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Analysis and ranking of corrosion causes for water pipelines: a critical review

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Corrosion is still the most common contributor to failures in Water Distribution Networks (WDNs), causing detrimental techno-socio-economic impacts. Although the corrosion process has been the subject of several studies, factors influencing this process remain a source of contention due to the complexity of the process and its influence by the surrounding environment. Considering the prior reviews, this comprehensive review is considered an early attempt to thoroughly cover the most influential corrosion factors in water pipelines. Corrosion factors have been classified into three main categories: 1) environmental factors; soil factors, external factors, and stray current factors; 2) pipe-related factors, and 3) operational factors. A fault tree analysis diagram was used to map, discuss, and analyze all significant corrosion causes of the buried water pipelines to facilitate easy visualization from basic factors to their intermediate and parent factors. Furthermore, the techno-socio-economic impacts of corrosion on water pipelines and beyond are appropriately addressed to demonstrate the issue's multi-dimensional importance. The research is expanded to rank these factors using the fuzzy analytical hierarchy process to provide a better understanding of the currently focused research investigation and to enable the extraction of gaps and existing limitations in scholarly literature. The findings revealed that water quality is the most investigated factor, followed by electrical infrastructure and soil quality. Conversely, operational factors exhibit the greatest relative weight (0.428), followed by environmental factors (0.337). These findings highlight areas where further research is needed, and the article proposes potential directions for future studies to address these gaps.

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INTRODUCTION

Motivation and incitement

Corrosion of buried water pipelines is a common issue that may lead to detrimental techno-socio-economic impacts. Water pipeline corrosion can have a variety of detrimental technical effects on the water or the pipeline itself[1,2]. For instance, its negative impacts can affect water quality, water coloring[3,4], restriction of water flow, and hydraulic loss[5,6]. In contrast, corrosion directly harms the pipe itself, contributing to longitudinal stress, metal loss, pipe wall perforation, and reductions in service life[7–9], as well as cathodic or coating disbanding and hydrogen embrittlement[10]. Furthermore, it is evidenced to be the main factor in water pipeline deterioration, leaks/bursts, and ultimate failure[11,12]. Therefore, the societal repercussions include but are not limited to potable water services disruption end-user discomfort, flooding roads, traffic congestion, and disruption of daily activities[12–14]. Changing the source water can cause various water quality concerns, such as physicochemical and microbiological issues, pathogenic bacterial growth, microbial regrowth, loose deposits, and a higher incidence of waterborne infectious diseases[4]. This can result in inadequate water for human consumption, decreased human quality of life, and increased epidemiological risks[5,15,16]. In brief, corrosion has both technical and social impacts, which cause together substantial economic losses. It can cost countries a lot of money, both directly and indirectly. The direct costs include water losses, rehabilitation expenditures, repair and replacement charges, maintenance costs, and labor costs. On the other hand, the indirect costs contain water damage, potable water service disruptions and traffic jams[12].

Literature review and research gaps

The eight existing reviews on corrosion causes of buried water pipelines are summarized in Table 1. Two reviews[12,17] discussed soil factors causing corrosion on buried pipelines. In[12], the authors focused on soil factors causing microbiologically influenced corrosion (MIC) on buried potable water pipelines, including soil chemistry, soil characteristics (backfilling, moisture, and microbial activities), bacteria, and biochemical mechanisms. The authors in[17] discussed the soil factors affecting the corrosion of metallic pipelines including soil resistivity, pH and moisture level, temperature, differential aeration, particle size, presence of bacteria, and soil type. The third review paper examined the factors that contribute to the deficiencies in drinking water distribution systems in developing countries[18]. The paper briefly discussed corrosion causes, including pipe material and composition, water quality factors such as disinfectant residual, temperature, pH, mineral content, and nutrient level, as well as biofouling, microorganisms, and bacteria. The fourth review paper[19], focused on the impact of water source blending on water quality in Water Distribution Networks (WDNs) and offered strategies for optimizing source water blends to prevent corrosion. The last four reviews[20–23] discussed the role of microorganisms/bacteria on corrosion of the water pipelines in drinking water systems.

Contributions and paper organization

Based on the prior reviews, it is evident that the articles[12,17–23] focused on specific factors influencing water pipeline corrosion, such as soil-related parameters and biofilms/bacteria/microorganisms. Importantly, none of them extensively discussed water

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Table 1. A Summary of the existing reviews on the causes of corrosion in buried water pipelines.

Ref.	Publication year	Research focus
Spark et al.[12]	2020	This review concentrated on soil factors causing MIC in buried potable water pipelines, which include soil chemistry, soil characteristics, bacteria, and biochemical mechanisms.
Wasim et al.[17]	2018	This review focused on soil factors affecting the corrosion of metallic pipelines such as soil resistivity, pH and moisture level, temperature, differential aeration, particle size, presence of bacteria and soil type.
Lee and Schwab[18]	2005	This review discussed factors contributing to drinking water distribution system deficiencies in developing nations, which are pipeline corrosion, inadequate disinfection residual, low water pressure, sporadic service, excessive leaks, unequal water pricing, and inequitable water usage.
Imran et al.[19]	2006	This review focused on the effect of blending water sources on the water quality in water distribution systems. Also, it discusses how to optimize source water blends to avoid corrosion.
Emerson and De Vet[20]	2015	This review discussed Iron-oxidizing bacteria, which can cause corrosion in water distribution pipelines.
Bachmann and Edyvean[21]	2005	This review focused on the causes, consequences, and control of Biofouling in drinking water systems to avoid corrosion.
McDougall et al.[22]	2001	This review discussed recent advances in understanding the role of biofilms (microorganisms) on copper corrosion in potable water systems.
Percival[23]	1998	This review focused on the formation and control of long-term and short-term microbial biofilms on pipe walls, which cause serious problems in potable water systems, such as corrosion and bacterial growth.

pipeline corrosion causes under the three main categories—environmental, pipe-related, and operational factors. As a result, this article is committed to bridging the information gaps in the previous reviews by providing valuable perspectives to guide future research. Additionally, this critical review is viewed as an early attempt to discuss, analyse, and rank the factors that contribute to corrosion in buried water pipelines. The objectives and major contributions of this article are summarized as follows:

- Mapping all significant and effective corrosion causes of the buried water pipelines through a fault tree analysis (FTA) diagram to facilitate easy visualization from basic factors to their intermediate and parent factors.
- Discussing, and analyzing in detail the different factors related to environment (soil factors, external factors, and stray current factors), pipe, and operation that contribute to the corrosion of buried water pipelines.
- Ranking the corrosion causes/factors of water pipelines using the Fuzzy-Analytical Hierarchy Process (FAHP) as a quantitative method to provide a better understanding/focusing of the current research investigation and to enable the extraction of gaps and existing limitations in academia.

This paper is organized as follows: "Research Methodology" covered the research methodology. The systematic review of the corrosion causes/factors for water pipelines are discussed and introduced in "Systematic analysis" while "Fault Tree Analysis for the corrosion causes of the water pipelines" presented the fault tree analysis for the corrosion causes/factors of the water pipelines. "Techno-socio-economic impacts of the corrosion of the water pipelines" discussed in depth the techno-socio-economic impacts of the water pipelines corrosion. "Ranking the corrosion causes of water pipelines using Fuzzy Analytical Hierarchy Process (FAHP)" covered and discussed ranking the corrosion causes of water pipelines using FAHP. Finally, the research challenges/gaps and future directions are summarized based on this critical review in "Research gaps and future directions", including the main conclusions.

RESEARCH METHODOLOGY

As displayed in Fig. 1, a comprehensive methodology was adopted to achieve this study's objectives. Figure 1 depicts two stages of this study: bibliometric search and systematic analysis. The bibliometric search involves the adopted strategy to retrieve the relevant articles, while the systematic analysis details the five distinct analyses of the existing scholarly literature on corrosion causes in water pipelines. The details of the methodology are expounded in the subsequent sub-sections.

Bibliometric search

To ascertain the need for this research, a preliminary search was conducted on Scopus and Web of Science. Eight review articles were found, and none extensively discussed water pipeline corrosion causes under the three main categories: environmental, pipe, and operational factors. Many of the articles focused on limited factors influencing corrosion in water pipelines, such as biofilms and soil-related parameters[12,17–23]. After validating the research topic, two prominent databases were chosen for literature retrieval: Scopus and Web of Science. The two databases were selected in order to have comprehensive search results[24], in addition to their wide content coverage, accessibility to bibliometric data, and strict content indexing[25]. Subsequently, different search strings were constructed and continuously refined until the desired result was obtained. The adopted search string was ("causes" OR "cause" OR "contributor" OR "contributors" OR "contribution" OR "reason" OR "reasons") AND ("corrosion" OR "corroded") AND ("water mains" OR "water main" OR "water pipe" OR "water pipes" OR "water pipeline" OR "water pipelines" OR "water distribution networks" OR "water distribution network" OR "WDNs" OR "WDN").

The string yielded 374 documents on Scopus, and the articles were filtered by defining some inclusion and exclusion criteria. Research articles focusing on corrosion causes of water pipelines without limitation on the publication year and publishing channels are the defined inclusion criteria. The exclusion criteria include 1) limiting the documents type to "article," 2) limiting the source type to "journal," 3) excluding articles written in languages other than English, 4) excluding articles with no full-text availability, and 5) excluding articles from non-related research fields such as arts and humanities, social sciences among others. These criteria were defined to describe the features of relevant characteristics of research articles needed to fulfill the objectives of this study. Additionally, the criteria help to avoid personal bias while retrieving the articles.

