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RESEARCH ARTICLE

ENHANCING PETROLEUM STORAGE TANK INTEGRITY IN SAUDI ARABIA UNDER VISION 2030: INTEGRATING API 653 INSPECTION, CORROSION RISK ASSESSMENT, AND RISK-BASED MAINTENANCE STRATEGIES

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Abstract

Petroleum storage tanks are indispensable buffers between Saudi Arabia's production, refining, distribution and export systems. Their apparently simple construction conceals interacting threats associated with floor pitting, shell thinning, settlement, deficient protective systems and accident escalation. This critical review evaluates how API 653 inspection can be combined with corrosion risk assessment and risk-based maintenance without confusing statutory or code requirements with predictive recommendations. Thirty DOI-identifiable studies published between 2020 and 2025 were synthesised by degradation mechanism, inspection capability, uncertainty treatment and maintenance implication. The evidence favours a layered strategy: establish a defensible mechanical-integrity baseline; characterise localised deterioration using complementary examinations; calculate remaining life with explicit uncertainty; and prioritise intervention according to failure likelihood, credible consequences and operational constraints. Reported advances in probabilistic pit modelling, acoustic emission, magnetic flux leakage, cathodic protection and image analytics offer useful decision support but do not replace qualified inspection or engineering judgement. A Saudi implementation framework is proposed that links assurance gates, auditable digital records and targeted interventions to environmental protection, operational continuity and domestic technical capability. The principal research gap is prospective validation across diverse tank services and climates, rather than further proliferation of isolated prediction models.

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Introduction:-

Saudi Arabian petroleum storage infrastructure connects oil fields, stabilisation plants, refineries, coastal terminals and inland distribution facilities. Disruption in a tank farm can propagate beyond the damaged vessel through interrupted product movement, contaminated soil, vapour exposure, emergency shutdown and fire. Integrity management consequently concerns a networked industrial asset, not merely the residual thickness of a steel plate. The priorities of Vision 2030, including energy-sector value creation, industrial localisation, logistics performance and environmental sustainability,make this distinction particularly relevant. The policy connection is strategic; it does not establish that a particular technology has already reduced Saudi tank failures. Tank degradation is difficult

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to evaluate because its most consequential manifestations can remain concealed. Water bottoms, deposits, aggressive interfaces and coating holidays encourage local attack on floor plates, whereas vapour-zone corrosion, external weathering, roof drainage defects and corrosion beneath insulation create different exposure histories. Foundation settlement may distort shell-to-bottom junctions and alter local stresses without producing a conspicuous corrosion signal. Failure can also arise from weld defects, overfilling and fire exposure. Studies of corrosion-driven leakage and major tank-farm accidents demonstrate why inspections must be linked to containment and consequence management rather than treated as isolated compliance exercises [1,2,10,16].

API 653 provides a framework for inspecting, assessing, repairing, altering and reconstructing in-service aboveground steel tanks within its scope. It addresses minimum requirements and fitness for continued operation; it should not be interpreted as a universal numerical prediction algorithm. Risk-based inspection, supported by the principles of API RP 580 and 581 where applicable, asks a different question: where does additional information or intervention most effectively reduce risk? These approaches are complementary only when risk optimisation remains subordinate to mandatory inspection provisions, appropriate engineering assessment and local regulatory obligations. Recent studies applying qualitative risk methods and advanced floor scanning illustrate the opportunity, while also revealing variability in assumptions and reporting [12,30].

The review's aim is to formulate an integrated, evidence-informed integrity management approach suitable for Saudi petroleum storage operations. Its objectives are to distinguish dominant degradation mechanisms from their observable indicators; compare complementary inspection technologies and their blind spots; critically appraise deterministic and probabilistic remaining-life estimates; translate likelihood and consequence into defensible maintenance priorities; and identify measurable implementation and research requirements. Unlike a project reporting experimental results from a particular tank farm, this article develops an analytical framework from published evidence and establishes testable propositions for future deployment.

Review Methodology:-

A structured critical literature review was selected because the research question spans engineering standards, corrosion mechanisms, nondestructive examination, reliability models, and process safety. Relevant work published during 2020–2025 was located through targeted searches combining terms such as atmospheric storage tank, API 653, floor corrosion, risk-based inspection, magnetic flux leakage, acoustic emission, cathodic protection, remaining useful life and domino accident. Publisher pages, scholarly records and DOI metadata were cross-checked to establish publication identity. Selection prioritised studies supplying explicit engineering methods, interpretable observations or transferable lessons; thirty DOI-bearing studies were retained for critical comparison. The resulting synthesis was purposive rather than an exhaustive census of available studies.

