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Original Research Article

Risk-Based Inspection and Corrosion-Informed Asset Integrity Management for Saudi Arabia's Oil and Gas Pipeline Networks: A Vision 2030 Framework for Reliability, Safety, and Lifecycle Cost Optimization

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Abstract: Saudi Arabia's extensive hydrocarbon transport infrastructure requires integrity decisions that simultaneously protect containment, sustain delivery reliability and allocate inspection expenditure efficiently. This critical review evaluates research published between 2020 and 2025 on corrosion prediction, in-line inspection, probabilistic failure assessment, risk-based inspection and lifecycle intervention planning. Rather than treating inspection intervals as fixed administrative periods, the paper develops a corrosion-informed decision framework linking threat identification, measurement uncertainty, remaining-strength assessment, consequence modelling and risk-constrained economic optimisation. Evidence is synthesised across buried transmission lines, offshore segments and operationally complex assets, with explicit attention to conditions relevant to Saudi Arabia: heterogeneous desert soils, saline coastal exposures, variable water chemistry, geographically dispersed routes and strategic dependence on uninterrupted energy transport. The review finds that probabilistic degradation models offer more defensible inspection scheduling than deterministic extrapolation where repeated observations exist, while data-driven predictors remain constrained by transferability, sparse failures and inconsistent defect matching. It argues for staged deployment: establish traceable asset data, classify governing threats, calibrate deterioration models, validate inspection performance and select interventions using both tolerable risk and expected lifecycle cost. Two conceptual figures and two synthesis tables translate this evidence into implementable decisions. The contribution is an integrative review and proposed governance architecture, not a claim of new pipeline measurements or validated Saudi field performance. Priorities for subsequent research include locally calibrated corrosion datasets, uncertainty-aware model evaluation, interacting-threat assessment and transparent economic verification of intervention policies.

Keywords: Pipeline Integrity, Risk-Based Inspection, Corrosion, Saudi Arabia, Probabilistic Reliability, Lifecycle Cost, Vision 2030.

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1. INTRODUCTION

Oil and gas pipelines concentrate substantial economic value within geographically extended assets whose condition is neither uniform nor directly observable. A defect that appears modest in isolation can become consequential when accompanied by pressure cycling, coating disbondment, external loading or delayed access. Equally, repairing every reported anomaly is neither practicable nor necessarily safer: interventions consume shutdown windows, introduce construction hazards and may disturb otherwise stable assets. The central engineering question is therefore not which pipeline has the largest recorded defect, but where additional information or corrective action most effectively reduces the probability and consequence of loss of containment. Recent reviews describe this transition from rule-driven inspection towards risk-informed, continuously revised integrity management [1, 2].

For Saudi Arabia, the problem intersects with the reliability of crude oil, natural gas and downstream supply chains, as well as the broader industrial productivity ambitions associated with Vision 2030. Long transmission corridors pass through distinct geotechnical and operational environments; coastal sections encounter different corrosion exposures from inland buried pipelines. The same nominal steel grade and diameter may consequently require different control measures. A credible national application cannot import a universal corrosion rate, assume identical inspection detectability or assign consequences by distance alone. It must use local evidence while retaining a common decision language across operators, contractors and asset classes.

The literature contains strong but partially disconnected strands. Inspection-planning studies establish risk-based scheduling principles [3], repeated in-line inspection records support statistical descriptions of deterioration [4]. Bayesian models represent causal uncertainty in external corrosion [5-8], and internal-corrosion models address flowing fluids with water and corrosive gases [6-10]. More recent work extends analysis to interacting dents and corrosion, machine-learning estimates of defect severity and predictive maintenance [11–16]. Yet a model with attractive predictive accuracy does not automatically yield a defensible maintenance decision. The evidence must pass through measurement reliability, physical failure criteria, consequences, feasible interventions and budget restrictions.

This review distinguishes three decisions frequently blurred in practice: whether an asset is safe to continue operating, when additional inspection is worthwhile and which risk-reduction action should be selected. The first is an engineering acceptance judgement; the second is an information-acquisition problem; the third is an intervention optimisation problem. Their separation makes assumptions auditable, clarifies accountability and avoids treating a single risk score as a substitute for detailed integrity assessment. The proposed synthesis integrates these decisions for Saudi pipeline networks while identifying where available research remains insufficient for quantitative local recommendations.