After applying the inclusion and exclusion criteria, 151 and 78 articles were retrieved from Scopus and Web of Science, respectively. Afterward, duplicated articles appearing in both databases were removed. A further assessment of the retrieved

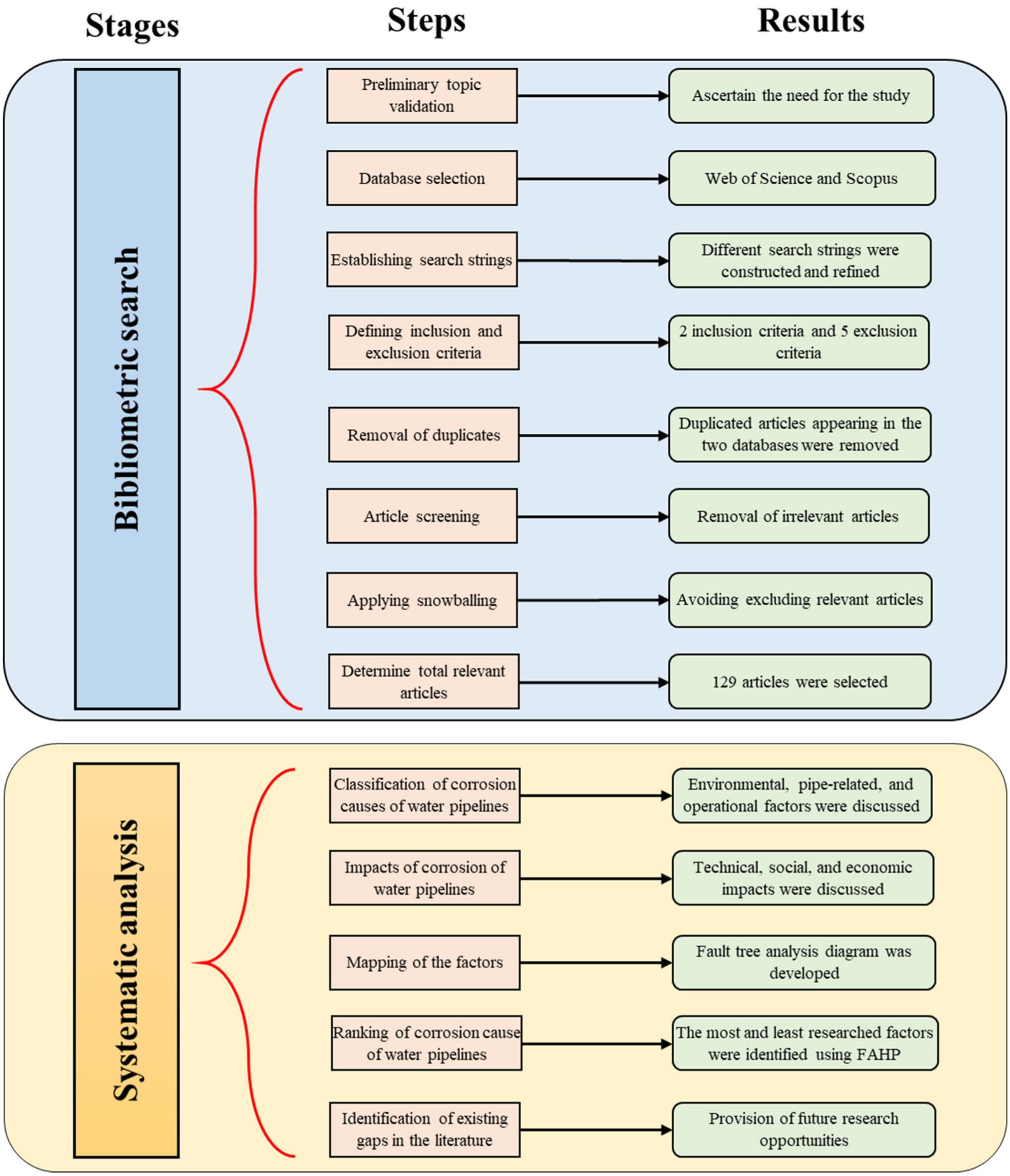

Fig. 1 Research methodology. A full description of the steps taken during the bibliometric and systematic analysis.

articles was conducted by reading the abstracts and screening the full text to make sure only relevant articles were included. This process returned 111 research articles used for backward and forward snowballing activities. Backward snowballing is the process of checking the references of each retrieved document for relevant articles, while forward snowballing identifies relevant articles by checking the documents that have cited the already-retrieved articles. This process returns 11 articles, making a total of 129 articles included in this study.

Systematic analysis

Systematic analysis is an organized approach to extracting, synthesizing, and discussing findings from an identified dataset[26,27]. Qualitative and quantitative methods are employed in the systematic analysis of existing scholarly literature in the domain of corrosion causes in water pipelines. The qualitative aspect involves extensive discussion on corrosion causes of water pipelines, including environmental, pipe-related, and operational factors. Furthermore, technical, social, and economic impacts of corrosion in water distribution networks were expounded. Additionally, to facilitate easy visualization of the factors causing corrosion of water pipes, a fault tree analysis (FTA) diagram was developed to map basic factors to their intermediate and parent factors. The fuzzy analytical hierarchy process (FAHP) was applied as a quantitative method to rank the factors causing water pipe corrosion. Finally, the gaps in the existing literature were identified, and research directions to fill them were proposed.

SYSTEMATIC REVIEW OF THE CORROSION CAUSES FOR WATER PIPELINES

Water pipelines are intricate systems situated in a multivariate environment rich with numerous factors that can cause or hasten corrosion in various forms. This phenomenon can manifest on the inner and/or outer pipe walls of water pipes. Researchers from various backgrounds have studied and investigated numerous factors over the past decades to better understand the main causes of corrosion forms in pipelines in general and water pipes. In this regard, a systematic review of 129 scientific papers was conducted with the goal of analyzing, extracting, and summarizing those factors. Based on the origin of the factor, three main categories are established: environmental, pipe, and operational related factors.

Environmental factors

Figure 2 shows the schematic representation of environmental factors influencing water pipeline corrosion. These environmental factors are discussed in detail in the following sections.

Soil factors. Soil represents the surrounding external environment for all buried water pipelines, interacting directly with the external pipe surfaces, which is considered to contain most of the properties to nucleate and aid the corrosion process. As a result of the systematic review, the soil factors can be regrouped as follows:

Soil type: Even though the water pipelines are covered in backfill soil, the soil type has an impact on the structure as it can cause corrosion if the appropriate conditions exist. Different soil types existed based on the texture of the soil and grain size such as clay, sandy, gravel, sand clay loam, clay loam, silty clay loam, silty clay and silt loam sand, and clay silt, among others[28]. Soil with high alkalinity such as in sandy soil may impose the general corrosion problem[29]. The soil particle size is an understudied factor related to the soil types and can influence the corrosion behavior[17]. In a study conducted on an X70 pipeline, results indicated that when the particle size of 3.5 wt% NaCl simulated sandy soil increased, the polarization resistance decreased, which implies a corrosion rate reduction[30].

Soil quality: Soil quality includes different properties of the soil that can initiate, accelerate, or reduce the risk of corrosion exposure in buried water pipelines. These properties include the water content, resistivity, pH, redox potential, chemical compositions and concentrations, acidity, aeration, and temperature, among others, where these proprieties may have interconnection or influence. Here we cite the most reported soil properties in the literature.

– *Soil pH:* Soil pH is considered one of the most significant factors affecting corrosion in many studies, as it directly impacts the solubility of corroding agents and microbiological activity. The pH value of soil is generally determined by the content of carbonic acid, minerals present in the soil, organic or inorganic acids, and acid rain or waste[31]. A normal soil pH range is between 5 and 8, and a soil pH of 4 or lower indicates highly acidic soil[32,33]. Therefore, when the soil pH is lower than 5, the corrosion rate may accelerate due to the unavailability of a forming a protective layer on the steel. However, other factors can contribute to these results. Among the most established experimental studies is the one conducted by Romanoff[34], which lasted 25 years (i.e. 1922–1957), where around 29,500 specimens were buried in different soil conditions. Results indicated a correlation between the mass loss and the soil pH. On the other hand, others found a poor correlation based on their experimentations such as Penhale[35], who used 33 different soils to investigate steel plates for a period of 20 years, Rajani and Makar[36] indicated that no correlation was found between corrosion rate and soil pH, and

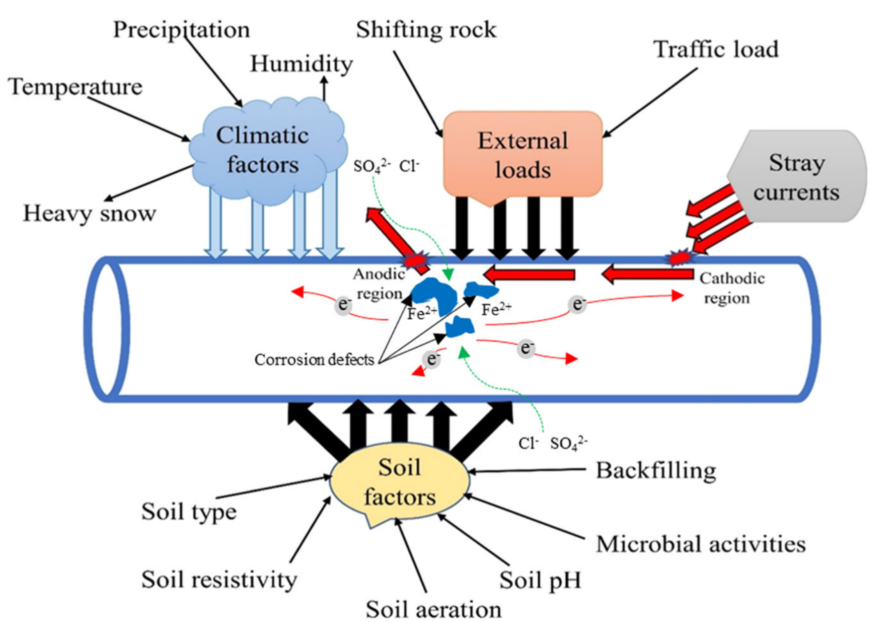

Fig. 2 Schematic representation of environmental factors influencing water pipeline corrosion. The factors impacting the corrosion level in water pipelines, including climatic factors, external loads, stray current and soil characteristics.

Doyle et al.[37] investigated 98 sites where the obtained correlation was insignificant. Overall, there is a lack of consensus in existing studies regarding the exact relationship between soil pH and the corrosion process. At the same time, it was noticed that acid rain and acid-producing bacteria can highly influence soil pH.

