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Review

Development of sustainable water infrastructure: A proper understanding of water pipe failure

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A R T I C L E I N F O

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A B S T R A C T

The need for sustainable water infrastructure systems continues to grow as clean water is essential for daily life. Despite efforts to sustain water distribution networks (WDNs), they often experience frequent failures, leading to several environmental, social, and economic consequences. Previous studies have investigated the causes of water pipe failure in different contexts. However, a comprehensive and holistic understanding of these causes is lacking in the literature. Therefore, this study contributes to the existing knowledge by presenting 1) a scientometric analysis of the previous literature, 2) a systematic discussion of the causes, 3) an Analytical Hierarchy Process model and fault tree logic to prioritize and map the causes, respectively, and 4) an overview of techniques used in developing failure prediction models. The scientometric analysis reveals that little attention has been paid generally to the operational causes of water pipe failure. The same trend was supported by the systematic review, which divides a total of 33 causes into three main categories: pipe-related, environment-related, and operation-related causes. This study gives insights to academics and practitioners working in this domain on the contributions of various factors to the failure of water pipes, which would be useful in designing a sustainable and resilient WDN.

1. Introduction

Water is an essential natural resource, which is transmitted from the sources to the point of consumption through different types of pipelines (Chen et al., 2021; Gurung et al., 2015). Despite the advancement in the material, manufacturing, and installation methods of these pipelines over time, water distribution networks (WDNs) still face the challenge of failure (Mahmoodian and Li, 2016; K. Pietrucha-Urbanik and Tchórzewska-Cieślak, 2017). Globally, water losses in most WDNs are more than 30%, which has a negative impact on the infrastructure's resilience and financial aspects (Prieto et al., 2015; Tariq et al., 2021). Similarly, a study conducted by Folkman (2018) showed that the failure rate of water pipes increased from 11.0 to 14.0 breaks per 100 miles per year in the USA and Canada within six years (2012–2018). In the UK, almost 22% of potable water is lost yearly due to the failure of the water pipe system (Farewell et al., 2012). Furthermore, the failure rate in Australia was estimated to be 20 bursts per 100 km per year. In Hong Kong, it was reported that 4953 bursts occurred in private water pipes between 2009 and 2013 (Ombudsman, 2014). Additionally, it was reported that about 780 million people have no access to potable water due to the lack of an appropriate water infrastructure system, including the failure of water pipes, and yearly, more than 3.41 million individuals die globally as a result of water-related diseases (Paradkar, 2012). These figures show that water pipe failure is a global issue that needs to be tackled. Therefore, it is not only important to provide water to humanity, but it is equally essential that the water is safe, clean, and consistent in terms of supply.

In addition, the consequences of water pipe failure are numerous. Some of them are property loss, repair and remediation costs, deterioration of human health, damage to the environment, and customer dissatisfaction (Dawood et al., 2021; Fares and Zayed, 2010; Katarzyna Pietrucha-Urbanik and Tchórzewska-Cieślak, 2020). Moreover, the failure of the WDN and its associated system affects global economic conditions. For instance, in 2006, although the original need to maintain and rehabilitate the WDNs in the US was $6 billion, only about $1.2 billion was spent because of the unavailability of funds (Paradkar,

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2012). Therefore, a WDN should be developed in such a way that several technical requirements, i.e., functionality, serviceability, and durability (Farshad, 2006), are achieved. To function optimally and sustainably, the material properties of components of a WDN in relation to mechanical, thermal, and durability, which determine the serviceability state of the network, are highly important. The system should be designed to provide adequate resistance against chemical, biological, and other aggressive elements from the environment (American Works Water Association, 2002). Importantly, to foster sustainability, the economic aspect of the system should not be overlooked in the design stage.

Numerous studies have been conducted to address the different causes of water pipe failure (Hekmati et al., 2020; Kutyłowska and Hotloś, 2013; Pawłowski et al., 2020; Pę;kala & Pietrucha-Urbanik, 2018; Katarzyna Pietrucha-Urbanik, 2015; Zamenian et al., 2017; Zywiec et al., 2019). However, a detailed review of these studies is lacking in the extant literature. Table 1 shows the existing reviews relating to failures in WDN, including their research focus and limitations. From Table 1, it can be observed that most of the existing literature review focused on estimation and prediction models for pipe failure, while a few studies reviewed limited factors influencing water pipe failure. Additionally, the exiting reviews did not conduct any scientometric or quantitative analysis of the causes, which is essential to avoid biasedness while selecting the research articles to be reviewed.

In order to fill the research gaps, this research contributes to the existing literature by conducting a critical and comprehensive review to identify and discuss the causes of water pipe failure in the existing literature. Specifically, the objectives of this study include the following.

1) To bibliometrically synthesize all relevant papers in the domain of causes of water pipe failure and provide an insightful discussion on the causes.
2) To present a comprehensive scientometric analysis, showing the publication trends, countries' contributions, journals' contributions, co-occurrence of keywords, and science mapping of scholars.
3) To map and prioritize the causes of water pipe failure using Fault Tree Logic (FTL) and the analytical hierarchy process (AHP), respectively.
4) To highlight the techniques used in developing failure prediction models for water pipes.
5) To make recommendations for future research.

Table 1
A summary of existing reviews relating to failures in WDN.

References	Research focus	Limitations
Rajani and Kleiner (2001)	This study reviewed deterministic and probabilistic physical models for estimating failure in water pipes.	• No review of factors influencing water pipe failure was presented.
Bubtiena et al. (2012)	This review study focussed on failure prediction models useful for rehabilitation strategies in WDN.	• No review of the causes of water pipe failures was presented.
(D. Wilson et al., 2017)	This research presented an overview of prediction models for large-diameter water pipes.	• A detailed review of factors used in the prediction model was missing.
Gheisi et al. (2016)	This review study focussed on mathematical methods for estimating the reliability of WDN.	• The study reviewed different types of failure in WDN. However, the causes of the failure were not discussed.
Mazumder et al. (2018)	This review study focussed on the techniques and models used in condition assessment, failure prediction, vulnerability assessment, maintenance, and renewal strategies of WDN.	• No detailed review of the causes of water pipe failures was presented.
Wasim et al. (2018)	This research presented a review of the soil-related factors influencing water pipe deterioration.	• Only soil-related factors influencing water pipe failure were reviewed. • An inter-relationship of the factors in a hierarchical manner was not presented.
Barton et al. (2019)	This study reviewed factors influencing the failure of water pipes for certain groups of pipe materials.	• Limited environmental and operational factors were reviewed. • The hierarchical structure of the factors related to the failure of water pipes was not presented.
Dawood et al. (2020)	The review study presented a critical overview of the use of artificial intelligence in modeling the deterioration of water pipes.	• No detailed review of the causes of water pipe failures was presented.

2. Research methodology

A mixed quantitative and qualitative research method was adopted in this study. The quantitative approach adopted is the scientometric analysis of previous studies and AHP for ranking the contributing factors. Whereas the qualitative approach includes a systematic discussion of the causes of water pipe failure, mapping the causes using the FTL, discussing the failure modes of water pipes, and highlighting the techniques adopted for developing failure prediction models. Fig. 1 shows the review framework of this study. The review process starts with identifying the research goals, followed by a bibliometric search via Web of Science (WoS) and Scopus databases and scientometric analysis, consisting of publication trends, journals, countries, organizations, and scholars' contributions. Subsequently, the systematic review is presented, including the failure modes, pipe-related, environment-related, and operation-related causes. Furthermore, the causes of water pipe failure are mapped using FTL and ranked using AHP. The techniques adopted to develop failure prediction models are discussed, and the sustainability dimensions of the impacts of water pipe failure are highlighted. Afterward, the research gaps and future directions are provided.

2.1. Search strategy and literature retrieval procedures

The complete literature retrieval and selection process is presented in Fig. 2. Firstly, a pilot search on the website of WoS was performed to validate the proposed topic. Afterward, to have comprehensive search results (Tawfik et al., 2019), higher content coverage with better availability of various bibliometric data, and strict content indexing criteria & inclusion policies (Pranckutė, 2021), the WoS and Scopus databases were selected. Different search strings were used and improved upon until one was finally chosen. The results (i.e., articles) were filtered by subject areas, downloaded, and the duplicates were removed.

The downloaded articles were further subjected to screening by reading their title and abstract. This is an important step to discard non-relevant and out-of-scope papers. Subsequently, the full text of the articles was evaluated. Inclusion and exclusion criteria were set at this stage. These criteria are important to avoid personal biases (Tariq et al., 2021). The inclusion criteria for this study include research papers focusing on physical, environmental, or operational causes of water pipe failure or factors contributing to the failure of water pipes and the techniques used for failure prediction models. Research studies from non-relevant areas, written in a language other than English, and papers with no full-text availability were excluded. As the search strings may not be absolutely perfect, the screened texts were subjected to forward and backward snowballing. The former refers to looking for papers that cite the paper being examined, while the latter refers to checking the reference list of the examined paper to find another relevant research paper(s). After the forward and backward snowballing, 105 articles were selected.

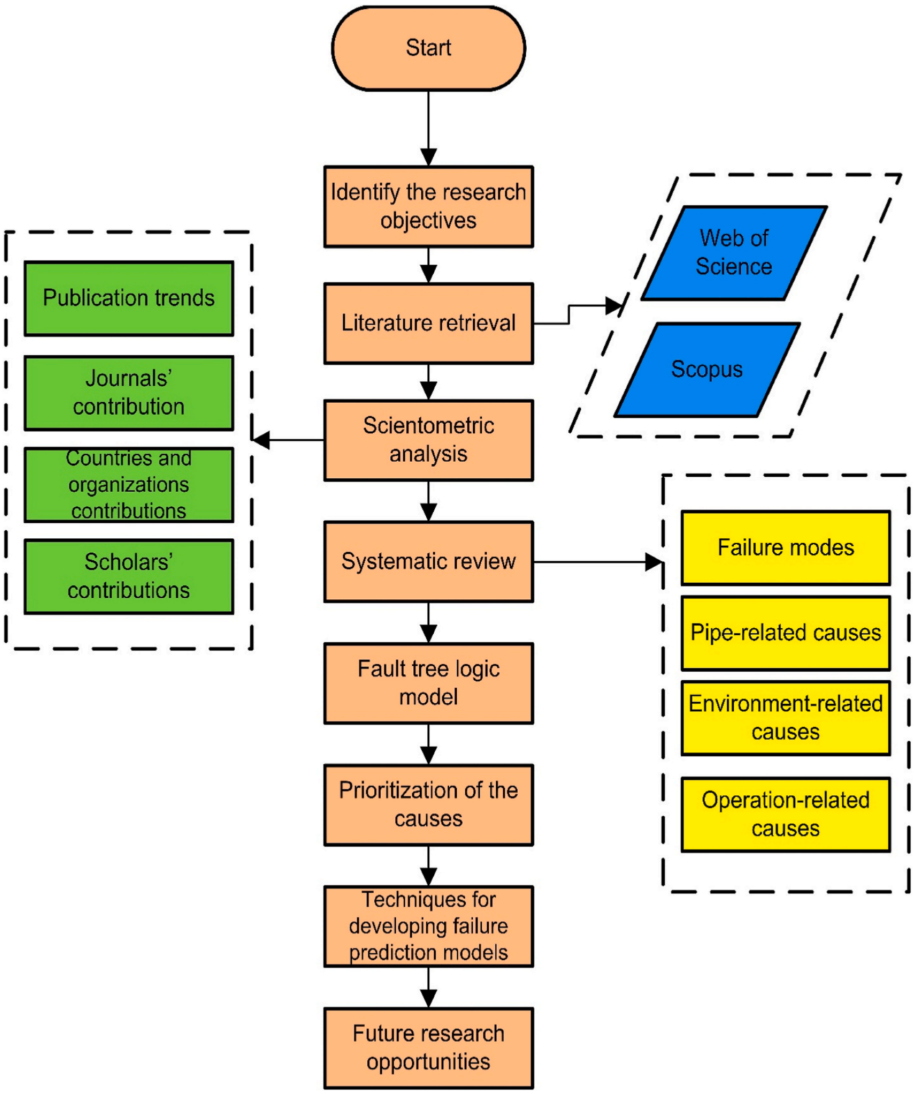


Fig. 1. The framework of the study.

2.2. Qualitative analysis

As indicated earlier, the qualitative analysis involves a systematic discussion of the causes of water pipe failure, mapping the causes using the FTL, failure modes of water pipes, and the techniques adopted for developing failure prediction models. After retrieving the articles relevant to the study's objectives, each article was read carefully to understand the causes of water pipe failure. For each article, data regarding the causes of water pipe failure, type of pipe material, techniques adopted for developing failure prediction models (where available), and failure modes were extracted and documented in an Excel sheet. Research gaps within the articles were identified and formed the basis for providing some recommendations for future directions. In the context of this study, the FTL is a systematic and graphical representation of the relationships between different causes of water pipe failure. The FTL identifies the combination of causes that either leads to another cause or the ultimate failure of water pipes. A typical FTL diagram consists of three types of events (i.e., causes): top, intermediate, and basic events. The top event is water pipe failure. The intermediate events are the causes of water pipe failure that contribute to the top event and can be further decomposed into basic events, which are the lowest event level in the FTL diagram.