2. Aim, Objectives and Contribution

The aim is to critically examine how corrosion evidence can be converted into transparent, risk-constrained inspection and maintenance decisions for Saudi Arabian oil and gas pipelines. Four distinct objectives guide the review: first, to evaluate internal and external corrosion mechanisms alongside interacting threats; second, to compare inspection and prediction methods in terms of uncertainty and decision relevance; third, to formulate a lifecycle risk-and-cost architecture with explicit decision gates; and fourth, to identify the local data, validation and governance arrangements needed for credible deployment. The intended contribution is a transferable synthesis rather than a new corrosion-rate equation, proprietary software tool or retrospective assessment of any named Saudi operator.

3. REVIEW METHODOLOGY

A structured critical narrative-review design was adopted because the research question spans mechanistic corrosion science, non-destructive inspection, probabilistic reliability, economics and organisational controls. A narrow meta-analysis would be misleading: the reviewed studies employ different materials, environments, defect definitions, inspection technologies and outcome measures. The evidence window was restricted to works published from January 2020 through December 2025. Searches were organised around combinations of “pipeline integrity”, “risk-based inspection”, “corrosion growth”, “in-line inspection”, “Bayesian network”, “remaining strength”, “lifecycle cost” and “oil and gas”. Publisher records and DOI landing information were used to establish bibliographic identity. This was a purposive critical synthesis, not an exhaustive database census.

Eligible publications addressed operational oil, gas or comparable steel pipeline integrity, presented a verifiable scholarly record, and offered evidence relevant to corrosion detection, degradation modelling, failure probability, consequence assessment or maintenance selection. Studies concentrating solely on unrelated industrial equipment, or lacking an identifiable publication record, were excluded from the core comparison. Review articles were used to map the field; methodological and case-study papers were examined for underlying assumptions, data provenance and transferability. The resulting thirty-source bibliography is an intentionally focused evidence set, not a claim that only thirty relevant studies exist.

Extraction followed five analytical dimensions: degradation mechanism, observable inputs, modelling assumptions, represented uncertainty and decision output. Each finding was interpreted against the distinction between model demonstration and operational validation. Published accuracy figures were not pooled because train-test partitions, class imbalance, synthetic data and field confirmation differed substantially. Likewise, reported intervention benefits were treated as context-specific unless counterfactual cost or incident outcomes were documented. The two tables classify evidence and propose decision controls; the figures visualise a synthesis constructed for this review, rather than results measured in Saudi pipelines. This approach supports reasoned comparison without inventing experiments or claiming a statistical estimate unsupported by the available studies.

The review has an explicit boundary: standards, regulations and operating-company rules must be consulted during implementation, but are not treated as peer-reviewed observations in the thirty-reference evidence base. No access was available to Saudi operators' defect inventories, inspection run comparisons, failure frequencies, consequence-model inputs or detailed expenditure histories. Accordingly, all implementation proposals below are conditional recommendations requiring local qualification. The limitations also prevent assigning a numerical national reduction in incidents, maintenance cost or emissions to the proposed framework.

Evidence appraisal was qualitative but rule based. A study received stronger interpretive weight when it described a real operating asset, a reproducible inspection basis, an appropriate physical failure model and an external or temporally independent validation set. Simulations were retained when they clarified mechanisms or decision structure, but their output was not treated as observed failure frequency. Reporting omissions were recorded conceptually as limitations rather than replaced by assumed values. This distinction is especially important when comparing industrial case studies with corrosion datasets generated under simplified boundary conditions.

4. Corrosion Threats and Integrity Evidence

4.1. External Corrosion and Environmental Heterogeneity

External corrosion is controlled by more than the presence of steel below ground. Coating defects, electrolyte availability, soil resistivity, chlorides, microbial activity, cathodic-protection performance and local potential gradients interact over time. Bayesian assessments for buried gas pipelines demonstrate why joint causes matter: the effect of a deteriorating barrier depends on the surrounding exposure and other protective conditions [5-8]. Experimental findings for pipe steel support incorporating material and environmental uncertainty rather than assigning one deterministic rate to an entire route [8]. Recently, spatial Bayesian models have connected environmental inputs and defect growth with geographical consequence estimates [9].

