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Review Article

Risk-Based Quality Assurance and Advanced Pipeline Integrity Management for Long-Distance Crude Oil and Gas Transmission Systems in Saudi Arabia

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Abstract: Long-distance crude oil and gas pipelines depend on a chain of assurance extending from material acceptance and girth-weld qualification to corrosion surveillance, defect assessment and intervention. These activities are frequently managed as separate programmes, although an undetected construction deviation can later appear as an integrity threat, while uncertain inspection data can distort repair priorities. This critical review examines research published between 2020 and 2025 to develop a joined-up, risk-based quality assurance and integrity management approach for Saudi Arabian transmission corridors. Thirty DOI-traceable scholarly contributions were evaluated through a structured thematic synthesis covering degradation mechanisms, construction controls, in-line inspection, probabilistic risk assessment, digital monitoring and decision governance. The literature supports combining threat-specific inspection with verified asset records and consequence-sensitive maintenance planning; it does not support indiscriminate use of predictive algorithms without representative field validation. An evidence-led framework is proposed in which construction quality records, spatially referenced condition measurements and uncertainty-aware risk calculations inform proportionate actions. Particular attention is given to desert soils, variable route exposure, crossings, corrosion protection and high-consequence pipeline sections. The contribution is a practical decision architecture, not an untested claim of predictive accuracy or a Saudi field trial. Recommendations identify how owners can improve auditability, target scarce inspection resources and preserve confidence in decisions throughout the asset lifecycle.

Keywords: Pipeline Integrity, Risk-Based Quality Assurance, Crude Oil Transmission, Gas Transmission, Corrosion, In-Line Inspection, Saudi Arabia.

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1. INTRODUCTION

Crude oil and gas transmission lines are geographically distributed pressure systems whose safety cannot be established by a single inspection certificate. Thousands of welds, coating interfaces, appurtenances and crossings accumulate distinct fabrication and operating histories. Although individual defects may be small, their significance changes with pressure cycling, corrosion progression, soil movement, nearby activity and the consequences of a release. Risk-based pipeline integrity management therefore requires more than a defect list: it needs a defensible explanation of what is known about each segment, how reliable that

knowledge is and what intervention follows from it [1-6].

The issue is especially pertinent to Saudi Arabia, where long-distance energy transport supports industrial continuity and export logistics across extensive and environmentally diverse corridors. Buried steel may traverse saline ground, dry terrain, wadis, industrial approaches and developing transport routes. These settings should not be treated as uniformly corrosive or equally exposed to external interference. A water-collecting depression and an undisturbed upland section can have markedly different threat profiles despite sharing a design specification. Internal chemistry and water management also distinguish crude service from dry or wet gas service. External corrosion literature identifies environmental, coating and electrochemical interactions as central to assessing these differences [2-21].

The conventional division between quality assurance during construction and integrity management during operation creates a consequential information boundary. Construction records identify pipe heat, wall thickness, weld parameters, repair history, coating tests and route coordinates; later assessments depend on many of the same variables. When those records are incomplete, asset teams compensate with assumptions, generic risk weights or additional excavations. A risk-based system should instead treat traceability as a measurable control and retain the connection between initial acceptance evidence and subsequent inspection findings [23, 24].

Recent scholarship has expanded available choices. Magnetic flux leakage, ultrasonic systems, geometry tools, condition monitoring and probabilistic models can characterise different features, while dynamic risk frameworks update estimates as evidence changes [3-25]. Yet sophistication alone cannot correct uncertain measurements or inappropriate assumptions. A model trained on simplified defects cannot automatically classify interacting corrosion and dents in an operating transmission system. Similarly, a lower computed probability of failure does not justify postponing action when a credible high-consequence scenario remains unresolved [8-19].

The aim of this review is to formulate an integrated assurance framework that links construction quality, degradation-specific evidence and risk-informed intervention for Saudi long-distance crude oil and gas transmission systems. Its objectives are to distinguish threat mechanisms and their verification needs; critically compare inspection and monitoring capabilities; examine how uncertainty enters failure and consequence estimates; and specify auditable decision gates for prioritising repair, protection and reinspection. The central argument is that risk-based management becomes credible only when each risk ranking can be traced backwards to qualified evidence and forwards to a verifiable action.