2.3. AHP methodology

AHP is adopted to rank the identified causes of water pipe failure. AHP is a method that is adopted in solving multi-criteria decision problems. This method, AHP, and its generalized form, known as Analytical Network Process (ANP), were both developed by Thomas Saaty (2005). AHP allows decision-makers to simplify their problems into hierarchical structures composed of various elements. AHP works on the basis of pair-wise comparison. That is, two elements are compared with one another based on an attribute common to both of them. The experts in a domain usually do the judgment of pair-wise comparison by assigning a numerical value within the range of 1–9 based on Saaty's scale of relative importance (Saaty, 2005). As developed by Saaty, the consistency ratio is used to check the consistency level of the pair-wise comparison's judgment, which easily allows inconsistent judgment to be discarded. In this study, the judgment of pair-wise comparison is based on the frequency of occurrence of the causes of water pipe failure in the reviewed literature. The frequency is used as the judgement based on the assumption that critical causes of pipe failure are given more attention than the less critical ones; hence, the former is more discussed and researched in previous studies. For instance, 23 pieces of literature mentioned "pipe diameter" as a cause of water pipe failure, while 12 pieces of literature mentioned "pipe length." During the pair-wise comparison of pipe diameter and pipe length, a

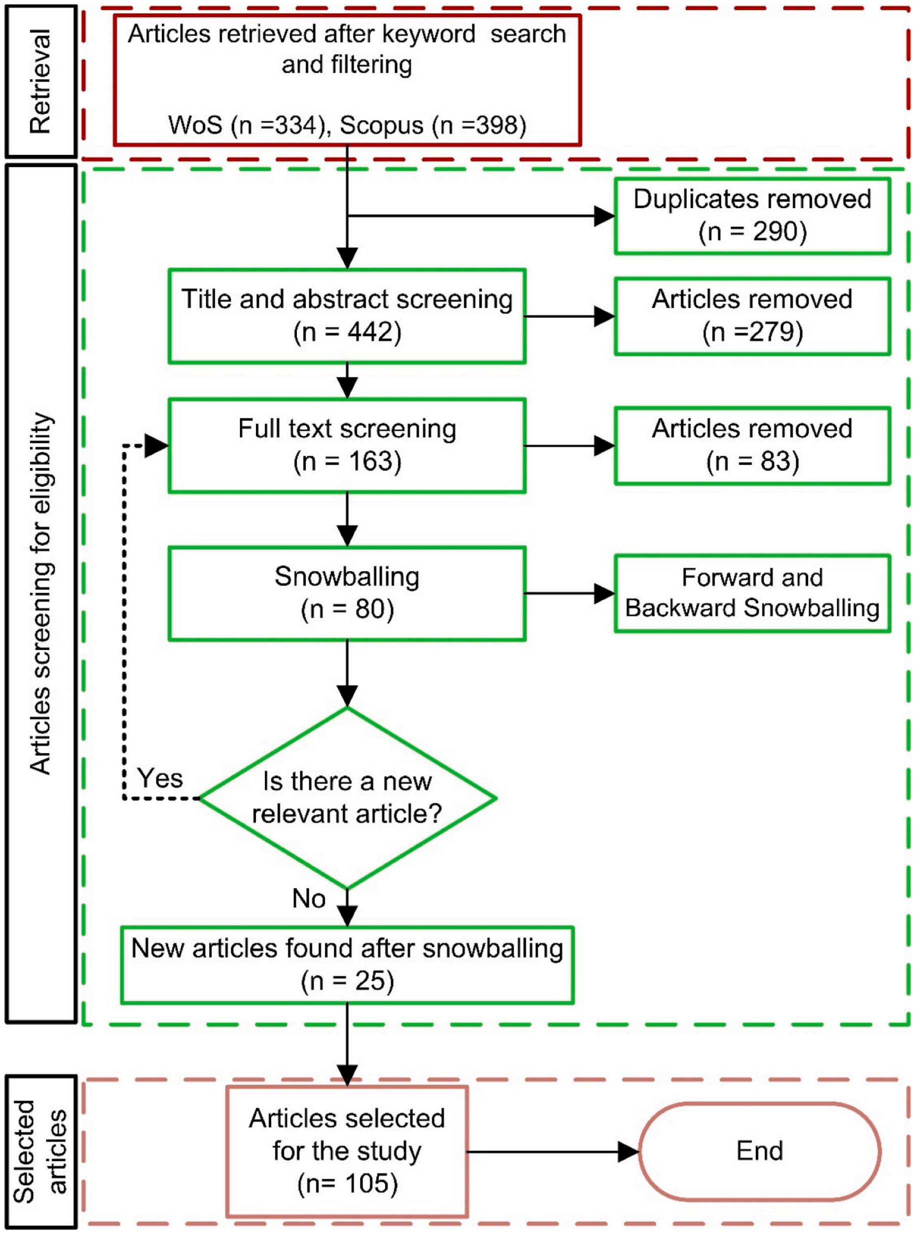


Fig. 2. Complete procedures for literature retrieval and selection.

value of 2 (as a round-off number of 23/12) is assigned to pipe diameter, showing that pipe diameter is equally to moderately more important than pipe length. The steps involved in developing an AHP model are highlighted below (Faqih et al., 2020; Yeung et al., 2020).

- **Define the problem statement**: The first step is to define the problem that needs to be solved or the decision that needs to be made. In this study, the decision to be made is to prioritize the causes of water pipe failure based on their relative weights.
- **Formulate the hierarchy**: At this stage, a hierarchy of the causes of failure will be formulated, showing the relationship between the causes at different levels. This is similar to the FTL diagram developed in this study.
- **Develop pairwise comparison matrices**: The third step involves the formation of pairwise comparison matrices. A matrix is developed to compare the causes of failure at each comparison level.
- **Determine the relative weights**: The weights at each level of comparison are determined and subsequently aggregated to calculate the overall relative weight of each cause of water pipe failure.

2.4. Scientometric analysis

A scientometric analysis is an approach of objectively mapping a scientific domain with the help of bibliographical data to critically assess the evolution and development of the scientific domain through various indexes (Andriamamonjy et al., 2019; Olawumi and Chan, 2018; G. Wang et al., 2020). VOSviewer was chosen for this study due to its unique features, including easiness in visualizing large maps with the zoom-in feature and well-labeled algorithms (Hussein and Zayed, 2021). The procedures employed for the analysis in this study are discussed in the subsequent section.

3. Results and discussion of the scientometric analysis

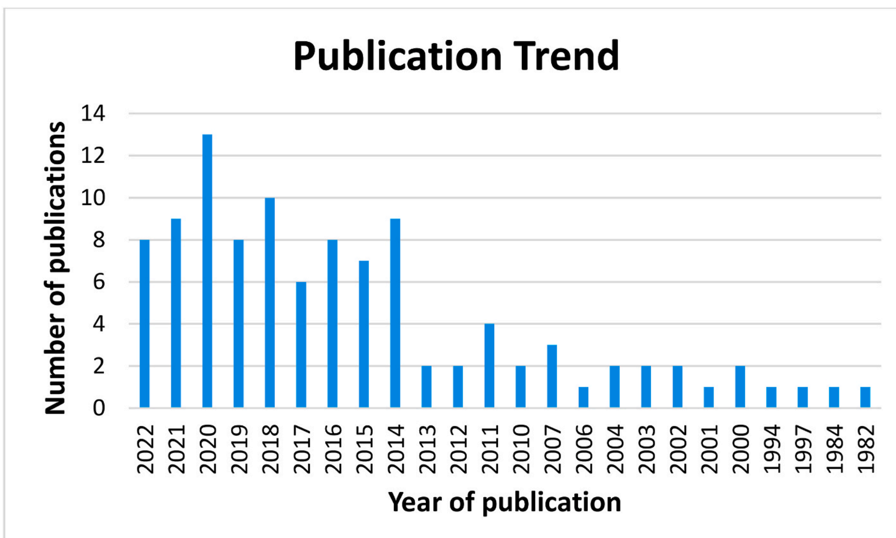
In this section, the results of the scientometric analysis, including the annual publication trends, analysis of keywords, and other science mapping analyses, are discussed.

3.1. Publication trends

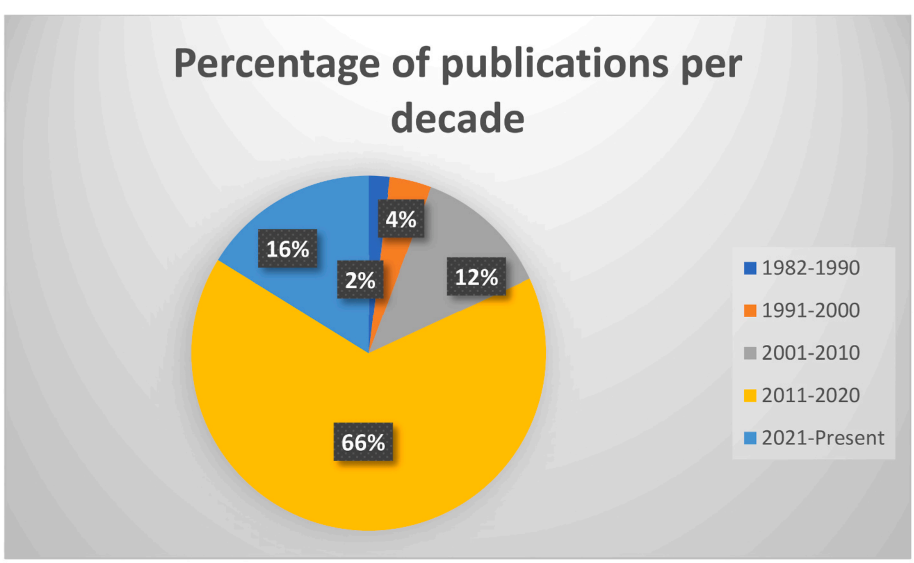
Fig. 3 shows the number of publications made annually for the 105 retrieved articles. The publication years ranged from 1982 to 2022. First, a bar chart (Fig. 3a) shows the number of publications per year. Second, Fig. 3b represents the number of publications grouped by decade. From these analyses, it is noticed that the study on the causes of water pipe failure did not attract the attention of researchers until the 1980s, despite the availability and usage of water pipes since the 1900s (Clair and Sinha, 2014). Additionally, as one may observe from Fig. 3b, studies on the causes of water pipe failure have gained momentum from one decade to another, as 2, 4, 12, and 66% of the papers were published in 1982–1990, 1991–2000, 2001–2010, and 2011–2020, respectively. Although only 12% of the articles were published within 2021–2022, there is the possibility that the number of articles will exceed that of the previous decade by 2030, based on the publication trend (see Fig. 3).

3.2. Keyword cluster analysis

Keywordsplay an important role in a research paper, as they show the paper's main focus, thereby giving potential readers an insight into what the paper entails (Rahman et al., 2020). Out of the 1106 keywords used in the 105 articles, only 122 of them met the VOSviewer criteria of occurring at least three times. The top 20 keywords are shown in Table 2. Moreover, some keywords with the same meaning but different wordings were noticed. These keywords were merged. For instance, keywords such as "pipeline failures" were replaced with "pipe failures." A.csv file containing the original keywords and the keywords that replaced them was later imported into the VOSviewer. This approach ensures that the appropriate node sizes, which indicate the number of



(a)



(b)

Fig. 3. Publication trend: (a) number of publications per year (b) percentage of publications per decade.

Table 2
Keyword occurrences.

Keyword	Occurrences	Total link strength
Failure analysis	42	39
Water distribution networks	30	26
Corrosion	27	24
Cast iron pipe	19	19
Pipe failures	16	18
Deterioration	14	15
Iron	11	12
Failure mechanism	9	11
Potable water	8	11
Soils	7	7
Asset management	7	6
Mechanical properties	6	6
Cracks	5	5
Failure rate	5	5
Leakage	5	5
Pipe material	5	4
Environmental factors	5	4
Fracture	4	4
Bacteria	4	4
Climate change	3	3

occurrences of each keyword, for the relevant keywords are generated.

From Fig. 4, it is observed that "corrosion" has the biggest node size in terms of the keywords that depict the factors contributing to the failure of water pipes, which implies that corrosion is the most common focus of the retrieved articles. Additionally, "soils" could be deemed a causal factor of "corrosion" as they are clustered together. However, "soils" have a smaller node, which means that the soil as a cause of corrosion has not been fully studied. It can also be inferred that the most common type of pipe that has been studied is "cast iron pipe."

According to Table 2, the keywords with the lowest occurrence and total strength link are "pipe material," "fracture," "bacteria," and "climate change," indicating a low level of research in these sub-domains of knowledge, as related to causes of water pipe failure.

3.3. Contributions of journals

The contributions of the research outlets are discussed in this section. This is important to show the most productive research outlets in terms of the different considered criteria and can guide researchers in making decisions based on these criteria. Using the VOSviewer software, the minimum number of documents for a source was set to 1, while the minimum number of citations was set to 25. There is no limit on this threshold setting in scientometric analysis (Tariq et al., 2021). Out of the 49 sources, 14 met this threshold, as shown in Table 3.

In terms of the number of citations, "Canadian Journal of Civil Engineering" is ranked as the most productive journal outlet, despite the fact that the outlet only published four articles used in this study compared to "Engineering Failure Analysis," which has 10 articles. The same trend is noticed in the total link strength, as presented in Table 3. This means that the nature of studies published by the "Canadian Journal of Civil Engineering" has the highest impact and significance in the domain, as they have received the highest recognition from researchers in terms of citations.

Table 3
Contribution of research outlets.

