Journal Homepage: -www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

Article DOI:10.21474/IJAR01/24469
DOI URL: http://dx.doi.org/10.21474/IJAR01/24469

RESEARCH ARTICLE

CORROSION-RESILIENT UNDERGROUND PIPELINE SYSTEMS IN SAUDI ARABIAN DESERT ENVIRONMENTS: ADVANCED MATERIAL SELECTION, PROTECTIVE DESIGN, AND RISK-BASED INTEGRITY MANAGEMENT

Shafiqur Rehman Shaikh

Manuscript Info

Manuscript History
Received: 14 August 2026
Final Accepted: 16 September 2026
Published: October 2026

Key words:-
buried pipelines; external corrosion; desert soils; Saudi Arabia; sabkha; cathodic protection; pipeline coatings; risk-based inspection; integrity management

Abstract

Underground pipelines in Saudi Arabia cross environments that appear uniformly arid but differ sharply in electrolyte availability, salt accumulation, groundwater exposure and electrical interference. This critical review evaluates how those contrasts affect corrosion initiation, protective design and long-term integrity decisions. Recent peer-reviewed evidence published between 2020 and 2025 is synthesised through four linked themes: ground aggressiveness, pipeline material behaviour, coating–cathodic protection compatibility and risk-based asset management. Particular attention is given to saline coastal sabkha deposits, intermittently wetted inland soils, defects beneath disbonded coatings, hydrogen-related damage and the limitations of uniform corrosion-rate assumptions. The synthesis favours coated carbon steel with demonstrably compatible cathodic protection for many transmissio n applications, while reserving alternative alloys or non metallic system s for explicitly justified service conditions. An integrated decision framework is developed that connects baseline corridor investigation, protective specification, field verification, repeat inspection and uncertainty-informed intervention. The review finds that the decisive engineering variable is not desert location alone, but the interaction of transient wetting, ionic conductivity, coating condition and exposure history. Saudi - specific evidence remains geographically uneven, making local validation, transparent inspection records and adaptable maintenance thresholds essential. The proposed approach provides a technically cautious basis for extending pipeline service life without conflating predictive modelling with demonstrated field performance.

"© 2026 by the Author(s). Published by IJAR under CC BY 4.0. Unrestricted use allowed with credit to the author."

Introduction:-

Saudi Arabia depends upon buried steel networks for transporting energy products and supplying industrial, utility and development corridors. Burial limits accidental contact and surface disruption, yet places the external wall in a concealed and spatially variable electrochemical environment. External metal loss can develop beneath coating holidays, at vulnerable girth welds or where protection is interrupted. Consequences extend beyond replacement cost: a leak may threaten workers, contaminate soil, interrupt supply and compromise nearby infrastructure.

Corresponding Author:- Shafiqur Rehman Shaikh

Contemporary reviews establish that coating condition, local soil chemistry, electrochemical protection and mechanical loading must be considered together rather than as independent asset attributes [1–3].

Desert engineering introduces a misleading simplification. Low annual rainfall can reduce the duration of electrolytic contact, but groundwater, irrigation, poorly drained trenches, coastal saline deposits and episodic storms may generate sustained or recurrent wetting. Soluble salts can concentrate as moisture evaporates and later dissolve during rewetting. Soil characterisation in the Jizan coastal sabkha provides direct Saudi evidence that chloride, sulfate, mineralogy and resistivity warrant site-specific investigation; it does not justify assuming identical severity across the Kingdom [4]. The distinction between regional climate and the actual pipe–soil interface underpins this review.

Existing literature often treats material specification, corrosion protection and integrity prediction as separate technical problems. That separation can produce incompatible decisions: a barrier coating is selected without considering current penetration at a disbondment, a cathodic-protection system is commissioned without confirming interference, or an inspection interval is fixed despite markedly different exposure along the route [5–7]. A practical framework must connect the design basis to evidence collected after burial, and then allow observed condition to change the maintenance strategy.

The contribution here is an exposure-led synthesis rather than an untested claim that any single alloy, coating or algorithm can prevent failure. It differentiates external soil-side corrosion from internal corrosion, identifies circumstances in which hydrogen or microbial mechanisms are credible, and relates defect measurements to engineering decisions. The evaluation also separates peer-reviewed observations from proposed applications to Saudi pipelines when direct local trials are unavailable. That distinction is important for defensible design, reproducible maintenance planning and responsible adoption of predictive technologies [8,9].

Aim, objectives and review questions:-

The aim is to develop an evidence-based route from desert exposure classification to material selection, layered protection and risk-based management of underground pipeline integrity in Saudi Arabia. Four objectives govern the analysis: identify location-dependent corrosion drivers; compare materials against credible damage mechanisms; establish protective design and verification requirements; and translate inspection evidence into maintenance decisions with explicit uncertainty. These objectives address what should be characterised before installation, what must remain effective in service, and which observations should trigger reassessment rather than routine continuation.

The guiding questions are deliberately engineering-oriented. When does an apparently dry corridor become electrochemically aggressive? Which combination of substrate, barrier and electrical protection is proportionate to that exposure? How should localised defects and imperfect measurements influence the next inspection date? Finally, which findings can reasonably be transferred from international laboratory or field studies, and which require validation against Saudi soil samples, operating histories and failure records?