2. REVIEW DESIGN AND ANALYTICAL METHOD

A structured critical review was undertaken rather than a pooled statistical meta-analysis. The literature was identified through focused searches of scholarly publisher records and academic discovery sources using combinations of pipeline integrity, risk-based inspection, quality assurance, corrosion, cracking, in-line inspection, third-party damage, reliability and digital monitoring. The publication window was restricted to 2020–2025. The resulting evidence set comprised thirty scholarly works with identifiable titles, publication years and DOI records. Priority was given to work containing methods, performance qualifications, field applications or transparent evaluations of model limitations, rather than unsupported technology advocacy [1-27].

Each source was read against four questions: which physical or organisational threat was addressed; what observations or assumptions supported the result; how uncertainty and transferability were treated; and what decision the evidence could reasonably change. The material was then synthesised into construction assurance, degradation control, inspection reliability, probabilistic assessment and operational governance. This form of qualitative synthesis is suitable because the studies vary in pipe geometry, media, experimental design, operating conditions and outcome measures. Aggregating their reported accuracies into one numerical performance estimate would obscure those differences.

The synthesis distinguishes three evidence levels. Field observations directly describe an operating asset, provided their calibration and location are credible. Laboratory and numerical investigations test mechanisms under specified boundary conditions, but require transfer checks before operational use. Conceptual frameworks support process design without demonstrating the effectiveness of a particular implementation. These categories are not a hierarchy in which modelling is inherently inferior; they identify different claims that a study can legitimately sustain. Where a proposed Saudi application extrapolates from international research, it is labelled here as a contextual engineering recommendation, not an observed local outcome [7-28].

Selection was judged for practical relevance as well as topic matching. A corrosion algorithm with a high reported classification score was not treated as stronger evidence than a modestly performing field inspection if the former lacked representative operating data. Studies were compared through the chain from input definition to decision consequence, with particular attention to how missing observations were handled. Conflicting findings were not forced into agreement; instead, differences in detection physics, asset populations and stated objectives were used to explain their implications. This approach favours transparent, transferable engineering reasoning over the appearance of a single universal answer.

The review has defined limits. It does not claim an exhaustive census of all published papers, access to confidential operator inspection databases, or independently measured Saudi failure frequencies. Nor does it calculate a universal inspection interval. The contribution is instead a reconciled interpretation of published evidence and a testable governance approach. Thematic consistency was checked by comparing different methodologies addressing the same threat, particularly corrosion forecasting, leak detection and damage interactions [4-12].

3. Threat Mechanisms and the Quality-Assurance Boundary

3.1. Construction Quality as a Future Integrity Variable

Pipeline quality starts with procurement and manufacture, not the final hydrostatic test. Material identification, grade confirmation, dimensional checks and traceable mechanical properties establish the design basis. During construction, fit-up, welding procedure compliance, consumable control, environmental protection and nondestructive examinations create evidence that discontinuities are acceptable under specified criteria. Research on long-distance automatic welding emphasises controlling personnel, equipment, material, method and site environment together; a nominally approved procedure cannot compensate for uncontrolled execution [23].

Girth weld records need to connect the actual joint, welder or machine, procedure revision, inspection images, indications, repair cycles and final disposition. A digital identifier without complete supporting records merely makes a gap searchable. Welding quality diagnosis based on fused models has shown the potential of combining several information sources, but it also illustrates why classifier output is not a substitute for independently qualified examination criteria [24]. For welds at transitions, crossings and constrained tie-ins, examination coverage, access limitations and loading conditions should be recorded explicitly rather than hidden inside aggregate acceptance percentages.

Coating and backfilling introduce another transition. Holiday detection, surface preparation checks, handling damage assessments and post-lowering inspection can prevent exposure pathways which cathodic protection may not completely offset. Experiments on shielded or disbonded coatings show that protective current distribution cannot safely be inferred from a single convenient measurement [22-29]. Acceptance records should consequently preserve coating type, application conditions, repair locations, soil-contact details and cathodic protection commissioning baselines. These records allow later investigators to differentiate a newly developing threat from an inherited construction vulnerability.