Name of research outlets	No. of documents	Citations	Total link strength
Canadian Journal of Civil Engineering	4	292	12
Engineering Failure Analysis	10	284	8
Journal of Water Supply: Research and Technology	3	256	6
Advances in Water Resources	1	230	2
European Journal of Operational Research	1	222	6
Journal of Infrastructure Systems	2	215	6
Journal of Pipeline Systems Engineering And Practice	6	209	5
Canadian Geotechnical Journal	1	197	6
Journal of Materials In Civil Engineering	2	134	4
Procedia Engineering	2	102	4
Computer-Aided Civil And Infrastructure Engineering	1	61	2
Arabian Journal for Science and Engineering	1	41	0
Journal of American Water Works Association	2	39	0
Journal of Hydroinformatics	1	37	2

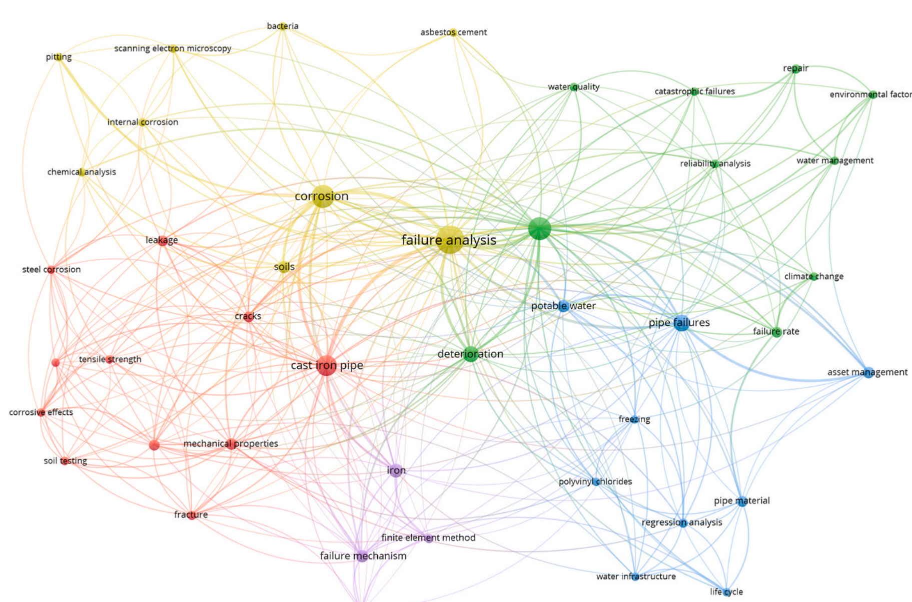


Fig. 4. Co-occurrence of keywords network map.

3.4. Contributions of countries and organizations

The contributions of countries and organizations in the domain of the causes of water pipes are discussed in this section. In terms of the number of publications and total link strengths, Canada is the most productive, with 24 documents and 38 link strengths (see Table 4), followed by the United States of America and Australia; while the United Kingdom and Turkey are the least productive countries with 2 documents each.

Consequently, the productivity of Canada in the research domain was also confirmed by the analysis of the organizations' contributions, as four organizations from Canada are among the top 5 organizations (see Table 5). This implies that Canadian researchers and the government paid more attention to the failure of water pipes than other countries and that Canada has the highest potential for future collaboration with other countries in related research. Additionally, the enormous effort of Canada in this domain can be traced to annual financial loss estimated at one billion dollars, generated by water loss due to failed pipeline systems in Canada (Renzetti and Dupont, 2013).

3.5. Science mapping of scholars

Citation and co-citation analyses of researchers were conducted. These analyses indicate scholars that are actively working in the scientific domain: causes of water pipe failure. The citation analysis indicates four clusters, typifying Rajani B., Sadiq R., and Kodikara J. as the most productive researchers in terms of the number of publications. In terms of citations, Rajani B., Sadiq R., and Tesfamariam are the most cited scholars, with 497, 389, and 260 citations, respectively (see Table 6). This analysis also indicates the existence of a strong relationship between the two top scholars – Rajani B. and Sadiq R. – as their nodes are close to each other, suggesting that they often collaborate. Thus, collaboration can increase the visibility of researchers' output.

A co-citation analysis of the authors was also conducted. In this context, co-citation refers to two authors that are cited together by a third author (Surwase et al., 2011). Rajani B. has the highest total link strength, at 1645, which could indicate how often the researcher collaborates with other researchers. As shown in Table 7, other top scholars include Kleiner Y., Sadiq R., Tesfamariam S., and Kodikara J., with a total link strength of 1203, 1148, 952, and 634, respectively. These analyses will assist individuals or organizations seeking consultations on the causes of water pipe failure to identify the top researchers in the domain.

4. Failure modes and the causes of water pipe failure

In this section, the findings from the systematic review of previous studies are presented. This includes a presentation of the most common failure modes of water pipes, as well as pipe-related, environment-related, and operation-related causes affecting the failure of water pipes.

4.1. Failure modes

Failure mode describes the exact manner in which the pipe fails rather than the cause of its failure. This largely depends on the pipe material and its diameter (Makar, 2000; Rajeev et al., 2014). The most common forms of water pipe failure are discussed in this section. Table 8 shows the schematic representation of the failure modes with their common causes and typical pipe material and sizes that exhibit the failure modes.

Table 4
Productivity of countries.

Country	No. of documents	Citations	Total link strength
Canada	24	925	38
United States	20	239	17
Australia	10	122	15
China	8	104	11
Poland	7	93	4
United Kingdom	2	88	4
Turkey	2	54	6

Table 5
Organizations' contributions.

Organization	Documents	Citations	Total Link Strength
National Res. Council, Canada	3	323	9
University of British Columbia, Canada	2	246	9
University of Johannesburg, South Africa	1	175	0
Concordia University, Montreal, Canada	1	102	5
University of Toronto, Canada	1	96	2

Table 6
Citation analysis of scholars.

Author	Documents	Citations	Total link strength
Rajani B.	4	497	29
Sadiq R.	4	389	26
Tesfamariam S.	3	260	21
Francisque A.	2	224	17
Seica M.V.	3	201	28

Table 7
Co-citation analysis of scholars.

Author	Citations	Total link strength
Rajani, B.	273	1645
Kleiner, Y.	188	1203
Sadiq, R.	81	1148
Tesfamariam, S	72	952
Kodikara, J.	59	634

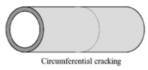
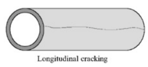
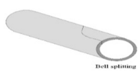
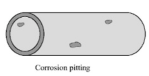
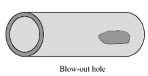
Circumferential cracking: This occurs when the pipe fails at its circumference. The circumferential mode of failure occurs due to the development of bending moments on the pipe, which may be attributed to external forces (Makar, 2000). Inadequate bedding conditions, frost penetration, and backfill, which may be sources of external forces, play important roles in this particular mode of failure (Grigg, 2017; Liyanage and Dhar, 2017; Trickey et al., 2016).

This mode of failure is the most common mode in grey cast iron (CI) pipes (Makar, 2000). Due to the development of tensile hoop stress, CI pipes with large diameters usually have circumferential cracking as their failure mode. The axial stress developed in large-diameter pipes is usually significantly lower than the hoop stress (Daniel Wilson et al., 2017). The failure mode is also common in asbestos (AC) and metallic pipes with a diameter of less than 200 mm (Barton et al., 2019).

Longitudinal Cracking: This is the failure mode that describes the failure of a pipe at its longest side. The failure mode occurs when a longitudinal crack appears on the pipe. This could result from compressive forces acting along the pipe or internal water pressure (Makar et al., 2001). In addition, longitudinal cracking can occur on pipes due to traffic loads, causing the development of cross-sectional tension; radial tension caused by water pressure (Farewell et al., 2012); expansion due to frozen water, causing the development of cross-sectional loads; and ground loads, causing the development of cross-sectional loads (Mora-Rodríguez et al., 2014).

This failure mode is common in small and large-diameter CI pipes. For instance, the data presented in the study by Ji et al. (2020) showed longitudinal fracture as the prominent failure mode of small-diameter pipes. Longitudinal, circumferential, piece blown out, and fitting

Table 8
Common failure modes of water pipes.

Failure modes	Schematic	Descriptions	Common causes	Typical pipe materials	Typical pipe diameter	References
Circumferential cracking		Failure of the pipe at its circumference	• Inadequate bedding condition • Inappropriate backfilling • Frost penetration	• Cast iron • Ductile iron • Steel • Asbestos cement • Copper	It can occur in all pipe sizes but is common in pipes with <200 mm diameter	(Grigg, 2017; K. T. H. Liyanage and Dhar, 2017; Rajeev et al., 2014; Trickey et al., 2016)
Longitudinal cracking		Failure of the pipe at its longer side	• Traffic loads • Internal water pressure • Frost penetration	• Cast iron • Polyvinyl chloride • Polyethylene • Asbestos cement	It can occur in all pipe sizes but is common in pipes with >300 mm diameter	(Barton et al., 2019; Farewell et al., 2012; Ji et al., 2020; Mora-Rodríguez et al., 2014)
Bell splitting		Splitting of the bell at the joint of the pipe	• Temperature • Internal water pressure	• Cast iron • Ductile Iron	It can occur in all pipe sizes but is common in pipes with >300 mm diameter	(Makar et al., 2001; Makar, 2000)
Corrosion pitting		Loss of metal at a localised region on the pipe	• Soil acidity • Bacteria • Soil resistivity • Water quality	• Cast iron • Ductile iron • Steel	It can occur in all pipe sizes but is common in pipes with <200 mm diameter	(Grigg, 2017; Pę;kala & Pietrucha-Urbanik, 2018; Rajeev et al., 2014)
Blown-out hole		Creation of large hole (s) on the pipe	• Corrosion • Internal water pressure	• Cast iron • Ductile iron • Steel • Polyvinyl chloride • Polyethylene	All pipe sizes	(Ji et al., 2020; Makar et al., 2001; Makar, 2000; Tang et al., 2019)

failures were responsible for 53, 21, 14, and 5% of the failures, respectively (Ji et al., 2020). On the other hand, out of four failure modes examined by Rajeev et al. (2014), the authors found that large-diameter pipes failed mostly via longitudinal cracking and bell splitting.

Bell* Splitting:* This is a failure mode that occurs when the pipe's bell (at the joint) splits due to differences in the coefficient of thermal expansivity of the pipe and the joint material (Makar et al., 2001; Makar, 2000). It should be noted that this mode of failure is also common in small-diameter pipes and is different from longitudinal cracking in that its (bell-splitting) cracking ends just below the bell. The common joint material in metallic pipes, leadite, has a coefficient of thermal expansion that differs from that of metallic pipes. This difference could cause stresses in the pipe, which could contribute to the pipe's failure (Makar, 2000).

Corrosion pitting: The localized form of corrosion that occurs on the inner surface of a water pipe, creating pits or small holes, is referred to as corrosion pitting (Rajeev et al., 2014). The formation of corrosion pits weakens the pipe and thus facilitates water loss (Rajani and Tesfamariam, 2005). Various factors, including poor water quality, the presence of corrosive substances such as high levels of chlorides and sulphates in water, and the presence of micro-organisms such as fungi and bacteria are responsible for corrosion pitting in water pipes (Sadiq et al., 2004).

Pitting corrosion is a common type of failure mode in both large and small-diameter metallic pipes. A study conducted by Pę;kala & Pietrucha-Urbanik (2018) indicated that corrosion pitting, fitting failure, and mechanical damage accounted for 51%, 26%, and 6% of all the water pipe failures, respectively, in a network.

Blown-out hole: This form of failure mode is the occurrence of a large hole or rupture on a water pipe due to the sudden release of pressure. The impact of the water pressure becomes more severe on the pipe, particularly when the pipe has been compromised by other faults such as corrosion pitting, mechanical damage, and manufacturing defects, among others (Ji et al., 2020; Tang et al., 2019). In the case of corrosion pitting, the localized corrosion weakens the pipe, and the pressure blows out the remaining thin pipe wall. In 2014, Rajeev et al. (2014) found that a blown-out hole is the major failure mode in five Australian utilities. Previous studies, such as the ones conducted by Makar et al. (2001) & Makar (2000), also confirm this type of failure mode in water pipes. This failure mode has been found to be dominant in CI and steel pipes (Rajeev et al., 2014).

4.2. Pipe-related causes

As highlighted earlier, the causes of water pipe failure are grouped into three main classes: pipe-related, environment-related, and operation-related causes. Therefore, in this section, pipe-related causes are explained based on the reviewed texts.

4.2.1. Pipe age

Pipe age describes how long a pipe has been in service. Some pieces of the literature showed that there is a linear relationship between age and the number of breakages (Ellison and Spencer, 2016; Jun et al., 2020; Mackey et al., 2014), while others showed otherwise, that is, complex and non-linear relationships (Doyle, 2000; Hekmati et al., 2020; Hu and Hubble, 2007). Many studies have established that newer pipes exhibited a lower break rate than older ones (Ellison and Spencer, 2016; Fares and Zayed, 2010; Jun et al., 2020; Mackey et al., 2014). For example, Ellison and Spencer (2016) found that pipes in the age bracket of 50–65 years old failed 10% more often than those within the age bracket of 35–49 years. This is explained by the fact that damages accumulate on water pipes from various sources over time after the installation of water pipes. Therefore, it could be expected that the breakage rate of older pipes could be higher than that of newer pipes.

On the other hand, researchers have also established an inverse relationship between the age of a pipe and its breakage rate. For instance, Hu and Hubble (2007) found the breakage rate of AC pipes installed between 1965 and 1974 in the city of Regina, Canada, to be 0.095 breaks/km/year, while the breakage rate of those installed between 1975 and 1984 was 0.120 breaks/km/year. A similar trend was noticed in the research conducted by Andreou et al. (1987). Furthermore, it was noticed that the pipe failure rate increases as the pipe's age increase until they reach 50–60 years. The pipes in this age bracket (50–60 years) exhibited the highest failure rate. Even pipes that had been in service for 60–130 years had a significantly lower failure rate (Hekmati et al., 2020). This shows that the higher failure rate of the pipes within 50–60 years could be attributed to the pipe material or installation techniques adopted, as indicated by the authors. This implies that "pipe age" alone cannot be affirmed as the only factor causing the failure of water pipes, as other factors may be prevalent. Besides, Doyle et al. (2003) noticed no correlation between pipe age and failure rate.

A general way to conclude is that pipes deteriorate over time, and as a result, older pipes can be expected to have higher failure rates, but this may not be true all the time if other contributing factors to failure are dominant.

