be conducted to understand the concerns of the public sector authorities regarding the new technologies. Recommendations on the involvement of experienced private sector in the form of service-based PPPs can also be provided. Literature has reported several types of WSNs but none of the studies has provided an assessment of the economic feasibility of WSNs for a district metering area. Comparative analysis of the most economically feasible WSN solutions is also missing.

6. Conclusions

High leakage rates in WDS has changed the focus of research from 'non-real-time monitoring' to 'real-time monitoring' in the domain of water leak detection and localization. Most of the existing literature has proposed Noise logger's based techniques for real-time monitoring. However, noise loggers are found to be 1) prone to false alarms, 2) less effective for plastic pipes, and 3) require high initial monitoring cost. To overcome these vulnerabilities, MEMS-based technologies including MEMS hydrophones, MEMS accelerometers, and MEMS WSNS are gaining researchers' attention. This study conducted a systematic literature review on these three MEMS-based technologies considering their application in water leak and detection.

The systematic review was comprised of scientometric analysis and qualitative analysis. Firstly, a scientometric analysis was carried out which used a combination of databases-based bibliometric analysis and science mapping analysis of the extracted data of the retrieved articles. The unfiltered search through three popular databases including *Scopus, Web of Science, and Google Scholar* revealed 292 related articles. After applying filters and screening through abstract and full-text reading, 67 articles were retrieved. Application of snowballing techniques on the retrieved articles led to the addition of 58 articles, thus 125 articles were finalized for further science mapping and qualitative analysis.

The publication trend in the science mapping analysis predicted an upward research growth in the MEMS-based technologies for leak and detection. Science mapping of research outlets in terms of average normalized citation scores revealed the 'Journal of Sensor and Actuator Networks', 'Structure and Infrastructure Engineering', and 'Applied Acoustics' as the most influential research outlets. In the same way, Anthony, C.J., Chapman, D.N., and Davoudi, S. are found to be the most influential research authors. In terms of research organizations and countries, 'University of Birmingham, UK' and 'Italy' has the highest average normalized citation score. Lastly, 'Wireless Sensor Network' and 'Leak Detection' are the keywords with the highest occurrence showing the authors' specific interest in these two research areas.

Qualitative analysis revealed that only three articles focused on MEMS hydrophones. Accelerometers are a popular technique but research on MEMS-based accelerometers is still limited to a few research articles. In comparison to the other two technologies, WSNs have attracted more research interests in the recent past. Two categories of WSNs were found namely static sensors-based WSNs and mobile sensors-based WSNs. Static WSNs were further categorized into seven types of categories: 1) Water Wise, 2) PIPEnet, 3) EARNPIPE, 4) MISEPIPE, 5) Smart Pipes, 6) PIPETECT, and 7) others. Whereas, Mobile WSNs were categorized into three main categories: 1) TriopusNET, 2) SPAMMS, and 3) Ad hoc WSNs. The qualitative analysis found nine future research opportunities: 1) on-filed real networks based experimental studies, 2) multi-leaks, 3) optimal placement of sensor nodes and other strategies for energy-savings in WSNs, 4) automated models, 5) Robot-based WSNs for small diameter pipes, 6) overall network coverage, 7) Comparative analysis of real-time technologies, 8) Integration of sewers and water supply monitoring, and 9) feasibility and challenges to the implementation from the policy perspective.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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