Review Methodology:-

A structured critical narrative review was used because the question spans corrosion science, geotechnical exposure, materials engineering, protective-system qualification and probabilistic integrity management. Peer-reviewed literature dated 2020–2025 was identified through targeted searches of scholarly publisher records and bibliographic discovery sources. Search concepts combined underground pipeline or buried steel with soil corrosion, sabkha, chloride, sulfate, coating disbondment, cathodic protection, AC interference, microbial corrosion, hydrogen damage, in-line inspection, defect growth and risk-based maintenance. The supplied reference article informed sectional organisation and numbered citation presentation, not the technical evidence base.

Selection privileged articles with an identifiable DOI and clear relevance to at least one review question. Review papers were used to establish mechanisms and competing interpretations; experimental investigations contributed conditional evidence; modelling studies were assessed for the representativeness of inputs, treatment of uncertainty and transferability to field operations. The literature was organised into four analytical themes: exposure, material response, prevention and integrity decisions. This is a focused synthesis, not a claim of exhaustive database retrieval or a quantitative meta-analysis. No article counts, pooled failure rates or field-test datasets were invented.

Evidence was interpreted against three transferability tests. First, the exposure must resemble plausible Saudi pipeline conditions rather than merely share the label “desert”. Secondly, the response variable must be

operationally meaningful: for example, a laboratory corrosion-current reduction does not directly establish a pipeline lifetime. Thirdly, the study design must support the proposed decision; numerical prediction and experimental coupons cannot substitute for verified coating condition or actual defect measurements. Contradictions are retained, especially where coating adhesion, protective-current access or microbial activity depend on local conditions [1,5,6,10].

Desert exposure and external corrosion pathways:-

Soil chemistry, wetting and spatial variation:-

The critical requirement for electrochemical soil-side attack is a conductive pathway that permits anodic dissolution and associated cathodic reactions. Dry, high-resistivity sand may restrict this pathway, but small pockets of persistent moisture can behave differently from the surrounding ground. Clay lenses, salinity gradients, trench backfill, groundwater contact and differential aeration generate local electrochemical cells. A corridor-wide average resistivity therefore conceals locations where aggressive conditions cluster. Multiscale external-corrosion models identify this mismatch between regional measurements and the microenvironment at exposed steel as a central source of prediction error [1,9].

Coastal sabkha should be distinguished from inland dune sands and engineered fill. Hakami and colleagues examined sabkha material in the Jizan area and identified high concentrations of corrosion-relevant salts alongside differences in soil characteristics [4]. This is a substantive geographic anchor for Saudi risk screening, but sampled coastal material cannot describe every pipeline depth or season. For a new alignment, soil sampling should resolve route segments, planned burial depth, anticipated water-table movement and representative wet and dry states. Groundwater chemistry, chloride and sulfate content, resistivity, moisture retention and drainage condition should be recorded as linked observations rather than detached laboratory values.

Episodic rainfall makes time dependence as important as geography. A pipe may experience long intervals of limited electrical conductivity followed by short periods of saline wetting; the resulting corrosion process need not be proportional to average monthly rainfall. Excavation trenches can act as preferential drainage routes, while compacted backfill may trap water near damaged coatings. At crossings, utility corridors and irrigated developments, anthropogenic water sources can dominate the nominal natural climate. Accordingly, the risk unit should be the actual exposure segment and its history, not an administrative region or a static desert classification [2,4].



Figure 1. Conceptual pipe–soil exposure regimes relevant to Saudi corridors. Schematic categories, not measured comparative corrosion rates.

The sampling design should also distinguish soil that was present before construction from imported material placed around the pipe. Imported backfill can alter drainage, electrical resistance and salt transport even when its initial laboratory chemistry appears benign. Moisture probes placed at a few representative depths may establish the timing of wetting, but they cannot by themselves describe electrolyte composition at every coating defect. Linking periodic

chemical testing to continuous moisture measurements would provide a more defensible account of exposure duration.

Localised attack, disbondment and electrical interference:-

Pitting becomes critical when metal loss is concentrated within a small area, reducing remaining wall thickness faster than an average loss rate suggests. Under disbonded coatings, moisture and dissolved ions can form an occluded electrolyte with chemistry unlike bulk soil. Evidence on this mechanism indicates that apparent coating continuity and a satisfactory potential measurement elsewhere do not guarantee protection at the hidden interface [5,6]. Inspection programmes must therefore distinguish visible coating holidays from disbonded regions where current access and diagnostic sensitivity may be impaired.

Stray direct current and induced alternating current introduce further location-specific uncertainty near electrical infrastructure, parallel transmission lines or crossing corridors. AC-related corrosion can occur on a cathodically protected pipeline, which rules out equating a single favourable pipe-to-soil potential with universal safety [7]. Field assessment should investigate the geometry of power-line proximity, current density where measurable, grounding arrangements and time-varying electrical loads. Mitigation may require electrical interference studies, decoupling or earthing arrangements and subsequent confirmation under realistic operating conditions.

