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Study on the Impact of Corrosion in Metallic Pipes on Drinking Water Quality

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دراسة حول تأثير التآكل في الأنابيب المعدنية على جودة مياه الشرب

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Abstract:
The internal corrosion of metallic pipes in drinking water distribution systems (DWDS) represents one of the most pressing challenges to public health and water infrastructure sustainability worldwide. This paper presents a comprehensive review of the mechanisms, influencing factors, and water quality implications of pipe corrosion in metallic drinking water pipelines. The electrochemical and microbiologically influenced corrosion processes are examined, alongside the critical water quality parameters including pH, alkalinity, dissolved oxygen, chloride, and sulfate concentrations that govern corrosion kinetics and corrosion scale formation. The impact of corrosion on drinking water quality is systematically analyzed through physicochemical degradation pathways, including heavy metal leaching (lead, copper, iron, nickel), discoloration phenomena, turbidity elevation, and microbial proliferation within corrosion scales and biofilms. Health risk assessments reveal significant non-carcinogenic and carcinogenic risks associated with prolonged exposure to corrosion-derived contaminants, particularly for vulnerable populations. Contemporary corrosion monitoring technologies, including ultrasound-based assessment coupled with convolutional neural networks, and corrosion control strategies encompassing pH/alkalinity adjustment, phosphate-based corrosion inhibitors, and protective lining systems—are critically evaluated. Emerging research directions, including machine learning applications for corrosion prediction and material-specific microbiologically influenced corrosion mechanisms, are discussed. This review provides guidance for water utilities and researchers in developing effective corrosion management strategies to ensure drinking water safety and infrastructure resilience.

Keywords: Corrosion, Drinking Water Quality, Metallic Pipes, Heavy Metal Release, Microbiologically Influenced Corrosion, Corrosion Inhibitors, Water Distribution Systems

الملخص
يُعدّ التآكل الداخلي للأنابيب المعدنية في شبكات توزيع مياه الشرب أحد أبرز التحديات التي تواجه الصحة العامة واستدامة البنية التحتية للمياه على مستوى العالم. تُقدّم هذه الورقة مراجعة شاملة لآليات التآكل في أنابيب مياه الشرب المعدنية، والعوامل المؤثرة فيه، وتأثيراته على جودة المياه. وتتناول الدراسة عمليات التآكل الكهروكيميائية والميكروبيولوجية، إلى جانب معايير

جودة المياه الأساسية - بما في ذلك الرقم الهيدروجيني، والقلوية، والأكسجين المذاب، وتركيزات الكلوريد والكبريتات - التي تُحدّد حركية التآكل وتكوّن طبقة التآكل. كما تُحلّل الدراسة تأثير التآكل على جودة مياه الشرب بشكل منهجي من خلال مسارات التحلل الفيزيائي والكيميائي، بما في ذلك ترشيح المعادن الثقيلة (الرصاص، والنحاس، والحديد، والنيكل)، وظواهر تغير اللون، وارتفاع العكارة، وتكاثر الميكروبات داخل طبقات التآكل والأغشية الحيوية. تكشف تقييمات المخاطر الصحية عن مخاطر غير سرطانية وسرطانية كبيرة مرتبطة بالتعرض المطول للملوثات الناتجة عن التآكل، لا سيما بالنسبة للفئات السكانية الأكثر عرضة للخطر. وتُقيّم هذه الدراسة تقييماً نقدياً تقنيات رصد التآكل الحديثة، بما في ذلك التقييم القائم على الموجات فوق الصوتية المقترن بالشبكات العصبية الالتفافية، واستراتيجيات مكافحة التآكل - التي تشمل ضبط درجة الحموضة/القلوية، ومثبطات التآكل القائمة على الفوسفات، وأنظمة التبطين الواقية. كما تُناقش اتجاهات البحث الناشئة، بما في ذلك تطبيقات التعلم الآلي للتنبؤ بالتآكل وآليات التآكل المتأثرة بالميكروبات الخاصة بكل مادة. وتقدم هذه المراجعة إرشادات لشركات المياه والباحثين لتطوير استراتيجيات فعالة لإدارة التآكل لضمان سلامة مياه الشرب ومرونة البنية التحتية.

الكلمات المفتاحية: التآكل، جودة مياه الشرب، الأنابيب المعدنية، إطلاق المعادن الثقيلة، التآكل المتأثر بالميكروبات، مثبطات التآكل، أنظمة توزيع المياه.

1. Introduction

Drinking water distribution systems (DWDS) constitute critical urban infrastructure that delivers treated water from treatment plants to consumers' taps. However, the water quality achieved at treatment facilities often deteriorates during transportation through distribution networks, primarily due to internal corrosion of metallic pipes. This phenomenon represents one of the most significant challenges facing the drinking water industry, affecting public health, consumer acceptance, and the economic sustainability of water supply systems.

Metallic pipes including cast iron, ductile iron, steel, copper, and galvanized steel remain prevalent in aging water infrastructure globally. The internal corrosion of these metallic pipes has been documented to reduce water quality and lead to increased levels of toxic heavy metals such as lead, copper, and nickel. These problems have been experienced to varying degrees by water utilities in many countries. The corrosion process converts refined metals into more chemically stable forms such as metal oxides, hydroxides, and sulfides, gradually degrading pipe materials through chemical reactions with the aqueous environment.

The complexity of corrosion processes in DWDS arises from the interplay of physical, chemical, and biological factors. Water quality parameters—including pH, temperature, alkalinity, hardness, dissolved oxygen, carbon dioxide, total dissolved solids, chloride, and sulfate—all influence the internal corrosion of distribution network pipes. Furthermore, microbiologically influenced corrosion (MIC), driven by bacterial activity within biofilms formed on pipe inner surfaces, adds another layer of complexity to corrosion mechanisms.