Pressure testing and baseline inspection provide valuable commissioning evidence but answer narrower questions than is sometimes assumed. A successful pressure test confirms the tested boundary endured a specified pressure-time exposure; it does not establish that all subcritical flaws have been detected or that future corrosion is absent. Equally, baseline intelligent inspection can identify manufacturing and construction features only within the tool's qualified sensitivity and coverage. Acceptance decisions should therefore document test medium, pressure, duration, instrumentation traceability, temporary boundaries and post-test preservation. Where testing water could remain trapped, dewatering and drying records become important information for later internal corrosion assessment.

Quality assurance is often judged by rejection rates, but such rates can be misleading. An unusually low weld rejection proportion may reflect sound workmanship, insufficient inspection sensitivity or inconsistent defect classification. A rise in repair counts may indicate either declining production quality or better detection. Useful indicators therefore combine completeness, method qualification, independent verification and defect recurrence rather than rewarding a low number alone. The crucial outcome is evidence that each pressure boundary element has been examined against the correct acceptance basis.

3.2. External Corrosion, Internal Degradation and Cracking

External corrosion involves more than soil aggressiveness. Coating discontinuities, moisture availability, dissolved salts, electrical interference and cathodic protection performance interact over time. Wasim and Djukic describe how corrosion, environmentally assisted cracking and hydrogen-

related mechanisms may share contributing conditions while requiring different integrity responses [2]. Saudi route sections near irrigated developments, saline ground or intermittent drainage deserve site-specific evidence; however, their risk should be determined by measured conditions, not geography alone.

Internal corrosion is similarly service-dependent. Deposited water, unstable phase behaviour, carbon dioxide, hydrogen sulphide, bacterial activity and inhibitor distribution may contribute under relevant conditions. Studies of top-of-line corrosion underline the importance of condensation and chemical environment, but they cannot establish its prevalence in every long-distance transmission line [21]. Effective assurance links fluid specifications, sampling locations, operating transients, water removal and corrosion monitoring to segment-specific exposure hypotheses. When data are absent, that absence should reduce decision confidence instead of being interpreted as evidence of negligible corrosion.

Stress corrosion cracking requires a susceptible material, tensile stress and an enabling environment. It may evolve beneath compromised coatings without providing a simple surface indication. Metal-loss tools should not therefore be assumed to exclude cracking. Interacting threats can be particularly important: a dent modifies local stress, while adjoining corrosion can reduce remaining strength. Huang and colleagues demonstrate that representing the coupling of dents and external corrosion changes risk-informed inspection planning [3]. A quality system that stores anomalies as isolated rows but suppresses their relative positions may miss precisely this interaction.

Third-party excavation, unintentional contact and ground movement present a different evidence problem. Threat probability varies with nearby activities, protection, location quality, public awareness and change over time. Bayesian approaches to excavation damage show the value of representing causal dependencies, rather than assigning one fixed score to every kilometre [13, 14]. Route surveillance and stakeholder coordination should therefore be integrated with integrity records. An apparently pristine wall does not make a pipe immune to external impact or loss of support.