For inland Saudi corridors, aridity should not be confused with an absence of corrosion. Episodic moisture, saline pockets, differential aeration and localised coating damage may create highly uneven exposures even where average surface conditions appear dry. Nearshore and offshore networks require a separate treatment of seawater chemistry, temperature and protection systems. Laboratory investigations of offshore steel show sensitivity to salinity, acidity and temperature, but their controlled conditions should not be read as directly measured Saudi field rates [24]. An appropriate programme therefore stratifies routes by credible exposure regimes, checks the stratification against observed metal loss and revises classifications after excavations or environmental changes.

Route segmentation should also reflect local drainage, road crossings, stray-current sources, buried infrastructure interfaces and the condition of protective coatings after construction or maintenance. A soil classification alone is insufficient because cathodic protection effectiveness is an operational property rather than a permanent site label. The strongest monitoring strategy triangulates electrical measurements, coating surveys, environmental indicators and direct metal-loss evidence. An apparent improvement after one control adjustment should be tested against subsequent observations rather than attributed to that intervention without a credible baseline.

4.2. Internal Corrosion and Interacting Mechanisms

Internal corrosion depends on whether corrosive water phases contact the wall and on their chemistry, temperature, flow regime, carbon dioxide exposure, solids and deposits. A probabilistic treatment of oil-line internal corrosion shows why uncertainty in operating inputs must propagate into predicted damage and failure likelihood [6]. Machine-learning investigations similarly indicate that physical chemistry and operating conditions contain useful predictive information [10]. However, a model trained using simulated fluids may reproduce its training assumptions better than the history of a pipeline whose composition, inhibition regime or water hold-up differs. Monitoring should therefore preserve changes in fluid specification and operating state, not merely annual averages.

Under-deposit and microbiologically influenced corrosion warrant special handling because spatially concentrated attack can be missed by average-rate indicators. Expert-system research on microbial corrosion highlights both the diagnostic value and the epistemic limitations of sparse case evidence [21]. Dynamic susceptibility modelling suggests that dependencies among deposits, flow and chemistry are

relevant to targeted risk evaluation [29]. Furthermore, dents, gouges and pressure cycling can interact with metal loss; a combined-defect assessment cannot be replaced by adding two independently calculated risk scores. A Bayesian inspection-planning study explicitly demonstrates the decision significance of corrosion–dent coupling [15]. Consequent classifications should name the governing degradation mechanism and identify combinations that trigger specialist assessment.

The distinction between initiating conditions and damage progression is decisive. Water accumulation or a failed inhibitor programme creates an exposure, but it does not reveal the depth of an existing pit; measured depth alone, meanwhile, does not establish future growth. A useful integrity record therefore preserves chemical exposure history, protective action, physical inspection and changes in operating pressure as different evidence streams. Observed pressure and location effects in transport pipelines illustrate why contextual variables should be investigated instead of presumed causally independent [30].

4.3. Inspection Technologies and Measurement Quality

In-line inspection converts inaccessible wall condition into measurable indications, but individual technologies observe different aspects of damage. Magnetic flux leakage can screen extensive ferromagnetic pipe lengths for metal loss; ultrasonic methods can provide thickness-related information where coupling and operating conditions permit. The resulting defect dimensions are estimates affected by resolution, orientation, tool speed, surface condition and interpretation. A contemporary technology review stresses that defect identification and sizing require methods appropriate to the inspection principle [27]. Image-based and signal-processing models can assist localisation; nevertheless, predictions need calibration against excavations or verified measurements rather than acceptance solely on algorithmic performance [20-28].

Repeated runs are particularly valuable when features can be reliably matched in space and when changes exceed sizing variability. Pipeline datasets spanning multiple inspections reveal opportunities for modelling corrosion progression while exposing the problems of feature matching and uncertain rates [4-14]. Inspection plans should document tool specifications, detection thresholds, probability of detection, false calls, and the traceability of repaired or replaced segments. If a model treats every difference between two defect depths as physical growth, it risks inflating deterioration estimates. Conversely, unrecognised under-sizing can postpone an urgent repair. Independent quality checks and field verification are therefore integral to risk estimation, not merely procurement procedures.