Not every loss of wall thickness is explained by one electrochemical route. Stress corrosion cracking and hydrogen-assisted mechanisms depend on combinations of stress, material response and environment; hydrogen uptake can compromise toughness under susceptible conditions [2,10]. Microbiologically influenced corrosion is also conditional. Sulfate-reducing organisms can contribute to severe local attack where water, nutrients and favourable microenvironments coexist, yet microbial films may show competing effects depending upon chemistry and experimental conditions [11–14]. Routine attribution of unexplained pits to bacteria is therefore inappropriate without microbiological and metallurgical evidence.

Interpretation of suspected microbial attack requires particular restraint. Laboratory identification of sulfate reducers demonstrates that organisms are present, but does not alone establish that they caused a specific pit in an operating line. A stronger diagnosis combines corrosion morphology, local chemistry, biofilm evidence and exposure history. It also considers whether oxygen gradients and conventional electrochemical reactions could explain the same damage. This distinction prevents unnecessary biocide programmes and encourages corrective action against the actual source of persistent wetting.

Material selection under desert service conditions:-

Carbon steel as an engineered system:-

Carbon steel remains a practical substrate for many large-diameter underground lines because its structural properties, manufacturing routes, joining methods, inspection methods and repair practices are well established. Its acceptability, however, depends upon an engineered system consisting of selected steel grade, wall thickness, qualified weld procedures, coating integrity, electrical protection and inspection capability. Increasing nominal wall thickness alone cannot compensate reliably for severe localised corrosion, which concentrates loss at individual defects [8]. Material selection should therefore begin with pressure, temperature, transported medium, expected external exposure, design life and credible combined loads.

Pipe steel microstructure, weld quality and strength level matter when corrosion-related cracking or hydrogen uptake is plausible. Recent evidence shows that microstructural features influence both corrosion behaviour and cracking resistance; higher strength is not an unqualified advantage if particular service conditions elevate susceptibility [10,16]. The designer must distinguish external soil exposure from internal under-deposit corrosion [15,27]. For example, an external coating cannot prevent internal sour-service degradation, while specifying an expensive corrosion-resistant alloy for an otherwise controllable external soil environment may deliver poor lifecycle value. Materials should be qualified against the governing mechanism, not selected through an undifferentiated corrosion-resistance ranking.

Material qualification should consider the interfaces at which design assumptions become vulnerable. Heat-affected zones, repaired coating, bends, tees, tie-ins and insulating joints introduce geometries and workmanship conditions absent from a straight-pipe laboratory specimen. Mechanical damage can also occur during lowering-in or subsequent excavation by third parties. Specifying inspection hold points for these interfaces is often more valuable

than marginally increasing the nominal corrosion resistance of the steel without controlling the conditions that expose it.

Alternative materials and the case for selectivity:-

Corrosion-resistant alloys, polymer-lined steel and non-metallic pipe systems have potential roles where the transported fluid, operation or maintenance constraints warrant their use. Their merits must be balanced against pressure and temperature capability, permeation, joint integrity, installation damage, inspection access, repairability, cost and the consequences of failure. In particular, resistance to an internal chemical exposure does not remove the need to assess external joint details, mechanical loading or ground movement. No reviewed source demonstrates that one premium material is universally optimal across Saudi underground networks; the appropriate comparison is a verified whole-life system rather than bare material price [3,10].

A defensible specification can use performance gates. Candidate materials must first meet pressure-containment and fabrication requirements; they must then be assessed for credible corrosion and cracking mechanisms, exposure temperature and available inspection technology. Finally, they should be compared through lifecycle cost, consequences of repair, local supply capability and documented field experience. If a design assumes compatibility with cathodic protection, that compatibility should be qualified as an assembled coating–pipe system. The analysis places substantial weight on evidence produced during procurement, construction and commissioning, because poor surface preparation or damaged field-joint coating can erase a theoretical materials advantage.

Table 1. Comparative material and protective-system selection considerations (qualitative synthesis; performance is exposure-specific).

System / candidate	Engineering advantage	Principal limitation or failure mode	Selection or verification gate
Coated carbon steel	Established joining, pressure capacity and inspection routes	Coating holidays, local pitting, weld-related exposure	Qualify coating plus protection; verify field joints
Fusion-bonded epoxy	Adherent thin barrier with established pipeline use	Impact damage; cathodic disbondment depends on conditions	Adhesion, holiday and disbondment testing
Three-layer polyolefin	High handling and soil-stress resistance	Disbondment and possible protective-current shielding	Interface integrity; ageing and current-access checks
Corrosion-resistant alloy	Potential resistance to specified internal corrosive media	High cost, weld and service-specific cracking concerns	Document chemistry, fabrication and whole-life case
Polymer-lined or non-metallic	Potential separation from selected internal corrosive fluids	Permeation, pressure, joints and inspection constraints	Full assembly qualification and repair strategy

Protective design and field verification:-

Coating functionality and interface control:-

External coating is the primary barrier separating steel from soil electrolyte; cathodic protection supplies an additional electrochemical defence at exposed locations. Fusion-bonded epoxy and three-layer polyolefin systems offer different balances of adhesion, toughness, impact resistance and installation tolerance. Their selection should address handling damage, burial temperature, soil stress, field-joint geometry, holiday testing and the behaviour of defects in service [3,5]. The decisive quality assurance question is not whether a product meets a catalogue specification, but whether the installed system retains continuity and adhesion after realistic handling, bedding and backfilling.

