



## Mechanical and Materials Aspects of Corrosion Protection and Rehabilitation in Buried Pipelines: A Structured Review

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### ABSTRACT

*Buried metallic pipelines lose structural integrity through soil-induced corrosion and interacting mechanical, microbial, and electrochemical processes. This structured narrative review synthesises studies, engineering standards, and reference works on degradation mechanisms, protective coatings, cathodic protection, composite repair, and fitness-for-service assessment. It proposes a conceptual multi-criteria framework for selecting protection and rehabilitation strategies according to pipe material, soil aggressivity, coating adhesion, operating stress, and remaining wall thickness. No method is universally superior across technical, economic, and operational criteria. Polymer coatings combined with cathodic protection are widely applied to new steel pipelines, while fibre-reinforced polymer composite sleeves offer a qualified option for localised wall-loss repair. Integrated coating, electrochemical protection, and inspection-based integrity management appear most suitable for high-consequence pipelines in aggressive soils. The framework is qualitative and not independently validated; practical selection requires site-specific testing, lifecycle cost analysis, and assessment against applicable standards.*

## 1. Introduction

Buried metallic pipelines are critical load-bearing structures that transport water, petroleum products, natural gas, and industrial fluids under sustained internal pressure and external soil loading. The global pipeline network represents a major capital asset whose long-term serviceability depends on the preservation of pipe wall thickness, coating integrity, and mechanical properties throughout the design life [1][2]. From a materials engineering perspective, the central challenge is that soil-induced corrosion progressively reduces the effective wall section and may alter the local metallurgical condition of the steel through hydrogen embrittlement, stress-assisted dissolution, or microbiologically accelerated material loss.

Soil is a heterogeneous and electrochemically active medium. Its interaction with buried metallic pipes initiates electrochemical, microbial, and mechanically coupled degradation processes that collectively reduce the structural capacity of the pipe section. Unlike atmospheric corrosion, soil corrosion is difficult to detect during routine operation and may remain latent until wall loss reaches a critical fraction of the nominal thickness or an in-line inspection (ILI) campaign reveals it. The consequences of undetected degradation include through-wall penetration, leak-before-break scenarios, and in severe cases, ductile or brittle fracture under operating pressure [3][4].

The mechanisms of soil corrosion are closely linked to the electrochemical properties of the pipe material including its carbon content, microstructure, yield

strength, and surface condition as well as to soil physical chemistry, hydrology, and microbiological communities. Key environmental drivers include soil pH, moisture content, chloride and sulphate ion concentrations, dissolved oxygen levels, electrical resistivity, redox potential, and the activity of sulphate-reducing bacteria (SRB) [5][6].

Corrosion protection has evolved from rudimentary coal-tar wrappings to sophisticated multi-barrier systems that integrate high-performance polymer coatings, impressed current cathodic protection (ICCP), and fibre-reinforced composite rehabilitation sleeves. These developments draw on advances in polymer science, electrochemistry, composite mechanics, and non-destructive evaluation (NDE) [3][7]. Despite the wide palette of available technologies, the central engineering challenge is selecting the most appropriate protection or rehabilitation method for a given combination of pipe material grade, soil aggressivity, operating stress, and remaining service life.

Existing reviews [3][8][9] provide valuable overviews of individual corrosion mechanisms or protection technologies, but do not offer an integrated, multi-criteria framework that combines materials performance data with mechanical integrity considerations in a structured manner. This gap is particularly significant for practising engineers who must balance corrosion-control effectiveness against mechanical strength retention, coating-steel adhesion, and residual life assessment. Table 1 positions the present review against four recent related reviews, illustrating the aspects covered and the principal contribution of the current work.

Accordingly, this article aims to: (i) review the principal mechanisms of soil-induced material degradation in buried metallic pipelines; (ii) assess the materials science and mechanical performance of current protection methods, including coatings, cathodic protection, and encasement; (iii) evaluate rehabilitation options with emphasis on the structural mechanics of composite sleeve repair and fitness-for-service assessment; (iv) propose a conceptual multi-criteria framework for comparing methods under project-specific material and operational constraints; and (v) identify priority research gaps in materials characterization, mechanical testing, and predictive modelling.

Table 1. Comparison of the present review with selected related reviews. ✓ = addressed; ○ = partially addressed; – = not addressed.

| Review                    | Scope and coverage                                                                                                                                                                                                                                                                 |
|---------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Wasim & Djukic (2022) [3] | <b>Focus:</b> Failure mechanisms & prevention<br><b>Materials science:</b> ○<br><b>Mechanical integrity:</b> –<br><b>Rehabilitation:</b> –<br><b>Decision framework:</b> –<br><b>Fitness-for-service assessment:</b> –<br><b>Principal limitation:</b> No decision tool; no rehab. |

| Review                   | Scope and coverage                                                                                                                                                                                                                                                                                                      |
|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Jamil & Ahmad (2020) [8] | <b>Focus:</b> Mechanisms & mitigation<br><b>Materials science:</b> ○<br><b>Mechanical integrity:</b> –<br><b>Rehabilitation:</b> ○<br><b>Decision framework:</b> –<br><b>Fitness-for-service assessment:</b> –<br><b>Principal limitation:</b> No mechanical integrity perspective                                      |
| El-Sherik (2017) [9]     | <b>Focus:</b> Oil & gas corrosion trends<br><b>Materials science:</b> ✓<br><b>Mechanical integrity:</b> ○<br><b>Rehabilitation:</b> ○<br><b>Decision framework:</b> –<br><b>Fitness-for-service assessment:</b> –<br><b>Principal limitation:</b> No multi-criteria framework                                           |
| Nayak & Singh (2023) [4] | <b>Focus:</b> SCC & CP management<br><b>Materials science:</b> ✓<br><b>Mechanical integrity:</b> ○<br><b>Rehabilitation:</b> –<br><b>Decision framework:</b> –<br><b>Fitness-for-service assessment:</b> ○<br><b>Principal limitation:</b> Narrow scope: SCC and CP only                                                |
| Present review           | <b>Focus:</b> Mechanisms, coatings, CP, composite repair, FFS<br><b>Materials science:</b> ✓<br><b>Mechanical integrity:</b> ✓<br><b>Rehabilitation:</b> ✓<br><b>Decision framework:</b> ✓<br><b>Fitness-for-service assessment:</b> ✓<br><b>Principal limitation:</b> Framework is conceptual; not yet field-validated |

## 2. Review Scope and Methodology

This article is a structured narrative review rather than a systematic review or meta-analysis. The following subsections describe the literature-search procedure, the rationale for selecting a narrative approach, and the principal limitations of the methodology adopted.