Continuous monitoring is complementary rather than interchangeable with in-line assessment. Operating pressure, temperature, corrosion probes, cathodic-protection records and anomaly reports can signal a changing threat environment, while remote sensing may detect intrusion or movement without quantifying remaining wall thickness. Digital-twin demonstrations show the potential of linking physical observations with simulation and model updates [25, 26]. Their applicability depends on an identifiable physical asset, trustworthy time stamps, model maintenance and known uncertainty. For non-piggable segments, a justified mix of direct assessment, targeted excavation and suitable external inspection must replace an assumption that uninspected pipe is low risk.

4.4. Corrosion Prediction and Remaining Strength

Predictive methods range from engineering extrapolation to stochastic processes and complex learning algorithms. Reviews of empirical and data-driven corrosion models emphasise that predictive skill depends on the operating domain and quality of source observations [11]. Theory-guided learning has been proposed for maximum pit depth [12], while attention-based models aim to predict buried-pipeline corrosion rates from environmental variables [13]. These contributions are relevant when model inputs reflect measured exposures, but black-box point forecasts should not be equated with an estimate of failure probability. The critical engineering output is a distribution of future defect severity and a justified relation to pressure containment.

A defensible calculation compares operating demand with a suitable remaining-strength criterion, accounting for wall thickness, diameter, material properties, flaw geometry and model error. Review evidence on machine-learning burst-pressure predictions documents substantial variation in training databases and modelling choices [19]. Probabilistic assessment of complex corrosion profiles further indicates that spatial flaw shape matters to residual strength [18]. For long-term forecasts, stochastic and time-series approaches are promising because they preserve variation in deterioration rather than assuming all segments share a constant rate [17]. However, none removes the requirement to select a validated limit-state model for the applicable pipeline configuration.

Table 1: Critical evidence synthesis for corrosion-informed pipeline integrity decisions

Evidence domain	Decision contribution	Principal limitation / control
Corrosion exposure	Distinguishes external, internal and localised degradation; supports threat-specific monitoring.	Routes require local environmental and operating evidence; one regional average is inadequate [5-24].
In-line inspection	Identifies and sizes anomalies; repeated runs permit growth estimation.	Tool performance, defect matching, uncertainty and field confirmation must be documented [4-20].
Predictive modelling	Forecasts defect progression and probability of threshold exceedance.	Synthetic datasets, data shift and poor calibration can overstate reliability [10-19].
Consequence analysis	Distinguishes safety, ecological and continuity exposure.	Location-specific receptors and release scenarios require separate inputs [7-9].
Maintenance optimisation	Compares inspection, repair, restriction and replacement over time.	Risk constraints must precede economic ranking; findings are asset-specific [15, 16].

5. Risk-Based Inspection Decision Architecture

5.1. From Defect Evidence to a Risk Register

The proposed framework begins with a segment-level register that records unique asset identifiers, pipe properties, commissioning history, route coordinates, protection systems, inspection findings and unresolved anomalies. Threat assessment then assigns a defensible dominant mechanism and a record of plausible interactions. Data sufficiency is evaluated before computing risk: missing wall-thickness data, outdated protection tests or uncertain defect alignment should be visible decision flags. A qualified engineering team selects a corrosion-growth representation commensurate with evidence, from conservative bounded scenarios to calibrated stochastic prediction. This staged approach is consistent with literature advocating risk-based integrity management while avoiding premature reliance on elaborate models [1-3].

At a defined future time, probability of failure should represent the chance that a specified limit state is crossed, conditional on current evidence and assumptions. Consequence assessment must remain separate, considering credible release quantity, ignition conditions where relevant, worker and public exposure, environmental receptors, service disruption and restoration complexity. Risk is then evaluated over a common time horizon; simply multiplying ordinal "high" and "medium" categories cannot produce an annual monetary expectation. Different loss categories also require careful treatment to avoid double counting. In Figure 1, technical evidence, assurance checks and management approval form a closed loop rather than a one-way scoring exercise.