Disbondment is especially consequential because a coating can remain visually intact while water reaches steel beneath it. Protective current may be diverted or attenuated within an occluded gap, although the severity of shielding varies with coating characteristics, electrolyte conductivity and defect geometry [5,6]. It is therefore misleading to label an entire coating family inherently safe or unsafe under all circumstances. Qualification should include ageing, cathodic disbondment behaviour, moisture exposure and construction-related mechanical damage under conditions reasonably representative of the route. Field joints merit explicit attention because they combine coating transitions, welding, surface preparation and construction variability.

Construction detailing deserves equal standing with material science. Trench geometry and bedding should minimise point loads and sharp contact with coating; appropriate selected backfill should control mechanical damage and avoid introducing unnecessarily aggressive material. Crossings and transition zones require management of differential settlement and external loading. Drainage measures may limit water residence in some settings but should not be credited without geotechnical evidence that they remain effective during intense storm events. Isolation joints, test leads and bonding provisions should be designed for long-term accessibility, traceability and protection-system maintenance.

Thermal exposure demands a distinction between temperature capability stated for coating manufacture and temperature experienced continuously during service. Burial generally buffers short surface peaks, although shallow sections, hot conveyed fluids and exposed transitions can experience different temperatures. Ageing tests should therefore reflect plausible thermal histories rather than an arbitrary extreme. Excessive conservatism can reject workable products, while insufficient temperature qualification can overestimate adhesion and mechanical robustness over the intended design life.

Cathodic protection and electrical assurance:-

A cathodic-protection design must account for coating area, predicted defects, soil resistivity, route length, power availability, interference and anticipated changes over the asset lifetime. Sacrificial-anode systems and impressed-current systems have different operational constraints; neither can be selected reliably from pipe diameter alone [3,7]. Commissioning should establish whether protection reaches relevant locations and whether survey measurements are distorted by voltage drops or external currents. Pipe-to-soil potential criteria are useful diagnostic controls, not unconditional guarantees of an absence of local corrosion beneath disbonded coatings.

Monitoring should combine suitable potential surveys, rectifier performance, interruption measurements where practicable, test-station checks and targeted coating-defect location methods. Close-interval potential data and direct-current voltage-gradient observations have complementary meanings; the former assesses electrical-protection behaviour along a route, while the latter can indicate coating defects under appropriate survey conditions. Where measurements disagree, excavation, direct examination or controlled testing may be required. Treating any one survey as an independent measure of remaining wall thickness would be an evidential error, since coating condition and actual metal loss are distinct variables [5,8].

Long corridors create operational challenges involving remote power, access permissions, measurement repeatability and records that survive contractor changes. A sound design should include geographic referencing for test points, durable asset identification, calibration records and responsibility for investigating abnormal results. Solar-supported power may be useful at isolated installations, but it demands resilience checks for storage, heat exposure, dust, telemetry and loss of supply. Remote monitoring reduces the delay in recognising faults only when alarms have defined thresholds, maintenance owners and response procedures; a disconnected dashboard is not a protection measure.