4.2.2. Pipe diameter

The diameter of water pipes has been documented by previous researchers as a factor that contributes to the failure of water pipes. Many previous studies have established a direct relationship between increasing diameter and decreasing failure rate (Bruaset and Sægrov, 2018; Hekmati et al., 2020; Kutyłowska and Hotloś, 2013; Kutyłowska and Orłowska-Szostak, 2016; Katarzyna Pietrucha-Urbanik, 2015; Rajeev et al., 2014; Rezaei et al., 2015; Singh, 2011; Zywiec et al., 2019). Rezaei et al. (2015) analyzed historical burst data to understand the impact of hydraulic and physical conditions on the failure of water pipes. They found that an increase in the diameter of the pipe brought about a decrease in the number of bursts recorded for the water pipes, as the number of bursts for pipes with a diameter greater than 600 mm was 87.5% less than those with a diameter of 100 mm or less. In the same vein, the study conducted by Rajeev et al. (2014) showed that a pipe with a 300 mm diameter failed 7 times per year per 100 km, while another pipe of 400 mm of the same age and material failed 0.8 times per year per 100 km. Furthermore, Hekmati et al. (2020) indicated that smaller-diameter pipes experienced a greater number of failures than their larger-diameter pipes counterparts. According to their results (Hekmati et al., 2020), a 150 mm diameter pipe failed 43 times in a year, while a pipe with a 600 mm diameter only failed twice in a year. The susceptibility of smaller diameter pipes to higher failure rates can be traced to their thinner wall thickness, resulting in low bending modulus (Bruaset and Sægrov, 2018; Ellison and Spencer, 2016) and high-pressure fluctuations (Kutyłowska and Orłowska-Szostak, 2016).

On the contrary, Wilson et al. (2017) argued that larger diameter pipes with corresponding thicker pipe walls could possess lower factors of safety compared to smaller ones. In their study, the factor of safety of a 750 mm pipe was about 0.1 higher than that of a 1050 mm pipe. This could be explained by the fact that an increase in the pipe's diameter from 500 mm to 750 mm brought about an increase in the pipe's yield strength that outweighed the increase in the hoop and axial stresses generated in the system. However, the increase in the pipe's diameter from 750 mm to 1050 mm resulted in an increase in the hoop and axial stresses that outweighed the increase in the pipe's yield strength. Nevertheless, a point to note is that both 750- and 1050-mm diameter pipes can be regarded as large-diameter pipes. Therefore, it can be concluded that large-diameter pipes (>300 mm) (Jiang et al., 2017; Kutyłowska and Hotloś, 2013; Katarzyna Pietrucha-Urbanik, 2015) exhibit a lower failure rate due to their larger thickness compared to pipes with a smaller diameter.

4.2.3. Pipe length

Some of the previous studies have shown a linear relationship between pipe length and failure rate. Vipulanandan et al. (2012) analyzed the data for water pipeline failure in 282 cities in the USA. They found that the average number of breaks per day increases with an increase in the pipe length, such that the average number of breaks per day moves from 0.3 to 12 when the length of the pipe changes from 2700 to 7500 miles. In another study, an increase in the length of small-diameter polyvinyl chloride (PVC) pipes tends to increase the failure rate. As reported by Zamenian et al. (2017), when small-diameter pipes of 152 mm and 203 mm increased by 1 km, their monthly breakage rate increased by 0.682 and 0.041, respectively. This is traced to the fact that the use of a small pipe diameter in WDNs would increase the number of joints and service connections along the pipes. This means that these pipes could be poorly installed at service line connections. A similar trend was observed in the study of Almheiri et al. (2020).

However, Andreou et al. (1987) argued that water pipe failure could not be linearly related to the length of the pipe. That is, a pipe with the same break history as another pipe of half its length cannot be predicted to have twice the failure rate of the other pipe. This is because the longer pipe might have been affected by localized corrosion or other factors pertinent to a particular point on the pipe.

4.2.4. Pipe wall thickness

Like pipe diameter, a positive correlation has been found between increasing pipe thickness and a decreasing number of failures on water pipes (Bruaset and Sægrov, 2018; Chang et al., 2021; Dawood et al., 2022; Gao, 2017; Liyanage and Dhar, 2018; Wilson et al., 2017). It should be noted that an increase in the diameter of a pipe does not necessarily mean that its wall thickness will also be increased at the same rate. Wilson et al. (2017) studied the soil and pipe-related factors that influence the factor of safety of water pipes. The higher the factor of safety, the safer the pipe. They concluded that regardless of the pipe diameter, the factor of safety of water pipes increases as their wall thickness increases. For instance, the factor of safety of a pipe with a 500 mm wall thickness was 2.0, while that of 1500 mm was 9.8 (Wilson et al., 2017). It should be noted that maximum hoop or axial stresses generated by the pipe and the tensile yield strength of the pipe were employed in determining the factor of safety. The better performance of pipes with larger wall thickness could be attributed to the increased yield strength of the pipe as its wall thickness increases. In addition, Chang et al. (2021) found that reducing pipe wall thickness increased the settlement displacement of water pipes, which eventually increased their breakage frequency.

4.2.5. Pipe material and manufacturing flaw

The type of material employed in manufacturing pipes has been reported in numerous studies as a factor determining the extent of failure in water pipes (Almheiri et al., 2020; Clair and Sinha, 2014; Fares and Zayed, 2010; García et al., 2018; Kutyłowska and Hotloś, 2013; Paradkar, 2012; Katarzyna Pietrucha-Urbanik, 2015; Pouri and Heidarimozaffar, 2022; Rajeev et al., 2014; Rezaei et al., 2015; Singh, 2011; Zamenian et al., 2017). The most common materials for the manufacturing of water pipes include CI, ductile iron (DI), steel, AC, concrete, polyethylene (PE), and PVC (Clair and Sinha, 2014).

In the late 19th century, CI pipes were introduced and cast statically (both horizontally and vertically). This method of manufacturing produces pipes with non-uniform thicknesses. Whereas in the early 20th century, the spun method of casting was introduced, which aids the production of uniform (in terms of thickness) CI pipes with a relatively higher strength compared to pipes made by static casting (Jiang et al., 2017). CI pipes, generally, have been found to exhibit a higher failure rate compared to others, mostly because of their high susceptibility to corrosion. For instance, out of five types of pipes used in two WDNs, CI pipes accounted for the most failure rates, representing 39.3% (Rezaei et al., 2015) and 40.3% (Folkman et al., 2012) of their total failures, respectively. DI pipe was introduced in the middle of the 20th century to replace CI because of its better features, such as higher strength, ductility, and toughness compared to CI (Clair and Sinha, 2014), such that the number of failures reported by Paradkar (2012) on pit CI and DI pipes was 13797, and 399 in numbers. However, proper caution should be taken when using DI pipe as it has the potential to corrode, both internally and externally; hence, it needs to be carefully protected. Different kinds of manufacturing flaws of CI and DI pipes include porosity, which can lead to the formation of micro-cracks on the pipe; cold shuts, which can lead to an incomplete fusion of two surfaces; and inclusions, which can cause weak points on the pipes (Rajkolhe and Khan, 2014). For instance, a laboratory investigation by Makar (2000) showed that inclusion lowers the tensile strength of CI pipe from 130 to 33 Mpa.

Steel is another metallic material used in the manufacture of water pipes. Although steel seems to be more ductile than CI pipes, it has lower strength than DI pipes (Jun et al., 2020). Like iron pipes, steel pipes have a high potential for corrosion, even more than DI pipes, hence their need for effective protection. The failure investigation conducted on four types of pipes by Zywiec et al. (2019) indicated that the highest number of failures was found in the CI pipes, which was followed by the steel pipe. Furthermore, the wrong combination of metallic elements has been found to be a contributing factor to the premature failure of steel water pipes. Microscopic analysis was conducted to determine the root cause of the corrosion of two steel pipes (Pawłowski et al., 2020). It was revealed that the occurrence of corrosion was attributed to the use of a yellow brass valve with galvanized steel. This phenomenon is termed contact corrosion or bimetallic corrosion. This occurs when two different metals are in contact with one another and with an electrolyte, such as water. In this case, dezincification occurs because the steel pipes are coated with zinc, which reduces the mechanical strength of the pipe.

AC and concrete pipes are the most common water pipes that employ Portland cement during their manufacturing process. An advantage of AC pipes over concrete pipes is the addition of fibers, which improves the mechanical strength of AC pipes (Coufal et al., 2014). The rigidity of the AC pipe allows it to offer good resistance to pressure surges (Clair and Sinha, 2014). However, AC pipes are prone to lime leaching, which can degrade the water pipes (Al-Adeeb and Matti, 1984). The manufacturing method also has an influence on the performance of AC pipes. For instance, the AC pipe manufactured with water curing breaks four times more often than the one manufactured using autoclave curing, as reported by Ellison and Spencer (2016).

PVC and PE are the most common plastic materials used to manufacture water pipes. PE and PVC pipes are available in high density, medium density, and low density, depending on their usage. These pipes have numerous comparative advantages over other types of pipes, including their capacity to absorb impact loads and ground movement, high corrosion resistance, less weight, ability to be used in trenchless applications, and flexibility (Clair and Sinha, 2014; Zamenian et al., 2017). This is the reason why plastic pipes have shown a lower breakage rate compared to other pipes in many previous studies (Clair and Sinha, 2014; Folkman et al., 2012; Rezaei et al., 2015; Zywiec et al., 2019). For instance, according to the results presented by Rezaei et al. (2015), 321, 187, 143, and 99 bursts in a pipe system were attributed to CI, AC, PVC, and PE pipes, respectively.

However, the disadvantages of PE and PVC pipes include the need for imported bedding, susceptibility to degradation by some organic substances, and buckling and fatigue failure (Clair and Sinha, 2014). Inclusion is also an issue in early-manufactured PVC pipes, causing micro-cracks formation during the manufacturing process (Breen, 2006). An inadequate tapping process is another problem attributed to plastic pipes. Yang et al. (2016) found that the catastrophic failure of a PVC pipe was due to an inefficient tapping process during the installation of the pipe, as a burnt mark was noticed on the failed pipe hole. The burnt mark was due to the occurrence of a high temperature during tapping, which is an issue for PVC pipes as they are not capable of dissipating heat at a fast rate when subjected to high temperatures. It should be noted that if any of these limitations of plastic pipes is dominant in a WDN, the rate of plastic pipe failure may be higher than other pipes, as seen in the study by Almheiri et al. (2020).

4.2.6. Protection efficiency and third-party damage

Around the 1920s, pipe lining (for internal protection) and coating (for internal and external protection) were introduced to iron pipes (Mordak and Wheeler, 1998). Due to their susceptibility to corrosion, steel and other metallic pipes also need to be lined. The investigation conducted by Lee (2011) revealed that an unlined CI pipe failed four times higher than a lined CI pipe. Further, the wrong coating was observed as a contributing factor to the failure of water pipes in a three-year investigation on the causes and failure modes of CI pipes in Canada (Makar et al., 2001). Some other protective methods include cathodic protection and wrapping with polyethylene (Kleiner et al., 2004; Rajani and Kleiner, 2003). Most times, PE and PVC are not coated or lined due to their high corrosion resistance. Cement mortar lining and epoxy resin are suitable lining materials for steel & iron, and AC pipes, respectively (Mordak and Wheeler, 1998).

Third-party damage, a contributing factor to water pipe failure, occurs when an individual or company accidently causes damage to the buried pipe without knowing, such as using a bulldozer on an adjacent road that houses buried pipes (Farshad, 2006). Careless handling, and storage of water pipes, especially during their transportation, can cause micro-cracks or large cracks, depending on the magnitude of the applied forces, on the pipes. For instance, exposure to PVC pipes for a long period to ultraviolet light can cause them to become more brittle (Tran et al., 2021).

4.2.7. Buried depth

An inverse relationship has been noted between the buried depth and the breakage rate of water pipes (Jun et al., 2020; Trickey et al., 2016; Wilson et al., 2015). This is because the soil pressure acting on a pipe of a shallow depth will be much higher than that of a deep depth. Trickey et al. (2016) found that decreasing the buried depth of CI water pipes from 2 m to 1.5 m increased the longitudinal bending moment of the pipe by more than 140%, causing the pipe to develop a circumferential fracture. Besides, the failure frequency of a pipe with a 0.5 m depth was almost ten times that of a pipe with a 1.5 m depth, despite the fact that the two pipes had a 750 mm diameter (Wilson et al., 2015). Jun et al. (2020) noted a similar observation in their study.

4.3. Environment-related causes

The environment, including the surrounding of the water pipes, can greatly influence the failure rate of buried water pipes. The environment-related causes have been divided into four main categories: soil-related, climate-related, location-based, and biological and chemical-related causes.

4.3.1. Soil-related causes

Soil corrosivity, which entails soil resistivity, aeration, moisture content, pH, and soluble salts present in the soil, is arguably one of the most critical factors alongside bedding conditions that influence water pipe failure (Demissie et al., 2016). In this context, soil corrosivity describes the properties of soil that can cause corrosion and, subsequently, failure of water pipes. Soil corrosivity can be difficult to understand properly due to its heterogeneity and complex nature (Pritchard et al., 2013). Ductile Iron Pipe Research Association (DIPRA) developed a 10-point scoring method as an index for soil corrosivity measurement (Ductile Iron Pipe Research Association, 2017; Najjaran et al., 2006), which is a function of 5 soil properties (soil moisture content, redox potential, sulphides, pH, and resistivity). The aim of this scale or method is to classify soil as non-corrosive or corrosive. However, the method does not account for the true severity of corrosion, as a scoring value of 10 indicates corrosive soil, while soil with a scoring value of 9.7, for example, will be termed non-corrosive. In the real sense, both values are not significantly different from each other, which means the two soils might actually be corrosive. The two main types of corrosion in metallic pipes are graphitization and corrosion pitting. The former mainly occurs in CI pipes, while the latter can occur in any metallic pipe. The former is referred to as the leaching of some or the total amount of iron from the pipe, leaving the graphite behind (Makar et al., 2001). It is worth noting that corrosion occurs when two metallic components are in contact with one another under the influence of a corrosive environment. When the two metals are in contact, an exchange of electrons between them occurs, thereby the metal with the higher potential becoming the cathode, whereas the other metal with lower electric potential turns out to be the anode, which is the corroded one (Lee, 2011).