For reproducibility, a minimal risk calculation can be expressed as the expected loss over a stated period: the sum, across mutually exclusive failure scenarios, of each scenario probability multiplied by its corresponding consequence. Where consequence categories cannot be defensibly monetised, the result should remain a vector of safety, environment, availability and financial indicators. Probabilities should describe a clearly defined event, for example leakage before the next scheduled inspection, and should not be confused with uncalibrated classification scores. This discipline enables decisions to be challenged and recalculated when evidence changes.

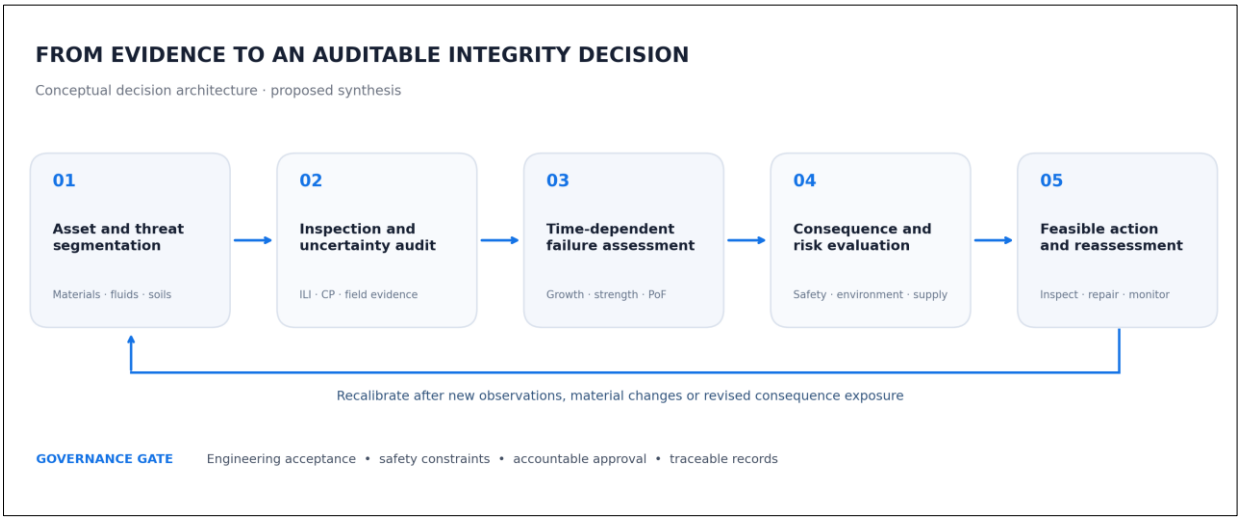


Figure 1: Proposed corrosion-informed integrity decision architecture. This is an original conceptual synthesis; it is not a Saudi field-study result

5.2. Inspection Value and Decision Rules

An inspection is valuable when its expected information changes an action or prevents an unacceptable risk trajectory. High uncertainty alone does not necessarily justify an expensive run if alternative actions would be identical under every plausible outcome. Conversely, an apparently moderate expected risk may require immediate verification if a low-probability but severe failure scenario breaches a mandatory safety threshold. The decision set should distinguish continued operation with monitoring, targeted inspection, pressure restriction, coating or protection correction, local repair and segment replacement. A newly discovered anomaly is subjected to engineering assessment before an economic optimiser is permitted to defer intervention.

The optimal future inspection date can be framed as a constrained choice: minimise expected discounted inspection, repair, disruption and failure-related losses, subject to mandatory acceptance criteria and risk tolerability. Bayesian maintenance studies demonstrate that corrosion trajectories and inspection observations can update decision probabilities [5-16]. Dynamic analyses addressing combined damage show that treating interactions explicitly can alter timing [15]. An expected-cost minimum is therefore not automatically a permissible policy; legal, process-safety and engineering constraints establish the feasible region first. Figure 2 depicts this qualitative trade-off without attributing numerical savings to the literature.

The expected value of sample information provides a useful conceptual test. It compares the best expected decision before an inspection with the expected best decision after possible inspection outcomes, net of the inspection cost. Although detailed calculations may require decision trees or simulation, the principle is simple: collect information when it has a credible prospect of improving a consequential choice. Tool selection, detection capability and inspection interval should therefore be co-designed, not purchased or approved as separate activities.