### 2.1 Literature Search Procedure

The literature search was conducted in three electronic databases: Scopus (Elsevier), Web of Science Core Collection (Clarivate), and Engineering Village (Compendex and Inspec). The search covered publications from January 2000 to December 2024, executed between January and March 2025. Search queries combined terms from three conceptual blocks: (i) the asset: buried pipeline, underground pipeline, buried metallic pipe; (ii) the degradation phenomenon: soil corrosion, external corrosion, cathodic disbondment, microbiologically influenced corrosion, stress corrosion cracking, galvanic corrosion, stray current; and (iii) the intervention: cathodic protection, fusion-bonded epoxy, pipeline coating, composite sleeve repair, CIPP, fitness-for-service, pipeline rehabilitation. Boolean operators

(AND, OR) and proximity operators were used to balance recall and precision.

The initial database search returned approximately 1,240 records. After de-duplication, approximately 950 unique records were identified. Title and abstract screening excluded approximately 750 records outside the scope criteria. Full-text review of approximately 200 records resulted in exclusion of a further 140 records for insufficient methodological detail, exclusive focus on internal corrosion, or unavailable full text. Approximately 60 primary studies, supplemented by authoritative engineering standards and reference handbooks, formed the final evidence base. Screening was carried out by two of the authors; disagreements were resolved by discussion.

## 2.2 Justification of the Narrative Review Approach and Scope Boundaries

A structured narrative review was selected for three principal reasons. First, the evidence base is methodologically heterogeneous, spanning electrochemical laboratory experiments, field case studies, finite element simulations, composite mechanics qualification tests, lifecycle cost models, and engineering standards; such diversity precludes quantitative pooling or meta-analytic synthesis. Second, the review integrates knowledge across multiple sub-disciplines: materials science, electrochemistry, composite mechanics, structural integrity, and multi-criteria decision-making, which a protocol-driven systematic review would not readily accommodate. Third, the proposed decision-support framework is explicitly conceptual, making narrative synthesis the most appropriate vehicle for its development. To minimise selection bias, the search was conducted across three databases with explicit search strings, inclusion and exclusion criteria were applied consistently by two authors, and the synthesis was organised against pre-specified sub-topics corresponding to the review objectives.

This article is a structured narrative review rather than a systematic review or meta-analysis. It synthesises selected peer-reviewed studies, engineering standards, and reference works relevant to the materials science and mechanical engineering aspects of external soil-induced corrosion, protection, and rehabilitation of buried metallic pipelines.

The scope is limited primarily to buried or underground metallic pipelines: carbon steel, high-strength low-alloy (HSLA) pipeline steels (API 5L grades), ductile iron, and cast iron used for water, hydrocarbons, natural gas, and industrial fluids. Studies dealing exclusively with internal corrosion, above-ground atmospheric corrosion, subsea immersion, or non-metallic pipe failure are considered only where they provide transferable context for material selection, rehabilitation design, or structural integrity assessment.

## 2.3 Limitations of This Review

The principal limitations of this review are as follows. (i) Database coverage: three major databases were searched; grey literature and non-English publications were not systematically retrieved. (ii) Selection bias: the narrative approach introduces some risk of subjective selection; two screeners were used to mitigate this. (iii) Material and environmental variability: findings from one context may not transfer directly to another. (iv) Experimental heterogeneity: differences in test methods and reporting conventions make direct quantitative comparisons unreliable. (v) Absence of quantitative meta-analysis: no attempt was made to pool numerical performance data. (vi) Limited long-term field validation: many cited laboratory results have not been confirmed by field performance data extending beyond 10 years, particularly for nano-modified coatings and advanced composite repair systems.

## 2.4 Decision Framework: Scoring Basis and Transparency

The conceptual decision-support framework in Section 8.3 uses a three-level qualitative scale (High, Medium, Low) for six criteria. Ratings were assigned by: (a) examining the relevant subset of screened literature for each method–criterion combination; (b) mapping qualitative descriptors from the cited studies to the three-level scale; (c) using the central tendency across available studies; and (d) assigning a conservative middle rating where evidence was sparse or contradictory. Scale definition: ‘High’ = performance characterised as favourable or superior by the majority of reviewed sources; ‘Medium’ = moderate or context-dependent performance; ‘Low’ = unfavourable or significantly constrained performance. These ratings are qualitative judgements and should not be interpreted as measured performance data. Future work should recalibrate the framework using site-specific quantitative data, expert elicitation, or a formal MCDA method such as AHP or TOPSIS.

The decision-support framework is presented as a conceptual synthesis tool. Its criteria and illustrative rankings are intended to structure engineering judgement rather than provide validated performance predictions. Practical application should be supported by site-specific material testing, soil characterization data, inspection results, fitness-for-service assessment (e.g. per API 579-1/ASME FFS-1), and, where possible, formal multi-criteria decision methods such as AHP or TOPSIS.