– - *Soil acidity*: Soil acidity is a biochemical mechanism aided by soil bacteria and is based on metal susceptibility to low pH environments[12]. Soil acidity is known to cause pitting (localized) corrosion and is affected by environmental factors such as acid rain and temperature. Biezma[38] stated that organisms could lower the local pH in soil due to bacterial hydrogen permeation, causing an increase in iron ions in that environment. Suflita et al.[39] reported that aerobic bacteria that respire carbon dioxide can cause soil acidification by acidifying the inner regions of biofilms. According to Pillay and Lin[40], microbes release various organic acid metabolites during nutrition, which acidify the local soil, while Boopathy and Daniels[41] showed that corrosion can be accelerated by an increase in soil acidity caused by heterotrophic microorganisms consuming organic carbon for growth, which increases hydrogen concentrations. However, the earliest studies do not adequately explain the relationship between soil acidity and corrosion rate.
– *Differential aeration:* Even though this factor has been extensively researched in various studies, the relationship between soil aeration and underground corrosion has yet to be further explored. In general, soil with low aeration acts as an anode, while soil with high aeration acts as a cathode, with soil resistivity and water content also influencing corrosion. Wasim et al.[17] demonstrated that the effect of oxygen concentration on corrosion severity varies with soil depth. It was discovered that high oxygen concentrations cause corrosion only when the soil is moist. This explains the corrosion process because water and oxygen are essential for cathodic and anodic reactions on the metal surface. Previous studies have also confirmed that the formation of a biofilm on the metal surface can limit oxygen diffusion in certain areas, creating an anodic region[42,43]. Additionally, biofilm can form solid tubercles and deposits on the metal surface through MIC, which can cause oxygen deficiency under the tubercles and create a flow of electrons to the cleaner cathodic regions, resulting in pitting corrosion[40,44]. It is important to note that climatic conditions, such as acid rain, can have a significant impact on soil aeration and bacterial activity.

Soil resistivity: According to various studies, soil resistivity has an inverse relationship related to corrosion whereas soil resistivity is the capacity of a soil to pass current. Furthermore, soil resistivity is related to moisture content, ion concentrations in soil, and temperature. In other words, as moisture and chloride concentrations increase, soil resistivity decrease, while temperature promotes ionic exchange. As a result, the cell's corrosion current leaves the anode where the soil resistivity is low, resulting in pitting corrosion. Malvin[45] conducted extensive experimental testing and established one of the first relationships between corrosion and soil resistivity. According to their findings, soil with a resistivity of 2000 Ω-cm or lower is considered highly risky for corrosion, while soil with a resistivity higher than 2000 Ω-cm is less risky. However, they noted that this correlation is subject to change and may vary depending on various factors. This limit was found to be 700 Ω-cm in another study by Hamilton[46] which was lower than that of Malvin[45], and Romanoff[34]. Booth and Tiller[47] classified 28 soil corrosivity sites based on the Ω-cm limit, but the results were limited to 21 sites due to insufficient data. Similarly, Kelly and Robinson[48] used soil resistivity to regroup the soil based on its corrosiveness. According to the researchers, the relative change in soil resistivity along the pipeline length is the main cause of corrosion failure because corrosion forms between areas with high and low soil resistivity. Soil resistivity is influenced by various factors, including moisture content, chemicals, and temperature. Therefore, these factors are important components to consider when assessing soil resistivity and are discussed below.

– ***Moisture content:*** This property can be an excellent conductivity metric for soil, indicating a high ion content and a high possibility of corrosion attacks. Numerous experimental studies have been conducted over the past decades to explain the impact of soil moisture on the initiation and growth of corrosion in metals that are buried in soils. Gupta and Gupta[49] investigated the influence of three types of soil (sandy, sandy loam, and loamy) from different areas of India on pre-measured steel specimens (50 mm × 25 mm × 1.6 mm). Before experimenting, all soils were oven dried at 105 °C, and the results of the experiment were determined in terms of mass loss after 6 months. A strong correlation was discovered between mass loss (i.e. corrosion) and moisture content in soils. Noor and Al-Moubaraki[50] investigated the effect of soil moisture content on the corrosion behavior of X60 steel buried in soils from various Saudi cities at ambient temperature. The results revealed that increasing the moisture content in all soil up to a maximum value of 10% increased the corrosion rate of X60 steel, but that corrosion decreased as moisture increased further. This brings us back to the fact that corrosion is influenced not only by moisture content, but also by the properties and type of soil. Moreover, the soil optimum moisture content varies with soil type and has a direct effect on corrosion rate, where the two values are proportional until the critical soil point, where corrosion rate begins to decrease due to a decrease in the oxygen supply to the metallic surface. The critical moisture value for soil is determined by various parameters such as soil type, metal type, and exposure duration.
– ***Soil temperature****:* When compared to water temperature influence on the internal corrosion in steel pipelines, soil temperature is an understudied parameter. This is due to the low variation of soil temperature, except when seasons change, which alerts the water inside the pipe more. The reported studies on this parameter included aqueous solutions as well as the effect of temperature in dry conditions. Nie et al.[51] investigated the temperature dependence of carbon steel electrochemical corrosion characteristics in real salty soil with a pre-selected moisture content of 10%. The results showed that corrosion can form on carbon steel at low soil temperatures, while as the temperature rises above 50 °C, the corrosion rate also increases. Restrepo et al.[52] conducted a study on the MIC risks for steel pipelines, and the results showed that the soil temperature measured along the pipeline was lower than the optimum temperature for Sulfate Reducing Bacterial (SRB) growth, making the risk negligible. Although the authors have contributed to temperature-related research on buried pipes, the findings are not fully established, and there is still a gap in understanding the temperature effect on buried metal pipe corrosion.
– ***Chemical substance in soil****:* These substances exist naturally and are exposed to soil, including chloride and sulfate, directly impacting soil resistivity. Furthermore, these chemical properties play a direct role in metal anodic dissolution reactions. The presence of chloride ions in naturally or brackish groundwater and historical geological sea beds, or as a source of salt from road services to sprinkle roads in urbanized areas, indicates that soil resistivity is decreasing. According to some studies[53], up to 50% of salt penetrates locally to surface water[54], and the content of chloride ions in some soils can reach up to

2700 mg/l[55]. Sulfate is another corrosive chemical substance whose presence poses a significant risk to metallic pipes because it is chemically harmful and highly corrosive, and it can be converted directly to sulfides by anaerobic SRB. Doyle et al. and Jarvis and Hedges[12] found a direct relationship between soil sulfide levels and a high risk of aggressive corrosion due to the presence of SRB. Despite the previous studies, the relationship between other substances and corrosion in pipelines has not been fully explored[56].

Microbial activities: The soil environment is rich in bacterial metabolic activities that can cause deterioration of water pipelines due to galvanic or electrolytic cell actions, which is referred to as MIC[12]. The process began with the contact of bacterial organisms to the pipe-surface caused by chemical and environmental changes in the soil. This interaction will produce several corrosive substances, including carbon dioxide, hydrogen sulphide, ammonia, and organic and inorganic acids[29]. The MIC and pitting corrosion will occur where these substances are present. Due to the presence of these organisms in the soil and the difficulty in sterilizing the soil along water pipes, controlling this factor is challenging. Coating seems to be the primary protective layer against it. Recent research on the impact of this factor on the corrosion process has shown that highly waterlogged, sulphate-bearing, and blue clay soils, depending on the season, are most conducive to bacteria that produce galvanic cells[29].

Backfilling: All water pipes are well understood to be buried in backfill soil, which are not natural soil, but a mixture of soil strata excavated from trenches. As a result, ensuring excellent compaction of the soil around the pipe is a critical procedure for ensuring soil homogeneity[57]. According to the National Bureau of Standards large experiment tests on metal buried in different backfill soil, pitting corrosion becomes deeper with time and increases with the degree of soil inhomogeneity around the pipe[58]. This is because the air adjacent to the pipe surface contains oxygen and moisture, allowing an environment to develop a corrosion process. Sand have the highest homogeneity among soil types, while stiff clays have the highest inhomogeneity[59]. The relationship between this factor and corrosion has been thoroughly investigated in early studies such as those of Burns and Salley[60], Romanaof[34], and others.

External factors. Buried water pipelines are also subject to ground changes over time due to external factors that can change soil behavior and provide favorable conditions for corrosion to begin. External factors are primarily determined by external loads and climate conditions, which are briefly discussed below:

External loads: Commonly, steel water pipelines are built to withstand water pressure, dead loads from the soil, live loads imposed, for example, by road traffic, as well as the weight of the pipes and the water flowing through them[61]. However, extensive, or overloading conditions, such as shifting rocks or high traffic loads, may expose the pipeline to differential stress, allowing for localized electrochemical action. In this case, the stressed section of the pipe acts as an anode, while the unstressed section acts as a cathode, thereby increasing the corrosion susceptibility of the pipe. External loads, on the other hand, are less likely to contribute to pipeline corrosion because most water pipelines are not subjected to external loads.

Climatic conditions: Pipelines are typically buried underground in backfill soil at a calculated depth. However, the upper ground is subjected to changing climatic conditions such as humidity, temperature, rain, natural hazards such as earthquakes, floods, and/or storms, and unwanted natural extreme events such as heavy snow and acid rain. The acid and chemical properties that emerged in soil from these climatic conditions as the rain, snow, clouds, floods and particulate matter contribute to approximately 15–35% of the soil acidity[15]. Thus, climatic conditions can alter soil quality, such as moisture content, pH level, and resistivity, among other properties. High soil acidity, for example, caused by acid rain, may pose a serious corrosion risk to common construction materials such as steel, cast iron, and zinc coatings[31]. Temperature is another climatic factor that can cause corrosion, particularly in extreme regions. Despite the importance of quantifying these factors and their influence on the corrosion of water pipes, these factors are understudied due to several constraints, such as cost and difficulties in simulating real-world climatic conditions during experiments.

Stray currents-related factors. Stray currents are one of the most common causes of exterior corrosion and thus failure of water pipelines, accounting for 7% of transmission mains and 4% of distribution mains, respectively[62,63]. Stray currents can be picked up by buried water pipelines, which are typically better conductors than the earth. In this case, water pipelines represent the earth-return circuit for this current, which means that current will flow into pipeline at one location, known as the cathodic region, and exit to the ground at another, known as the anodic region, resulting in corrosion[62]. Stray currents can occur due to (1) Electrical infrastructure like trams, railways, and AC power lines, (2) Defects and insulation failure, and (3) Improper CP design as shown in Fig. 3. According to the type of stray current source, stray current can be classified as static or dynamic. Neighboring cathodically protected pipelines are the primary culprit (CP interference) for causing static stray currents. Time-varying sources such as trams, railways, metros, welding, and so on create dynamic stray currents[64].