Soil resistivity: Soil resistivity is the property of soil that shows how well it can conduct or resist the flow of electricity. Generally, as seen in previous studies (Doyle et al., 2003; Najjaran et al., 2006; Pritchard et al., 2013; Seica et al., 2002), corrosivity increases with a decrease in soil resistivity. For instance, Seica et al. (2002) attributed the main failure cause of iron-based pipes to corrosion by testing more than ninety soil samples, with most of the samples exhibiting a resistivity value that ranged between 1000 and 3000 Ω-cm, indicating their high potential for corrosion. Although resistivity is an important factor that determines soil corrosivity, it cannot be solely used as an absolute index for corrosion (Arriba-Rodriguez et al., 2018).

Soil type: Soil that acts as a foundation for the pipe and soil used as backfilling play an important role in the number of loads applied to the pipe. For instance, external loading can get increased on the water pipe due to soil compaction, frost penetration, and shrinking and swelling. These phenomena are common in clayed soils (Mackey et al., 2014). Additional stresses are induced on the pipes when soil shrinks due to a decrease in soil volume. This means that the pipe will not be supported uniformly (bedding), which makes it act like a beam, thus, creating high bending moments. Apart from the produced bending moments, shear forces are also developed as a result of differential soil movement (Hu and Hubble, 2007). Furthermore, soft soil, such as organic soil, is not suitable for bedding support due to its high retention capacity of moisture and low bearing capacity of the soil (Pritchard et al., 2013). On the other hand, sandy soil contributes less to pipe failure due to its higher drainage capacity and resistivity (Doyle et al., 2003). Singh (2011) attributed the lowest number of failures to sandy soil (722 breaks), while materials such as mud and coral had a higher number of failures (1080 and 1423 breaks, respectively). However, due to their larger particle size, care must be taken when using sandy soil for bedding support in locations prone to excessive erosion (Pritchard et al., 2013).

Soil pH: Some studies have shown a correlation between water pipe failure and pH, while others have shown otherwise. Pritchard et al. (2013) stated that soil with a low pH value tends to cause corrosion as the passive protective film on the metallic pipes will not be stable at this stage. The analyzed water pipe failure data in the study by Pę;kala & Pietrucha-Urbanik (2018) indicated the average pH of the soil to be 5.3, acidic enough to stimulate corrosive activity on the pipes. Similarly, the laboratory simulated experiment carried out by Hou et al. (2016) for 9 months showed that iron and steel water pipes subjected to soil solutions of 3.5 and 5.5 pH values corroded more than those in a solution of 8.0 pH. On the other hand, while developing a method for estimating the service life of water pipes, Rajani and Makar (2000) discovered that there was no relationship between corrosion rate and pH. This indicates that pH alone is not suitable for determining the soil corrosivity of water pipes, as other contributing factors may be more dominant in one situation than in others.

Soil moisture content: Soil corrosivity increases with an increase in moisture until an optimum moisture content is reached, which then declines afterward (Murray and Moran, 1989). In their research, Noor and Al-Moubaraki (2014) investigated the relationship between the moisture content of the soil in three cities in Saudi Arabia and the corrosion of buried water pipes. Methods such as electrochemical impedance spectroscopy and open circuit potential were employed in their analysis. It was found that the corrosion rate of the pipes increases as the soil moisture content increases up to a critical point of 10%, after which the corrosion rate decreases. In another investigation, 50–65% was reported as the optimum moisture content of soil for the pipe to experience the highest rate of corrosion (Pritchard et al., 2013). This implies that the optimum moisture content of the soil in terms of corrosivity differs from one location to another, depending on other environmental contributions.

Soil aeration: This is a phenomenon that describes the exchange of oxygen between the atmosphere and the soil particles. Differential cells will occur when there is a difference in the concentration of oxygen in the surrounding soil, which can contribute to the corrosion of water pipes (Wasim et al., 2018). It should be noted that excavation can increase the degree of soil aeration (Arriba-Rodriguez et al., 2018). Furthermore, redox potential measures the degree of soil aeration. Soil with low redox potential can be said to exhibit a low concentration of oxygen (Fiedler et al., 2007). It is worth noting that the relationship between soil aeration and the failure of water pipes has not been well-studied.

Bedding conditions and backfilling: In this context, bedding refers to materials laid underneath the water pipes to support the pipes against load exerted from adjacent and topsoil (Makar, 2000). Materials that have a low bearing capacity, such as organic soil, and a high potential for shrinking/swelling, and water content retaining capacity, such as clay, have been found inadequate for bedding materials (Hu and Hubble, 2007; Pritchard et al., 2013). In the study of Affolter et al. (2018), it was stated that a 12-year-old pipe failed due to its poor bedding condition and ageing.

Backfilling is the process of refiling an excavated area. It is important to note that backfill soil, especially if it is transported from somewhere else (referred to as "made ground" or "borrow soil"), can influence corrosion or mechanical damage of water pipes. This is due to the difference in soil properties between the natural and borrow soil, in which their combinations can result in aggressive materials (Pritchard et al., 2013). According to the study by Trickey et al. (2016), when frozen native soil was replaced by granular material for backfilling the trench, about 20 and 200% increases in the maximum deflection and maximum moment were noticed, respectively, which contributed to the pipe failure. This failure could be attributed to the lower stiffness of the granular material compared to that of the native frozen soil.

4.3.2. Climate-related causes

The link between climate-related causes such as seasonality, frost, precipitation, and water pipe failure is discussed in this section. This includes discussion relating to the performance of water pipes in various seasons, especially the winter and summer seasons.

Seasonality: In this context, seasonality refers to a change in the climatic conditions (i.e., summer season, winter season, autumn season, and spring season) that is majorly dependent on temperature. A myriad of past studies has established an inverse relationship between temperature and the rate of water pipe failure (Fuchs-Hanusch et al., 2013; Haurum and Moeslund, 2020; Kutyłowska and Orłowska-Szostak, 2016; Laucelli et al., 2014; Makar et al., 2001; Rezaei et al., 2015; Tran et al., 2021; Xuehan Wang et al., 2019; Zamenian et al., 2017). As the temperature of a material drops, it experiences contraction. However, if the contraction is restricted by an external force, the material would build up tensile stresses, which are directly related to the temperature drop, coefficient of thermal expansivity of the material, and its elastic modulus. In the case of a water pipe, a drop in the temperature of the atmosphere and surrounding soil will affect the pipe's temperature. Therefore, water pipes will tend to contract radially. However, if the contraction is restricted longitudinally, tensile stress would develop, and thus, the pipe would break circumferentially if its strength is exceeded (Habibian, 1994).

A statistically significant correlation was found between the increasing rate of failure and decreasing temperature by analyzing a large database of water pipe failures in Norway (R^2 value = 81.3%). About 70% of the pipes are iron-based (Bruaset and Sægrov, 2018). The analysis showed that the rate of failure increased by 86% when the temperature decreased from 23 °C to −15 °C. This indicates that the warmest season in the country experienced fewer than half the failures of the coldest period. Tran et al. (2021) also noted that temperature drops contributed to the failure of PVC pipes. This could be explained in two ways. Firstly, additional stresses that result from the contraction and freezing of surrounding soil due to low temperatures could exceed the residual strength of the pipe. For instance, a decrease of 10 °C in temperature brings about a shortage of 11 mm in a 10 m water pipe. Secondly, the new-type PVC pipes tend to be more brittle when their temperature is within -5 °C to – 10 °C (Tran et al., 2021).

Due to low temperatures in the winter season, the failure rate of water pipes has been found to be higher in this season compared to other seasons. As a result, there would be an increase in the earth loads exerted on the pipes during the freezing and expansion of water during the winter period (García et al., 2018; Hekmati et al., 2020; Hu and Hubble, 2007; Kutyłowska and Hotloś, 2013; Kutyłowska and Orłowska-Szostak, 2016). Although the failure rate is always seen to be higher during the winter months, pipe failure does occur during the summer months, too, though maybe less than that of the winter months. It was reported that a high breakage rate was reported in both winter and summer compared to the spring and fall seasons in some parts of the UK (Gao, 2017). The former was due to frost-induced stresses on the pipes, while the latter was attributed to dried and shrinking soil. In addition, during the summer season, glaciers melt, and as a result, there is an increase in the content of chloride in the soil, which disturbs the protective layer on the metallic pipes.

It is important to note that temperature alone cannot be used as the sole indicator for water pipe breakage. According to the data of Habibian (1994), an increase in temperature drop caused an increase in the number of failures for most of the investigated pipeline systems, but this was not true for a few of them. For instance, as reported, the number of pipe breakage when there was a temperature drop of 5 °C was 18. The number of breakages increased by 2–20 when the temperature drop was 10.6 °C. This indicates that there is no linear relationship between temperature drop and pipe breakage rate.

Furthermore, due to the accumulation of damage over time on the pipe, there would be a number of weak points on the pipe at a particular time, with each point needing one degree or another (as the case may be) to fail. Hence, there would be a rise in the number of failures when there is a drastic drop in temperature acting on the weakest points of the pipe. The number of breaks stabilizes as the temperature remains constant or rises. However, the number of failures will increase again when the temperature drops below the previous value. This cycle will continue until the weak points are significantly reduced, although newer weak points will be developed with time. This phenomenon explains why a higher temperature drop, 10.6 °C, brought about fewer breakages as the number of weak points has been significantly reduced, leaving only fewer points to break (Habibian, 1994).

Precipitation: The amount of precipitation in a season can directly affect the amount of moisture in the soil. For instance, a season characterized by a high amount of rainfall will increase the swelling potential of clayed soil, which will eventually induce some extra stresses on water pipes (Hekmati et al., 2020; Rak et al., 2021). As such, it was reported that the months with the highest amount of rainfall in Australia (July, August, and September) were associated with the highest number of pipe failures compared to the other months (Hekmati et al., 2020). A similar correlative relationship between rainfall and pipe failure was also indicated in the study conducted by Alhumoud and Almeshaan (2021).

Frost action: When frost penetrates the soil or ground, it causes soil movement, which induces additional stress on water pipes (Tang et al., 2019; Zywiec et al., 2019). Upon the solidification of water to ice due to the change in temperature that occurs during the frost heave process, the volume of water tends to expand, but the pipe wall rather constrains it. This restriction generates ice expansion pressure on the pipe. The extent of damage to the pipe due to this process, the transition of water to ice, depends on the magnitude of the generated ice expansion pressure, which is dependent on factors such as the ratio of pipe stiffness to ice stiffness, the ratio of the pipe diameter to the wall thickness, the rate of water solidification, and the material characteristics of the pipe. When these factors favor the frost heave process, the pipe undergoes elastic-plastic deformation. Upon thawing, the pipe will regain its original size under the influence of the working water pressure. The pipe will expand when the temperature is lowered again, and the cycle continues as described earlier. Zheng et al. (2020) research show that Polypropylene Random Copolymer (PPR) plastic pipes such as S2 and S3.2 will not be affected by freezing and thawing cycles as their elastic deformation can be recovered, on the condition that ageing and fatigue factors are kept constant.

4.3.3. Biological and chemical-related causes

Corrosion of water pipes is also influenced by biological and chemical activities. Microbiologically induced corrosion (MIC), lime leaching, and concentration of soluble salts or chemical substances as related to water pipe failure are explained in this section.

Microbiologically induced corrosion (MIC): Microbial activity in the absence of oxygen is always assumed to cause water pipe corrosion in metallic and concrete pipes. However, MIC occurs predominantly with a partial supply of oxygen. The mechanism behind MIC is the reduction of sulphate to hydrogen sulphide under the influence of a metabolic organism. Sulphate reducing bacteria (SRB) has been found to be the major driver of MIC in water pipes (Pritchard et al., 2013). It should be noted that alkaline soil may provide a conducive medium for MIC. This is because an alkaline medium favors the growth of anaerobic bacteria (Doyle et al., 2003; Seica et al., 2002).

San et al. (2012) carried out an experimental study to examine the effects of two bacteria: Aeromonas salmonicida and Delftia acidovorans, on the corrosion of water pipes. The inoculation of these bacteria on the water pipe was observed to decrease the mass of the steel water pipe by 1.86 and 2.01 μg, respectively, due to the formation of corrosion products on the pipe. Furthermore, the pH value of the medium was decreased by 0.4 and 0.8, respectively, indicating the latter bacterium to be more aggressive. As Wang and Cullimore (2010) reported, AC pipes were tested for the presence and influence of bacteriological activity on the water pipes. Some masses of black bulbous were found inside the pipe, dominated by heterotrophic aerobic bacteria (HAB), slime forming bacteria (SLYM) sulphate reducing bacteria (SRB), denitrifying bacteria (DN), and iron-related bacteria (IRB). A 2–4 mm layer of patina was also formed inside the pipe. The presence of these organisms in the AC pipe reduces the structural strength of the pipe and contributes to the development of pitting corrosion.

Lime leaching: A change of pH from a high value (i.e., >12.5) to a low value (i.e., <6.5) is usually attributed to the loss of free lime, portlandite, from AC and concrete pipes. Calcium silicate hydrate, a major source of strength for concrete, is protected by the presence of portlandite. The most common method of measuring the pH is the use of an indicator called phenolphthalein. When the AC pipe is carbonated (through carbon dioxide penetration), the pH of the pipe is low, and the carbonated area does not change color when the indicator is applied. On the other hand, the uncarbonated area turns pink when the pH is above 8.2 (Ellison and Spencer, 2016). However, a low pH does not always indicate the absence of portlandite. The calcium carbonate formed from the reaction of carbonic acid with free lime sometimes fills the pores of the concrete matrix, thereby increasing its strength. However, if the calcium carbonate is undersaturated with water, it will eventually leach out of the concrete, thereby degrading the water pipes (Ellison and Spencer, 2016).