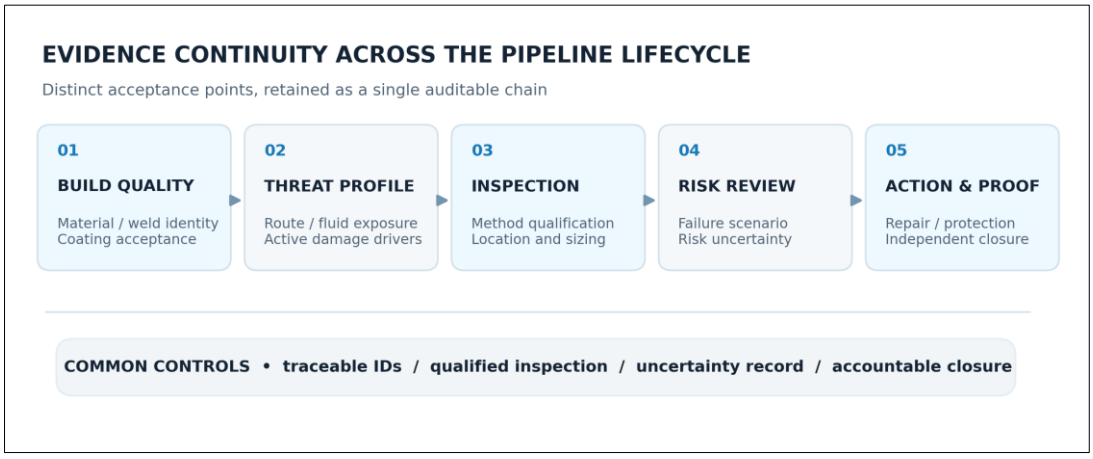


Figure 1: Lifecycle evidence chain proposed for risk-based pipeline integrity governance. Original conceptual synthesis

4. Inspection Selection, Verification and Monitoring

4.1. Fitness of Inspection Methods to Damage Hypotheses

An inspection technique is useful only when its measurement physics match the threat being investigated. Magnetic flux leakage is established for many metal-loss applications, while ultrasonic methods can characterise wall thickness and selected crack-like features, subject to coupling and operating constraints. Geometry measurements assess deformation; complementary technologies may be needed where coating condition, stress or small planar flaws dominate. Recent technology surveys stress the difference between detecting an anomaly, identifying its mechanism and sizing it accurately enough for engineering assessment [25, 26].

The consequences of a wrong match are substantial. A metal-loss signal may be confounded by material variation or geometry, while a crack-oriented tool may have limited coverage for certain orientations, openings or wall conditions. Laboratory simulation combined with neural networks has improved interpretation of magnetic signatures, yet reported accuracy depends on training distributions, sensor behaviour and the availability of representative defect shapes [17, 18]. Reconstruction

of three-dimensional defect profiles is promising for engineering calculations, but reconstructed surfaces should be treated as estimates carrying error, not direct replicas of the pipe wall [19].

A useful inspection qualification statement should identify probability of detection, probability of identification and sizing accuracy separately. Confidence in detecting metal loss of a given depth does not automatically imply equal confidence in differentiating a crack, groove or manufacturing feature. Sensor lift-off, magnetisation, tool speed, wall thickness and signal processing may change error distributions. Acceptance criteria should distinguish random variation from systematic bias, because repeated measurements with the same bias can appear reassuringly consistent while remaining wrong. When vendors use proprietary processing, owners still need sufficient performance evidence to support independent engineering decisions and contractual acceptance.

Field verification is the essential bridge between tool output and maintenance priority. Targeted excavation, calibrated ultrasonic mapping, visual examination and metallurgical evaluation can test both sizing bias and feature classification. Verification locations should include challenging anomalies and a defensible sample of apparently benign signals; otherwise, confirmation selectively favours findings already considered serious. Records must reconcile chainage, joint identity, depth reference and spatial uncertainty across successive surveys. Inadequate feature matching can create false corrosion-growth rates, with serious implications for the next inspection date [5-25].

Inspection selection should also account for operational feasibility. Launcher dimensions, bends, valves, pressure, product flow and cleaning history govern whether a tool can traverse a line safely. A digital representation of inspection-tool movement may improve planning under low-flow conditions, as investigated by Yoo and colleagues, but validated tool passage is a prerequisite to trusting downstream measurements [28]. Where a line is not readily inspectable, alternate methods require an explicit statement of coverage and blind spots. A convenient substitute does not automatically offer equivalent assurance.