Electrical infrastructure: Electrical infrastructure; like trams, railways, AC power stations, and overhead lines; is one of the major sources of stray currents that cause severe corrosion and failure of the pipelines[65]. In the case of trams and trains, as they act as electrical loads, the electrical circuit is closed, and the current is returned to the traction substation via the running rails. The flow of current through the running rails results in an increase in the rail's electric potential. However, due to the inability to fully isolate the rails and their attachments, some of the current leaks from the rails to the surrounding soil. This stray current can then be picked up by third-party infrastructure, such as buried water pipelines, which act as an earth-return circuit for the stray current. As a result, the current flows into the pipeline at one cathodic zone and exits at another anodic zone, leading to corrosion and failure of the pipeline (Fig. 3). Many factors influencing the stray current intensity were observed on the buried water pipelines, including soil parameters (like resistivity and conductivity that are dependent on soil moisture) and the distance between the pipeline and railways[64]. Stray currents can flow long distances (hundreds of meters to kilometers) from the source types, depending on soil conductivity[65]. For example, the influence of stray currents on the water-pipe network in Kraków, Poland, was obvious despite being around 1 km away from the tramway[16]. To reduce stray current, one or more of the following can be done: a) Lowering the rail-return resistance; b) Increasing the leakage path to ground resistance; c) Increasing the resistance between ground and underground metallic pipelines; d) Increasing the metallic pipelines resistance[66]. In brief, the stray current can be alleviated by controlling rail return mode, blocking current leakage, and protecting affected pipelines[67].

Defects and insulation failure: Defects, degraded, or failed insulation of rails or the pipelines can facilitate the stray currents to flow through the water pipes resulting in corrosion of the rails and pipelines. A portion of the return current via running rail will leak into the surrounding soil and nearby water pipelines due to rail insulation flaws and finite longitudinal rail resistance[56]. In addition, stray currents can flow through the external surface of water pipelines in places where the insulation has been wetted

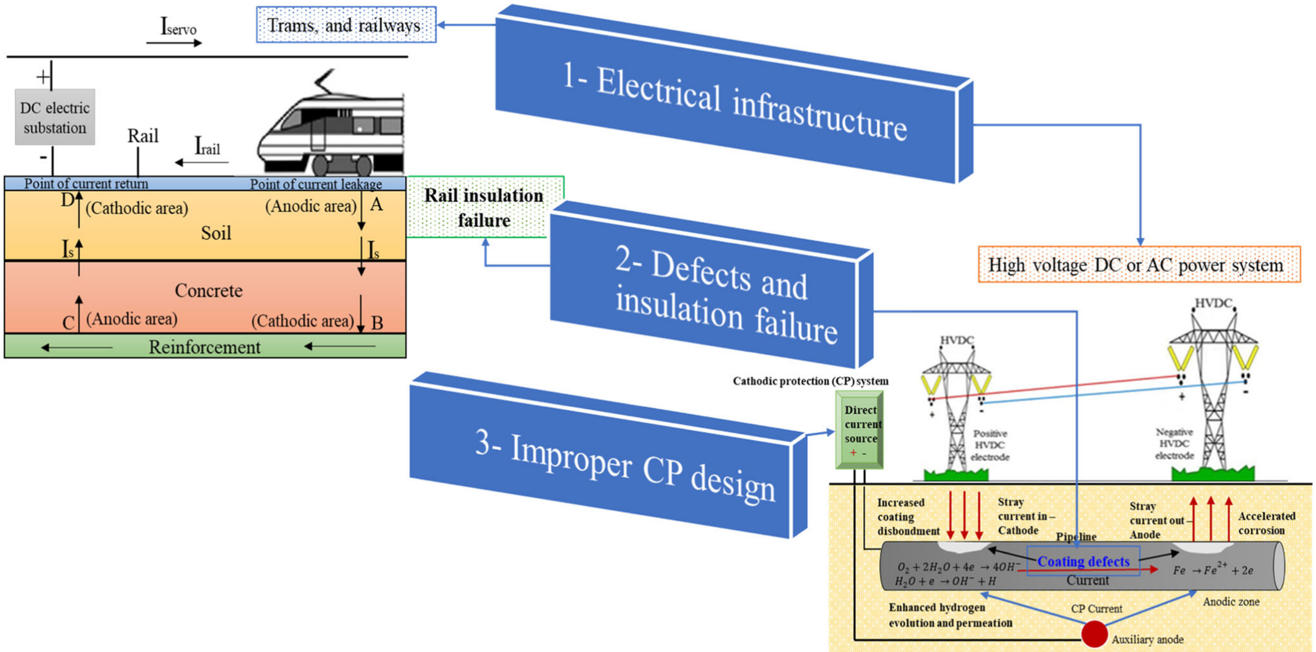

Fig. 3 Different causes of stray current corrosion. A detailed description of the most common causes of stray current as the principal cause of corrosion in water pipelines.

due to underground water, rainwater, leaks/burst, etc. Even though buried pipelines are protected by passive protection like high-quality insulating coatings, stray current can flow in and out from pipelines in the areas where there are insulation imperfections, thereby corroding the pipeline at the anodic zone (higher positive potential values). As a result, additional mitigation measures for buried pipelines are required. Cathodic protection or drainage circuits (direct, polarized, or forced drainage) can be used to prevent the pipeline from being damaged by stray currents[56].

Improper CP design: Improperly designed and installed CP systems can cause stray currents to migrate into nearby water pipelines resulting in corrosion. This stray current flows down the water pipelines until it drains into the earth through defects/insulation failure and rejoins the electrical circuit[68]. The reasons behind this are the electrical interference occurrence from nearby CP systems or other different sources. Therefore, CP system of certain pipelines can affect another pipeline system causing DC interference. Moreover, anodic stray currents due to other sources resist cathodic current from the pipeline's CP system, which is installed away from stray current hotspots and keeps the pipeline potential at around −0.9 V[64]. Misapplication and improper CP design can cause not only stray current corrosion but also unbound coating from the pipes and cause hydrogen embrittlement[62]. Proper CP design is essential to prevent DC current interference and ensure that stray currents do not damage other pipeline infrastructure[69]. Proper CP design can be attained through (1) selecting and installing appropriate CP type (Sacrificial anode or impressed current) based on pipe materials, soil resistivity, electrical continuity, electrical isolation, coating conditions, stray currents, and remaining life, (2) avoiding DC interference due to electrical infrastructure or nearby CP systems.

Pipe-related factors

Based on various material-related factors, the state of the pipeline as a physical structure buried underground and in contact with the surrounding environment can help to initiate the corrosion process. This includes pipeline age and exposure time, manufacturing process, design geometries (such as pipeline length and diameter), welding/joint process, and protection layers. The pipe-related factors are regrouped and detailed in the following sections based on the systematic review.

Pipeline age/exposure time. Pipeline age/exposure time can be defined as the time at which the pipe began operating or was exposed to the soil, where the exposure time has been identified in many studies as a factor causing corrosion and leading to the failure of metallic pipelines[70]. Numerous studies have shown pipe susceptibility to corrosion increases with age; however, this has been found to vary depending on the pipe type. Cast iron pipes are thought to have been in use for the last two decades, with breaks and leaks more common in older pipes than in newer pipe types. Furthermore, long-term exposure to internal and external environments is conductive to corrosion development. A study discovered that among 800 pipes, corrosion has the highest impact on pipes within 20–30 years[71]. The relationship between the exposure time and corrosion rate is estimated to be nonlinear in different studies conducted by Melchers et al.[72], as the corrosion shows aggressive progress in the beginning then a lower rate after a specific period of time due to the development of a protective oxide layer on the metallic pipe surfaces. Song et al.[73]. conducted a similar experimental study on an X70 pipeline, and the results confirmed the nonlinearity of corrosion with the exposure time, however, results revealed also that corrosion rate can further be accelerated if other factors interfere.

Materials. The metal type used in pipeline construction during the manufacturing process, the alloy composition (metallurgy), surface conditions and surface roughness are important pipe-related factors that play an important role in identifying and understanding corrosion mechanisms. Based on[74,75], there are three types of steel: ordinary/mild steels, low alloy steels, or high strength steels, and stainless or chromium steels, whose corrosivity varies depending on numerous conditions. Among these conditions, alloy composition can influence corrosion initiation and growth under different soil conditions[76]. The steel composition influence on corrosion was summarized in an early study by Schultze and Wekken[77], where results indicated the preference of particle alloys to corrosion resistance while others do not, under specific conditions. Ting et al.[78] found that for corrosion processes caused by oxygen diffusion, minor changes in alloying elements should have no effect on corrosion severity. As a result, specialized steel with higher alloy compositions will have a lower initial corrosion rate. This applies to alloying elements such as chromium, molybdenum, aluminum, nickel, silicon, titanium, and vanadium to a lesser extent. On the other hand, the condition of the metal surface, on the other hand, is known to influence corrosion susceptibility, where increasing the surface homogeneity implies higher corrosion potential[79,80].

Dissimilar metals. Galvanic corrosion can occur when water pipes of different materials are welded together, or when polished surfaces on some areas of the pipe walls encounter suitable electrolytic soil, resulting in what are known as dissimilar metals. This dissimilarity can imply the shape of anodic areas in comparison to the rest of the pipe surfaces. The polished surfaces corrode at a faster rate in highly ionized soil, weakening the pipe at that point. The current flows from the pipe to the cinders and back to the pipe. At the points where the current exits the pipe, severe corrosion occurs[17].

Manufacturing defects. Although this factor has no direct chemical relationship to the corrosion process, its impact can cause severe corrosion at an accelerated rate. Defects in pipelines caused by operators or engineering activities can easily cause the appropriate environment for unexpected corrosion process to occur. These defects include improper pipe bending or backfilling during installation, coating defects, or during service such as inadequate water quality/supplying control or CP.

Pipeline diameter. Large diameter (300 mm) pipelines are commonly used for water transmission, including raw water from natural water sources and treated water to storage reservoirs, with cast iron being the most commonly used material type[81]. Small-diameter pipelines are typically used for distribution and connecting customers[13]. Despite the fact that no precise studies on the influence of pipeline design geometries, including diameter, on the corrosion process have previously been conducted, researchers indicated that corrosion attacks might occur for both small and large-diameter pipelines depending on the pipeline situation and this may lead directly to failure of the buried pipelines[8,82,83]. Corrosion can occur in small diameter pipelines because they frequently experience higher loads and are usually in unprotected areas, whereas large diameter pipes have a larger exposed surface to more severe conditions if other conditions, as described earlier, are present. Overall, the relationship between the corrosion process and the diameter of water pipes is still unknown.