### 3. Material Degradation Mechanisms in Buried Pipelines

#### 3.1 Electrochemical Corrosion and Anodic Dissolution

The predominant mechanism governing soil corrosion of metallic pipelines is electrochemical in nature. When a buried steel pipe contacts a moist soil electrolyte, spontaneous galvanic cells form between anodic and cathodic regions. At anodic sites, iron dissolution proceeds as:  $\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$ , resulting in progressive wall thinning. At cathodic sites in aerobic conditions, oxygen reduction proceeds as:  $\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^-$ . In anaerobic conditions, hydrogen evolution becomes the dominant cathodic reaction:  $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$ . The resulting metal loss reduces the effective wall thickness and, consequently, the hoop stress capacity of the pipe section [6].

#### 3.2 Microbiologically Influenced Corrosion (MIC) as a Material Degradation Process

MIC is a significant degradation mechanism in which the metabolic products of soil microorganisms, principally sulphate-reducing bacteria (SRB) of the genera *Desulfovibrio* and *Desulfotomaculum*, alter the local electrochemical environment at the steel surface and accelerate material loss [10]. From a materials perspective, SRB generate hydrogen sulphide ( $\text{H}_2\text{S}$ ), which acts as both a cathodic depolariser and a source of atomic hydrogen. The latter can diffuse into the steel lattice, accumulate at microstructural trap sites (grain boundaries, inclusions, dislocation tangles), and promote hydrogen-induced cracking (HIC) or sulphide stress cracking (SSC) in susceptible steel grades [11][10]. The corrosion product morphology under MIC conditions, typically a layered iron sulphide scale with poor adhesion, differs fundamentally from the magnetite films formed under purely abiotic conditions and offers negligible protective barrier function [3].

#### 3.3 Stray Current Corrosion

Stray currents, unintended electrical currents flowing through soil and metallic structures, constitute a significant corrosion hazard, particularly in urban environments near DC traction systems, adjacent cathodic protection installations, or high-voltage DC transmission lines. Where stray current exits a pipeline, anodic dissolution occurs at rates that can substantially exceed natural soil corrosion rates, sometimes exceeding 1 mm/yr of wall loss [5][8]. The resulting defect geometry is typically a broad, shallow groove aligned with the current exit path, which creates a stress concentration under internal pressure loading.

#### 3.4 Galvanic Corrosion at Dissimilar Metal Junctions

Galvanic corrosion arises when dissimilar metals are in electrical contact within a common electrolyte. In buried pipeline systems, galvanic couples form at connections between carbon steel pipe and copper service fittings, cast iron and ductile iron junctions, or where new higher-grade steel pipelines adjoin existing corroded infrastructure. The magnitude of galvanic corrosion is governed by the difference in open-circuit potentials, the cathode-to-anode area ratio, and the soil electrolyte conductivity [6]. Isolation joints and dielectric flange kits are standard measures to interrupt the galvanic circuit.

#### 3.5 Stress Corrosion Cracking (SCC) and Environmentally Assisted Fracture

Stress corrosion cracking (SCC) is an environmentally assisted subcritical fracture mechanism requiring the simultaneous presence of a susceptible material, a specific corrosive environment, and sustained tensile stress. In high-pressure gas transmission pipelines fabricated from API 5L X52–X80 steels, two distinct SCC forms are recognised: near-neutral pH SCC (transgranular, associated with dissolved  $\text{CO}_2$  in dilute groundwater at coating disbondment sites) and high-pH SCC (intergranular, associated with concentrated carbonate–bicarbonate solutions at temperatures above approximately 40 °C) [12][4].

From a fracture mechanics perspective, SCC initiation occurs when the local stress intensity factor at a surface flaw exceeds the threshold stress intensity for SCC ( $K_{\text{ISCC}}$ ) in the given environment. Crack propagation then proceeds at a rate governed by the material's susceptibility (yield strength, microstructure, hydrogen trapping characteristics) and the environmental severity (pH, potential, temperature). The practical consequence is that SCC can lead to catastrophic rupture in pipelines with no prior measurable wall loss detected by conventional metal-loss ILI tools, because the crack dimensions may remain below the detection threshold of magnetic flux leakage (MFL) inspection until a late stage of growth [12][4].

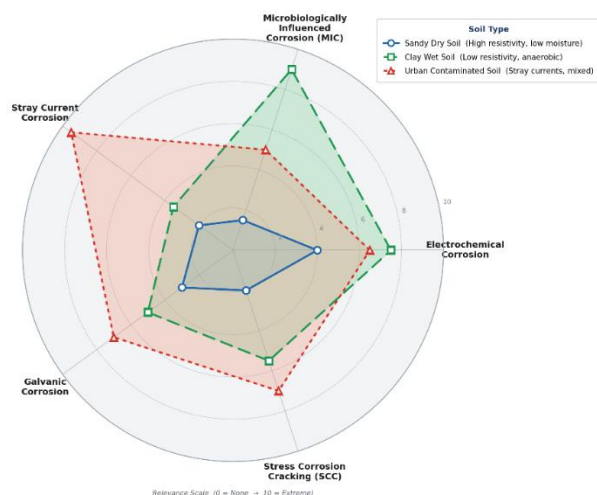


**Figure 1.** Conceptual overview of the relative relevance of selected material degradation mechanisms across representative soil conditions. The figure is an author-generated conceptual synthesis based on the reviewed literature; the relative positions are illustrative and are not derived from quantitative measurement. See Section 2.4 for the scoring basis.

## 4. Key Environmental Factors Affecting Material Performance

### 4.1 Soil pH and Oxide Film Stability

Soil pH is one of the most important environmental determinants of corrosion aggressivity because it directly affects the thermodynamic stability of protective oxide films on the pipe surface [13][14]. Strongly acidic soils ( $\text{pH} < 4.5$ ) dissolve the passive magnetite ( $\text{Fe}_3\text{O}_4$ ) and ferric oxyhydroxide films that provide a degree of natural protection to carbon steel, promoting active anodic dissolution and accelerated wall thinning. The least aggressive zone lies between  $\text{pH}$  6.0 and 8.0. Strongly alkaline soils ( $\text{pH} > 9.5$ ) can promote high-pH SCC in susceptible pipeline steels under cathodic protection, particularly where concentrated carbonate–bicarbonate solutions accumulate beneath disbonded coatings [6].