Al-Adeeb and Matti (1984) carried out some experimental investigations to estimate the content of free lime in AC pipes. New and used AC pipes were used in the investigation. It was observed that the average free lime content in the new pipes was 16.8%, while that of the used pipes was 8.7%, indicating the leaching out of free lime in the buried AC pipes. The permeability of the AC pipe, the aggressiveness of the flowing water, and the presence of carbon dioxide in the surrounding soil are the major factors that determine the content of free lime in AC pipes. Autoclaved AC pipes were found to be more chemically stable than water-cured pipes. A similar trend was noticed in the studies of Gong et al. (2016) and Hu and Hubble (2007).

Chemical substances: The presence of aggressive chemical substances around water pipes has been documented as a contributing factor to the failure of water pipes (Lee, 2011; Pę;kala & Pietrucha-Urbanik, 2018; Rezaei et al., 2015; Vipulanandan et al., 2012). The presence of a high concentration of sulphides, especially the sulphides of iron and chlorides, has been identified as the primary cause of water pipe corrosion (Pritchard et al., 2013). The sulphate attack is categorized into two. First, the attack that results in the formation of gypsum and ettringite – is often regarded as a "conventional sulphate attack." The second attack, which severely impacts concrete pipes, results in the formation of a "Thaumatic Sulphate Attack."

It should be noted that PVC and PE pipes are not vulnerable to electrochemical corrosion, unlike metallic pipes. However, they can be degraded by exposure to aggressive chemical substances such as chlorine in chlorinated water. This is because chlorine oxidation leaches out the protective antioxidants on the pipes (Mikdam et al., 2017). Pę;kala & Pietrucha-Urbanik (2018) conducted a chemical analysis on failed water pipes and found that the surrounding soil consists of a substantial amount of pyrite, which accelerates the corrosion process of the water pipes.

4.3.4. Location-based causes

Traffic: Traffic load can cause the buried water pipes to shear or collapse due to the differential loading from passing vehicles (Farewell et al., 2012; Nguyen et al., 2022). Moerman et al. (2016) examined the relationship between pipe failure rate and traffic load. They found that the water pipe failed at both the crossing section and the bump section of the road, though the failure rate was higher at the crossing section due to higher traffic at that section. However, the failure rate attributed to pipe age and diameter was higher than that due to traffic. Furthermore, it was reported by Mackey et al. (2014) that traffic loading could exert pressure on water pipes, which can cause cyclic fatigue effects, thus contributing to the failure of buried water pipes.

Land use: Land use such as commercial, industrial, or residential use of land can have a linkage with pipe failure as some dynamic loads can be transmitted to the pipes from these structures. Andreou et al. (1987) found commercial use of land to contribute to the failure of buried pipes. It is important to note that the influence of "land use" on the failure of the water pipe is yet to receive more attention from researchers; hence, it is a factor that needs to be fully explored in future studies.

4.4. Operation-related causes

If pipe failure does not occur due to the pipe and environment-related causes, the failure may occur due to operation-related causes, which are often not discussed extensively in previous studies (Barton et al., 2019). This section discusses internal water pressure, water quality, water pH, number of leaks, water hammer, installation, and pump operation, and maintenance practices in relation to the failure of water pipes.

4.4.1. Internal water pressure

Many studies have established a direct relationship between the internal water pressure and the breakage rate of water pipes (Andreou et al., 1987; Clair and Sinha, 2014; Ellison and Spencer, 2016; Greyvenstein and Van Zyl, 2007; Grigg, 2017; Jiang et al., 2019; Kabir et al., 2015; Kutyłowska and Hotloś, 2013; Makar, 2000; Poojitha and Jothiprakash, 2022; Rezaei et al., 2015; Tang et al., 2019). The case study results presented by Rezaei et al. (2015) indicated that pressure variation increased the rate of water pipe failure as the fluctuations would create additional hoop stress on the pipe, which leads to longitudinal or circumferential failure. Robert et al. (2017) carried out an experiment to determine the bursting capacity of ex-service corroded CI pipes. Two critically corroded patches were found on the exhumed pipes. When the pipes were pressured up to 3.25 and 3.60 MPa, small cracks were observed at the two critical patches, respectively, with water leakage becoming apparent at these points. As stated in the study by Ellison and Spencer (2016), AC pipes with low pressure failed 2.5 times less than those with high pressure. Moreover, moderately pressurized pipes failed about 1.8 times more often than the pipes subjected to low pressure.

In some cases, it should be noted that an increase in water pressure may not have a significant effect on the failure rate of water pipes due to the conservative approach that might have been employed while designing the WDN or the fact that another contributing factor of failure is dominant. Martínez García et al. (2020) analyzed the annual pressure survey (APS) data acquired for 8 years from 5 districts in California, USA. A correlation coefficient was found between high internal water pressure and a district surrounded by mountains, while a low correlation was noticed for non-mountainous districts. However, a negative correlation was also found for the two districts. This could be that water pressure is not a contributing factor to failure in these regions or that the effect of high-water pressure might be related to some regions, such as mountainous areas, where there are usually elevation changes along with the WDNs.

4.4.2. Water quality

According to Kabir et al. (2015) and Lee (2011), water's aesthetical, microbiological, and physicochemical properties are referred to as water quality. Water quality not only affects the suitability of water for its intended purpose (i.e., consumption) but also contributes to the failure of water pipes. As part of water quality-relating factors, corrosive substances, water temperature, and velocity are discussed in this sub-section.

Corrosive substances: The presence of corrosive substances in water, such as chlorine, or a high concentration of dissolved salts and minerals, degrade the material of a pipe, which can ultimately cause its failure (Rehan Sadiq et al., 2010). For a WDN located in Greece, Kanakoudis (2004) found that the presence of high levels of iron concentration turns the flowing water to red, which contributes significantly to the corrosion of the pipes and, eventually, their failure.

Water temperature: Due to low viscosity, an increase in the temperature of water leads to an increase in its diffusivity, thereby activating the transfer of electrons, which can accelerate the corrosion process. The study by Jun et al. (2020) implies that an increase in the water temperature tends to increase the corrosivity of the water, negatively impacting the pipe.

Water velocity: Most often, small-diameter pipes fail more than large-diameter pipes, all other factors being kept constant. One of the reasons for this is the low velocity of water in the smaller pipes, which provides a conducive medium for the growth of bacteria due to the settlement of some suspended materials in the water (Dao et al., 2021; Gao, 2017). Hence, the velocity of water should be properly controlled.

4.4.3. Water pH

The pH of water has also been found as a cause of water pipe failure (Arriba-Rodriguez et al., 2018). This sub-section discusses water acidity and alkalinity as they relate to water pipe failure.

Water acidity: Water can be said to be neutral when it has a pH of 7, acidic when the pH is below 7, and alkaline when the pH is above 7 (Shull, 2021). Water with pH values between 6.5 and 9.5 has been referred to as safe drinking water (United Utilities Water Limited, 2019). Calcium silicate hydrate (CSH), the main source of strength for the cement matrix, and lime can be leached out from concrete and AC pipes under the influence of acidic and soft water attacks (Hu and Hubble, 2007). Furthermore, while monitoring the corrosion activity of water pipes, Zraick et al. (2019) discovered that corrosion rates varied between 20 and 40 μm/year, with the higher rates occurring when the pH values are below 7.5. This shows that water acidity is a significant factor that contributes to the internal corrosion of water pipes and their consequent failure.

Water alkalinity: The alkalinity of water can also contribute to water's corrosivity. Jun et al. (2020) found the alkalinity of the flowing water to have a positive correlation with pipe failure. This is due to the presence of dissolved oxygen (from the air), which reacts with the flowing water to produce the oxygen needed for the corrosion process (Arriba-Rodriguez et al., 2018). Furthermore, water alkalinity could accelerate MIC by providing a medium for the growth of sulphate reducing bacteria (Doyle et al., 2003). Hence, regular monitoring and adjustment of water pH can help prevent the failure of water pipes.

4.4.4. Number of leaks

Leak-Before-Break (LBB) is a concept that has gained momentum in the domain of pipeline infrastructure management within the last few decades (Wilkowski, 2000). LBB simply refers to a concept that argues that the occurrence of leakage will precede any catastrophic pipe breakage or failure (IAEA, 1993; Wilkowski, 2000). While carrying out a laboratory investigation into the appropriateness of the LBB concept on large-diameter CI pipes, Rathnayaka et al. (2017a,b) machined corrosion patches into the CI pipes and reduced their wall thickness to study how the pipes would fail. They found that all the pipes exhibited leakage before breaking.

In a similar vein, the breakage rate of water pipes tends to increase as the number of leaks increases (Greyvenstein and Van Zyl, 2007; Ma et al., 2022; Pouri and Heidarimozaffar, 2022). Moreover, a leaking pipe can slowly erode the surrounding soil, thereby disturbing the bedding condition of the system Liyanage and Dhar (2017). This phenomenon is capable of inducing excessive stress on the pipe's wall thickness (Liyanage and Dhar, 2018).

4.4.5. Water hammer

Water hammer occurs in water pipes due to a sudden change in the flow velocity of the water, causing a pressure shockwave to travel through the pipe. Factors such as the sudden closing of a valve, the start-up of a pump, and the rapid filling of a tank are responsible for water hammer in pipes. Damages such as leaks, cracking, bursts, and fittings separation are caused to the pipe due to this shockwave (Roy and Pijush, 2014). The severity of the shockwave depends on various factors, including the diameter of the pipe, flow velocity, and the pipe material (Roy and Pijush, 2014). In the USA and Canada, 25% of all the annual failures of water pipes are associated with water hammers (Leishear, 2019).

4.4.6. Installation and pump operation

Poor installation practices, such as not following the manufacturer's guidelines or inadequate support (i.e., soil type, buried depth) for the pipes, can result in leaks and pipe failure over time. Further, incorrect alignment or positioning of pipes, inappropriate handling and storage of pipes before installation, and improper connection and sealing of joints are among the poor installation practices identified in the existing literature (Farshad, 2006). According to Burn et al. (2005), about 16% of all failures exhibited by PVC pipes were attributed to joint defects, which were associated with poor installation practices. Similarly, improper operation of pumps, such as overloading or excessive pressure, can cause damage to the pipes and contribute to their failure. Improper pump operation includes the use of pumps that are not properly sized for the system and the inability to maintain pumps and replace worn or damaged components (Barton et al., 2019).

4.4.7. Maintenance practices

Another operation-driven problem in WDN is the lack of effective maintenance practices. Neglecting to carry out regular maintenance and upkeep can lead to a variety of issues that can result in water pipe failure. These maintenance-related issues include neglecting to replace worn-out components, neglecting to address water quality issues, inadequacy in pressure adjustment when needed, lack of regular inspection of the pipes, and inadequate repair procedures, among others (Barton et al., 2019).

5. Fault-tree logic for mapping the causes of water pipe failure

This section presents a mapping model for the causes of water pipe failure. The model was developed using the FTL as it can show the link between the failure of a water pipe and its causes. This model can be beneficial to infrastructure managers in focusing on measures or strategies that can be used to mitigate the occurrence of the basic causes of the system failure. As shown in Fig. 5, the FTL diagram summarises the output of the above systematic review. The interpretation of the symbols used in the FTL diagram is shown in Table 9. It could be observed that the FTL diagram consists of several intermediate and basic events and one undeveloped event. Several benefits can be derived from the use of FTL in mapping the failure causes, as highlighted below.

- **Structured Approach**: FTL provides a structured procedure for mapping and analyzing the causes of failures in a complex water pipe system. With the FTL model, all the relevant causes of water pipe failure are considered, and a systematic examination of the interdependencies between various causes can be established (Kim et al., 2021).
- **Risk Identification**: The use of FTL helps identify the likelihood of failure events and failure modes, allowing decision-makers to prioritize areas for improvement and allocate resources effectively. The results of the analysis can also be used to develop risk management strategies, such as identifying critical components and taking measures to improve their reliability (Lindhe et al., 2009).
- **Improved Decision-Making**: FTL can provide deeper insight into the behavior of a WDN and the factors that contribute to its failures. This improved understanding can help inform decisions related to system design, maintenance, and operation.

The FTL diagram starts with the top event named "root causes of water pipe failure," which is directly connected to three intermediate events — pipe-related, environment-related, and operation-related causes — by the "OR" gate, indicating that any of the intermediate events can cause the occurrence of the top event. For instance, "pipe diameter" — an element of a pipe-related intermediate event and "internal water pressure" — an element of an operation-related event caused the failure of water pipes, as discussed by Hekmati et al. (2020) and Robert et al. (2017), respectively. The first intermediate event – pipe-related causes – consists of another intermediate event named "Protection Efficiency" and 6 basic events that are connected to the intermediate event with the "OR" gate. The same case is applicable to the intermediate event of the operation-related causes. Subsequently, the intermediate event of the environment-related causes is connected by the "OR' gate to four intermediate events: soil-related, climate-related, location-based, and biological and chemical-related causes, indicating that each of the events can cause water pipe failure. For example, "bedding and backfilling condition" — an element of a soil-related intermediate event and "microbiologically induced corrosion" — an element of a biological and chemical-related event caused the failure of water pipes as indicated in the studies by Trickey et al. (2016) and San et al. (2012), respectively. Moreover, the intermediate event of soil-related causes is connected by the "OR" gate to five basic events and another intermediate event named "Resistivity". It should be known that the "Resistivity" event is connected by the "AND" gate to three basic events, typifying that these three events must occur simultaneously to produce the "Resistivity" event (Arriba-Rodriguez et al., 2018). Similarly, the intermediate events of "climate-related causes" and "biological and chemical-related causes" are individually connected to three basic events by the "OR gate," while the event of the location-based causes is connected by the "OR gate" to a basic event — traffic — and an undeveloped event, land use. An undeveloped event is used for "land use" because very limited literature has suggested it to be a contributing factor to the failure of water pipes.