Protection problems/layers. Water utilities use combined protection layers, including passive and active corrosion protection, to protect water pipelines from corrosion. Coating, lining, and painting the external surface are examples of passive protection layers, whereas CP represents active protection[65]. These measurements are required by authorities to reduce breaks and leaks in city main water systems. Significant research has been conducted in this area to investigate the effectiveness of corrosion protection layers[69]. Adnan *et al*[10]. evaluated the efficiency of CP in conjunction with the passive layer (lining) in order to implement the proposed CP system for their WDNs. The results revealed that the complete lining significantly reduces corrosion rate by providing a higher pH to passivate the pipe and achieve perfect protection. Corrosion was found to be more intense in areas without CP, the corrosion degree is three times higher than that with CP[16]. Protection layers are well known to protect against corrosion, otherwise their unavailability will facilitate corrosion.

Operational factors

The third group of factors that cause corrosion in water pipelines is operational factors, which are primarily related to the quality of the internally transported water and human management. These factors are thus regrouped into two classes: physical factors and bio-electro-chemical factors (Fig. 4), which are detailed below based on the systematic review:

Physical factors

Water pressure: Water pressure is an important parameter related to the pumped water flow in the pipeline, and it is a primary parameter that can cause corrosion in the internal surface of the water pipes. The water pressure inside the pipes is not constant, and the loading fluctuation can cause fatigue, resulting in micro-cracks, which, in the presence of a rich water environment, will allow the development of corrosion defects with a rapid growth rate. Furthermore, the high flow rate caused by increased water pressure can cause erosion and eventually corrode the pipelines internally. Lower pressure, on the other hand, caused by a decrease or even a temporary stop in water pressure due to

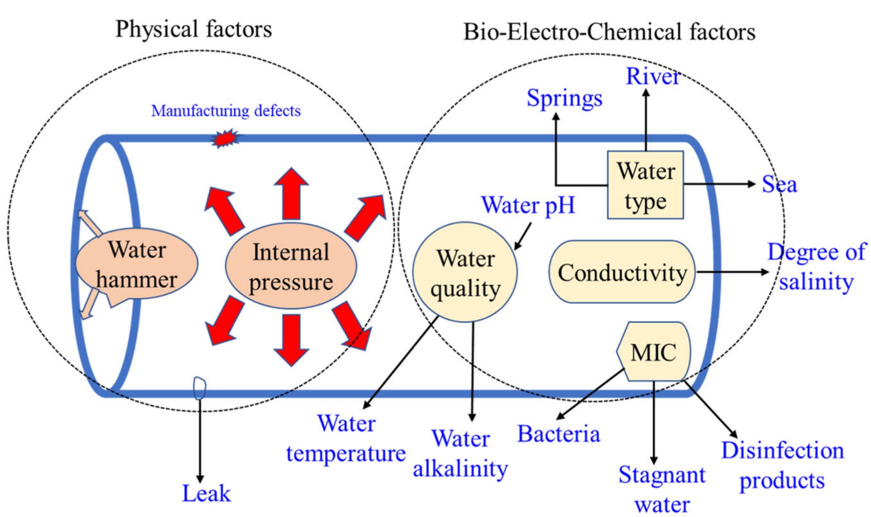

Fig. 4 Schematic representation of operational factors influencing water pipeline corrosion. The operational factors that induce corrosion in water pipes are split into two categories: physical factors and bio-electro-chemical factors.

power failures at pump stations, will lead to water stagnation and the development of a corrosive environment. Makar et al.[84] discovered longitudinal fractures in large diameter CI water mains caused by circumferential stresses caused by internal pressure. These fractures allow for pitting corrosion nucleation[85]. According to Ratnayake et al.[86], corrosion and cracks on the internal surfaces of water pipelines are related and primarily cause internal pressure loading. Operating pressures, according to Ji et al.[87], cause severe fatigue-corrosion damage. As a result, if this factor is poorly managed, water pressure fluctuation as an operating factor can accelerate corrosion rates.

Water hammer: Water hammer is a problem caused primarily by two causes: water waves raised by sudden valve closures and/or reflected waves caused by initial pressure waves in water pipelines. Aside from the high risk of bursting the pipeline, water hammer can cause corrosion problems if it occurs frequently. According to Leishea[88], cracks are most likely caused by water hammers, and cracks exposed to moisture and acidic soil have the potential to accelerate corrosion, specifically galvanic corrosion.

Human errors: Human errors may have a considerable impact on the corrosion in water pipes, especially in developing countries, because the deterioration rate is more influenced by the technology selected, design engineering, and spatial planning of the distribution system[89]. In ref. [90], a damaged external protective coating of a steel pipeline caused by a sharp object (such as stones) from the improper installation can cause dents and, eventually, corrosion problems. Jacek Ryl et al.[53], indicated that while building a new road and removing the surface of the old one, the pipeline may be exposed to overload and other factors, which can be a motivator for corrosion to occur. Furthermore, human errors can occur during manufacturing, such as irregular mortar coating thickness, inconsistent prestressing wire spacing, and low mortar quality, as stated in ref. [91]. Summarily, human errors during the manufacturing, installation, or operation of water pipelines can result in severe corrosion problems.

Leaks/bursts: Leaks/bursts are another indirect factor that can significantly contribute to water pipeline corrosion. Water distribution pipelines can be installed close to each other, and if breaks or leaks happened, the unaccounted/ nonrevenue water will spread to the area, increasing the moisture content and enriching the surrounding environment with corrosive factors found in water such as sulfate and chlorine[18]. This will eventually accelerate corrosion on other surfaces of the nearby water network. This factor can generally appear in any country; however, the World Health Organization reports that developing countries suffer the most from this issue due to poor management and human and manufacturing errors. Water pipe breaks, for example, account for 187 per 100 km per year in Colombia, compared to 17 per 100 km per year in the USA[92].

Bio-electro-chemical factors

Water quality: The pH, temperature, oxygen, alkalinity, chloride, sulfate, phosphate, and organic matter are all measurable water parameters[7,93]. Each of the preceding factors can have an impact on the inside environment of the pipe, potentially leading to the initiation of the corrosion. In ref. [94], the physical and chemical properties of the water supplied significantly impact the deterioration and corrosion rates in infrastructure. According to Liu et al.[95], the implications of changing water quality due to alternative water sources can cause physiochemical and microbiological destabilization of pipe material, biofilms, and loose deposits in the distribution system. Chlorine and chloramines are commonly employed as secondary disinfectants in water pipelines to deter bacterial regrowth. However, their usage can significantly impact the formation of localized corrosion[4,96,97]. Darren et al.[7], stated that pinhole (severe pitting corrosion) was observed in low temperature pipes, with high pH level, sulfate and chloride levels and low alkalinity. In contrast, high-temperature water pipes tend to exhibit accelerated uniform corrosion. Manganese content is another factor that has been studied, and high levels of nitrate ions can increase water acidity, leading to increased corrosion aggressiveness in water pipes[98]. High copper concentrations in water can cause uniform corrosion, which favors low pH and high alkalinity[15]. Overall, water quality can have corrosive properties, which can lead to pipes degradation.

Water type: Water type is another important factor to consider as a highly influencing parameter on the corrosion in water pipelines. Water quality is an essential factor that affects the corrosion of metallic pipelines. The type of water transported through pipelines varies at different stages before reaching consumers, and this variation can result in different water quality parameters and reactions with the metallic pipelines. When compared to water transported from rivers, springs, or lakes, desalinated water is thought to be the most corrosive[99]. In other words, water characteristics are primarily related to water type, with high alkalinity and hardness having lower corrosion aggressiveness than low alkalinity water.

Conductivity: Water conductivity is a parameter that is proportional to the salinity of the transported water. As the salt content in the water increases, conductivity also increases, and this parameter can be measured using conductivity cells. According to Xu et al.[100], water conductivity is one of the factors that influence the acceleration of the corrosion process in water pipelines. High conductivity, along with other parameters, can cause cold pitting corrosion, as reported by Bastidas et al.[15]. On the other hand, low conductivity can cause soft pitting corrosion. However, the precise relationship between the corrosion process and water conductivity is not well established in the existing literature.

Bacteria/microorganisms: These bacteria can form biofilms on the surfaces of water pipelines and promote corrosion under certain conditions[101]. SRB is a well-known type of bacteria that causes MIC. Several factors, such as stagnant water, disinfection products, and low water quality, can form and grow bacteria and microorganisms inside water pipelines[102]. Even though monitoring the drinking water quality using chlorine as a disinfectant is common, the water network is quite large and complex, and some pipelines may not be adequately monitored[103]. Ki et al.[104] discovered pitting corrosion near the heat-affected zone of the water pipeline, where MIC was the primary cause of perforation failure. According to Yazdi[105], SRB is one of the most common causes of MIC on steel structures, including pipelines, which causes their deterioration.

FAULT TREE ANALYSIS FOR THE CORROSION CAUSES OF THE WATER PIPELINES

Fault Tree Analysis is a logical method that aims at finding the causes of a single incident or major system breakdown, called a Top Event. The diagram depicts the logic behind the factors and causes that led to a certain failure or occurrence. The fault tree diagram employs Boolean logic gates (e.g., AND and OR gates) to depict the logical combination of several elements and causes that lead to an incident[106]. This approach can help industrial sectors and managers to focus on measures or tactics that can be utilized to prevent the basic causes of system failure from occurring. Figure 5 shows the fault tree model of water pipelines corrosion causes as a top event. Based on the systematic review, this figure summarizes all corrosion causes of the water pipelines. This top event; corrosion of the water pipelines; in the fault tree are directly interconnected using the “OR” gate to three intermediate events: (1) Environmental factors, (2) Pipe-related factors, and (3) Operational factors. The “OR” gate indicates that any of these three intermediate events have a direct impact and can cause the occurrence of the top event “corrosion of the water pipes”.