This paper provides a comprehensive review of the impact of metallic pipe corrosion on drinking water quality. The objectives are to: (1) examine the fundamental mechanisms of corrosion and corrosion scale formation in drinking water pipes; (2) analyze the key factors influencing corrosion processes; (3) evaluate the effects of corrosion on physicochemical and biological water quality parameters; (4) assess the health risks associated with corrosion-derived contaminants; and (5) review contemporary monitoring technologies and control strategies for corrosion management.

2. Corrosion Mechanisms and Types

A. Electrochemical Corrosion

The corrosion of metallic pipes in drinking water systems is fundamentally an electrochemical process involving redox reactions between pipe substrates and aqueous oxidants. In ferrous pipes, the anodic dissolution of iron ($Fe \rightarrow Fe^{2+} + 2e^-$) is coupled with cathodic oxygen reduction ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$). This process creates microgalvanic cells on pipe surfaces, where areas with different electrochemical potentials serve as anodes and cathodes, driving localized corrosion.

The electrochemical corrosion of carbon steel in potable water systems is typically a slow process measured in tens of micrometers per year, and it can take many years or even decades before significant damage occurs. However, the cumulative effects over extended service periods often exceeding 50 years in aging infrastructure—result in substantial material degradation and water quality deterioration.

B. Corrosion Scale Formation

Corrosion scale formation is a critical aspect of pipe corrosion that significantly influences water quality. The scales that develop on inner pipe surfaces are driven by the interplay between electrochemical corrosion and microbiologically influenced corrosion (MIC), in which microbial biofilms foster localized corrosion that accelerates overall degradation.

Corrosion scales formed on iron pipe surfaces exhibit a typical multilayered structure comprising different iron oxide and hydroxide phases. These scales are not merely passive barriers but actively participate in water quality dynamics. They serve as sinks for potential water contaminants, including various metals. Conversely, the destabilization of these corrosion scales can release accumulated contaminants back into the water column, causing water discoloration and quality deterioration.

The composition and stability of corrosion scales are affected by pipeline physical attributes, water quality parameters, and microbial activities. Scale transformation is influenced by water quality changes and microbial activity, with corrosion-related bacteria playing significant roles in scale modification.

C. Microbiologically Influenced Corrosion (MIC)

Microbiologically influenced corrosion represents one of the main causes of water deterioration in DWDS. Pervasive microorganisms inhabit various ecosystems within distribution systems, and their interactions can induce significant corrosion. The complexity of MIC processes has not yet allowed a general mechanism to be established, and the compositions of microbial communities in DWDS are not fully understood.

Recent research has identified material-specific enrichment of corrosion-associated microorganisms. Unlined metal pipes harbor iron-oxidizing bacteria such as Sideroxydans and sulfate-reducing bacteria (SRB) such as Desulfovibrio. Sulfate reduction by Desulfovibrio species has been identified as a key contributor to accelerated corrosion in unlined iron pipes. In contrast, cement-lined ductile iron pipes foster acidogenic Streptococcus proliferation, correlating with iron dissolution through lactic acid production.

Biofilms are heterogeneous bacterial formations that grow on the inner surfaces of DWDS pipes. These biofilms consist of a great variety of cellular polymers and, through their aggressive metabolites, enhance the rate of metal corrosion. Bacteria that colonize pipe substrates can oxidize divalent iron and manganese cations to insoluble compounds, contributing to both corrosion and deposit formation.

D. Types of Corrosion

Several distinct types of corrosion affect drinking water pipes:

- Uniform Corrosion involves relatively even metal loss across the pipe surface and is typically associated with acidic or aggressive water conditions.
- Pitting Corrosion is a localized form of corrosion that creates small pits or holes in the pipe wall. Chloride ions can penetrate through passive films or oxide layers and encourage an acidic environment on metal surfaces, accelerating pitting corrosion.
- Galvanic Corrosion occurs when dissimilar metals are in contact in the presence of an electrolyte. In copper pipes containing lead solder, changes in chloride and sulfate concentrations can result in a galvanically induced increase in lead concentrations in water. Lead within premise plumbing, especially at pipe connections, can act as anodic zones where galvanic corrosion occurs.
- Intergranular Corrosion affects the grain boundaries of metallic materials. Owing to the higher impurity content in the inner grain of metal materials, grain boundaries are more susceptible to corrosion than the interior. Chloride ions in the medium further accelerate this type of corrosion.

3. Factors Influencing Pipe Corrosion

A. Water Quality Parameters

The corrosivity of drinking water is governed by a complex interplay of physicochemical parameters.

pH is among the most critical parameters influencing corrosion. Low pH values increase the solubility of metal oxides and hydroxides, accelerating metal release. Alkalinity, pH, and carbonate ion concentration have been identified as important parameters controlling iron release.

Dissolved Oxygen (DO) serves as the primary cathodic reactant in aerobic corrosion. Higher DO concentrations generally accelerate corrosion rates, although the relationship is nonlinear and influenced by other factors.

Chloride and Sulfate ions are aggressive anions that disrupt passive films and accelerate corrosion. Chloride can penetrate through passive layers and encourage acidic conditions on metal surfaces. Sulfate tends to generate anaerobic conditions, inducing corrosion scales to accept electrons and promoting iron dissolution. These ions also enhance the formation of unstable green rusts in iron corrosion scales, which are prone to release under external disturbances.

Temperature affects corrosion kinetics, with higher temperatures generally accelerating corrosion rates. Seasonal variations in water temperature thus influence corrosion dynamics throughout the year.

Hardness and Alkalinity influence the formation of protective calcium carbonate scales. Water with low hardness and alkalinity tends to be more corrosive.

B. Pipe Material Characteristics

Different pipe materials exhibit varying corrosion susceptibilities. Unlined steel pipes show more accelerated corrosion compared to cement-lined systems. Biofilm quantification has demonstrated 13.5-fold higher bacterial densities on unlined surfaces, attributed to corrosion-induced microtopography.