The unit of analysis was a technical claim rather than a paper count. Each publication was considered against four questions: what failure mechanism was investigated; what information was actually measured; which assumptions connected observations to a safety or maintenance decision; and what uncertainty or transferability limitations remained? Direct tank-floor evidence was weighted more heavily for corrosion forecasting than general plant-risk discussion. Fire and flooding studies were retained to evaluate consequences and competing failure modes, not to infer corrosion rates. Articles addressing intelligent inspection were assessed separately from those validating mechanical acceptability, because classification accuracy is not equivalent to verified wall thickness or leak prevention.

Synthesis followed five linked domains: condition characterisation, inspection evidence, deterioration forecasting, risk estimation and maintenance execution. Contradictory findings were interpreted in light of tank geometry, material, product, inspection coverage and statistical assumptions rather than averaged indiscriminately. The approach has two limitations. Full company inspection databases were unavailable, and the literature seldom reports common validation measures across fleets. Accordingly, numerical examples are omitted, conceptual figures are explicitly non-empirical, and recommendations are expressed as engineering decision rules requiring site validation. Standards define compliance boundaries but are discussed as governing practice rather than counted among the thirty DOI-bearing journal and conference sources.

Degradation mechanisms and Saudi exposure conditions:-

Floor corrosion and concealed loss of containment:-

The floor is often the controlling integrity component because its soil-facing surface cannot be examined directly in normal service. Product-side water, sediments and microbial activity may produce geographically concentrated pits, while underside corrosion depends on foundation moisture, electrical conditions, coating quality and cathodic protection effectiveness. Field investigations describe corrosion intensities that depart materially from assumptions based on uniform metal loss [6]. Studies using tank inspection histories similarly identify extreme pit depth, rather than fleet-average thinning, as a decisive predictor of penetration [7,18,28]. This distinction matters operationally: an acceptable mean plate thickness can coexist with a dangerous local defect.

Pitting should therefore be represented by both spatial extent and severity. Measurements need location, bottom-side attribution where defensible, detection threshold, remaining ligament and any associated weld or annular proximity. Corrosion growth may accelerate when pit chemistry becomes self-sustaining; the empirical comparison by Povše and colleagues questions the reliability of long linear extrapolations under such conditions [18]. Local attack also interacts with uneven floor support. Decisions about patching, replacement and recoating must consider load paths and weld integrity, rather than assume that covering a visually corroded area restores original structural capacity. An explicit uncertainty register is important when overlapping defects cannot be measured reliably.

Shell, roof, connections and mechanical conditions:-

Shell courses are exposed to hydrostatic loading that generally increases towards the base. The same absolute thickness loss therefore has different implications depending on course location, steel specification, diameter and operating fill height. Ultrasonic measurements must be interpreted against the applicable required thickness and service conditions, not judged simply by whether corrosion appears visually severe. The case assessment reported by Widiyati and Aliyah demonstrates the value of evaluating individual shell courses rather than reporting one tank-wide remaining-life figure [26]. Roof drainage defects, failed seals, external atmospheric corrosion, nozzles and appurtenances require separate examination plans because their damage mechanisms and consequences differ from those affecting floors.

Mechanical condition cannot be reduced to corrosion alone. Differential settlement may generate out-of-roundness and distortion near the shell-to-bottom weld; thermal cycling, seismic demand and poor repair geometry may further influence acceptability. Flood-related modelling indicates that bottom-plate failure can compete with shell instability under certain loading scenarios [24]. That finding is not a direct prediction for Saudi sites, but it demonstrates the danger of applying a single-degradation model to every exposure. A credible assessment combines dimensional surveys, operational history, foundation evaluation, weld examination and competent fitness-for-service review where indicated.

Environmental specificity without unsupported generalisation:-

Saudi tank farms span coastal and inland environments, differing in saline aerosol, temperature fluctuations, dust loading, groundwater, industrial emissions and maintenance accessibility. High ambient temperature may accelerate selected reactions or change coating behaviour, but it does not justify assigning one national corrosion multiplier. Actual degradation depends upon moisture availability, electrolyte conductivity, surface condition and service chemistry. Coastal atmospheric exposure can dominate external appurtenances while an inland tank may experience local floor corrosion driven principally by accumulated water. Each site requires its own mechanism register and evidence hierarchy, with assumptions revised when inspections contradict expectations.