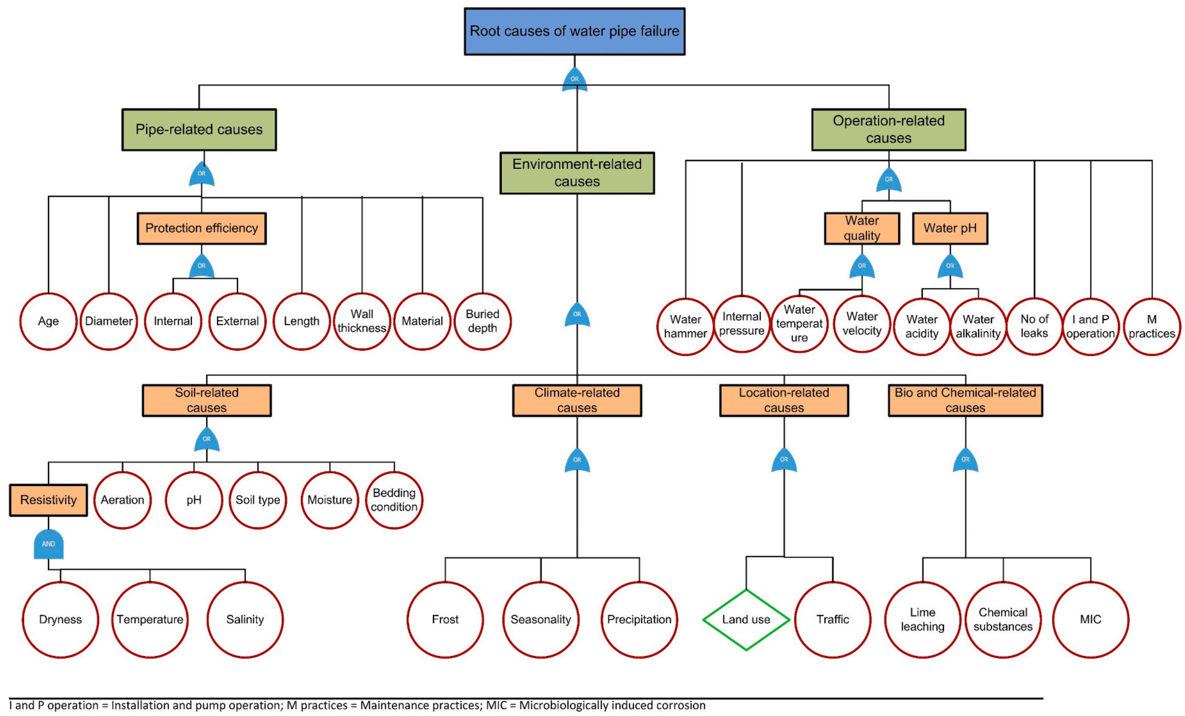
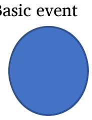
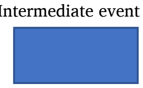
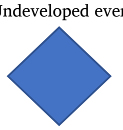
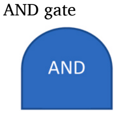


Fig. 5. Fault tree logic (FTL) diagram for causes of water pipe failure.

Table 9
FTL event symbols, logic gates, and interpretations.

Event symbols and logic gates	Interpretation
Basic event 	It represents a component of failure that cannot be developed further.
Intermediate event 	It represents a fault event that is between basic and top events. It is developed through logic gates
Undeveloped event 	It represents an event that cannot be developed further due to minimal information available about it.
OR gate 	It is used to show that the output event will occur if any of the inputs occur.
AND gate 	It is used to show that the output event occurs only when all the inputs exist at the same time.

6. Prioritization of the causes of water pipes failure

While the FTL is adopted in this research as a qualitative method of categorizing and grouping the causes of water pipe failure based on the systematic review, the AHP is employed as a quantitative approach for ranking the causes of water pipe failure (i.e., prioritization).

It should be noted that AHP methodology allows the removal of bias associated with ranking the factors using their frequency of occurrence alone since the factor's occurrence may be inconsistent across the scale. AHP provides the relative ranking of factors in the same hierarchy in such a way that their importance will be well-captured. As discussed in section 2.3, the AHP pairwise comparison matrices are developed based on the frequency of occurrence of the causes in the existing literature (see Fig. 6). A similar approach of using frequency occurrence for the AHP pairwise comparison has been adopted for calculating the relative weight of factors affecting physical and environmental building conditions (Faqih et al., 2020) and factors influencing supply chain management for modular integrated construction (Arshad and Zayed, 2022). The AHP result is presented in Table 10.

While the hierarchy (i.e., the AHP results) of the causes is estimated using the frequency of their occurrence in the extant literature, the results are quite in agreement with previous studies that have ranked these causes based on empirical evidence (Al-barqawi & Zayed, 2006; Asnaashari et al., 2013; Fares and Zayed, 2010). The AHP results indicate that the critical pipe-related causes are "diameter," "age," "length," and "material." This agrees with the results of Al-Barqawi and Zayed (2008) and Sattar et al. (2017). The justification for the criticality of these causes is explained in section 4.2. For the environment-related causes, "seasonality," "pH," "chemical substance," and "resistivity" are ranked as the most critical causes of failure. This result is in line with the studies of Fahmy and Moselhi (2009) and Fan et al. (2022), where factors relating to seasonality (i.e., cold and hot days), soil pH, and soil resistivity are highly ranked among other factors. On the other hand, the AHP result shows that "traffic," "land use," and "lime leaching" are less critical compared to other causes. This may be attributed to the fact that traffic and land use-related causes can be controlled to a certain degree. Similarly, "internal pressure," "water quality," and "number of leaks" are the top operation-related causes.

Conclusively, it can be seen from Table 9 that environment-related causes have received the closest attention from researchers across the globe, followed by pipe-related causes, as their relative weights are 0.413 and 0.396, respectively. Although operation-related causes such as "internal pressure" and "water quality" are well studied in the literature as reflected in their relative weights, showing their criticality, causes such as "water hammer," "installation and pump operation," and "maintenance practices" have received low attention in previous studies and should be further explored to affirm their criticality (Barton et al.,

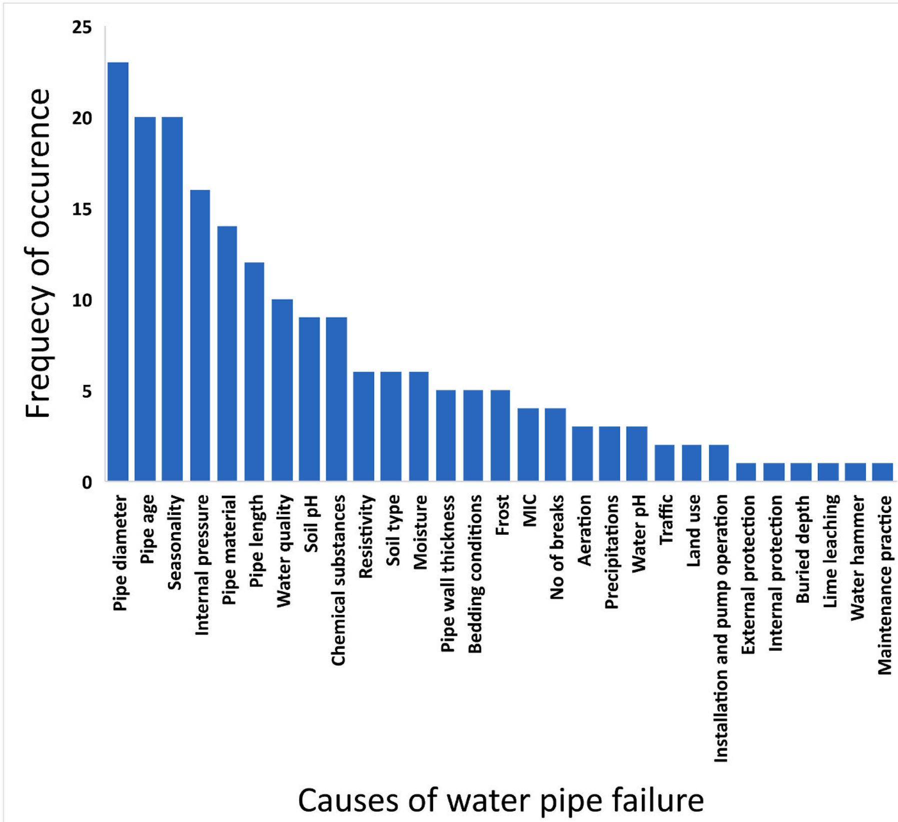


Fig. 6. Frequency of occurrence of factors causing water pipe failure.

Table 10
Relative weights of the causes of water pipe failure.

Categories	Causes of water pipe failure		Relative weights	Category-relative weights
Pipe-related	Age		0.102	0.396
	Diameter		0.118	
	Length		0.064	
	Wall thickness		0.026	
	Material		0.073	
	Buried depth		0.005	
	Internal protection		0.004	
	External protection		0.004	
Environment-related	Soil-related	Resistivity	0.031	0.413
		Aeration	0.014	
		pH	0.046	
		Soil type	0.031	
		Moisture	0.031	
		Bedding conditions	0.026	
	Climate-related	Frost	0.026	
		Seasonality	0.103	
		Precipitation	0.015	
	Location-based	Land use	0.010	
		Traffic	0.010	
	Biological & Chemical related	Lime leaching	0.004	
		Chemical substance	0.046	
		Microbiologically induced corrosion	0.020	
Operation-related	Internal pressure		0.083	0.191
	Water quality		0.054	
	Water pH		0.015	
	Number of leaks		0.021	
	Water hammer		0.004	
	Installation and pump operation		0.010	
	Maintenance operations		0.004	

2019).

7. Techniques for developing failure prediction models

One of the ways of establishing a sustainable WDN is to develop accurate failure prediction models for the pipes in the network. Depending on the priority of each water utility, the outcome of the prediction for each pipe or group of pipes can include the probability of failure, time to failure (i.e., survival analysis model), and failure rate (Fan et al., 2022; Mazumder et al., 2019, 2021; Rachman et al., 2021; Xiaowei Wang et al., 2022). This section briefly discusses the techniques that have been adopted to develop water pipe failure prediction models.

7.1. Probability of failure models

The probability of failure model predicts the likelihood of failure of a given water pipe. The prediction outcome from this model is expressed as a value between 0 and 1, with 0 indicating that the pipe is functioning properly, and 1 indicating complete failure of the pipe with no residual reliability. The prediction outcome provides valuable information to water utilities in assessing the condition of the pipes in their network and in making decisions related to maintenance, repair, and replacement. Probability of failure models can be broadly grouped into two: physical and statistical-based models. For the physical models, the probability of failure is determined by making a comparison between the stress exerted on a pipe and the pipe resistance (Amaya-Gómez et al., 2019; Li et al., 2021). While experimental data are used to develop physical models, historical data of WDNs are often used for statistical-based models. The statistical-based models include classical mathematical models such as logistic regression (Fan et al., 2022), Poisson distribution (Singh and Adachi, 2012), Weibull distribution (Ward et al., 2017), proportional hazard (Debón et al., 2010), hierarchical beta process (Luo et al., 2017) and machine learning algorithms such as artificial neural network (ANN) (Fan et al., 2022), support vector machine (SVM) (Robles-velasco et al., 2020), random forest (Raspati et al., 2022), and light-gradient-boosting machine (Fan et al., 2022), amongst others.

7.2. Time to failure models

Time to failure (TTF) models, also known as survival analysis models, estimate the amount of time it takes for a water pipe to fail. These models can be categorized as physical and statistical-based models. It should be noted that with TTF estimation, the remaining service life of the pipe can be determined. The physical models involve fracture mechanics-based models and kinetic models. The time-to-failure models can be classified into two categories: structural and kinetic. The fracture mechanics-based models estimate the pipe's TTF based on its response to different loading and pressure conditions, as well as slow crack propagation and ultimate tensile strength. These models are developed using experimental data and finite element modeling to analyze the impact of pipe wall corrosion and prior defects. The kinetic models, on the other hand, estimate failure time due to chemical degradation caused by varying water quality using stochastic modeling techniques. Statistical models of TTF that have been applied to water pipes include proportional hazard modeling (Suwan Park, 2011), Bayesian belief network (Demissie et al., 2016), logistic regression (Rifaai et al., 2022), gene expression programming (Sattar et al., 2016), artificial neural network (Harvey et al., 2014), and amongst others.

7.3. Failure rate models

Failure rate models estimate the rate of occurrence of failures in a given water pipe or group of pipes over time for a particular location. The prediction outcome of the failure rate model can be expressed as the number of failures per unit of time, such as failures per year or failures per 100 km of pipes per year. Failure rate models can be broadly divided into two main categories: parametric and non-parametric methods. Parametric methods assume that the underlying distribution of the failure data follows a specific mathematical form, such as the Weibull or exponential distribution(Park et al., 2008; Yamijala et al., 2009). These models make assumptions about the shape and parameters of the distribution and then estimate these parameters based on the data. Once the parameters are estimated, the failure rate can be calculated and used to make predictions about future failures. In the context of machine learning, parametric methods include traditional statistical models, such as regression analysis, and also some neural network models. Non-parametric methods, on the other hand, do not make assumptions about the underlying distribution of the data. Instead, they use techniques such as density estimation or regression trees to model the data directly. Non-parametric methods are more flexible and can better capture the underlying structure of the data, but they may also require more data to achieve a good fit. Non-parametric methods that have been applied to model the failure rate of water pipes include decision trees (Winkler et al., 2018), least squares SVM (Aydogdu and Firat, 2015), and Bayesian networks (Kabir et al., 2016), among others.