### 4.2 Soil Moisture and Oxygen Transport

Moisture content governs both the conductivity of the soil electrolyte and the rate of oxygen transport to the metal surface [13]. Corrosion rates are negligible in completely dry soils (resistivity  $> 100,000 \Omega \cdot \text{cm}$ ) and reach their maximum in partially saturated conditions (30–80 % water-holding capacity), where both adequate electrolyte conductivity and cathodic oxygen supply co-exist. In fully waterlogged soils, oxygen depletion suppresses the cathodic reaction and shifts the dominant degradation mechanism towards anaerobic processes, including MIC [10].

## 4.3 Electrical Resistivity

Soil electrical resistivity is the primary field screening parameter for corrosion aggressivity. NACE SP0169-2019 classifies soils with resistivity  $< 500 \Omega \cdot \text{cm}$  as severely corrosive,  $500\text{--}2,000 \Omega \cdot \text{cm}$  as corrosive,  $2,000\text{--}10,000 \Omega \cdot \text{cm}$  as moderately corrosive, and  $> 10,000 \Omega \cdot \text{cm}$  as mildly corrosive [15]. Low resistivity correlates with high ionic strength and elevated corrosion current density at the pipe surface [5].

## 4.4 Chloride and Sulphate Ion Effects on Pitting and MIC

Chloride ions destabilise passive films and promote localised pitting corrosion, a morphology that concentrates wall loss into small areas, creating stress-raising defects disproportionate to the total volume of metal removed [11]. Sulphate ions serve as electron acceptors for SRB metabolism and contribute to the formation of poorly adherent iron sulphide corrosion products [11].

## 4.5 Redox Potential and Anaerobic Conditions

Soil redox potential ( $E_h$ ) determines whether conditions favour aerobic or anaerobic degradation pathways. Soils with  $E_h < -100 \text{ mV}$  (vs. SHE) are strongly anaerobic and create favourable conditions for SRB-mediated material loss and hydrogen generation [5].

## 4.6 Temperature Effects on Reaction Kinetics and Mechanical Properties

Soil temperature influences corrosion kinetics following an Arrhenius-type relationship, with rates generally increasing up to approximately  $60^\circ\text{C}$ . In addition, elevated pipe operating temperatures above the glass transition temperature ( $T_g$ ) of FBE coatings (typically  $90\text{--}110^\circ\text{C}$ ) can reduce coating adhesion and barrier performance. Freeze–thaw cycling in cold climates imposes cyclic mechanical stresses at the pipe–coating–soil interface, promoting disbondment and fatigue-assisted coating failure [6].

## 5. Corrosion Protection Methods: Materials and Mechanical Considerations

### 5.1 Protective Coating Systems

**5.1.1 Fusion-Bonded Epoxy (FBE) Coatings.** Fusion-bonded epoxy (FBE) coatings are the most widely specified primary corrosion barrier for new buried steel pipelines [16][14]. FBE is a thermosetting polymer applied to grit-blasted steel surfaces (surface profile  $\text{Sa } 2\frac{1}{2}$  per ISO 8501-1) at substrate temperatures of  $220\text{--}260^\circ\text{C}$ , producing a crosslinked epoxy matrix with strong adhesion to the steel substrate through mechanical

interlocking and chemical bonding with the oxide layer. Mono-layer FBE typically achieves a dry film thickness of 400–600  $\mu\text{m}$ . The material properties of cured FBE relevant to pipeline service include glass transition temperature ( $T_g \approx 90\text{--}110^\circ\text{C}$ ), water absorption rate, dielectric strength, and cathodic disbondment resistance [17].

The principal material failure mode of FBE coatings is cathodic disbondment (CD), an electroosmotic loss of adhesion at the coating–steel interface driven by alkaline conditions generated by cathodic protection current at coating defects. CD propagation rate depends on coating crosslink density, steel surface preparation quality, soil moisture, temperature, and applied CP potential. Research into nano-silica and nanoclay-modified FBE formulations has shown improvements in CD resistance and thermal stability in laboratory evaluations; however, long-term field performance data remain limited [16][14].

### **5.1.2 Three-Layer Polyolefin Systems (3LPE/3LPP).**

Three-layer polyethylene (3LPE) and three-layer polypropylene (3LPP) systems combine an FBE primer, a copolymer adhesive interlayer, and an outer polyolefin jacket. This multi-layer architecture provides both the corrosion barrier function of FBE and the mechanical impact and abrasion resistance of the polyolefin during handling, transportation, and installation. 3LPE is specified for operating temperatures up to approximately  $80^\circ\text{C}$ , while 3LPP extends this to approximately  $140^\circ\text{C}$  [9][17]. Cold-applied polyethylene tape wrapping systems (AWWA C214, EN 12068) and bituminous coatings remain in service as legacy technologies but are susceptible to soil stress disbondment and moisture ingress at spiral seams [9].

## **5.2 Cathodic Protection (CP) and Electrochemical Considerations**

### **5.2.1 Impressed Current Cathodic Protection (ICCP).**

ICCP applies an external DC current through inert or semi-consumable anodes (mixed metal oxide coated titanium, high-silicon cast iron) to polarise the pipeline to a potential at which anodic dissolution is thermodynamically suppressed [18][19]. The protection criterion in NACE SP0169-2019 is a pipe-to-soil potential of  $-0.85\text{ V}$  (instant-off) vs.  $\text{Cu}/\text{CuSO}_4$  for aerobic conditions, with  $-0.95\text{ V}$  recommended in anaerobic or MIC-susceptible environments [15]. The statement that ICCP provides high corrosion-control efficacy is qualified: this holds when the system is correctly designed, powered, and maintained, and when the protection potential remains within the recommended window. Over-protection (potentials more negative than approximately  $-1.2\text{ V}$ ) generates hydrogen at the steel surface, which can promote coating disbondment and hydrogen embrittlement of high-strength steel grades (X70 and above) [18].