Table 1. Mechanism-specific inspection evidence and interpretive safeguards for petroleum storage tanks.

Component / mechanism	Core evidence	Interpretive limitation	Assurance response
Floor / internal pitting	Full-floor screening, targeted UT, water and sludge history	Extreme pits may escape sparse sampling	Confirm critical indications; control water; repair or renew
Floor / underside loss	Scanning evidence, foundation moisture, CP potential surveys	Side of attack and unscanned zones may remain uncertain	Validate protection; investigate local defects
Shell / atmospheric loss	Course-specific thickness, coating and visual records	External appearance alone is not a strength assessment	Compare with course-specific acceptance limits

Component / mechanism	Core evidence	Interpretive limitation	Assurance response
Roof, seals, nozzles	Visual, dimensional, leak and weld examinations	Condition depends on design and service	Restore drainage, seals and local containment
Foundation / settlement	Survey levels, geometry, interface and weld condition	Corrosion models cannot represent distortion	Assess settlement; address support and load paths

Inspection architecture and evidence quality:-

Establishing the API 653 baseline:-

An effective programme starts by confirming tank identity, original design basis, modifications, service history, drawings, materials, minimum required thicknesses and previous inspection findings. Qualified personnel then define external examinations, internal inspection needs, measurements, repair acceptance and record retention in accordance with the applicable edition and addenda of API 653. Inspection frequency and authorised alternatives must be assessed against governing requirements, not inferred from a proprietary risk score alone. Historical gaps, unknown repairs or uncertain construction details should increase inspection conservatism until the data are reconciled. Engineering ownership of the asset record is central to defensibility.

External assessment includes corrosion, leaks, foundation settlement, shell deformation, roofs, drainage, nozzles, attachments and protective-system performance. Internal examinations offer access to floors and inaccessible welds but require cleaning, isolation, confined-space precautions and lost operating capacity. These constraints create an understandable incentive for condition monitoring. The appropriate response is to make each examination answer a defined question: does it locate active corrosion, measure remaining ligament, indicate a crack or verify a previous repair? A method that performs one task well must not be credited with unverified capability in another.

Complementary inspection technologies:-

Ultrasonic thickness testing provides direct local measurements with traceable calibration, yet point sampling can miss isolated pits between measurement locations. Scanning ultrasonic methods improve coverage at higher processing and access costs. Magnetic flux leakage efficiently screens ferromagnetic floors for probable metal loss, although signal strength depends on magnetisation, lift-off, geometry and defect orientation. Experimental floor studies support its use for screening while underscoring the need for confirmatory measurements where classification affects integrity decisions [8,13]. The associated inspection map should preserve inaccessible zones, detection limitations and areas needing manual follow-up, rather than presenting nominal scan coverage as complete confidence.

Acoustic emission offers evidence of active processes while the tank remains in service and can help prioritise subsequent opening and local examination. Olszewska's testing on crude-oil tanks demonstrates its practical diagnostic potential, whereas investigations of signal attenuation, noise and sensing conditions reveal limits to localisation and interpretation [5,23,27]. A quiet result does not prove that dormant pits or historical thinning are absent. Similarly, magnetic sensors intended for continuous monitoring provide promising sensitivity in controlled arrangements but must be validated against temperature variation, installation drift, electromagnetic interference and specific floor geometries before operational claims are expanded [3]. Inspection strategies should combine surveillance and direct verification rather than set them in competition.

Visual examination has benefited from remote platforms and image processing. Drone-based inspection can improve access to roofs and shell exteriors, and recent image classifiers report encouraging discrimination of visible corrosion patterns [17,22]. Nevertheless, photographs measure appearance rather than structural wall loss. Training data may be biased towards particular coating colours, lighting conditions or tank types; false negatives are especially important when a model is used to defer human inspection. Field qualification should therefore report defect-level sensitivity, missed critical indications and performance under unfamiliar conditions. Digital imagery becomes stronger evidence when tied to georeferenced thickness readings and inspector-approved defect records.

Corrosion risk and remaining-life assessment:-

Separating minimum acceptance from forecasting:-

Integrity decisions require a clear distinction between present acceptability and future degradation. The former evaluates measured dimensions and flaws against current requirements. The latter forecasts when an acceptance boundary may be reached. For a simple uniform-thinning case, the illustrative relationship remaining life equals

measured thickness minus required thickness, divided by an estimated corrosion rate, makes its assumptions visible. It is inappropriate where the numerator is negative, the rate is unknown, or damage is dominated by local pits. Nor should a single inferred rate be extrapolated through changing service, coatings, chemistry or repair events. A defensible estimate is tied to a dated measurement set and an explicit range of plausible future rates.