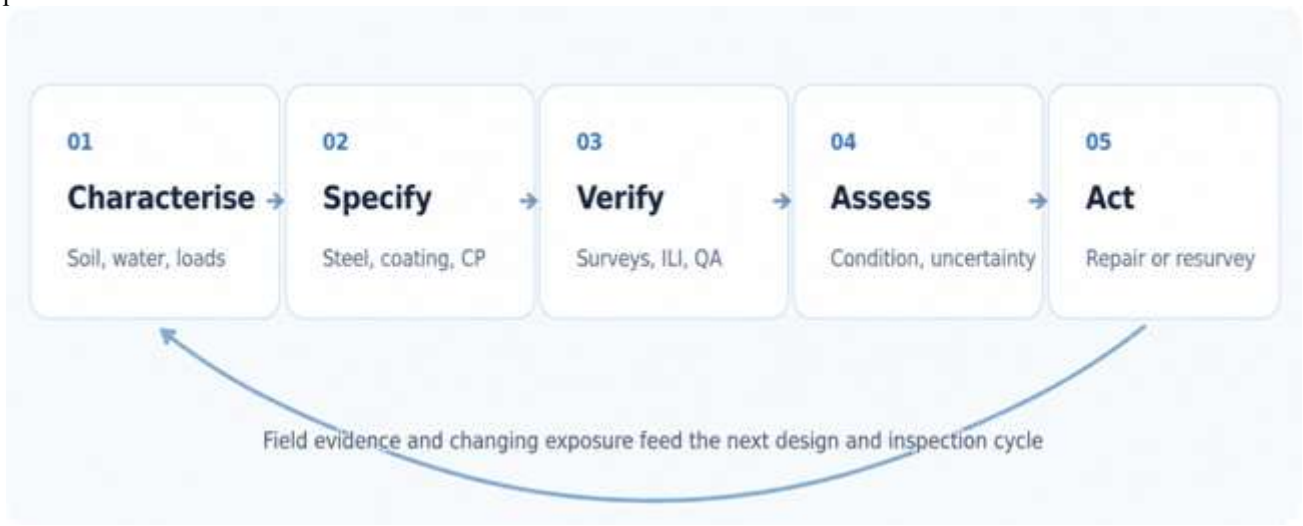


Figure 2. Evidence-led lifecycle pathway linking exposure assessment, system protection, verification and risk-informed intervention. Author-developed conceptual synthesis.

Evidence quality matters when cathodic protection is adjusted. A change that improves the reading at one test post can alter current distribution elsewhere or increase interaction with neighbouring metallic structures. Changes should be planned as controlled interventions with documented pre- and post-adjustment conditions. Operators also need an escalation route when readings suggest excessive polarisation, interference or unexpected coating behaviour. A record of the justification is as important as the numerical setting because future engineers must understand why the protection system was altered.

Integrity assessment, inspection and decision modeling:-

Combining heterogeneous evidence:-

Risk-based integrity management begins by integrating design documentation with observed condition. Useful sources include original wall thickness, weld and coating records, soil tests, cathodic-protection surveys, defect-location studies, repairs, leaks, and repeated in-line inspection where the pipeline can accommodate suitable tools. In-line magnetic flux leakage and ultrasonic techniques can detect or size certain defect classes, but inspection performance depends on wall geometry, tool configuration, operating conditions and data quality. Studies demonstrate that adjacent corrosion indications and measurement matching between successive runs complicate estimates of defect severity and growth [18,20,29].

Data integration requires more than placing records on one map. Depth readings must refer to the same defect and location, coating surveys must be interpreted in their survey conditions, and soil observations require consistent spatial units. Missing or contradictory observations should remain visible rather than be silently averaged away. Machine learning can identify nonlinear associations between corrosion, potential, age and environmental descriptors, but published accuracy measures may depend heavily on the composition of the training data [19,21,22]. Before operational use, models require temporal and geographic validation against independent pipeline sections, not only random splitting of neighbouring records.

Inspection data governance is an engineering control. Each measurement should carry a source, instrument configuration, date, coordinate system, expected error and link to the affected asset segment. Defect identifiers must remain stable when a new contractor reprocesses a later survey. Otherwise, apparent growth may reflect incompatible positioning or reporting thresholds rather than genuine deterioration. Maintaining a clear audit trail enables reanalysis when integrity criteria, software or understanding of local exposure changes.

Growth, remaining strength and uncertainty:-

Corrosion growth models range from conservative deterministic extrapolation to stochastic processes, physical simulations and data-driven approaches. Each represents a different compromise between interpretability, data demand and uncertainty treatment [8,30]. Localised attack should not automatically be represented as a constant annual thickness loss. Some defects remain relatively stable, whereas others respond to a changing electrolyte or protective-system defect. Multiple correlated indications, repairs and exposure transitions introduce further non-stationarity. A practical assessment should report both a predicted condition and the uncertainty surrounding it, alongside the evidence used to form the estimate.

Recent Bayesian and theory-guided models offer approaches for quantifying uncertainty rather than producing only a single depth prediction [19,22,24,25]. Nevertheless, a statistically sophisticated model remains a conditional decision aid. If its training data originate from other climates, pipe grades or inspection technologies, apparent precision may be misleading when applied to a Saudi desert route. Appropriate validation includes calibration of prediction intervals, testing against held-out corridor segments, comparison with conservative baselines and sensitivity analysis for soil and protection variables. Mechanism-informed models are preferable when physical constraints can be stated clearly and checked against observations.

The final integrity limit must reflect structural capacity, defect shape, pressure cycling, mechanical interaction and applicable engineering assessment procedures. A shallow but extensive colony is not equivalent to an isolated narrow pit of the same maximum depth. Published models comparing remaining strength in corroded pipelines emphasise defect geometry and methodology choice [8]. Combined damage deserves additional caution: a dent overlapping corrosion can alter failure probability and undermine separate-threat ranking [17]. Where calculated margins approach the acceptance limit, targeted examination and engineering review are more defensible than automatic reliance on model outputs.

Model uncertainty has at least two practical components. Natural variability arises because corrosion environments and defect progression differ between locations and times; limited knowledge arises from sparse monitoring, imperfect measurement or simplified assumptions. Additional inspection can reduce the second component but cannot eliminate the first. A useful integrity report should state which uncertainty dominates the decision and whether the recommended action is more sensitive to wall-thickness measurement, future growth or uncertainty in operating pressure.