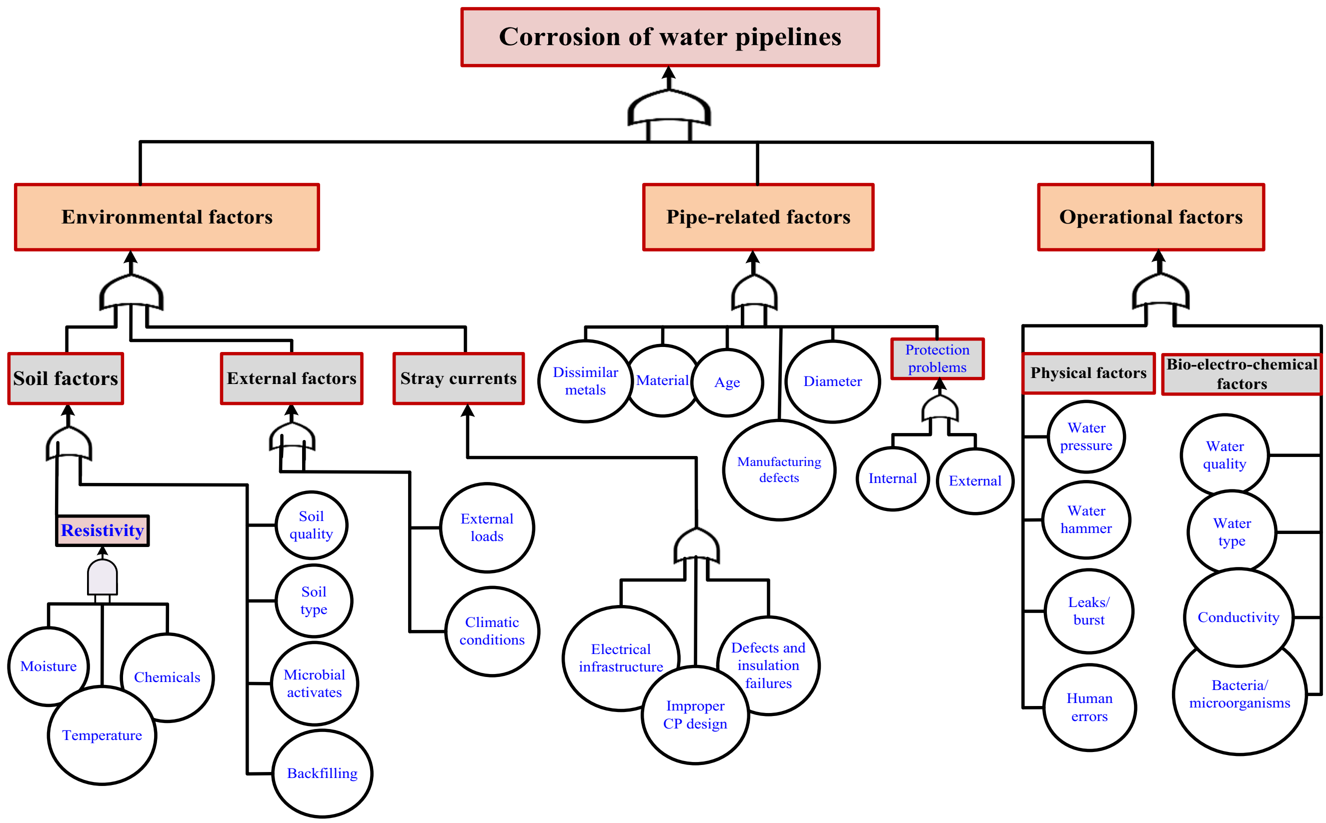

Fig. 5 Fault tree diagram of the corrosion causes for water pipelines. A comprehensive summary of the corrosion causes in water pipes based on bibliometric and systematic analysis.

Environmental factors are the first major intermediate event that directly leads to the corrosion of water pipeline. They made up of three other intermediate events: soil factors, external factors, and stray currents causes; implying that any of these three intermediate events can lead to water pipeline corrosion. For example, soil factors are connected by the "OR" gate to one intermediate event; soil resistivity; and four primary/basic events; soil quality, soil type, microbial activities, and backfilling. Soil resistivity, which gives an indication of the soil corrosivity, is connected to three basic events by the "AND" gate. This shows that "moisture", "temperature", and "chemicals" need to occur simultaneously before the resistivity of soil could be affected. Soil with low resistivity are more corrosive than soils with high resistivity[107]. Soil resistivity decreases with increasing moisture and chloride concentration[17]. External factors are connected by the "OR" gate to two primary/basic events; climatic conditions, and external loads. Stray currents causes are connected by the "OR" gate to three primary/basic events, which are electrical infrastructure, defects and insulation failure, and improper CP design.

Pipe-related factors are the second major intermediate event that directly leads to the corrosion of water pipelines. They are connected by the "OR" gate to one intermediate event; protection problems, and five basic events, which are dissimilar materials, pipe material, age, diameter, and manufacturing defects. Finally, operational factors are the last major intermediate event that directly leads to corrosion of water pipelines. The operational factors have two intermediate events, physical and bio-electro-chemical factors, interconnected by the "OR" gate. The physical factors have four basic events: water pressure, water hammer, leaks/burst, and human errors. In comparison, the bio-electro-chemical factors include another four basic events water quality, water type, conductivity, and bacteria/microorganisms.

TECHNO-SOCIO-ECONOMIC IMPACTS OF THE CORROSION OF THE WATER PIPELINES

Corrosion of water mains is a common problem resulting in negative techno-socio-economic consequences. The technical impacts of corrosion lead directly to social impacts and result in significant economic losses. The techno-socio-economic consequences of the water pipelines corrosion have been summarized in Fig. 6 and are discussed in detail in the following sections.

Technical impacts

Corrosion is a prevalent problem in water pipelines that can lead to various negative consequences for both the water and the pipeline. One of the most significant impacts is on water quality, with corrosion leading to discoloration of the water. When iron and copper are released into the water due to corrosion, it can change the water's colour from colourless to red or blue, respectively[3,12]. In addition, water quality can be deteriorated below the acceptable level due to source water changing, microorganisms, microbial activities and loose deposits, iron and copper release, and contaminants[3,4]. Similarly, corrosion scales in corroded pipes can obstruct water flow causing hydraulic loss[4,5]. On the other hand, corrosion has a has been found as the leading cause of pipeline failure across the globe[11,12]. In Australia, the yearly average failure rate is 20 breaks per 100 km; 189,600 out of 240,000 breaks (79%) occur due to corrosion[12,17]. In USA, water pipes are estimated to break 240,000 times annually while the annual pipe break rate in Toronto, Canada, was 25–30 per 100 km, and most of the failures were attributed to corrosion[12]. Pitting corrosion can contribute to pipe longitudinal stress and metal loss, resulting in pipe wall perforation, service life reduction, and ultimately failure of the pipe[7–9]. Furthermore, the segment of the pipe that is stressed becomes anodic, whereas the sections that

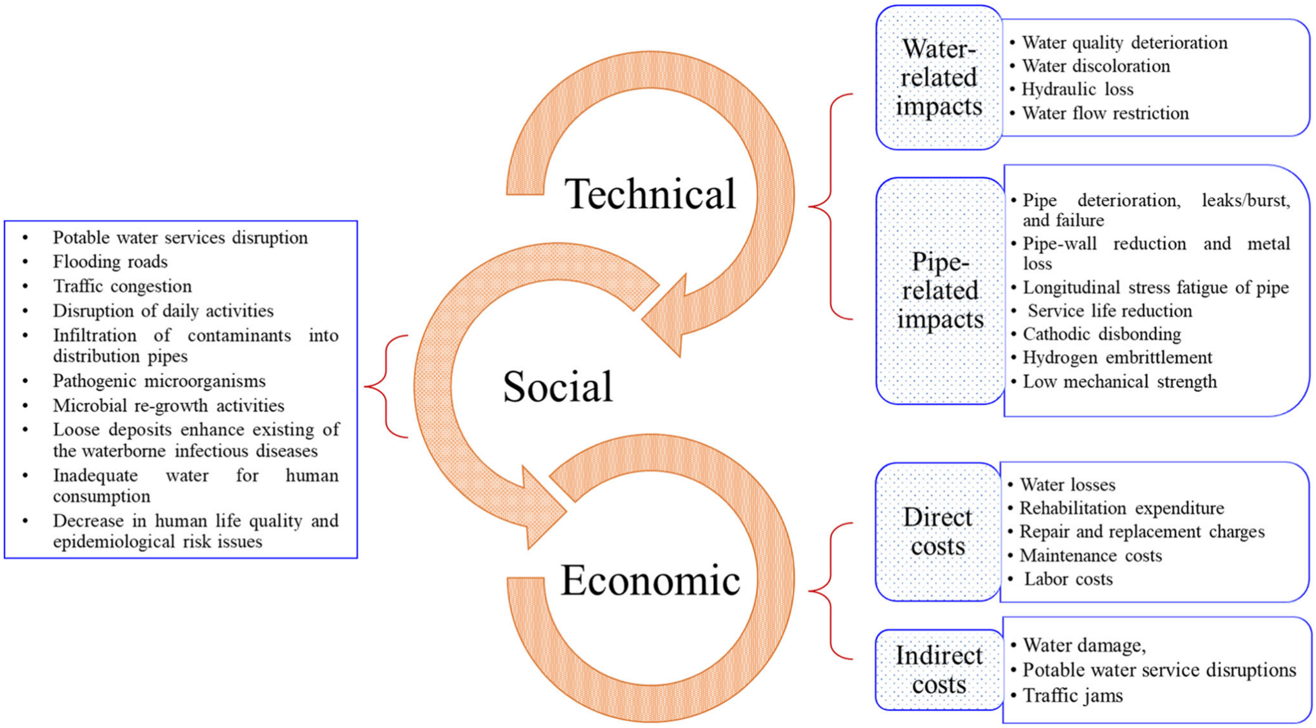

Fig. 6 Corrosion impacts. A summary of techno-socio-economic impacts of the water pipelines corrosion.

are not stressed become cathodic. As a result of the corrosive activity, the pipe under stress begins to corrode and becomes weakened[29]. Cathodic or coating disbandment and hydrogen embrittlement can occur if the electrical voltage is low enough to trigger a hydrogen evolution process[10]. This occurs when a stray current enters the pipeline where the electrical voltage shifts to a large negative side, generating electrochemical reactions such as oxygen reduction and hydrogen evolution causing cathodic or coating disbandment[64]. Apart from that, hydrogen embrittlement occurs and the pipe material become brittle due to the entrance and diffusion of hydrogen into it[67]. Corrosion can also cause graphitization in cast-iron pipes, in which the iron dissolves and only the graphite remains. Cast-iron pipes are mechanically weakened as a result of this operation leading to the pipe failure[9].