### **5.2.2 Sacrificial Anode Cathodic Protection (SACP).**

SACP exploits the galvanic potential difference between the pipeline steel and a more electronegative anode alloy, typically zinc, magnesium, or aluminium, to provide protection current without external power. Anode material selection is governed by soil resistivity, required current output, and the anode consumption rate (typically  $4\text{--}5\text{ kg/A}\cdot\text{yr}$  for magnesium in soil). SACP is preferred for shorter pipeline sections, isolated structures, or locations where power supply is impractical [18][20][15].

## **5.3 Chemical Inhibitors (Adjunctive Measures)**

Chemical corrosion inhibitors are noted here briefly as adjunctive measures. They are primarily deployed for internal corrosion control via injection into the transported product and are therefore outside the primary scope of this review on external soil-induced degradation. Their relevance to external corrosion is limited to soil-applied inhibitor compounds in backfill material, which have seen only limited adoption [16][21][22].

## **5.4 Polyethylene Encasement**

Polyethylene encasement (ANSI/AWWA C105, ISO 8180) provides passive protection for ductile iron and cast iron water mains by limiting direct electrolyte contact and suppressing differential aeration cells. Field studies have documented substantially lower corrosion rates for encased pipelines relative to bare pipe in comparable soils [19].

## **5.5 Monitoring, Inspection, and Material Condition Assessment**

The principal monitoring and inspection technologies applicable to buried pipelines include: close-interval potential surveys (CIPS) for evaluating CP effectiveness; direct current voltage gradient (DCVG) surveys for locating coating defects; and in-line inspection (ILI) using magnetic flux leakage (MFL) for metal-loss sizing or ultrasonic testing (UT) for wall thickness measurement and crack detection. MFL-based ILI provides a probabilistic estimate of remaining wall thickness at each reported anomaly, which feeds directly into fitness-for-service (FFS) assessment per API 579-1/ASME FFS-1. Emerging applications of machine-learning algorithms to ILI data for automated defect classification and corrosion growth rate prediction represent an active area of development [7].

Table 2. Qualitative comparison of selected buried-pipeline corrosion protection and rehabilitation methods across the framework criteria. Ratings are qualitative judgements derived from the procedure in Section 2.4 and should not be interpreted as measured performance data. Scale: High = performance characterised as favourable or superior by the majority of reviewed sources; Medium = moderate or context-dependent performance; Low = unfavourable or significantly constrained performance.

| Method                  | Qualitative assessment                                                                                                                                                                                                                                   |
|-------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| FBE Coating             | <b>Corrosion efficacy:</b> High<br><b>Cost efficiency:</b> Medium<br><b>Durability:</b> High<br><b>Environmental impact:</b> Medium<br><b>Maintenance:</b> Medium<br><b>Site applicability:</b> Suitable for new pipelines                               |
| ICCP                    | <b>Corrosion efficacy:</b> High<br><b>Cost efficiency:</b> Low (power-dependent)<br><b>Durability:</b> High<br><b>Environmental impact:</b> Medium<br><b>Maintenance:</b> Low (skilled monitoring)<br><b>Site applicability:</b> Suitable for long lines |
| SACP                    | <b>Corrosion efficacy:</b> Medium–High<br><b>Cost efficiency:</b> Medium<br><b>Durability:</b> Medium<br><b>Environmental impact:</b> Medium<br><b>Maintenance:</b> Medium<br><b>Site applicability:</b> Suitable for remote, short sections             |
| PE encasement           | <b>Corrosion efficacy:</b> Medium<br><b>Cost efficiency:</b> High (low cost)<br><b>Durability:</b> Medium<br><b>Environmental impact:</b> Medium–High<br><b>Maintenance:</b> High (passive)<br><b>Site applicability:</b> Suitable for DI/CI water mains |
| Composite sleeve repair | <b>Corrosion efficacy:</b> High (localised)<br><b>Cost efficiency:</b> Medium<br><b>Durability:</b> Medium–High<br><b>Environmental impact:</b> Medium<br><b>Maintenance:</b> Medium<br><b>Site applicability:</b> Defect geometry constraints           |
| Full replacement        | <b>Corrosion efficacy:</b> High<br><b>Cost efficiency:</b> Low (high CAPEX)<br><b>Durability:</b> High<br><b>Environmental impact:</b> Low<br><b>Maintenance:</b> High (new asset)<br><b>Site applicability:</b> When repair not viable                  |

## 6. Damage Assessment and Structural Rehabilitation of Corroded Buried Pipelines

Note on organisation: This section covers the damage assessment and structural rehabilitation stages of the corrosion management hierarchy: fitness-for-service assessment, composite sleeve repair, CIPP, and full replacement. Corrosion prevention and control are addressed in Section 5.

### 6.1 Engineering Decision Chain: From Corrosion Damage to Rehabilitation

Connecting corrosion damage to rehabilitation requirements follows a sequential engineering assessment chain: (i) corrosion morphology characterisation, whether uniform wall loss, localised pitting, or crack-like SCC, determines the applicable fitness-for-service (FFS) assessment method; (ii) remaining wall thickness ( $t_{rem}$ ) relative to nominal thickness ( $t_{nom}$ ) determines the hoop stress capacity at MAOP; (iii) stress concentration at the defect boundary amplifies the nominal hoop stress by  $K_t$ , dependent on pit aspect ratio; (iv) remaining strength expressed as predicted failure pressure ( $P_f$ ) per modified ASME B31G, RSTRENG, or API 579-1 determines whether the pipeline can operate at MAOP with an acceptable safety factor (typically 1.25–1.40); and (v) if  $P_f/MAOP$  falls below the applicable safety factor, rehabilitation or replacement is required [23].