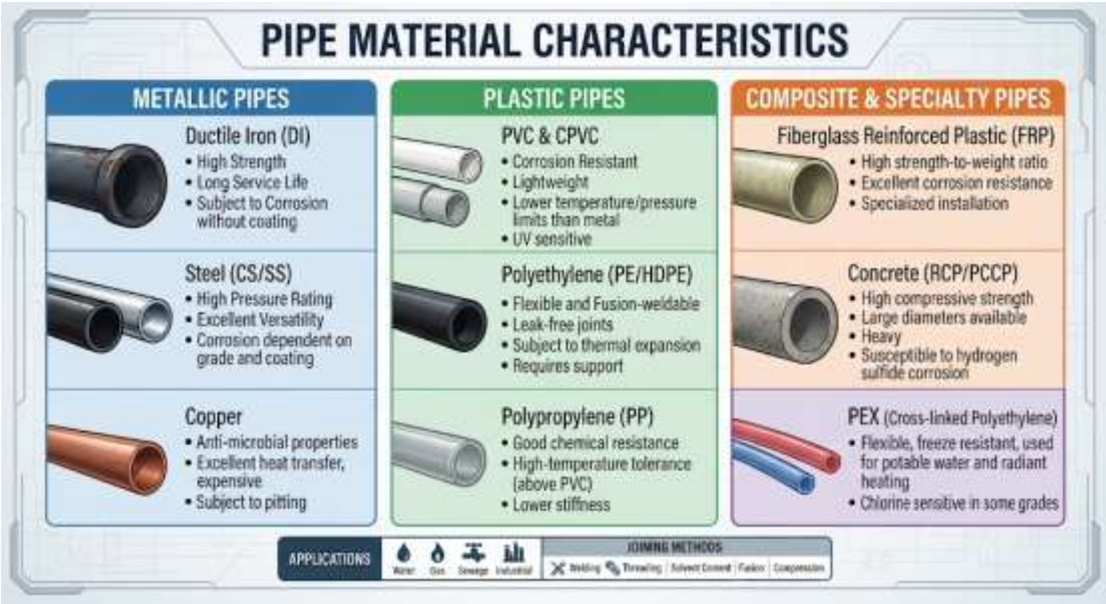

Figure 1: Pipe Material Characteristics

Corrosion scales formed on different iron pipe materials vary in composition and stability. Old corroded pipes made of different materials and exposed to different water qualities develop distinct corrosion product characteristics.

C. Hydraulic Conditions

Flow conditions significantly influence corrosion processes. Stagnation periods can increase metal concentrations due to prolonged contact between water and corroded surfaces. Transient hydrodynamic regimes can destabilize corrosion scales, releasing contaminants and causing water discoloration.

D. Microbial Activity

Microbial communities in DWDS influence corrosion through multiple mechanisms. The composition of microbial communities is affected by pipe materials, flow conditions, and residual disinfectants. Varying temperature and sulfate addition drive shifts in bacterial community composition.

4. Impact Of Corrosion On Drinking Water Quality

A. Heavy Metal Release

Iron Release is the most common manifestation of corrosion in ferrous pipe systems. When drinking water quality and hydraulic conditions change, the solid-liquid balance between pipe scales and water is destroyed, causing iron release and secondary pollution. Iron release leads to "red water" problems characterized by discoloration, turbidity, and metallic taste. Significant linear correlations of corrosion indices (Langelier Index, Ryznar Stability Index, Puckorius Scaling Index) to iron concentration have been observed in distribution systems.

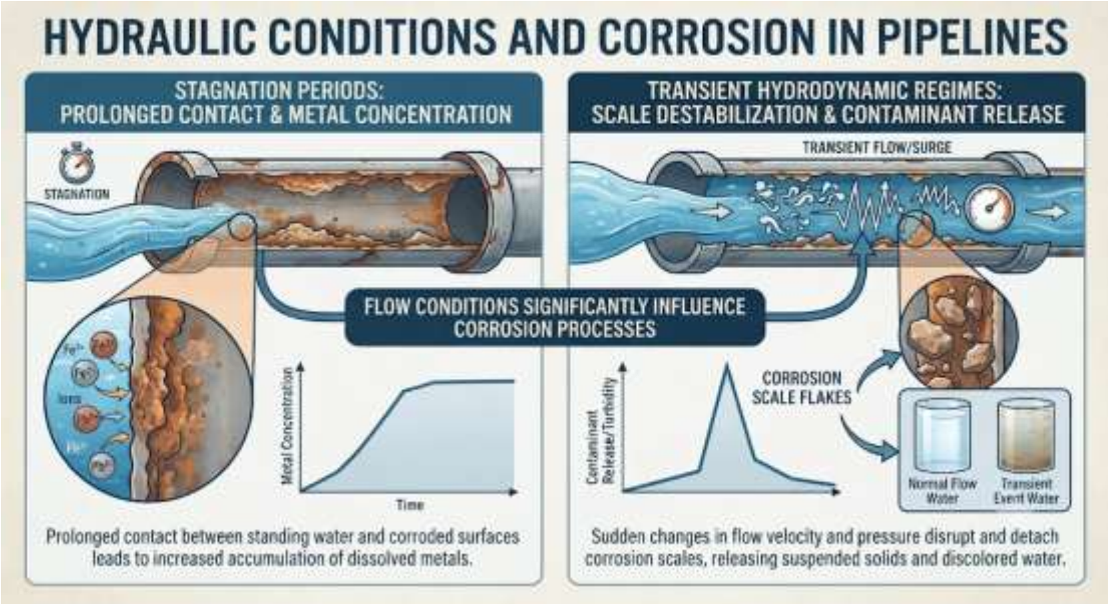

Figure 2: Hydraulic conditions and corrosion in pipelines

Lead Contamination represents one of the most serious public health concerns associated with pipe corrosion. Lead exposure is responsible for approximately 0.9 million deaths annually and 30% of the global burden of developmental intellectual disability of undetermined origin. Lead contamination in drinking water is primarily driven by corrosion in metal pipes, particularly where water has high acidity, alkaline pH, or low mineral content. A study in Islamabad, Pakistan, found that Zone I water from metal pipes showed median lead values above 0.1 mg/L, exceeding WHO's permissible limit of 0.01 mg/L. Regression analysis revealed that pipe material, water chemistry, and stagnation time were significant contributors to lead contamination.