Case studies employing ultrasonic data and remaining-life calculations show how inspection trends can support decisions, but they do not establish universal service intervals [12,26]. The 2022 probabilistic study of twenty-three storage tanks incorporated extreme-value statistics and Bayesian updating to estimate the chance that floors reach a critical condition [7]. A later empirical model likewise found that accounting for accelerating pitting can generate more conservative forecasts than a constant-rate model [18]. Together, these findings support a tiered approach: deterministic calculations for relatively uniform, well-characterised damage; probabilistic local-loss models where adequate spatial data exist; and conservative engineering review when either model lacks support.

Uncertainty and the probability of failure:-

Risk-based inspection generally represents risk through the likelihood of a defined failure event and its consequences. For tanks, the event must be explicit: a detectable leak, bottom perforation, major rupture or loss of function produce different probabilities and consequences. The probability assessment should distinguish physical deterioration from inspection uncertainty and management factors. Corrosion exposure, age, protective-system evidence, operational upset and prior defects inform the damage model, while inspection effectiveness modifies confidence about unobserved damage. Treating an inspection as if it physically reduces corrosion is a category error: inspection changes knowledge; repair or prevention changes the asset.

Semi-quantitative scoring may be suitable for ranking a large fleet, especially where data are incomplete, but uncalibrated risk categories can conceal large differences between assets. Sulistomo and Surjosatyo illustrate an inspection planning approach based on corrosion exposure, failure likelihood and consequences [12]. Zhang and colleagues demonstrate a multicriteria assessment for underside corrosion when influencing factors interact and input judgements are imprecise [19]. Jing and colleagues use observable evidence with a dynamic inference framework for tank corrosion probabilities [21]. These methods have distinct merits, yet their outputs are not interchangeable without common failure definitions, calibration data and uncertainty measures. Transparent assumptions are more valuable than numerical sophistication unsupported by inspections.

Consequence estimation and escalation:-

Consequence analysis should examine stored product, operating inventory, credible leak rate, secondary containment, detection and isolation, ignition sources, vulnerable receptors, emergency response and recovery time. An isolated minor seepage within sound containment is materially different from a large release that reaches drainage, ignites or disables adjacent tanks. Published investigations of refinery-tank accidents show that corrosion-related release can combine with shortcomings in bunding and emergency management [16]. Fire models similarly demonstrate how radiation, filling level and protective measures affect time to failure and escalation [2,4]. Consequences should be evaluated at the tank-farm level when adjacent inventories and shared utilities create dependency.

Studies of combined blast and thermal loading show that sequential hazards can weaken a vessel beyond predictions based on either load alone [9,15]. Network-oriented modelling further indicates that coupled fire and explosion scenarios may increase domino propagation probabilities [11,14]. The environmental-risk literature highlights receptors and pollution pathways beyond immediate equipment damage [10]. These findings justify including credible low-frequency, high-impact scenarios in prioritisation, while avoiding the opposite mistake of allowing worst-case events to eclipse routine corrosion control. Decision makers need separately reported personnel, environmental, business-interruption and asset-replacement consequences; aggregation weights should be authorised and documented.