For general or local metal-loss defects,  $P_f$  is governed primarily by  $t_{rem}$ ; for SCC,  $P_f$  is governed by crack depth and length, assessed using Level 3 fracture mechanics methods per API 579-1 Appendix D. Composite sleeve repair restores  $P_f$  by providing circumferential load sharing; full replacement restores the full nominal wall capacity. Method selection therefore depends on defect type, morphology, severity, and the required post-repair safety margin.

### 6.2 Fibre-Reinforced Polymer (FRP) Composite Sleeve Repair

FRP composite sleeve repair systems are the principal non-intrusive structural rehabilitation technology for in-service corroded pipelines. Qualified to ASME PCC-2 Article 4.1 and ISO 24817, these systems restore the burst pressure capacity of corroded pipe sections by providing external circumferential reinforcement that transfers hoop stress from the weakened steel wall to the composite wrap [23][24]. The composite typically comprises high-modulus carbon fibre (CFRP), E-glass fibre (GFRP), or aramid fibre in an epoxy, vinyl ester, or cyanate ester resin matrix.

The structural design of a composite repair requires calculation of the minimum composite thickness to compensate for the measured wall loss, taking into account the hoop stress at the maximum allowable operating pressure (MAOP), the tensile modulus and strain-to-failure of the composite laminate, and the shear transfer capacity of the adhesive bond at the steel–composite interface [25][24]. Long-term performance is governed by the durability of the adhesive bond under sustained loading, moisture ingress, and potential microbiological attack of the resin matrix. Qualification testing per ISO 24817 and ASME PCC-2 includes short-term burst testing, long-term survival testing (typically 1,000 h at elevated temperature and pressure), and impact resistance evaluation [23][24]. The structural

mechanics involves several key elements: (i) Fibre orientation and laminate architecture: circumferential (hoop) fibre layers are the primary load-carrying plies; CFRP laminates ( $E \approx 120\text{--}150$  GPa) are stiffer than GFRP ( $E \approx 40\text{--}70$  GPa), enabling thinner sleeves for equivalent stiffness. (ii) Adhesive and interface behaviour: the filler must transfer shear load across the defect zone; inadequate adhesive application is a principal field failure mode [23]. (iii) Creep and fatigue: composite laminates under sustained hoop loading exhibit viscoelastic creep, particularly in GFRP/vinyl ester systems above  $40^\circ\text{C}$ ; ISO 24817 requires a 1,000-h hydrostatic test at  $1.5 \times \text{MAOP}$  to characterise creep-rupture behaviour [24]. (iv) Environmental and temperature effects: moisture absorption reduces interlaminar shear strength and  $T_g$  over service life; qualification testing must be conducted at the maximum operating temperature [24].

### 6.3 Cured-in-Place Pipe (CIPP) Lining

Cured-in-place pipe (CIPP) lining is a trenchless rehabilitation technology in which a resin-impregnated flexible liner is inverted into the host pipe and cured thermally or by UV light to form a structural liner. The cured liner acts as a load-bearing structural member that restores the hoop strength and eliminates leakage. CIPP is applicable to gravity sewers, pressure water mains, and gas distribution mains [26].

### 6.4 Full Pipeline Replacement

When the remaining wall thickness is insufficient to support the operating pressure with an acceptable safety margin, as determined by fitness-for-service assessment per API 579-1/ASME FFS-1 or equivalent [23], full replacement is the only reliable long-term solution. Pipe bursting is a trenchless technique that fractures the existing pipe while pulling in a new HDPE or PVC pipe. The lifecycle economics of replacement versus repair must be evaluated on a net present value (NPV) basis incorporating failure probability, consequence, and residual strength modelling [27].

## 7. Representative Study Synthesis

Table 3 summarises a selection of cited studies that illustrate the range of pipeline materials, soil conditions, protection strategies, and rehabilitation contexts discussed in this review. The table is representative rather than exhaustive.

Table 3. Selected cited studies on underground pipeline corrosion protection and rehabilitation. Data are drawn directly from the cited publications; no unverified numerical claims are included.

| Study                         | Study evidence                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Wasim & Djukic (2022) [3]     | <b>Pipe material:</b> Carbon steel; ductile iron<br><b>Soil conditions:</b> Varied (review)<br><b>Method:</b> Review of degradation mechanisms<br><b>Key findings:</b> MIC by SRB identified as significant material loss driver in anaerobic soils; multiple mechanisms interact synergistically<br><b>Limitations:</b> No quantitative decision tool<br><b>Framework criterion:</b> Efficacy; Applicability                                                     |
| Alexander & Worth (2006) [25] | <b>Pipe material:</b> API 5L steel gas pipe<br><b>Soil conditions:</b> Mixed terrain (external defect)<br><b>Method:</b> CFRP composite sleeve per ISO 24817<br><b>Key findings:</b> Full pressure containment restored; multi-decade design life demonstrated in qualification testing<br><b>Limitations:</b> Limited to localised defects; requires FFS assessment<br><b>Framework criterion:</b> Structural integrity; Efficacy                                |
| Nayak & Singh (2023) [4]      | <b>Pipe material:</b> API 5L X65 gas pipeline<br><b>Soil conditions:</b> Near-neutral pH; carbonate soil<br><b>Method:</b> CP potential management for SCC prevention<br><b>Key findings:</b> Controlled CP potential window reduces SCC initiation in susceptible steel grades<br><b>Limitations:</b> Requires precise CP tuning and knowledge of steel SCC susceptibility<br><b>Framework criterion:</b> Efficacy; Maintenance                                  |
| Rajani & Kleiner (2004) [27]  | <b>Pipe material:</b> Cast iron water mains<br><b>Soil conditions:</b> Urban; variable<br><b>Method:</b> Lifecycle cost model: replacement vs. repair<br><b>Key findings:</b> Replacement favoured above a breakeven failure rate threshold<br><b>Limitations:</b> Dependent on utility failure records quality<br><b>Framework criterion:</b> Cost efficiency; Maintenance                                                                                       |
| Parkins (2000) [12]           | <b>Pipe material:</b> High-pressure gas pipeline steels<br><b>Soil conditions:</b> Near-neutral and high pH soils<br><b>Method:</b> Review of SCC failure mechanisms<br><b>Key findings:</b> SCC leads to catastrophic fracture with no prior measurable wall loss on conventional MFL ILI<br><b>Limitations:</b> Requires crack-detection ILI and site-specific fracture mechanics assessment<br><b>Framework criterion:</b> Structural integrity; Applicability |
| Papavinasam (2014) [16]       | <b>Pipe material:</b> Carbon steel; multiple grades<br><b>Soil conditions:</b> Various (textbook)<br><b>Method:</b> FBE coating systems<br><b>Key findings:</b> FBE CD resistance and $T_g$ are primary material selection criteria; surface preparation is the strongest predictor of field performance<br><b>Limitations:</b> Lab data; limited long-term field validation<br><b>Framework criterion:</b> Durability; Site applicability                        |