Risk-based inspection and intervention:-

Risk represents both the likelihood of a defined failure scenario and its consequences. The same wall-loss morphology can justify different inspection priorities in an isolated, accessible corridor and beside a populated industrial complex or sensitive water resource. A site-specific consequence assessment should consider product release, isolation time, exposure of people, environmental receptors, operating interruption and repair access. Dynamic Bayesian models illustrate how failure likelihood can change as condition evidence accumulates; they are frameworks for reasoning under uncertainty, not substitutes for a verified hazard inventory [17,23,24].

Inspection intervals should be shortened when protection failures recur, corrosion growth accelerates, data confidence deteriorates or consequence severity increases. Conversely, stable verified condition may support a different schedule where regulatory and technical requirements permit. Optimal inspection planning studies explicitly account for imperfect detection and sizing; ignoring such errors risks false assurance or unnecessary excavation [26]. Maintenance choices should compare coating repair, cathodic-protection adjustment, local sleeve or section replacement, pressure management and broader renewal against their ability to reduce the relevant failure mode.

The recommended decision cycle is iterative. Establish an initial exposure class; collect baseline condition and protection information; calculate a defensible range of failure likelihood and consequences; select mitigation or examination; and update the record after intervention. Where there is inadequate evidence, conservative treatment and additional inspection should take precedence over numerical confidence. Research on geographically integrated risk assessment and future-risk maintenance policies supports this shift from rigid calendar inspection towards justified, condition-dependent decisions [25,28].

Table 2. Risk-based integrity decision matrix linking observed evidence to action and recorded uncertainty.

Evidence or trigger	Primary interpretation	Engineering response	Residual uncertainty to document
Low resistivity with persistent wetting	Electrolyte likely available at local interface	Review coating condition, drainage and protection	Seasonal variability; depth of sampled soil
Protection survey anomaly	Possible poor current delivery or interference	Repeat controlled survey; test electrical sources	Measurement error; voltage-drop effects
Coating defect / disbondment indication	Potential electrolyte pathway and shielding	Locate, examine and repair where risk warrants	Actual metal loss beneath coating
ILI metal loss or interacting indications	Reduced wall capacity may be developing	Assess geometry, remaining strength and growth	Detection, sizing and matching errors
Rising predicted risk / higher consequences	Expected failure impact exceeds tolerance	Shorten interval or intervene after review	Model transportability and consequence assumptions

Consequence ranking must also consider response capability. Remote isolation valves, leak detection, emergency access and access to repair crews can materially affect the development of an incident. Conversely, a low population density does not make environmental consequences negligible where groundwater, sensitive ecosystems or industrial dependencies are present. Risk matrices that collapse these differences into a single unexamined “remote” category may direct inspection effort away from environmentally critical locations.

Implementation priorities for Saudi pipeline operators:-

A national implementation strategy need not begin with complex analytics. The first priority is consistent corridor segmentation and traceable information: georeferenced soil samples, coating specifications, commissioning baselines, electrical-interference studies, field-joint acceptance records and inspection history. Asset owners should preserve the connection between a laboratory sample, its geographic context and the decision it supports. This would enable more meaningful comparisons between coastal sabkha, irrigated urban fringe, remote inland sands and industrial crossing corridors without assuming that their exposure distributions are interchangeable [1,4].

The second priority is system qualification under representative conditions. Laboratory screening should include cyclic wetting and drying where relevant, saline soil chemistry, elevated exposure temperature, coating defects and appropriate protection conditions. Test acceptance should distinguish barrier integrity, loss of adhesion, protective-current access and actual corrosion damage. Field trials should then examine whether laboratory rankings survive burial, construction damage and realistic maintenance practices. A small number of well-instrumented, transparently reported Saudi test corridors could be more informative than extrapolating many unrelated overseas datasets.

Third, digital tools should be introduced around a defined operational decision. A corrosion-growth predictor is useful if it tells an engineer which segment to investigate and expresses uncertainty honestly. A remote protection monitor is useful if it triggers a timely diagnostic response. A geographic risk map is useful if it changes prioritisation with documented reasons. None of these tools should conceal missing data or circumvent responsible sign-off by qualified integrity engineers. Recent work on uncertainty-aware corrosion prediction reinforces the importance of separating predictive performance from decision usefulness [19,21,25].

Evidence gaps and research agenda:-

Design assumptions require review when groundwater regimes change or new electrical equipment is installed near the route. Such reviews must connect updated exposure evidence to qualified engineering judgement, with explicit responsibilities for corrective action, measurement and subsequent verification.

The largest evidence gap is the scarcity of longitudinal, openly described measurements across distinct Saudi underground settings. The available Jizan sabkha investigation demonstrates local corrosivity factors, but cannot establish decades of pipeline damage under particular coatings and protection settings [4]. Future programmes should record soil moisture transitions, seasonal groundwater movement, resistivity at multiple depths, salt accumulation and observed metal loss over time. Paired monitoring of exposed steel coupons and actual coated assets would help determine when environmental indicators correspond to meaningful corrosion rates.