Table 1: Threat-led inspection and assurance requirements for transmission pipelines

Threat	Quality/route evidence	Targeted verification	Decision limitation
External metal loss	Coating records; CP surveys; soil and interference data	MFL or UT; direct examination; protection checks	Shielding and sizing errors may persist
Internal corrosion	Fluid and water history; deposits; inhibitor records	ILI wall measurements; sampling; targeted UT	Average rate may conceal localised attack
Cracking and welds	Weld map; stress history; procedure deviations	Qualified crack-sensitive UT/EMAT; field NDE	A metal-loss-only run is not proof of absence
Dents / movement	Crossing design; depth of cover; route change records	Geometry tools; strain assessment; geospatial survey	Damage interactions require joint assessment
Third-party contact	Activity permits; protection; crossing surveillance	Patrols; excavation review; targeted examinations	Low corrosion risk does not equal low overall risk

4.2. Surveillance, Leak Detection and Complementary Evidence

Continuous surveillance and periodic condition inspections answer different questions. In-line inspection identifies accumulated structural features; pressure, flow, acoustic and other monitoring systems can indicate changing operating states or potential loss of containment. Reviews of pressure-wave approaches identify trade-offs between localisation, sensitivity and susceptibility to transient background signals [9-30]. Leak-detection literature also shows that single-phase and multiphase conditions change what models can reliably distinguish [11, 12]. These observations argue for layered detection with alarm performance assessed against realistic operations.

For crude transmission, changing flow regimes, pumping events and thermal effects can resemble disturbances requiring attention. For gas lines, compressibility, linepack and valve operations complicate interpretation. A leak algorithm calibrated under steady conditions may fail during start-up or shutdown. The review by Yuan and colleagues emphasises the range of competing methods and the importance of application context [10]. Operational procedures should therefore define alarm verification, escalation, sectional isolation and post-event analysis, rather than treating each software indication as conclusive.

Data-driven monitoring can recognise complex patterns, but model development and field deployment remain distinct stages. Zuo and co-workers used self-supervised methods to address scarce labelled leak data, demonstrating one route toward practical classification [20]. Wang and colleagues integrated physics-based and data-driven

components in a pipeline monitoring prototype that explicitly represents uncertainty [7]. Such advances strengthen monitoring when they are tested for drift, false alarms, missed events and changes in operating envelope. They do not remove the need for instrument calibration, hydraulic knowledge or accountable human decisions.

A high-quality integrity programme uses discordant evidence diagnostically. A stable cathodic protection record alongside accelerated external metal loss should trigger an investigation of shielding, interference or feature matching. A new leak alarm without corresponding mass-balance evidence calls for careful discrimination, not automatic dismissal. Combining independent measurements can strengthen confidence only when their errors and common dependencies are understood. Two algorithms trained on the same flawed dataset are not two independent confirmations.

5. Risk Modelling, Uncertainty and Intervention Economics

Risk is commonly understood as the combination of failure likelihood and consequence, but the calculation is meaningful only if both components are defined for the physical scenario under consideration. Corrosion depth, wall thickness, material resistance, operating pressure and growth rate contribute to structural failure probability; release volume, ignition conditions, exposure and isolation capability shape the consequences. Khan and colleagues outline risk-based management as a route to resilience, while later work develops consequence-dependent maintenance timing and explicit treatment of corrosion-rate uncertainty [1-4].

Risk maps should not be confused with proof of safety. An integer matrix may support transparent initial screening, but multiplying subjective scores can conceal uncertainty and produce an unjustified sense of precision. Probabilistic approaches can improve this by treating uncertain inputs as distributions and estimating leak or rupture probabilities under stated assumptions. Zelmati and colleagues use inspection-derived degradation information to examine remaining life, while Li and colleagues analyse multiple corrosion-related failure modes [5-15]. Their methods demonstrate useful directions, not numerical parameters transferable unchanged between countries, pipe grades or operating histories.

A single average corrosion rate also deserves scrutiny. Localised attack may advance irregularly and inspection errors can make apparent growth negative. The engineer should assess feature matching, minimum detectable size, systematic tool bias and time between inspections before fitting a trend. Correlated defects across a pipeline segment require care because treating every pit as independent can distort aggregate reliability. Model output should therefore include uncertainty intervals, sensitivity to assumptions and the evidence needed to narrow those intervals. The objective is a defensible decision, not a visually impressive risk score.