Figure 3: impact of corrosion on drinking water quality

Copper Release results from corrosion of copper plumbing. High cuprosolvency is expected in new plumbing and may persist for days, months, years, or decades until low-solubility mineral coatings, or "protective scales," form inside pipes. Severe copper corrosion by microorganisms can lead to the "blue water" phenomenon. In copper pipes, common corrosion products include cupric oxide (CuO) and cuprous oxide (Cu_2O).

Nickel and Other Metals are also released during corrosion of various pipe materials and fittings. The metal release sequence from corroding iron coupons follows Fe > Mn > Ni > Al.

B. **Physicochemical Water Quality Deterioration**

Turbidity and Color are significantly affected by corrosion. The release of corrosion products, particularly iron oxides, causes water discoloration ranging from yellow to red-brown. Corrosion and corrosion scale formation negatively impact water quality by altering its chemical, physical, and microbiological stability.

Taste and Odor problems arise from corrosion-derived metal ions and microbial metabolites. Red water, caused by iron corrosion, is associated with metallic taste and aesthetic complaints.

Disinfectant Decay is accelerated in corroded systems. Corrosion products and biofilms consume residual chlorine, reducing disinfection efficacy throughout the distribution system.

C. Biological Water Quality Deterioration

Corroded pipes provide niches for microbial colonization and biofilm formation. Biofilms are reportedly leading causes of undesired taste, odor, and color of drinking water, corrosion of pipes, decay of disinfectants, and proliferation of pathogenic microbes, giving rise to public health concerns.

Bacteria associated with corrosion processes, including Desulfovibrio, Sulfuricella, Hyphomicrobium, and Methylobacterium, are prevalent in DWDS biofilms. Old cast iron pipes have been found to contain more trihalomethanes and antibiotic resistance genes (ARGs) compared to new pipes. Corroded cast iron pipes induce a unique interaction system of biofilms, chlorine, and corrosion products.

5. Health Risk Assessment

A. Toxicological Impacts of Heavy Metals

The release of heavy metal ions from corroded pipelines poses potential long-term health risks for consumers. Health risk assessments conducted in various regions have revealed significant concerns:

- Lead: Health risk assessments in Islamabad indicated high non-carcinogenic and carcinogenic risks, particularly for children in low-income sectors. The hazard quotient (HQ) for lead in pipe-borne water consumed by children and infants exceeded acceptable levels, indicating potential adverse effects.
- Cadmium, Chromium, and Other Metals: Health risk assessments of potentially toxic elements in public pipe-borne water revealed that the HQ for Cd, Cr, and Pb exceeded safe thresholds in water consumed by children and infants.

B. Vulnerable Populations

Children are particularly vulnerable to the health effects of corrosion-derived contaminants due to their higher water consumption per unit body weight and developing physiological systems. Low-income communities are disproportionately affected, often relying on aging infrastructure with greater corrosion problems.

C. Bioaccessibility of Corrosion Scale Metals

Recent research has investigated the bioaccessibility of metals accumulated in corrosion scales. The US-EPA Method 1340 (gastric juice simulation) dissolved significantly higher amounts of Pb, Cu, Mn, Fe, Cr, and Sn compared to other extraction methods. This suggests that ingestion of corrosion scale particulates through tap water consumption could pose health risks beyond those estimated from dissolved metal concentrations alone

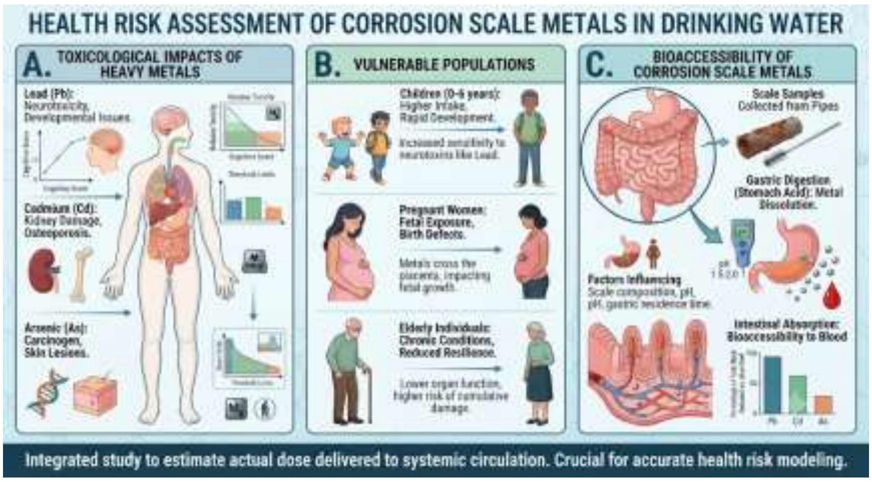

Figure 4: Health Risk Assessment. (A) Toxicological Impacts of Heavy Metals, (C) Vulnerable Populations, (D) Bio accessibility of Corrosion Scale Metals.

6. Corrosion Monitoring and Assessment

A. Water Stability Indices

Several indices have been developed to assess the corrosion and scaling potential of drinking water:

Langelier Saturation Index (LSI) indicates whether water is supersaturated (scaling) or undersaturated (corrosive) with respect to calcium carbonate. In a study of rural water networks in Urmia, Iran, LSI values ranged from −1.94 to −2.22, indicating highly corrosive conditions.

Ryznar Stability Index (RSI) and Puckorius Scaling Index (PSI) provide complementary assessments of corrosion/scaling tendency. Studies in Morocco found corrosive tendencies of 41%, 75%, 97%, and 13% based on different indices.