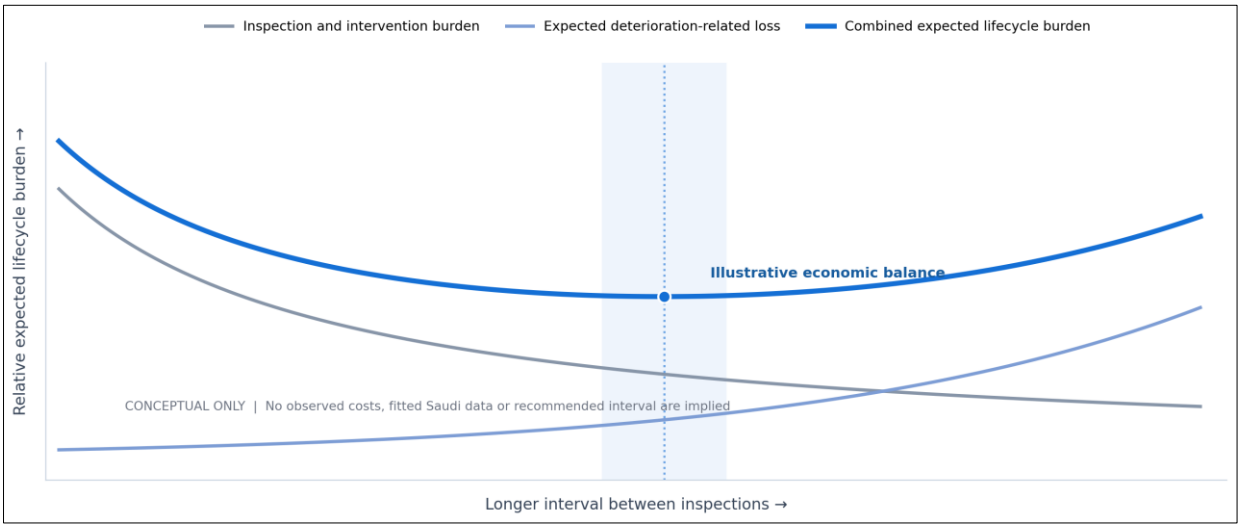


Figure 2: Qualitative lifecycle trade-off for inspection scheduling. Curves are illustrative only and contain no observed or calibrated numerical data

5.3. Uncertainty, Validation and Model Governance

Three uncertainty classes should be distinguished. Aleatory variability represents physical differences among locations or future loading; epistemic uncertainty arises from limited knowledge of corrosion processes; and measurement uncertainty reflects inspection error. Bayesian neural-network applications can communicate uncertainty in external pitting predictions [9], while empirical learning may provide a narrower forecast that is poorly calibrated beyond its training domain. Decision records should show which uncertainty components have been quantified, which remain judgemental and how they affect the chosen inspection date. Where available data are weak, sensitivity analysis and conservative screening are more credible than unsupported decimal precision.

Validation must follow the complete decision pathway. Predictive error on historical defect depth is useful, but a production programme also needs checks against field-measured depth, observed defect growth, safe-operation decisions and the frequency of avoidable interventions. Calibration should be tested across geography, vintage, diameter, coating type and operating service to uncover systematic bias. Data leakage between training and test inspection runs can make algorithms appear stronger than they are; temporal and asset-level holdouts are preferable. Models should be version-controlled, independently reviewed after significant changes and suspended if monitoring shows material performance drift. Advanced analytics can support engineering authority but cannot replace it.

Table 2: Proposed decision controls and minimum evidence for a Saudi pipeline integrity pilot

Decision stage	Minimum supporting evidence	Release / escalation rule
Screen and segment	Unique asset ID, pressure service, material, environment and threat history.	Escalate missing identity or unresolved high-consequence threats.
Assess anomaly	Calibrated sizing, growth assumptions, pressure demand and strength acceptance.	Immediate engineering disposition if acceptance may be breached.
Quantify risk	Time horizon, uncertainty basis, distinct leak/burst scenarios, exposure map.	No deferral where mandatory risk or safety thresholds fail.
Select action	Comparable costs, operational constraints, access and expected benefit.	Authorised choice among feasible strategies; record sensitivity.
Revalidate	Post-action inspection, protection tests, incidents and performance drift.	Reopen decisions when new evidence changes material assumptions.