Consequence assessment deserves equivalent technical discipline. A crude release scenario should examine inventory, terrain, drainage pathways, environmental receptors and realistic valve isolation performance; a gas scenario additionally needs dispersion and ignition assumptions appropriate to its composition and surroundings. Remote location does not guarantee low consequence where access constraints or sensitive receptors exist. Conversely, proximity to infrastructure should not be converted mechanically into catastrophe without considering credible release size and effective barriers. Scenario assumptions must be version controlled, since development near the right of way, pressure changes and emergency response capability can alter consequences independently of the pipe's measured strength.

Compounding threats challenge traditional segment-by-segment ranking. Huang and colleagues explicitly couple dent and corrosion deterioration in their inspection planning model [3]. Gholami and colleagues address the remaining strength of externally damaged pipe by linking geometry and failure analysis [16]. These studies imply that the assessment unit should be an interacting defect cluster where the physics warrant it. Likewise, third-party damage probability may rise sharply during nearby construction despite unchanged wall condition. Dynamic Bayesian approaches offer a mechanism for updating risk when such contextual information changes [13, 14].

Interventions should be evaluated against both risk reduction and execution burden. Excavation is not harmless: access, traffic, line pressure, weather, permits and the risk of accidental contact create additional exposure. Pressure reduction may offer a controlled interim measure, while immediate repair can be appropriate where uncertainty is unacceptable. Cost-based optimisation is useful when it includes realistic mobilisation, production disruption, environmental consequence and monitoring expenses. A least-cost inspection interval that overlooks credible severe outcomes cannot be regarded as optimal. De-León-Escobedo's consequence-based formulation reinforces the need to align tolerable reliability targets with potential harm [4].

Digital tools are best used to expose and test these judgements. Xiao and colleagues propose rapid learning-based risk estimation for corroded gas lines, and Wahono and co-workers review the expansion of analytical methods within asset integrity management [8-27]. However, rapid inference is useful only after a model's operating domain, calibration, input completeness and retraining procedures have been established. Human engineering review remains vital for rare failure modes, unusual combinations and major changes in operating conditions. A model should make its uncertainty visible enough to justify deferral, not obscure it.

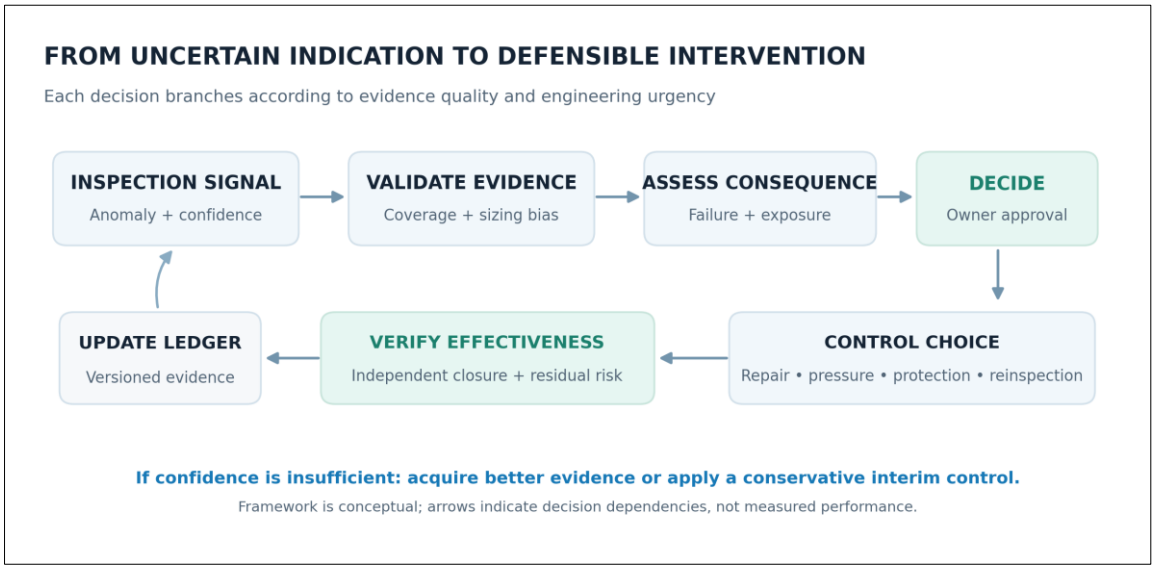


Figure 2: Evidence qualification and intervention loop. Decision dependencies are illustrative, not field performance data