| Study                       | Study evidence                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|-----------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Venzlaff et al. (2013) [11] | <b>Pipe material:</b> Carbon steel<br><b>Soil conditions:</b> Anaerobic; SRB-active<br><b>Method:</b> Electrochemical MIC study<br><b>Key findings:</b> Direct electron uptake by SRB demonstrated; H <sub>2</sub> S generation promotes HIC in susceptible steels<br><b>Limitations:</b> Laboratory study; field MIC rates may differ<br><b>Framework criterion:</b> Efficacy; Material susceptibility                                              |
| ASME PCC-2 (2022) [23]      | <b>Pipe material:</b> All metallic pipelines<br><b>Soil conditions:</b> N/A (standard)<br><b>Method:</b> FRP composite repair qualification<br><b>Key findings:</b> Specifies minimum composite thickness calculation, 1,000-h survival test, burst test requirements<br><b>Limitations:</b> Standard requires site-specific engineering input<br><b>Framework criterion:</b> Structural integrity; Efficacy                                         |
| ISO 24817 (2017) [24]       | <b>Pipe material:</b> All metallic pipelines<br><b>Soil conditions:</b> N/A (standard)<br><b>Method:</b> FRP composite repair design<br><b>Key findings:</b> Provides laminate thickness design, adhesive shear stress assessment, and high-temperature qualification requirements<br><b>Limitations:</b> Qualification data must be specific to the composite system<br><b>Framework criterion:</b> Structural integrity; Durability                |
| Pikas (2006) [7]            | <b>Pipe material:</b> Carbon steel; multiple<br><b>Soil conditions:</b> Various (field)<br><b>Method:</b> ILI monitoring and inspection<br><b>Key findings:</b> CIPS, DCVG, MFL, and UT ILI identified as complementary; MFL detection threshold ~10% wall loss; ILI feeds into FFS assessment<br><b>Limitations:</b> ML/AI enhancement of ILI is emerging and requires standardised datasets<br><b>Framework criterion:</b> Inspection; Maintenance |

## 8. Results and Discussion

### 8.1 Synthesis of Material Degradation Mechanisms

The reviewed literature indicates that material degradation in buried pipelines is rarely governed by a single mechanism. Electrochemical dissolution, MIC-induced material loss and hydrogen generation, coating adhesion failure, and mechanically assisted cracking (SCC, fatigue) may interact synergistically. MIC by SRB may be underestimated when risk assessments rely solely on bulk soil physicochemical parameters rather than on direct microbiological or molecular indicators [3]. From a mechanical integrity perspective, the critical concern is that MIC-induced pitting creates localised stress concentrations that reduce the burst pressure capacity of the pipe section disproportionately to the total volume of metal removed.

Stray current corrosion produces broad, shallow grooves that can be assessed using standard FFS methods

for general or local metal loss (API 579-1, Level 1 or 2 assessment). SCC, by contrast, produces tight, branched cracks that require fracture mechanics-based assessment (API 579-1, Level 3) and are poorly detected by conventional MFL-based ILI [5][8][12].

### 8.2 Performance Comparison of Protection Methods

No single method achieves superiority across all criteria (Table 2). FBE coatings provide a well-balanced barrier for new construction when applied to properly prepared surfaces, but their performance is governed by the crosslink density of the cured resin, the quality of the surface profile, and the avoidance of thermal damage during field joint application. ICCP delivers the highest level of corrosion-control efficacy for long-distance steel pipelines but introduces the risk of hydrogen embrittlement in high-strength grades (X70+) if over-protection occurs [18][19].

Composite sleeve repair is the principal structural rehabilitation option for localised corrosion defects. Its applicability is constrained by the remaining wall thickness (the steel must retain sufficient strength to support the adhesive bond), defect geometry, operating pressure relative to MAOP, and the qualification status of the specific composite system under the applicable standard [25][23][24].

### 8.3 Proposed Conceptual Decision-Support Framework

The proposed framework organises method selection around six criteria: corrosion-control efficacy, cost efficiency, durability, environmental impact, maintenance requirements, and site applicability. The qualitative ratings in Table 2 and Figure 2 were assigned using the procedure described in Section 2.4. These criteria recur across the reviewed literature on coating material performance, cathodic protection electrochemistry, composite repair design, and pipeline structural integrity.

The framework is conceptual rather than validated. No formal Delphi exercise, expert elicitation, AHP weighting, TOPSIS ranking, or statistical meta-analysis was undertaken. The framework should be regarded as a qualitative reasoning scaffold rather than a validated quantitative model. Future work should validate it using site-specific data and a formal MCDA method (AHP, TOPSIS, or Delphi-based expert elicitation), supplemented by sensitivity analysis of criterion weights. Any site-specific application should use measured material properties, soil characterisation data, ILI-derived wall thickness profiles, and FFS assessment results per API 579-1/ASME FFS-1.