6. Lifecycle Economics and Reliability

Lifecycle assessment integrates capital repairs with the recurring costs of inspection, monitoring, access, shutdowns, remediation and deferred maintenance. These cash flows must be compared on a consistent horizon and discount basis, with explicit treatment of failure consequences rather than only inspection contractor expenditure. A very frequent inspection policy can consume resources while adding little decision value; a long interval can increase expected deterioration-related loss. Risk-based optimisation studies support searching between these extremes [15, 16], although a published cost minimum from one pipeline is not transferable as a Saudi-wide optimal period. A change in product, pressure, route accessibility or consequence exposure can reverse the ranking.

Reliability benefits should be expressed through measurable service outcomes: unplanned interruption duration, throughput availability, containment incidents, emergency repair rates and integrity-driven operating restrictions. These outcomes differ from the number of inspections completed. An operator could improve inspection compliance without improving containment reliability if detected anomalies are not assessed and repaired appropriately. Similarly, an aggressive replacement programme may reduce technical risk while imposing unnecessary interruption or capital cost. Comparing alternatives requires a baseline, common operating assumptions and uncertainty bounds. The evidence from pipeline case studies is methodologically informative but does not support a universal percentage improvement [22, 23].

A practical implementation should maintain two related ledgers: an engineering risk register and an economic decision register. The first records limit-state margins, data quality, deadlines and mandatory action; the second records feasible policy alternatives, expected expenditure, interruption effects and assumptions about loss. This separation safeguards non-negotiable safety requirements while making discretionary expenditure traceable. Scenario analysis should test high-corrosion growth, inspection under-sizing, reduced access and escalation in repair costs before a preferred plan is authorised.

Economic models must also distinguish prospective expenditure from sunk cost. Past installation costs should not determine whether a present repair is warranted, whereas future replacement expenditure, downtime and the cost of creating access are decision relevant. Discounting should never obscure imminent safety requirements; sensitivity to discount assumptions is most informative for discretionary long-horizon replacements. Risk transfer through insurance also does not eliminate physical exposure. The preferred programme is therefore the lowest-cost feasible strategy that meets independent engineering and societal requirements, not the option with the smallest immediate maintenance budget.

7. Application to Saudi Pipeline Networks and Vision 2030

Saudi deployment should start with segmentation that recognises environment and service rather than administrative boundaries alone. Inland buried oil lines, sour-gas transport, coastal facilities and offshore connections are unlikely to share the same corrosion processes or consequence models. For each class, local operating histories should establish credible exposure indicators, inspection feasibility, corrosion-control performance and potential release receptors. A common data dictionary can then support portfolio comparisons without suppressing site-specific engineering judgement. The framework does not presume that all Saudi assets are ageing or deficient; it proposes a method for identifying where evidence demonstrates elevated risk.

The link to Vision 2030 is operational rather than rhetorical. More reliable hydrocarbon logistics can support industrial continuity, while risk-targeted expenditure may release resources for modernisation without weakening containment protection. National capability can be strengthened through traceable inspection data, competence development, technically rigorous procurement and collaboration between pipeline operators, inspection suppliers and research institutions. The policy value lies in measurable reliability and safety improvements, not a claim that digitisation alone constitutes innovation. Demonstrated performance should be assessed by independent

engineering review and documented before claims of cost or environmental benefits are made.

A phased programme is preferable to immediate network-wide automation. Phase one would reconcile asset registers and identify critical gaps. Phase two would pilot repeated-inspection alignment and deterioration modelling on a limited set of technically comparable segments. Phase three would test alternative inspection intervals prospectively under unchanged acceptance criteria. Phase four would extend methods where calibration, decision quality and organisational readiness have been demonstrated. Governance should assign responsibility for threat identification, model approval, inspection execution, emergency response and the sign-off of residual risk. This prevents analytical outputs from becoming unowned recommendations.