Social impacts

A summary of the social impacts due to corrosion has been introduced in Fig. 6. Corrosion of water pipelines has a variety of negative social consequences. The failure of pipeline causes potable water services to be disrupted at first, which leads to the end-user discomfort. In addition, failure due to leaks/burst causes flooding roads, traffic congestion and disruption of daily activities[12,13]. For instance, in Canada, severe repercussions due to water pipes failure include flooding a power transformer station, the erosion of highways, and the infiltration of contaminants into distribution pipes[12]. In a similar vein, stray current corrosion can destroy road, water pipelines and railway bridges, putting people's health and lives in jeopardy[65]. On the other hand, corrosion of water pipelines can lead to numerous negative health consequences. It happened due to a change in the water source that led to physiochemical/microbiological water destabilization or water quality issue (change in sulfate content) in a northern China. Also, it leads to pathogenic microorganisms, microbial re-growth activities and loose deposits in the drinking water system, which can enhance existing waterborne infectious diseases[4]. Corroded water pipelines can release by-products like lead, iron, copper, arsenic, and other minerals into drinking water systems, posing a health risk to the population[3]. Also, high quantities of manganese and nitrate ions in drinking water may endanger the health of water consumers[98]. These contaminants can cause many problems such as water quality deterioration below acceptable levels, which makes it not only inadequate for human consumption but also poses serious health risks[5,15,16].

Economic impacts

Like technical and social impacts, the economic consequences of corrosion-related water pipeline failure are summarized in Fig. 6. The economic losses include both direct and indirect expenses. Direct expenses refer to the costs associated with rehabilitation, repair and replacement, maintenance, labour, and water losses. Indirect expenses, on the other hand, can include water damage, service disruptions, and traffic congestion, among other things, which are ultimately passed on to customers[12]. In USA, the yearly pipes break was estimated to 240,000, the majority of which are due to corrosion. Over the next 25 years, it is estimated that repairing and replacing all critical infrastructure will cost $1 trillion[12]. According to a recent estimate, the cost of transit system stray current corrosion to both transit and third-party infrastructure is $500 million per year (USA spends roughly $10 billion per year on corrosion and its negative impacts)[66]. A water main break in Tucson, Arizona, costs USD 4.3 million and resulted in the loss of 38 million gallons of water. In Australia, corrosion is responsible for 79 percent of Australia's 26,700 yearly pipeline failures, costing an estimated AUD 123 million. The average yearly failure rate in Australia is 20 breaks per 100 km, and the cost of replacement has climbed by 10% annually since 2006[12]. Corrosion in China's WDNs costs an estimated 10 billion RMB in 2014, excluding indirect costs such as water loss[101]. All these statistics show the severity of the economic impacts of water pipeline failure due to corrosion.

Table 2. Scale of importance for pairwise comparison.

Linguistic scale	Discrete scale (AHP)	Fuzzy scale (FAHP)
Equal importance	1	(1, 1, 1)
Equal to moderate importance	2	(1, 2, 3)
Moderate importance	3	(2, 3, 4)
Moderate to strong importance	4	(3, 4, 5)
Strong importance	5	(4, 5, 6)
Strong to very strong importance	6	(5, 6, 7)
Very strong importance	7	(6, 7, 8)
Very strong to extremely strong importance	8	(7, 8, 9)
Extremely strong importance	9	(9, 9, 9)

RANKING THE CORROSION CAUSES OF WATER PIPELINES USING FUZZY ANALYTICAL HIERARCHY PROCESS (FAHP)

This study adopts the FAHP to rank the corrosion causes of water pipe failure. FAHP is an integration of fuzzy set theory (FST) and analytical hierarchy process (AHP), which usually employed to explore the strength of the two techniques[108,109]. The AHP is one of the most used multi-criteria decision methods (MCDM) developed by structuring a set of criteria and sub-criteria into a hierarchical structure[110,111]. AHP uses the eigenvalue method to obtain the relative weight of each element (e.g., criteria or sub-criteria) to the same hierarchy. The relative weights are obtained by making pairwise comparisons between the elements in the same hierarchy using experts' opinions or any available evidence. A 9-point scale proposed by the AHP developer is usually adopted for the pairwise comparison[111] (Table 2). However, the discrete scale of 1-9 could not handle imprecision associated with the pairwise comparison judgment; hence, FST was integrated with AHP to cater for the limitation[112]. Table 2 shows the linguistic, discrete, and fuzzy scales of importance adopted in this study.

FAHP extends the AHP method by allowing for vague and ambiguous judgments to be taken into account. In traditional AHP, decision-makers provide crisp judgments, which are based on a scale of 1–9, to evaluate the relative importance of different criteria and the performance of each alternative. However, in many real-world situations, decision-makers may have difficulty in providing precise and exact judgments due to incomplete or ambiguous information. FAHP addresses this issue by introducing fuzzy logic to AHP. Fuzzy logic is a mathematical framework that deals with uncertain and ambiguous information by allowing for degrees of membership in sets.

The adopted procedures for the FAHP analysis in this research are presented in Fig. 7. The first step was the formulation of the hierarchical structure (Fig. 5). The first level of the hierarchy is the overall goal of the FAHP – prioritization of corrosion causes of water pipelines. The second hierarchy is the three main categories of the causes, where the third and fourth (where applicable) hierarchies are extracted. A pairwise comparison matrix for every comparable factor was developed using triangular fuzzy numbers (TFN). The frequency (i.e., the number of studies that discussed each factor) of each factor was utilized to establish the pairwise comparison matrices. Figure 8 displays the frequencies of all the basic factors influencing the corrosion of water pipes. Subsequently, geometric mean values were calculated using Buckley's method[113], which forms the basis for deriving the fuzzy weights of each factor. To obtain crisp interpretable values, the relative weights were de-fuzzified using the centroid method (also known as the center of area method). Subsequently, the weights were normalized to obtain a sum value of 1. It should be noted that the local weights of all the matrices were aggregated to obtain the global weights of the factors, which are presented in Table 3.

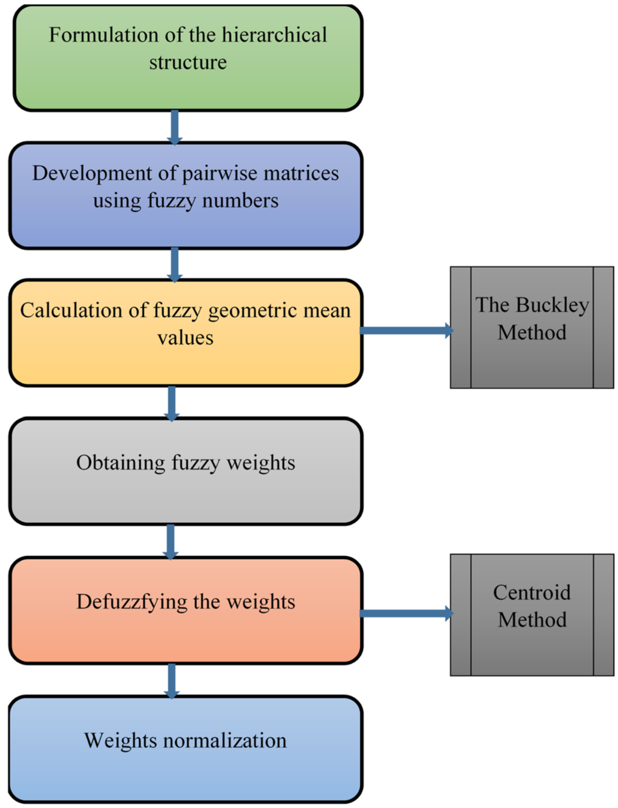

Fig. 7 Sequential flow of FAHP. The steps of the FAHP technique to extract the frequency of the factors causing corrosion based on the conducted studies from the literature.

The result of the FAHP analysis, which elucidates the relative weights assigned to factors influencing water pipe corrosion, is summarized in Table 3. This assessment of relative weights serves as a valuable indicator of the significance attributed to each factor in relation to water pipe corrosion. Upon scrutinizing the outcomes, it becomes evident that certain factors have garnered substantial attention within the domain of corrosion research. In particular, "water quality," "bacteria/microorganism," and "water pressure" emerge as the most extensively investigated factors, exhibiting relative weights of "0.150," "0.099," and "0.074," respectively.

The pronounced emphasis placed on these factors underscores their critical role in driving water pipe corrosion processes. Their higher relative weights suggest a stronger influence on the corrosion phenomenon, thereby accentuating the need for diligent examination and proactive measures to mitigate their impact. On the other hand, "Backfilling," "human errors," and "temperature" are identified as the factors with the lowest relative weights, amounting to "0.014," "0.016," and "0.017," respectively. It is important to recognize that the factors with comparatively lower relative weights should not be disregarded or underestimated. In fact, they warrant greater attention and further exploration to unravel their potential contributions to the failure of water pipes through corrosion.

Additionally, an intriguing pattern emerges when examining the broader categories of factors influencing corrosion causes. The results divulge that the operational factors denoted by a relative weight of "0.428," have been the focal point of extensive scholarly exploration. These factors pertain to the day-to-day operational

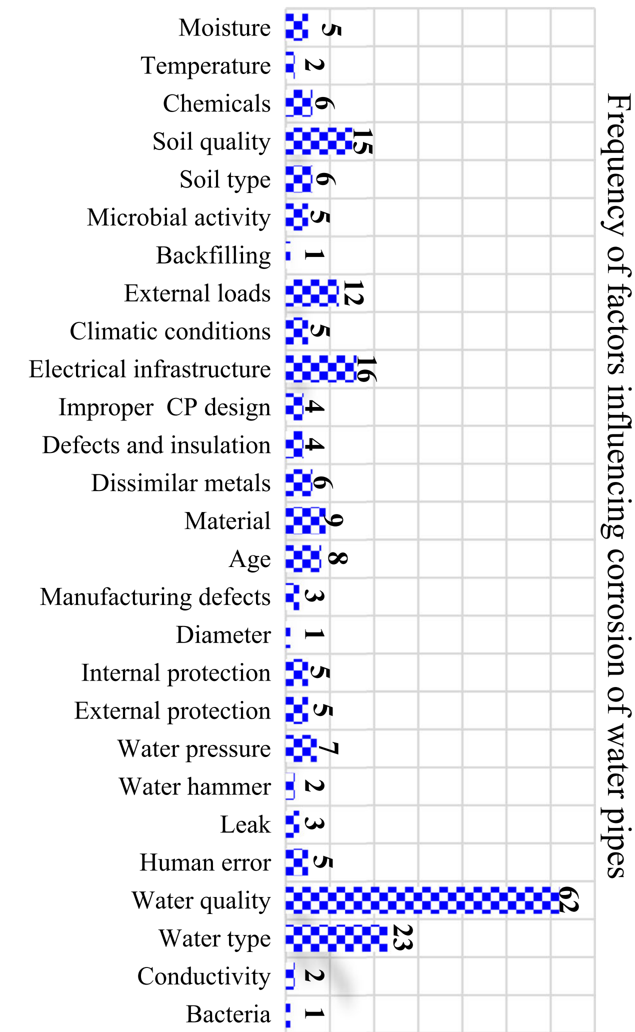

Fig. 8 FAHP results. Obtained frequency of factors influencing corrosion of water pipes.

aspects of water pipe systems and as such, they have garnered the well-deserved focus of researchers and practitioners alike. Conversely, pipe-related factors, material composition, and structural characteristics, have received relatively limited attention from researchers, as evidenced by their lower relative weight of "0.235" in the analysis.