6. Integrated Assurance Framework for Saudi Transmission Systems

6.1. Segment-Level Evidence Architecture

The proposed framework divides a transmission corridor into engineering segments based on relevant differences in design, coating, ground conditions, access, third-party exposure and consequences. Administrative kilometre markers remain useful identifiers but should not dictate risk boundaries. Each segment receives an evidence ledger connecting design and construction records to inspection runs, protection monitoring, operating history and interventions. The ledger distinguishes verified measurements from inferred properties and unknowns. Cheng's lifecycle perspective supports retaining this continuity beyond the construction-to-operations handover [6].

The first assurance gate concerns asset identity: pipe properties, weld mapping, wall thickness, material documentation, coating condition and spatial location must agree. The second gate establishes threats, including internal chemistry, external protection, cracking susceptibility, dents, geohazards and human interference. The third tests evidence fitness, asking whether the selected inspection can reveal the suspected mechanism and whether its uncertainty is quantified. The fourth assesses failure and consequence under the actual operating envelope. The fifth authorises action, records its rationale and specifies how effectiveness will be verified. Each gate has an accountable owner and an auditable outcome.

For a dry inland segment with sound coating history and low activity nearby, surveillance and scheduled inspection may be proportionate. A segment at a wadi crossing with damaged coating and variable ground moisture could require additional electrochemical surveys and targeted verification. A pipeline approaching a built-up industrial connection warrants particular consideration of response time, isolation, access and third-party activity even where degradation measurements are similar. These are illustrative decision situations, not reported Saudi case studies or preset risk rankings. The framework's value lies in how it changes the questions asked before resources are allocated.

6.2. Governance and Escalation

Decision quality requires an explicit distinction between acceptance, tolerability and uncertainty. A pipeline feature may satisfy one screening calculation while remaining insufficiently characterised for a final disposition. Accordingly, every material decision should carry four elements: the observed threat and evidence source; method limits and unresolved assumptions; the approved

engineering criterion; and the next verification or mitigation deadline. Holding this record allows later reviewers to determine whether an earlier decision was reasonable when made, rather than judging it only with subsequent knowledge.

Escalation should be governed by technical triggers. Newly discovered cracking, unexpectedly rapid metal loss, unexplained protection changes, a failed inspection run or credible third-party contact can require immediate reassessment. Routine risk dashboards should not delay safety-critical responses pending a periodic committee meeting. Conversely, numerous minor indications do not justify blanket excavations when verified engineering assessment shows low urgency. A disciplined programme balances prompt action where necessary against unnecessary disturbance, while preserving a clear route for independent challenge.

Implementation can be staged rather than imposed across an entire network at once. A pilot should select contrasting segments with sufficiently complete historical records, reconcile identifiers and establish a documented baseline before introducing predictive rankings. Engineering reviewers can then run the new framework in parallel with existing decisions, recording where recommendations differ and why. Independent confirmation of selected anomalies, near misses and apparently low-risk areas is important to avoid learning only from successfully detected defects. Expansion should depend on demonstrable improvements in traceability, timeliness and decision consistency, not merely on dashboard adoption or the volume of digitised documents.

A second governance problem is organisational fragmentation. Construction contractors, welding inspectors, corrosion specialists, operations teams and analysts may each use different identifiers and databases. Interface failures can generate inconsistent joint counts, duplicated anomalies and incomplete closure records. The owner should maintain controlled reference data and change history, with independent assurance sampling across contractual boundaries. Inspection vendors should submit machine-readable measurement definitions and quality limitations alongside reports. Data ownership, access permissions and cybersecurity also matter because the integrity ledger becomes an operationally significant information system.