A second gap concerns current distribution beneath aged or disbonded coatings. Debate over shielding persists because different gap geometries, electrolytes and coating types yield different results [5,6]. Research should reproduce plausible Saudi backfill conditions, wetting cycles and temperatures rather than relying only on continuously immersed specimens. Experiments should measure local potential, current access, corrosion morphology and microbial conditions together, enabling stronger explanations of coupled damage rather than attributing observed results to one mechanism after the event. Third, prediction studies should demonstrate transportability and clinical-style calibration discipline without borrowing inappropriate claims of universal accuracy. Pipeline integrity models require corridor-level holdout tests, measured uncertainty, explicit inspection error and documentation of when recalibration is mandatory. The largest practical value may come from combining interpretable mechanism-based limits with modest statistical updating rather than prioritising increasingly complex algorithms [22,26,30]. Failure investigations should also capture non-corrosion stresses and human factors so that corrosion prediction does not become detached from overall structural integrity.

Conclusions:-

Corrosion resilience for buried Saudi pipelines is achieved through an integrated system rather than a single advanced material. The evidence supports distinguishing dry, resistive soils from saline or persistently wetted local environments, specifying compatible coatings and cathodic protection, and verifying the installed system throughout service. Disbondment, interference, localised pits and uncertain defect growth demand particular attention because they undermine simple assumptions based on regional climate, nominal material grade or one survey reading [2,5,7]. For many large transmission applications, qualified coated carbon steel remains a rational starting point; alternative materials should be justified by documented service conditions and lifecycle requirements. Risk-based inspection must then connect trustworthy measurements, uncertainty-aware degradation assessments and route-specific consequences to actionable repair decisions. The essential next step for Saudi practice is longitudinal validation

across representative soils and operating environments. Such evidence would make protective design more targeted, modelling more credible and long-term pipeline integrity decisions more transparent.

References:-

[1] Kim, C., Chen, L., Wang, H., & Castaneda, H. (2021). Global and local parameters for characterizing and modeling external corrosion in underground coated steel pipelines: A review of critical factors. Journal of Pipeline Science and Engineering, 1, 17–35. https://doi.org/10.1016/j.jpse.2021.01.010

[2] Wasim, M., & Djukic, M. B. (2022). External corrosion of oil and gas pipelines: A review of failure mechanisms and predictive preventions. Journal of Natural Gas Science and Engineering, 100, 104467. https://doi.org/10.1016/j.jngse.2022.104467

[3] Farh, H. M. H., Ben Seghier, M. E. A., & Zayed, T. (2023). A comprehensive review of corrosion protection and control techniques for metallic pipelines. Engineering Failure Analysis, 143, 106885. https://doi.org/10.1016/j.engfailanal.2022.106885

[4] Hakami, A., Ghrefat, H., Elwaheidi, M., Galmed, M., & Yahya, M. A. (2022). Assessment of the corrosivity of the Southern Red Sea coastal sabkha soil: An integrated mineralogical, geochemical, and GIS approach. Environmental Earth Sciences, 81, 225. https://doi.org/10.1007/s12665-022-10316-w

[5] Meroufel, A., Gordon, A., & Thierry, D. (2024). Cathodic protection shielding of coated buried pipeline. Journal of Coatings Technology and Research, 21, 445–459. https://doi.org/10.1007/s11998-023-00850-y

[6] Tan, M. Y. J., Varela, F. B., & Huo, Y. (2023). An overview of recent progresses in probing and understanding corrosion under disbonded coatings. Corrosion Engineering, Science and Technology, 58. https://doi.org/10.1080/1478422X.2023.2182458

[7] Farahani, E. M., Su, Y., Chen, X., Wang, H., Laughorn, T. R., Onesto, F., Zhou, Q., & Huang, Q. (2024). AC corrosion of steel pipeline under cathodic protection: A state-of-the-art review. Materials and Corrosion, 75, 290–314. https://doi.org/10.1002/maco.202313955

[8] Zhu, X.-K. (2023). Recent advances in corrosion assessment models for buried transmission pipelines. CivilEng, 4, 391–415. https://doi.org/10.3390/civileng4020023

[9] Farh, H. M. H., Ben Seghier, M. E. A., Taiwo, R., & Zayed, T. (2023). Analysis and ranking of corrosion causes for water pipelines: A critical review. npj Clean Water, 6, 65. https://doi.org/10.1038/s41545-023-00275-5

[10] Nnoka, M., Jack, T. A., & Szpunar, J. (2024). Effects of different microstructural parameters on the corrosion and cracking resistance of pipeline steels: A review. Engineering Failure Analysis, 108065. https://doi.org/10.1016/j.engfailanal.2024.108065

[11] Bairi, L. R., Bhuyan, P., Ghosh, A., Narang, M., & Mandal, S. (2024). Microbially induced corrosion issues in the underground buried crude oil and natural gas bearing pipelines: A review. Materials and Corrosion, 75, 197–211. https://doi.org/10.1002/maco.202313950

[12] Liu, W., Bi, W., Hu, Y., Lu, W., Feng, W., Wang, Y., Li, Y., & Liu, J. (2024). Influence of initial pH and sulfate-reducing bacteria concentration on the microbiologically influenced corrosion of buried pipeline steel. Materials and Corrosion, 75, 1193–1203. https://doi.org/10.1002/maco.202414320