However, it is essential to recognize the indispensable role played by pipe-related factors in the corrosion mechanisms of water pipes. Their significant contribution to corrosion causes should not be overlooked or underestimated, as it is through a comprehensive understanding of these factors that effective preventive and remedial strategies can be formulated. Thus, the outcomes of the systematic review unequivocally highlight the imperative to allocate careful consideration and concerted efforts toward comprehending and exploring pipe-related factors in future studies.

In conclusion, the results of the FAHP analysis shed light on the relative weights of factors influencing water pipe corrosion. While certain factors have been extensively investigated, there remains a critical need to examine the understudied factors to unravel their potential impact on water pipe failure. Moreover, the findings underscore the significance of pipe-related factors, urging researchers to allocate due attention to their intricate relationships with corrosion causes. By embracing a holistic approach that encompasses both quantitative (i.e., FAHP) and qualitative (i.e., systematic review) analysis, researchers and practitioners can foster a comprehensive understanding of water pipe corrosion and facilitate the development of effective corrosion management strategies.

Table 3. Relative weights of factors influencing corrosion causes of water pipes.

Categories	Causes of water pipe failure		Relative weights	Category-relative weights
Environmental	Soil factors	Moisture	0.022	0.337
		Temperature	0.017	
		Chemicals	0.024	
		Soil quality	0.049	
		Soil type	0.024	
		Microbial activities	0.022	
		Backfilling	0.014	
	External factors	External loads	0.042	
		Climatic conditions	0.026	
	Stray current	Electrical infrastructure	0.057	
		Improper CP design	0.020	
		Defects and insulation failures	0.020	
Pipe-related	Dissimilar metals		0.037	0.235
	Material		0.047	
	Age		0.044	
	Manufacturing defects		0.027	
	Diameter		0.020	
	Internal protection problems		0.030	
	External protection problems		0.030	
Operational	Physical factors	Water pressure	0.074	0.428
		Water hammer	0.025	
		Leak/burst	0.020	
		Human errors	0.016	
	Bio-electro-chemical factors	Water quality	0.150	
		Water type	0.021	
		Conductivity	0.023	
		Bacteria/microorganisms	0.099	

RESEARCH GAPS AND FUTURE DIRECTIONS

Based on the thorough critical review, Fig. 9 summarizes the identified research gaps as well as the corresponding future research directions. The gaps and future directions are expounded below:

- Although it is well established in the literature that water pipelines undergo corrosion even when advanced protection technologies are put in place. This highlights the complexity of the phenomenon and the need for proper understanding before designing effective protection systems. As such, the literature lacks extensive empirical investigation of factors contributing to water pipeline corrosion. Therefore, future research should conduct extensive investigations on pipe-related, environmental, and operational factors influencing

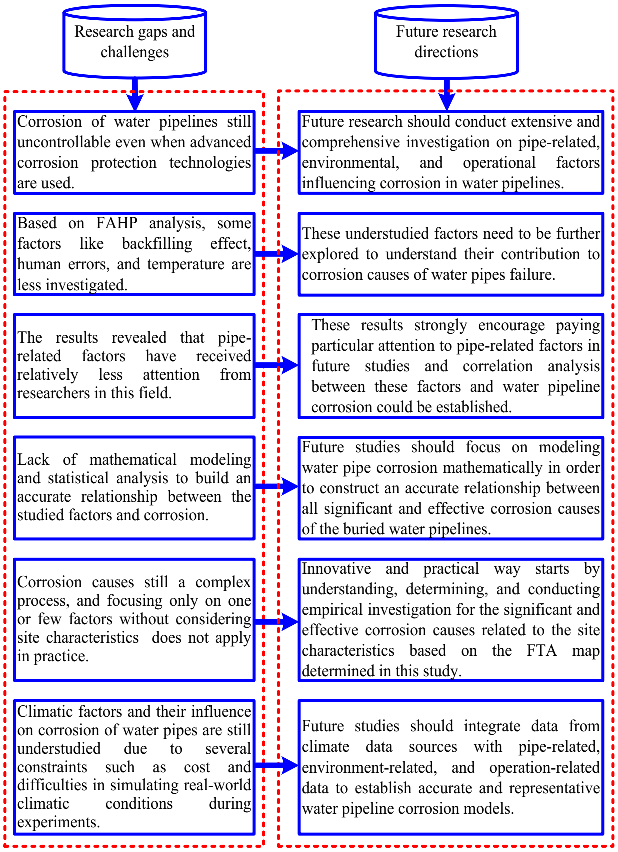

Fig. 9 A summary of the research gaps. Detailed description of the challenges and research future directions summarized based on this critical review.

corrosion in water pipelines.

- According to the FAHP analysis, the emphasis on the investigating factors is not balanced, with some being extensively studied in relation to water pipeline corrosion, such as water quality, bacteria/microorganism, and water pressure, while others, such as backfilling effect, human errors, and temperature are less investigated. These understudied factors need further exploration to understand their contribution to corrosion and water pipes failure.
- In terms of the three classifications of water pipeline corrosion causes, pipe-related causes have relatively received little attention from researchers in this field. However, according to the systematic review, it is evident that the importance of pipe-related factors in the water pipe corrosion cannot be overlooked. These results strongly encourage paying particular attention to pipe-related factors in future studies. Additionally, correlation analysis between these factors and water pipeline corrosion could be established especially the analysis of the metallic composition materials being used in the construction of water pipelines as different composited metallic materials have different susceptibilities to corrosion.
- The systematic analysis of the existing literature reveals the lack of mathematical modeling and statistical analysis to build an accurate relationship between the studied factors and corrosion in water pipelines. The most experimental studies do not provide such relationship and are limited in terms of experimental sampling. Consequently, future studies should mathematically model water pipe corrosion to construct an accurate relationship between all significant and effective corrosion causes of the buried water pipelines.
- Corrosion causes are still a complex process and focusing only on one or few factors without considering site characteristics during the study does not apply in practice. Site characteristics play a major role to accelerate or limit this detrimental process. Therefore, the innovative and practical way starts by understanding and determining the significant and effective corrosion causes related to the site characteristics. The FTA map developed in this study can give some insights into such relationship. Hence, future studies should give much importance to the characteristics of their sites by conducting empirical investigations while analyzing water pipeline corrosion.
- Although the scholarly literature has contributed to temperature-related research on buried pipes, the findings are not fully established, and there is still a gap in understanding the temperature effect on buried metal pipe corrosion. Similarly, despite the importance of quantifying the climatic factors and their influence on corrosion of water pipes, these factors are understudied due to several constraints such as cost and difficulties in simulating real-world climatic conditions during experiments. Therefore, it is recommended that future studies should integrate data from climate data sources with pipe-related, environment-related, and operation-related data to establish accurate and representative water pipeline corrosion models.

To summarize, corrosion in water metallic pipeline is a serious problem that can compromise the pipeline network's resiliency, particularly in hostile regions. The corrosion problem has been thoroughly investigated in the literature and addressed in various ways depending on numerous factors identified as impacting the corrosion process in terms of initiation and growth. In this review paper, a systematic analysis of 129 papers was conducted through a bibliometric search, revealing three main categories of corrosion-to-pipe impacting factors: environmental, pipe-related, and operational. Environmental factors encompass soil-related, external, and stray current factors, while pipeline-related factors involve the pipeline mechanical, characteristic and design factors/properties. Operational factors refer to physical and Bio-Electro-Chemical factors. These factors were ranked based on their occurrence in the literature using the Fuzzy Analytical Hierarchy Process (FAHP) technique, in which results indicate that water quality is the most investigated factor, followed by the electrical infrastructure and soil quality. The operational factors, on the other hand, have the highest relative weight (0.428), followed by environmental factors (0.337). Using the analysis and ranking findings, research gaps and limitations are detailed. The main research challenges and recommendations/future directions are summarized as follows:

- Lack of studies on the effect of pipe-related factors in water pipe; specifically, the behavior of the material composition utilized for pipeline construction in prone corrosion. These understudied aspects must be investigated extensively, both experimentally and numerically, in order to understand their role to corrosion causes that contribute to water pipe failure.
- Lack of mathematical modeling and statistical analysis of corrosion-related data based on inspections or experimental reports. This is critical for establishing an accurate relationship between the factors examined and corrosion behavior in terms of initiation, growth rate, or damage dimension.
- Climatic factors and their influence on corrosion of water pipes are still understudied due to several constraints such as cost and difficulties in simulating real-world climatic conditions during experiments; therefore, to build reliable and representative water pipeline corrosion models, future studies should incorporate data from climate data sources with pipe-related, environment-related, and operation-related data.
- According to FAHP analysis, some factors, such as backfilling effect, human errors, and temperature are less investigated;

these understudied factors need to be further explored to understand their contribution to corrosion causes leading to water pipe failure.

This review study can provide valuable insights for water utility management in understanding the causes of water pipeline corrosion and ultimately assisting them in developing effective corrosion protection strategies, proposing efficient frameworks for modeling corrosion in water pipelines and insights into the factors considered when scheduling maintenance.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request

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COMPETING INTERESTS

All authors declare no financial or non-financial competing interests.

ADDITIONAL INFORMATION

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