Implementation metrics should be defined before selecting pilot assets. Suitable indicators include the share of segments with verified identifiers, completeness of protection histories, agreement between tool sizing and field measurement, time from anomaly detection to disposition, and the proportion of decisions that change after new evidence. Strategic performance indicators should track actual containment and delivery outcomes over sufficiently long periods. Reporting the number of algorithms installed, dashboards created or inspection kilometres completed would otherwise mistake activity for verified integrity improvement. Cross-functional review should include operations, corrosion engineering, inspection specialists, risk management and emergency preparedness.

8. Critical Discussion and Research Priorities

A recurrent weakness across the field is the mismatch between the complexity of proposed models and the quantity of independent evidence used to test them. Simulated training cases can support algorithm development, yet they do not capture every coating condition, inhibitor failure, measurement bias or interaction encountered in service. Machine-learning studies have expanded prediction possibilities [10–19], but stronger predictive fit is not sufficient unless uncertainty is calibrated and interventions improve decisions. Research should report not only statistical error but also the proportion of missed safety-critical defects, sensitivity to dataset shift and operational costs of false alarms.

A second weakness concerns temporal interpretation. Two defect measurements do not uniquely identify a stationary corrosion process, especially when each includes sizing uncertainty. Studies using repeated inspection data offer a stronger basis for time-dependent modelling [4-14], but more research is needed on feature matching, censored repairs and variable operating conditions. Future Saudi studies should report provenance and inspection characteristics alongside corrosion-depth trajectories, with appropriately protected mechanisms for cross-operator learning. Even anonymised datasets should preserve service and environmental context needed to judge external validity.

Third, consequence assessments must become more transparent and location-sensitive. A remote desert segment and a segment near people, sensitive ecosystems or major infrastructure can have similar predicted defect severity yet different priorities. Geographical decision frameworks are valuable precisely because they join structural and contextual evidence [9]. However, social and environmental consequences cannot always be reduced responsibly to a single monetary value. Multi-criteria reporting can preserve these distinctions while maintaining enforceable limits on intolerable outcomes. Dynamic assessments should also consider changing occupancy, construction activity and emergency access along the route.

Finally, the most useful prospective comparison is not algorithm against algorithm, but decision policy against decision policy. A credible pilot would compare a transparent baseline programme with a risk-updated programme, document the rules applied to the same asset population and follow predeclared safety and cost outcomes. Decision analysts should distinguish the benefit of better measurement from the benefit of a more sophisticated forecast. Studies of digital twins and rapidly updated risk demonstrate promising infrastructure for such comparisons [25, 26], but governance, interoperability and organisational uptake remain decisive barriers.

An additional research priority is to compare uncertainty communication formats. Engineers may understand a distribution of future pit depths, while finance or operational teams may prefer scenario bands and deadline-based actions. Both representations must lead to the same underlying acceptance decision. Studies should test whether users interpret probability, confidence and consequence consistently, especially when a model forecasts rare failures from small datasets. A sophisticated method that cannot be interrogated during a critical operating decision is of limited practical value.

9. CONCLUSIONS

Corrosion-informed risk-based inspection offers a coherent route from pipeline evidence to better prioritised integrity actions, provided it remains anchored in physical failure assessment and independent safety constraints. The literature supports combining mechanism-specific threat models, credible inspection characterisation, probabilistic deterioration and consequence analysis; it does not justify transferring a single corrosion rate, model accuracy or inspection interval to all Saudi assets. Effective lifecycle optimisation asks whether additional information or intervention changes a defensible action, rather than simply ranking defect severity.

For Saudi Arabia, the immediate priorities are trustworthy segmented asset records, validation against local field evidence, transparent uncertainty statements and accountable approval of risk-reduction choices. Staged pilots should establish whether the proposed architecture improves containment reliability and total lifecycle performance under actual operating conditions. Future research must evaluate interacting damage, non-piggable assets, changing environmental exposure and the decision consequences of prediction errors. These requirements connect practical pipeline safety with sustainable industrial reliability under Vision 2030 while remaining explicit about the limits of currently published evidence. Independent replication across different Saudi operating environments is necessary before adopting any proposed decision thresholds at national scale.

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