Larson–Skold Index (LRI) evaluates the corrosivity of water toward iron based on chloride and sulfate concentrations. Significant linear correlations of corrosion indices to iron concentration have been observed, confirming their utility for estimating iron release potential.

These indices can be used to estimate, monitor, and minimize the potential for metal release from distribution systems. However, concordance between chemical water quality analysis and national standards is not sufficient to confirm water quality balance in terms of corrosion and scaling potential.

B. Advanced Monitoring Technologies

Ultrasound and Convolutional Neural Networks (CNN): A dual-mode methodology utilizing advanced ultrasound technology and CNN has been developed to quantify pipe corrosion. Internal pipe corrosion within water distribution systems leads to iron oxide deposits on pipe walls, potentially contaminating the water supply. This approach offers precise and reliable monitoring without requiring system downtime.

Wireless Sensor Networks have been proposed for continuous corrosion monitoring in water systems. These systems can detect early-stage corrosion before significant damage occurs.

Machine Learning Models have been proposed as a promising approach for predicting corrosion conditions and pipeline performance, addressing gaps in dynamic modeling. Artificial neural network-based corrosion prediction models have been developed for optimizing pipe renewal investment planning.

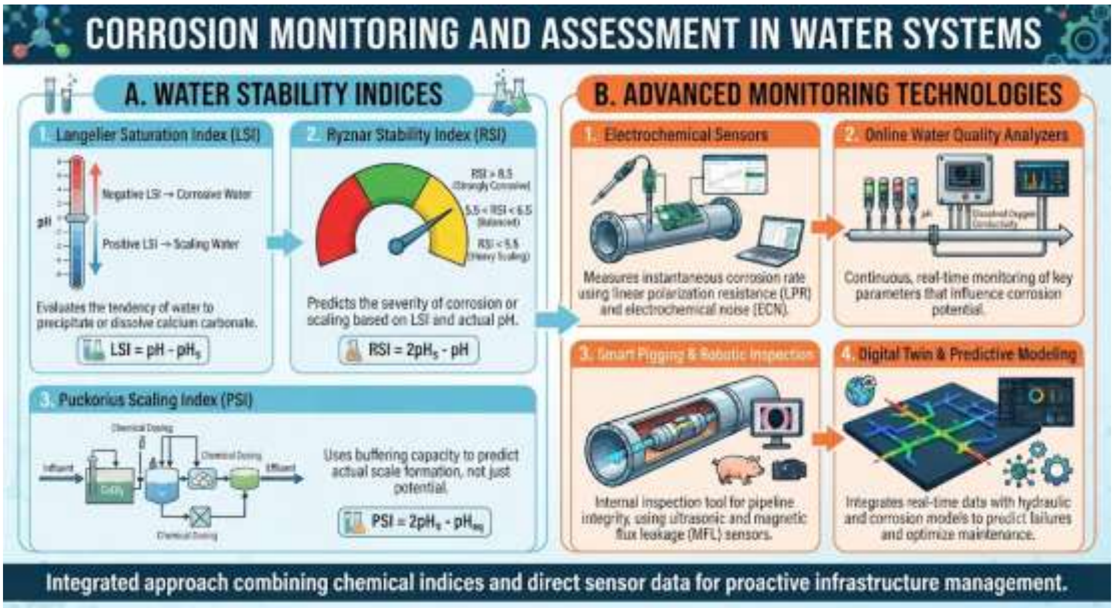

Figure 5: Corrosion monitoring and assessment in water systems

Ground Penetrating Radar (GPR) has been evaluated for assessing corrosion damage in buried pipes, with 500 MHz GPR systems found suitable for this application.

7. Corrosion Control Strategies

A. pH and Alkalinity Adjustment

Adjusting pH and alkalinity is a primary corrosion control strategy. Water with appropriate pH and alkalinity promotes the formation of protective calcium carbonate scales on pipe surfaces, reducing metal release. Studies have examined the effects of chemicals used for pH and alkalinity control to produce optimal corrosion control methods.

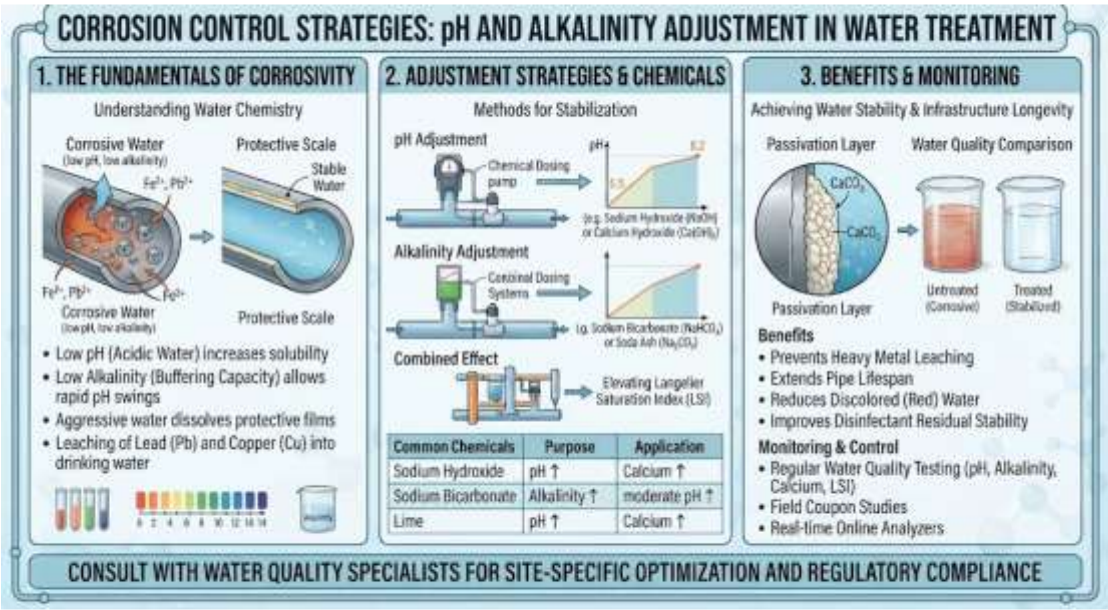

Figure 6: Corrosion control strategies: Ph and Alkalinity adjustment in water treatment.