The principal project variables that should guide method selection include: pipe material grade and mechanical properties (yield strength, toughness, SCC susceptibility); soil aggressivity (pH, resistivity, Eh, ion chemistry, MIC indicators); coating condition (adhesion, holiday density, disbondment extent); operating stress

level (hoop stress as a fraction of SMYS); remaining wall thickness; design life; access constraints; consequence of failure; and local cost structure.

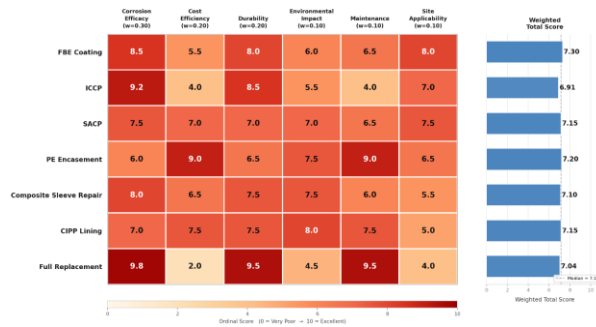


**Figure 2.** Illustrative conceptual decision matrix comparing buried-pipeline protection and rehabilitation options. Scores are ordinal values assigned using the procedure described in Section 2.4; they require project-specific recalibration before practical use. The bar chart uses equal criterion weights for illustration only; site-specific weighting is essential.

## 9. Research Gaps and Future Directions

- Nano-enhanced coating materials: Laboratory evaluations of nano-silica, graphene oxide, and nanoclay-modified FBE have demonstrated improved barrier properties and cathodic disbondment resistance. However, long-term field performance data and accelerated ageing protocols validated against field exposure are needed to qualify these materials for pipeline service.
- Quantitative MIC modelling from a materials perspective: Current risk models treat MIC as a binary factor. Integration of genomic-based SRB quantification with electrochemical modelling and steel-specific hydrogen susceptibility data would enable predictive degradation rate estimation for susceptible steel grades in untested soil environments.
- Machine learning for ILI defect characterisation: Application of convolutional neural networks to MFL and UT inspection data for automated defect classification, corrosion growth rate prediction, and remaining strength estimation is an emerging area requiring standardised training datasets across diverse pipeline materials and defect morphologies [7].
- Optimisation of coating–CP interaction: Few studies have quantified the minimum coating quality threshold (in terms of holiday density and disbondment extent) at which CP current demand remains technically and economically manageable without risking hydrogen embrittlement of the substrate steel.
- Climate change effects on soil aggressivity: Long-term changes in precipitation, groundwater depth, and soil temperature are expected to alter corrosion environments over typical 50-year pipeline design lives. No studies within the reviewed literature quantify projected impacts on material degradation rates.

- Composite repair durability under combined loading: Long-term performance data for FRP composite sleeve repairs under combined sustained pressure, thermal cycling, and soil moisture exposure are limited. Fatigue and creep-rupture testing protocols specific to buried pipeline composite repairs require further development.
- Digital twins for pipeline integrity management: Integration of real-time sensor data, ILI results, and corrosion growth models into digital twin frameworks enables probabilistic remaining-life prediction and optimised inspection interval setting. This area requires further validation against field failure records [32].
- Hydrogen embrittlement of high-strength pipeline steels: The risk of hydrogen embrittlement under ICCP over-protection is recognised but incompletely quantified for X80–X100 pipeline steel grades. Systematic K<sub>ISCC</sub> mapping as a function of steel grade, microstructure, and cathodic potential is a priority research need [4][18].
- Probabilistic remaining-life prediction: Current FFS assessment methods for pipeline corrosion defects are largely deterministic. Integration of ILI measurement uncertainty, corrosion growth rate variability, and failure consequence modelling into probabilistic frameworks would support more rational inspection interval optimisation.

## 10. Conclusions

This review has examined the materials science and mechanical engineering aspects of soil corrosion mechanisms, protection methods, and structural rehabilitation strategies for buried metallic pipelines. The following conclusions are drawn:

- Soil corrosion of buried pipelines is a multifactorial process in which electrochemical dissolution, MIC-driven material loss, hydrogen-assisted degradation, and mechanically coupled cracking mechanisms interact in ways not predictable from any single environmental parameter. Material characterization including steel grade, microstructure, inclusion content, and hydrogen susceptibility is essential for accurate risk assessment.
- No single protection method demonstrates universal superiority across all material performance, economic, and operational criteria. FBE and 3LPE coatings provide effective barriers for new construction when material selection, surface preparation, and application quality are controlled. ICCP delivers the highest corrosion-control efficacy but requires careful potential management to avoid hydrogen embrittlement of high-strength steel grades.
- FRP composite sleeve repair, qualified to ISO 24817 and ASME PCC-2, is the principal structural rehabilitation option for pipelines with localised external corrosion defects. Its design requires fitness-for-service assessment of the remaining steel wall and

qualification testing of the composite–adhesive–steel system under representative service conditions.

- The engineering decision chain from corrosion morphology characterisation through remaining wall thickness assessment, stress concentration analysis, predicted failure pressure calculation, and rehabilitation selection provides a coherent basis for connecting inspection findings to engineering action. Fitness-for-service assessment per API 579-1/ASME FFS-1 is the appropriate quantitative tool for this chain.
- The conceptual decision-support framework proposed in this review is a qualitative reasoning scaffold, not a validated quantitative model. It organises engineering judgement and is not a substitute for site-specific material testing, fitness-for-service assessment per API 579-1/ASME FFS-1, lifecycle cost analysis, or compliance with applicable design standards. Future validation using formal MCDA methods (AHP, TOPSIS, or Delphi-based expert elicitation) and sensitivity analysis is required before the framework can be applied as a quantitative decision tool.
- Priority research needs include long-term field validation of nano-enhanced coating materials, quantitative MIC degradation modelling linked to steel microstructure, machine-learning-based ILI defect characterisation, and durability testing of composite repairs under combined mechanical and environmental loading.

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