8. Sustainability dimensions of impacts of water pipe failure

Water pipe failure is a global issue that has been affecting the sustainability of WDNs for several decades. The failure of water pipes can lead to a range of impacts on the environment, economy, and society (Prieto et al., 2015). These impacts can be immediate and long-lasting, making it crucial to understand the sustainability dimensions of water pipe failure. This section discusses the environmental, economic, and social impacts of water pipe failure and their implications for sustainability.

8.1. Environmental impacts

The failure of water pipes has significant environmental impacts, particularly in flooding, traffic congestion, and soil erosion, among others (Piratla et al., 2015). Flooding is a common consequence of water pipe failure. When pipes break, water can overflow and flood streets, homes, and businesses, causing significant damage to the built environment. Furthermore, surface water sources can be contaminated via flooding, creating potential health hazards for humans and wildlife. For instance, the failure of a 762 mm steel pipe in California, USA, in 2014 flooded different walkways and garages, causing significant damage to hundreds of cars (Piratla et al., 2015). Traffic congestion is another environmental impact that could arise from water pipe failure, which has far-reaching consequences. When pipes break, water can flood roads, causing traffic disruptions and making it difficult for vehicles to move through the area. This leads to increased traffic congestion and air pollution, as vehicles are forced to idle in traffic for longer periods of time (Kim et al., 2019). In addition, the overflow of water from broken pipes can also damage roads and make them unsafe for vehicles, further contributing to traffic congestion and making it more difficult for people to access essential services and businesses. Similarly, the failure of water pipes results in soil erosion, reducing soil fertility (Wasim et al., 2018). In areas where the soil is already weakened, such as those prone to flooding, soil erosion can have even more significant impacts, leading to the degradation of land and the loss of habitats for wildlife.

8.2. Economic impacts

The economic implication of water pipe failure is noteworthy. This includes direct and indirect expenditures associated with the failure. The cost of rehabilitating or repairing damaged pipes, managing water supply disruptions, and mitigating the impacts of water losses can be substantial. The direct cost of rehabilitating broken pipes can be expensive, especially when the pipes are situated in challenging areas such as under roads, buildings, factories, and amongst others. Moreover, the rehabilitation cost can be further exacerbated by the need to disrupt traffic and access to businesses and homes during the repair process. For instance, over $1 trillion is expected to be spent on repairing and rehabilitating existing WDNs in the USA for the next few decades (Fan et al., 2022). In Australia, AUD 123 million is estimated to repair water pipe failures associated with corrosion (Spark et al., 2020). In 2014, more than 10 billion RMB was spent on rehabilitating WDNs in China (Xu et al., 2020). Similarly, the failure of water pipes can lead to decreased economic activity in the affected region. When pipes break and water supplies are disrupted, businesses in the affected areas can be forced to close or reduce their operations, resulting in reduced economic output. This can contribute to negative long-term impacts on the overall health of the economy (Fares and Zayed, 2010).

8.3. Social impacts

Water pipe failure can have far-reaching impacts on society, with consequences that can ripple through communities and affect individuals, industries, and institutions. One of the most pressing social impacts of water pipe failure is increased health risks, as contaminated water can spread waterborne illnesses and diseases. In the USA, it is estimated that around 7.2 million people become sick each year due to waterborne illness, according to the Centers for Disease Control and Prevention (2023). Globally, the World Health Organization estimates that 3.41 million deaths are associated with water-related diseases each year (Paradkar, 2012). Additionally, when water supplies are disrupted, individuals, organizations, and businesses may struggle to access clean water, which can have consequences for health, hygiene, and overall quality of life. In some cases, people may have to travel long distances or bear costs to find alternative water sources, which can be a significant burden. Another important social impact of water pipe failure is the potential for decreased quality of life in affected regions. Disruptions to water supplies can cause stress, inconvenience, and decreased economic opportunities, as individuals and industries struggle to adapt.

8.4. The need for sustainable WDNs

As highlighted in the previous sections, it is evident that the consequences of failed WDNs are numerous. Therefore, the development of sustainable WDNs is sacrosanct. One of the ways to achieve that is to effectively understand the causes of water pipe failure, as explained in previous sections. By gaining a deeper understanding of the causes of water pipe failure, it is possible to design and implement effective strategies that promote the sustainability of WDNs. Moreover, understanding the contribution of each cause to the ultimate failure of water pipes will allow an accurate selection of predictors during the development of failure prediction models. Another important step towards developing a sustainable WDN is to prioritize preventative maintenance and rehabilitation strategies. This may involve the use of advanced monitoring and diagnostic tools, as well as the adoption of best practices in water distribution management. For example, proactive measures such as regular pipe inspections, pressure management, and leak detection can help to prevent water pipe failure and reduce the consequences of failure.

9. Research gaps and future directions

Following a comprehensive review of the causes of water pipe failure, some research gaps have been identified that can be explored in future work by researchers in this domain. Fig. 7 highlights the existing gaps and future directions, which are explained in detail in the following paragraphs.

From the keyword cluster analysis, it was observed that none of the operation-related causes made it to the list of the 20 most frequently occurring keywords except "leakage." This demonstrates that more research is needed on operation-related factors concerned with the failure of water pipes. Additionally, it can be seen that African and South American countries are lagging in the domain of failure of water pipes, as per the countries' analysis. Hence, researchers in these continents are encouraged to pay attention to this domain, as the consequences of water pipe failure can be detrimental to every nation on the globe.

The AHP analysis also supports the finding from the scientometric analysis, as the relative weight of the operation-related causes is the least of the three main categories of the causes. This indicates the need for more research on operation-related causes. Although generally, the environment-related causes are the most investigated factors according to the previous studies, factors such as "lime leaching," "land use," and "traffic" have not been properly investigated as reflected by their relative weights. Hence, it is recommended that researchers pay more attention to these factors to know their level of contribution to the failure of water pipes.

Apart from temperature, whose level of correlation has been explicitly investigated with the failure of water pipes, other factors have received low attention in this regard. Therefore, it is recommended to investigate the level of correlation between each factor and the failure of

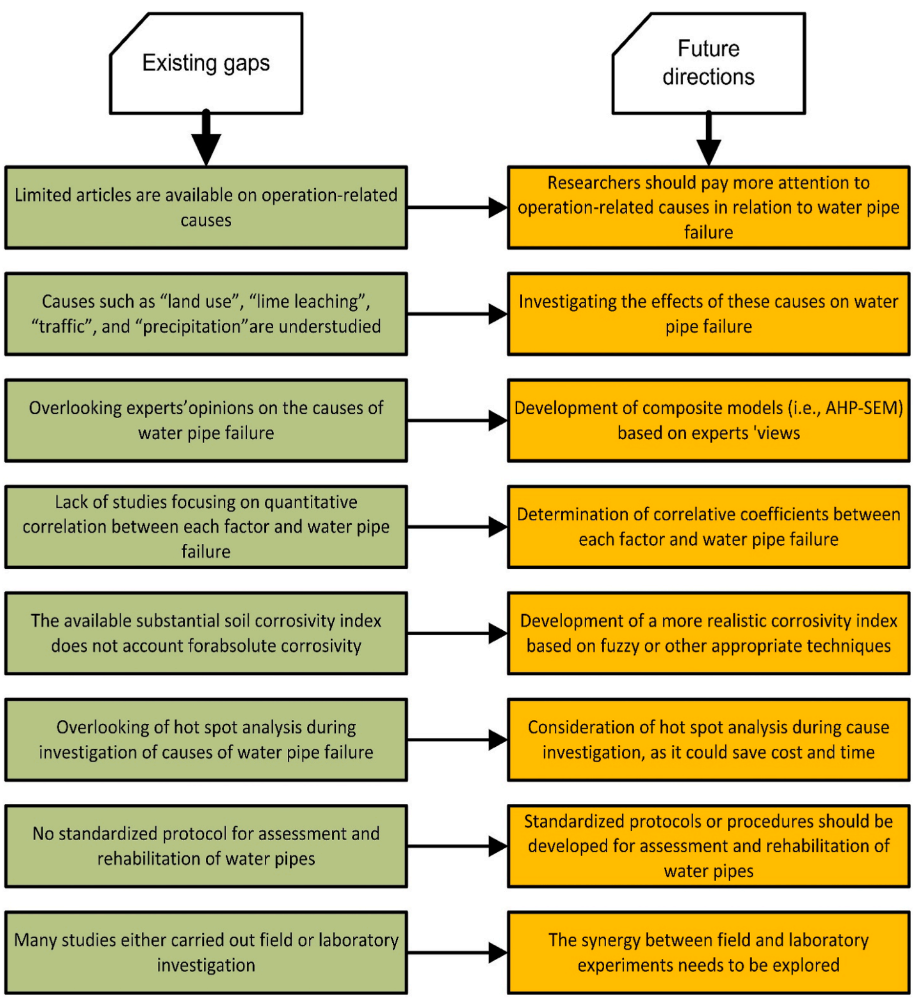


Fig. 7. Research gaps and future directions.

water pipes, as this will give more insights into the relative importance of these factors and assist utility managers in focusing more on the critical factors based on their correlation levels.

Although some studies have employed AHP and ANP to gather professionals' opinions regarding the performance and condition rating of water pipes, it should be noted that the condition of a water pipe network can be assessed without conducting a detailed investigation into the causes of the failure of such a network. Having noted that, the use of these techniques - AHP and ANP – is limited in the domain of causes of water pipe failure in relation to the collection of experts' opinions. Additionally, in conjunction with AHP/ANP, a composite model can be built with structural equation modeling to give a robust causal relationship among the factors.

As per the reviewed texts, only one substantial soil corrosivity index was found. This index was developed by the Ductile Iron Pipe Research Association (DIPRA). However, the index does not account for the absolute severity of corrosion as it categorizes soil, for example, with an index value of 10 and 9.9 to be corrosive and non-corrosive, respectively. In the real sense, both values are not significantly different from each other, which means that they might be actually corrosive. Therefore, a more efficient method, such as the fuzzy technique or Monte Carlo method, should be developed to score soil corrosion in a more realistic way. A similar index can also be developed for water corrosivity.

Only a very few pieces of literature considered carrying out hot spot analysis, which is the identification of locations on the pipe that are characterized by a high concentration of failure during condition assessment of water pipes. The hot spot analysis can be done by calculating the number of failures within a buffer area (a distance specified based on the features of a system) and its neighbors, which could be done using ArcGIS or other similar tools. Hence, water utility managers are encouraged to carry out hot spot analysis during their condition assessment of WDNs to prioritize those locations during the renewal and rehabilitation period. This may also save some unnecessary costs where applicable.

In most cases, minor failures of water pipes are treated as maintenance events, while major ones are treated as rehabilitation or replacement events but with no adherence to any standardized procedures. Like the assessment of natural gas pipe failures, standardized protocols or procedures should be established for tracking water pipe failures. This is a task that research scholars and industry experts could jointly work on.

It is important to carry out field and laboratory experiments simultaneously concerning factors contributing to water pipes' failure (where applicable). This will give a better understanding of the contribution of each factor to the failure of water pipes in different environments. For instance, most of the previous studies focused on finding the correlation between pH and pitting rate either by conducting a laboratory experiment or field investigation. Therefore, to accurately determine the effect of pH on the corrosion of water pipes, laboratory (controlled environment) and field investigations should be carried out simultaneously on simulated and natural soil, respectively, and their results should be compared.

10. Conclusions

Considering the consequences of water pipe failure on the survival of humanity, proper identification of factors contributing to the failure of this strategic infrastructure is of high importance. This research conducts a systematic review of previous studies in identifying the causes of water pipe failure. These causes are broadly classified into three: pipe-related, environment-related, and operation-related causes. Apart from the systematic review, other methodologies employed in this study include scientometric analysis, fault tree logic, and analytical network process. Firstly, the topic idea was validated through a simple search on the website of Web of Science. Subsequently, the two prominent databases, Scopus and Web of Science, were employed to retrieve relevant research documents in the domain of the topic. From the bibliometric data, scientometric analysis was conducted, such as assessing the publication trends, journals', countries', and organizations' contributions, science mapping of researchers, and keyword cluster analysis. The keyword cluster analysis shows that corrosion is the most prominent and encompassing cause of water pipe failure, as it was found to be the most researched cause. In addition to the cause of failure that was systematically discussed, the common failure modes and techniques used for developing failure prediction models were discussed.

From the systematic review, it could be observed, from a general perspective, that a direct relationship exists between water pipe failure and pipe age, pipe length, soil moisture, frost, traffic, precipitation, aggressive chemical substances, internal pressure, number of leaks, and water temperature. On the other hand, an inverse relationship seems to exist between water pipe failure and pipe diameter, wall thickness, efficient protection methods, buried depth, atmospheric temperature (seasonality), soil and water pH, and soil resistivity. In addition, the methods and materials used in manufacturing water pipes have witnessed advancement and improvement over time. A good example of this is the improvement in the way of manufacturing cast iron pipes. The introduction of the centrifugal method in casting makes the uniform wall thickness of CI achievable, coupled with an increase in the pipe's strength. A general way to conclude would probably be that each type of pipe has its advantages and limitations. For example, PVC pipe is more corrosion resistant than steel pipe, while steel pipe can withstand more external load than PVC pipe. It is worth mentioning that water pipes' failure mechanism is a complex one. Hence, the direct and inverse relationships mentioned above in relation to water pipe failure and its contributing factors may not be entirely applicable in some cases, as the level of dominance amongst the factors may differ in a system.

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.

Data availability

All the data used in this study appears in the body of the article.

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