B. Corrosion Inhibitors

Phosphate-Based Inhibitors are widely used for corrosion control in drinking water systems. Orthophosphates can control lead, copper, and iron corrosion through the formation of durable, low-solubility scales. A composite phosphate corrosion inhibitor has been shown to enhance water quality stability in DWDS.

The effectiveness of phosphate-based inhibitors varies by pipe material. When corrosion inhibitor at 10 mg/L is injected, the corrosion rate for carbon steel pipe, galvanized steel pipe, and copper pipe reduces by 37%, 66%, and 61%, respectively. A phosphate-zinc based inhibitor formulated for efficient corrosion control achieved 99% reduction in corrosion rate in continuous-circulation tests.

Zinc Orthophosphate is used as a corrosion inhibitor within drinking water pipes. However, research has shown that corrosion inhibitors can influence antibiotic resistance in drinking water.

Calcium Hydroxide (Lime) has been used to prevent corrosion in tap water supply pipes. Homogenization technology for calcium hydroxide can be applied to tap water and desalinated water.

C. Protective Linings and Coatings

Cement-mortar lining is commonly applied to ductile iron pipes to prevent corrosion. However, cement-mortar lining failure and metal release can occur due to electrochemical corrosion. Development of corrosion-resistant coatings is a promising approach for MIC prevention.

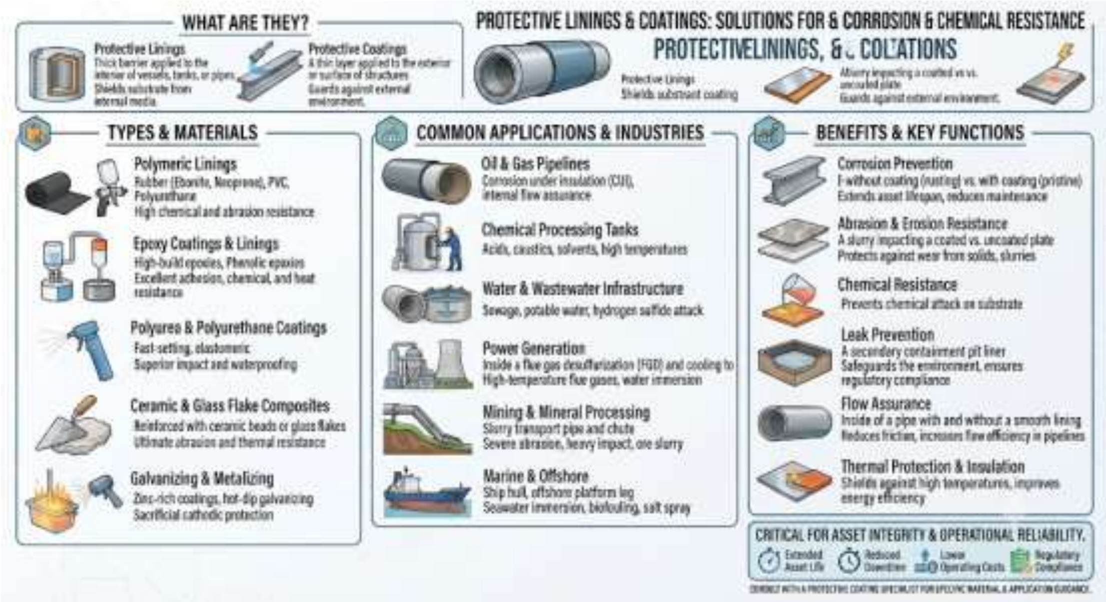

Figure 7: Protective Linings and Coatings

D. Pipe Material Selection and Replacement

The replacement of metallic pipes with corrosion-resistant materials such as PVC and HDPE is increasingly common. Identification and replacement of lead and galvanized metal pipes is a priority for utilities worldwide. In the United States, regulations require all drinking water systems to identify and replace lead and galvanized metal pipes in their systems by 2037.

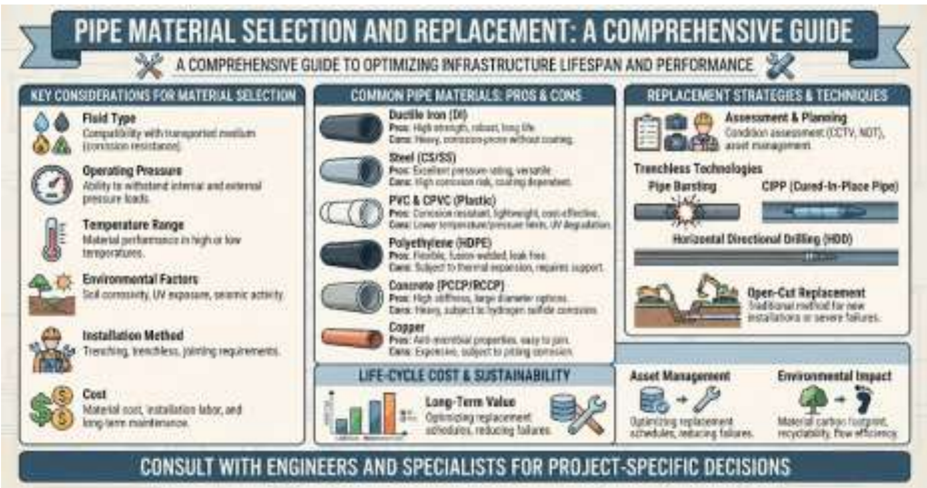

Figure 8: Pipe material selection and replacement: a comprehensive guide.

E. Microbial Corrosion Control

Preventive methods for MIC include microbial community engineering, replacement of pipeline materials with enhanced corrosion resistance, or development of corrosion-resistant coatings. Understanding material-driven MIC mechanisms enables new non-invasive monitoring strategies for corrosion risk assessment.