Table 2: Five evidence gates for auditable integrity decisions in transmission systems

Decision gate	Required evidence	Owner question	Escalation or acceptance
1 Asset identity	Joint-level acceptance and verified coordinates	Is the assessed section correctly identified?	Correct record gaps before risk credit
2 Threat credibility	Mechanisms linked to local operating exposures	Could another plausible mechanism be missed?	Expand sampling or add inspection modality
3 Data qualification	Detection coverage, sizing error, field confirmation	Can the method support the proposed decision?	Qualify or repeat measurement when necessary
4 Risk tolerance	Failure assessment, scenario consequences, uncertainty	Is deferral defensible under current conditions?	Control pressure, monitor, repair or inspect
5 Verified closure	Evidence of mitigation and remaining exposure	Did the intervention reduce the intended risk?	Independent check and ledger update

7. Research Implications and Limitations

The most promising direction is not a universal artificial intelligence score but reproducible integration of field evidence. More paired inspection and excavation datasets are required to test tool sizing errors across defect morphologies, soils and operating conditions. Research should also examine how missed defects affect decisions, rather than reporting only average prediction error. Corrosion forecasts need external validation against changing protection conditions and product chemistry. Current studies already demonstrate valuable methods, yet transfer from finite-element datasets or limited routes to national-scale operations remains a significant challenge [17-27].

Future studies in Saudi Arabia could compare matched segments using prospectively specified acceptance indicators: record completeness, confirmed defect classification, uncertainty in failure probability, timely mitigation and reinspection closure. Comparisons must adjust for differences in route exposure and inspection opportunity, not simply count repairs. Independent assessment of false-negative rates would be particularly useful for advanced analytics. Such research could establish whether integrated records improve outcomes beyond conventional document repositories, providing evidence that the present conceptual synthesis cannot supply.

An additional research priority is calibration over time. A model may initially discriminate serious

defects but deteriorate when measurement technology, pipe population or operating practice changes. Prospective validation should test drift, sensitivity to missing fields and the stability of thresholds under plausible stress cases. Decision trials should record disagreements between specialist judgement and automated output, along with resolution and subsequent observations. Such studies would reveal whether machine learning complements engineering knowledge or simply reproduces historical maintenance choices. Careful study design is essential because the absence of recorded failure is not proof that an inspection or model was effective.

There are limitations to this review. Sources use heterogeneous methods and reporting standards, and not all provide field-level validation or directly comparable economic outcomes. The thirty-work evidence set is focused rather than exhaustive; it cannot support claims about the prevalence of threats on Saudi assets. The proposed gates require piloting, regulatory alignment, operator-specific criteria and ongoing professional judgement. Nevertheless, linking construction assurance to measurable threats and accountable interventions is a testable route toward more reliable decision making.

8. CONCLUSIONS

Risk-based quality assurance and pipeline integrity management should be treated as one continuing evidence problem, not as separate construction and maintenance disciplines. The review finds strong reasons to retain traceable weld and coating records, select inspection technologies against defined damage mechanisms, verify uncertain anomalies and include failure consequences explicitly in maintenance decisions. Probabilistic methods can sharpen priorities, while data-driven monitoring can make emerging problems more visible; neither eliminates the effects of incomplete inputs, model bias or unverified operating assumptions.

For Saudi crude oil and gas transmission systems, the proposed contribution is a segment-level evidence ledger linked to five assurance gates from asset identity to verified intervention. It accommodates changing ground conditions, route activities, operating chemistry and high-consequence areas without pretending that all lines share one risk profile. The next step is controlled field evaluation with measurable outcomes and clear stop criteria. Programme performance should be judged not by how frequently inspections occur, but by whether verified findings alter proportionate decisions before threats escalate. Transparent evidence trails also permit structured learning from false alarms, late discoveries and interventions that did not deliver lasting, measurable protection. An integrity programme earns credibility when engineers can explain not only why a segment is ranked highly, but also what observation would change that ranking and how the resulting action will be checked.

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