[13] Hua, W., Sun, R., Wang, X., Zhang, Y., Li, J., Qiu, R., & Gao, Y. (2024). Corrosion of Q235 carbon steel induced by sulfate-reducing bacteria in groundwater: Corrosion behavior, corrosion product, and microbial community structure. Environmental Science and Pollution Research, 31, 4269–4279. https://doi.org/10.1007/s11356-023-31422-7

[14] Lv, X., Wang, C., Liu, J., Sand, W., Etim, I.-I. N., Zhang, Y., Xu, A., Duan, J., & Zhang, R. (2024). The microbiologically influenced corrosion and protection of pipelines: A detailed review. Materials, 17, 4996. https://doi.org/10.3390/ma17204996

[15] Wang, Z. B., Pang, L., & Zheng, Y. G. (2022). A review on under-deposit corrosion of pipelines in oil and gas fields: Testing methods, corrosion mechanisms and mitigation strategies. Corrosion Communications, 7, 70–81. https://doi.org/10.1016/j.corcom.2022.03.007

[16] Shehata, M. F., & El-Shamy, A. M. (2023). Hydrogen-based failure in oil and gas pipelines: A review. Gas Science and Engineering, 115, 204994. https://doi.org/10.1016/j.jgsce.2023.204994

[17] Huang, Y., Qin, G., & Yang, M. (2023). A risk-based approach to inspection planning for pipelines considering the coupling effect of corrosion and dents. Process Safety and Environmental Protection, 180, 588–600. https://doi.org/10.1016/j.psep.2023.10.025

[18] Cui, B., & Wang, H. (2023). Analysis and prediction of pipeline corrosion defects based on data analytics of in-line inspection. Journal of Infrastructure Preservation and Resilience, 4, 14. https://doi.org/10.1186/s43065-023-00081-w

[19] Cui, B., & Wang, H. (2024). Pipeline corrosion prediction and uncertainty analysis with an ensemble Bayesian neural network approach. Process Safety and Environmental Protection, 187, 483–494. https://doi.org/10.1016/j.psep.2024.05.011
[20] Shen, Y., & Zhou, W. (2024). Development of a convolutional neural network model to predict the size and location of corrosion defects on pipelines based on magnetic flux leakage signals. International Journal of Pressure Vessels and Piping, 105123. https://doi.org/10.1016/j.ijpvp.2023.105123
[21] Guang, Y., Wang, W., Song, H., Mi, H., Tang, J., & Zhao, Z. (2024). Prediction of external corrosion rate for buried oil and gas pipelines: A novel deep learning method with DNN and attention mechanism. International Journal of Pressure Vessels and Piping, 209, 105218. https://doi.org/10.1016/j.ijpvp.2024.105218
[22] Miao, X., & Zhao, H. (2024). Maximum pitting corrosion depth prediction of buried pipeline based on theory-guided machine learning. International Journal of Pressure Vessels and Piping, 210, 105259. https://doi.org/10.1016/j.ijpvp.2024.105259
[23] Wu, W., He, Z., & Luo, Z. (2025). Risk analysis of the failure of oil and gas pipelines due to external corrosion based on a dynamic Bayesian network. Journal of Performance of Constructed Facilities, 39. https://doi.org/10.1061/JPCFEV.CFENG-5016
[24] Ruggeri, F., Cagno, E., Caron, F., Mancini, M., & Pievatolo, A. (2024). Bayesian assessment of corrosion-related failures in steel pipelines. Entropy, 26, 1111. https://doi.org/10.3390/e26121111
[25] Woldesellasse, H., & Tesfamariam, S. (2025). Risk assessment of gas pipeline using an integrated Bayesian belief network and GIS: Using Bayesian neural networks for external pitting corrosion modelling. The Canadian Journal of Chemical Engineering, 103, 98–109. https://doi.org/10.1002/cjce.25393
[26] Sahraoui, Y., Nahal, M., & Chateauneuf, A. (2024). Optimal inspection planning for corroded pipelines considering repair decision error. Journal of Pipeline Systems Engineering and Practice, 15. https://doi.org/10.1061/JPSEA2.PSENG-1549
[27] Dao, U. (2025). A Bayesian network-based susceptibility assessment model for oil and gas pipelines suffering under-deposit corrosion. The Canadian Journal of Chemical Engineering. https://doi.org/10.1002/cjce.25234
[28] Zheng, Y., Dong, Z., Zhang, X., & Shi, H. (2025). Random risk assessment model and risk-based maintenance decisions for natural gas pipelines. Journal of Loss Prevention in the Process Industries, 95, 105591. https://doi.org/10.1016/j.jlp.2025.105591
[29] Shen, Y., & Zhou, W. (2024). Classification and regression of pinhole corrosions on pipelines based on magnetic flux leakage signals using convolutional neural networks. Algorithms, 17, 347. https://doi.org/10.3390/a17080347
[30] Ma, H., Zhang, W., Wang, Y., Ai, Y., & Zheng, W. (2023). Advances in corrosion growth modeling for oil and gas pipelines: A review. Process Safety and Environmental Protection, 171, 71–86. https://doi.org/10.1016/j.psep.2022.12.054