8. Results And Analysis

A. Synthesis of Corrosion Impact on Water Quality

The literature reviewed demonstrates that metallic pipe corrosion systematically degrades drinking water quality through multiple interconnected pathways. The electrochemical dissolution of pipe materials introduces metals into the water column, while the destabilization of corrosion scales releases accumulated contaminants. The magnitude of these effects depends on the complex interplay of water chemistry, pipe material, hydraulic conditions, and microbial activity.

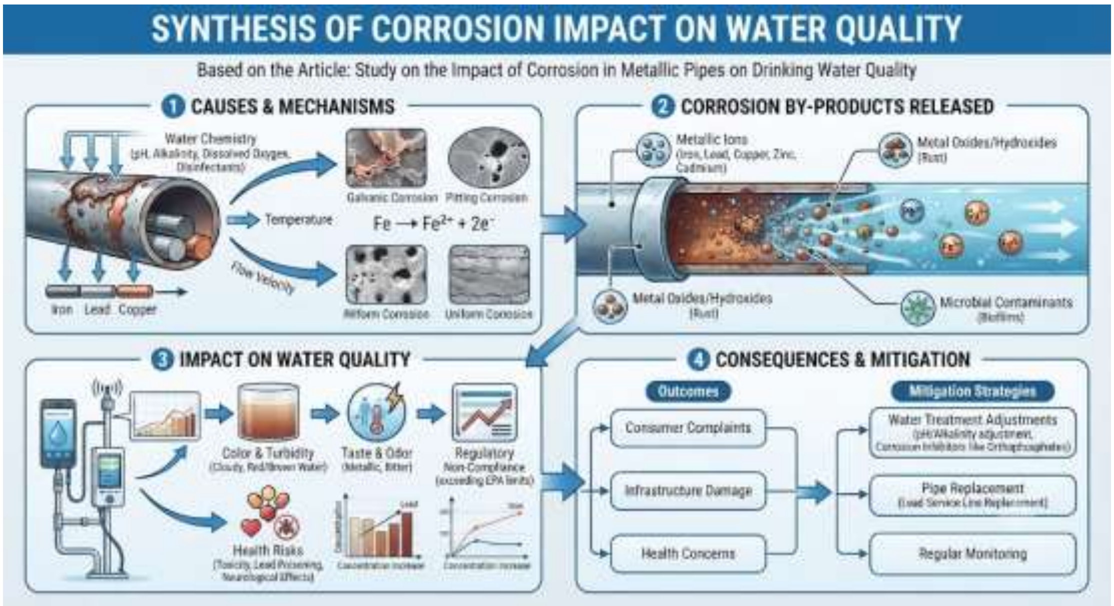

Figure 9: Synthesis of corrosion impact on water quality.

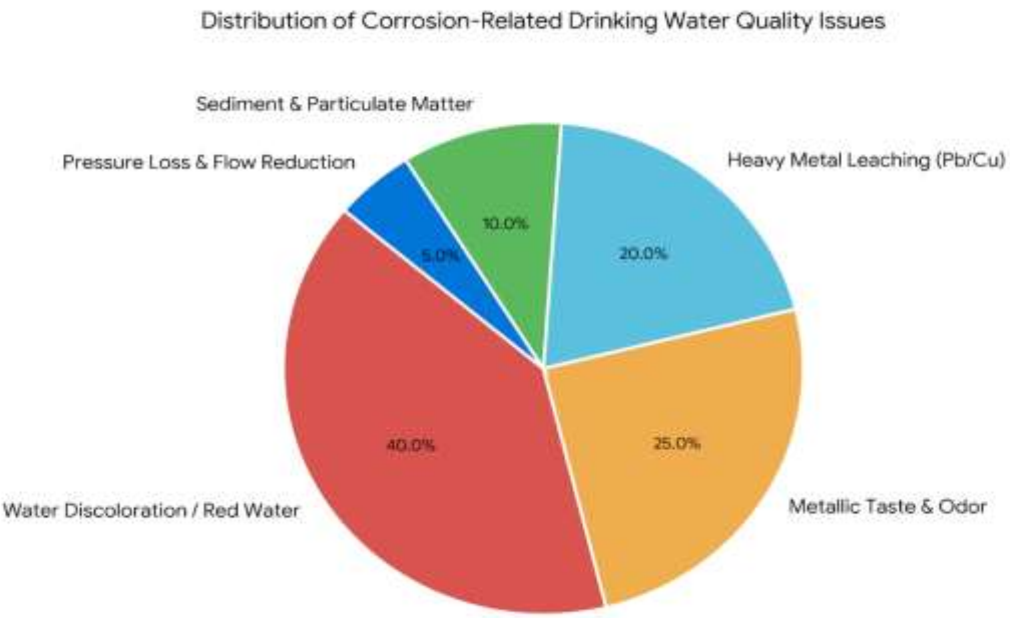

Figure 10: Distribution of corrosion-related drinking water quality issue

Table I summarizes the key water quality impacts associated with different types of pipe corrosion.

TABLE I Water Quality Impacts Of Metallic Pipe Corrosion

Pipe Material	Primary Corrosion Products	Water Quality Impacts	Health Concerns
Cast/Ductile Iron	Fe oxides/hydroxides	Red water, turbidity, metallic taste	Iron overload (rare)
Copper	CuO, Cu_2O	Blue-green staining, metallic taste	Gastrointestinal effects, Wilson's disease risk
Lead	Pb carbonates/oxides	No immediate aesthetic indicators	Neurodevelopmental effects, cardiovascular disease
Galvanized Steel	Zn, Fe compounds	Rust-colored water, turbidity	Zinc toxicity (rare)
Stainless Steel	Cr, Fe, Ni compounds	Minimal aesthetic impacts	Allergic reactions (Ni)

B. Geographic Variability in Corrosion Risk

Case studies from different regions reveal substantial geographic variability in corrosion risk, primarily driven by source water quality and infrastructure age. In Iran, water entering rural distribution networks was found to be highly corrosive based on LSI, RSI, and PSI indices. In Morocco, water samples showed corrosive tendencies ranging from 13% to 97% depending on the index used. In Pakistan, metal pipes in urban areas showed lead concentrations exceeding WHO guidelines by an order of magnitude.

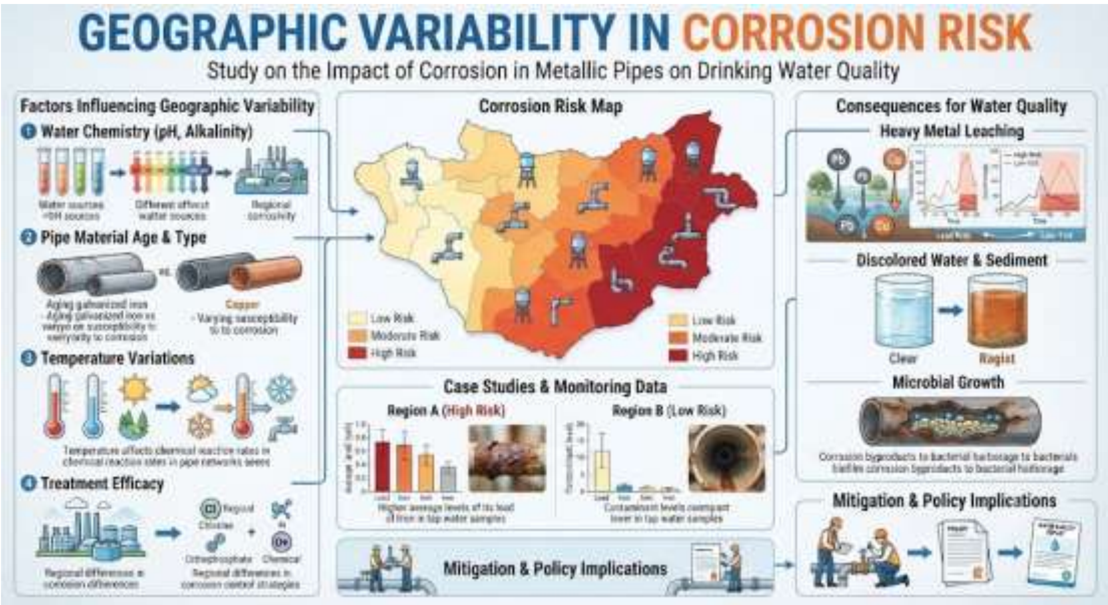

Figure 11: Geographic variability in corrosion risk

This variability underscores the importance of localized corrosion assessment and tailored control strategies rather than universal approaches.

C. Temporal Dynamics of Corrosion

Corrosion is not a static process but exhibits temporal dynamics at multiple scales. Seasonal temperature variations affect corrosion rates. The initial stages of pipe corrosion involve rapid metal release until protective scales form.

Long-term corrosion leads to scale accumulation and eventual destabilization. Understanding these temporal dynamics is essential for effective corrosion management.

D. Effectiveness of Corrosion Control Measures

The reviewed studies indicate that corrosion control measures can be highly effective when properly implemented. Phosphate-based inhibitors achieve corrosion rate reductions of 37-66% depending on pipe material. pH and alkalinity adjustment, when optimized for local water chemistry, can promote protective scale formation. However, the effectiveness of these measures depends on careful monitoring and adjustment, as water quality changes can destabilize previously stable corrosion scales.

E. Knowledge Gaps and Research Needs

Several gaps in current knowledge have been identified:

1. Dynamic Modeling: There is a lack of dynamic models addressing corrosion and corrosion scale growth in water pipelines.
2. Microbial Corrosion Mechanisms: The complexity of corrosion processes has not yet allowed a general mechanism for MIC to be established.
3. Scale Composition and Stability: Identifying crystalline minerals using XRD alone is insufficient for predicting the potential of corrosion scales to contaminate potable water.
4. Long-term Effects of Corrosion Inhibitors: The effects of corrosion inhibitors on antibiotic resistance and other unintended consequences require further investigation.

Conclusion And Future Directions

This review has demonstrated that metallic pipe corrosion in drinking water distribution systems poses significant threats to water quality and public health. The electrochemical and microbiologically influenced corrosion processes release heavy metals—including lead, copper, iron, and nickel—into drinking water, while corrosion scale destabilization causes discoloration, turbidity, and microbial contamination. Health risk assessments reveal substantial non-carcinogenic and carcinogenic risks, particularly for children and vulnerable populations.

Effective corrosion management requires a multi-faceted approach integrating: (1) comprehensive water quality monitoring using stability indices and advanced sensing technologies; (2) optimized corrosion control through pH/alkalinity adjustment and phosphate-based inhibitors; (3) targeted infrastructure renewal prioritizing lead and galvanized pipe replacement; and (4) consideration of microbial corrosion mechanisms in system design and operation.

Future research directions should focus on:

- Machine Learning Applications: Developing ML models for predicting corrosion conditions and pipeline performance to enable proactive maintenance.
- Material-Specific MIC Mechanisms: Elucidating how pipe materials and protective linings interact with attached biofilms to drive corrosion.
- Non-Invasive Monitoring: Establishing effluent biomarkers as indicators of pipe wall biofilm dynamics for corrosion risk assessment without excavation.
- Corrosion Scale Geochemistry: Investigating the speciation and bioaccessibility of metals in corrosion scales to better predict health risks.
- Integrated Water Stability Assessment: Developing comprehensive frameworks that address chemical, physical, and biological stability in DWDS.

The challenge of metallic pipe corrosion in drinking water systems is substantial but not insurmountable. Through continued research, technological innovation, and strategic infrastructure investment, water utilities can ensure the delivery of safe, high-quality drinking water to consumers while extending the service life of critical water infrastructure.

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