An integrated risk-based maintenance strategy

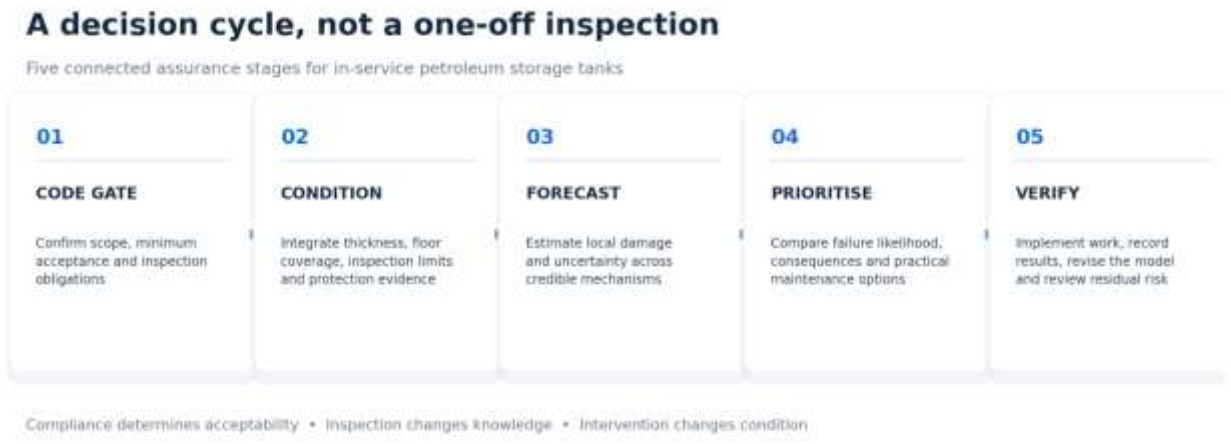


Figure 1. Proposed integrity assurance cycle connecting inspection, corrosion forecasting, risk prioritisation and maintenance verification. Original conceptual synthesis; no field observations are plotted.

From evidence to intervention:-

The proposed framework places a mandatory integrity gate before optimisation. A tank that fails the relevant acceptance assessment is not made acceptable by a favourable economic risk calculation. For compliant tanks, the next decision is whether information is sufficient to forecast degradation and choose an inspection horizon. High uncertainty may justify targeted testing even when current estimated likelihood appears low. Once probability, consequence and information quality are understood, work packages can be ranked by expected risk reduction, inspection feasibility, residual life and outage coordination. The sequence is illustrated in Figure 1; it is a conceptual synthesis, not the output of a Saudi experimental trial.

Maintenance actions address distinct causes. Water removal, sludge management and chemistry controls reduce internal exposure; bottom linings and coating repairs create barriers; cathodic protection targets underside electrochemical corrosion where its applicability and performance can be demonstrated. Experimental and numerical work on impressed-current protection shows that current distribution, anode position and coating condition can change protection effectiveness [20]. Electrical measurements and periodic surveys are thus needed to verify actual performance rather than infer it from installed equipment. Where deterioration exceeds allowable limits, engineered repair, replacement, controlled decommissioning or operating restrictions are required according to applicable procedures.

Choosing intervention timing:-

Inspection planning should account for the lead time between identifying a defect and executing work. A tank nearing its required thickness cannot be managed safely by setting the next inspection at the median predicted failure date. The preferred horizon incorporates an appropriate confidence bound, implementation time, possible measurement error and a contingency for unexpected growth. Where the estimated damage process is poorly calibrated, shorter surveillance intervals or a full examination may be more defensible than a model-generated extension. Recent operational work combining risk classification with advanced bottom scanning illustrates the principle but does not establish a universal savings percentage [30].

The economic objective is lifecycle value rather than the cheapest individual inspection. A planned cleaning outage entails preparation and lost capacity, yet postponement can increase spill exposure, emergency repairs and correlated disruption of connected operations. A decision model should therefore compare preventive actions on a common basis: inspection expenditure, repair cost, loss of throughput, expected release consequences and the value of improved information. One practical option is to coordinate tank opening with planned logistics slack while using non-intrusive screening to identify assets requiring earlier attention. However, operational convenience must never override a required corrective action.

Digital records and model governance:-

Digitalisation is useful only if a tank record remains technically auditable. The minimum dataset should contain component identifiers, geometry, material and coating history, product and water histories, inspection dates, calibrated thickness readings, defect coordinates, floor coverage, measurement quality, protection-system results, repair records and authorised decisions. Each revision should preserve who changed the assessment, why it changed and which measurements supported it. Without these controls, a sophisticated dashboard may merely amplify historical inconsistencies. Continuous sensors and machine-learning tools add another requirement: calibration drift, data gaps and algorithm changes must be monitored like conventional inspection equipment.

Emerging work on defect imaging and physics-informed interpretation could strengthen prioritisation where adequate labelled measurements exist [13,25,29]. Predictive accuracy obtained in a laboratory, however, does not demonstrate reliable performance on a new Saudi tank farm. Models should be trained and tested with tank-level separation to prevent leakage between related images, and critical-error rates must be reported. Human reviewers need access to raw readings, not only coloured risk displays. The most credible digital system is therefore an evidence management and decision-traceability platform, with automation assisting rather than replacing accountable corrosion engineers and authorised inspectors.

Implementation also requires a clear distinction between inspection coverage and inspection effectiveness. Coverage describes where measurements were attempted; effectiveness describes the likelihood of detecting a defect of consequential size under actual conditions. An operator should report both values separately. When corrosion is concentrated beneath inaccessible supports or at complex geometric transitions, nominally high floor coverage can still leave important uncertainty. Independent spot checks and records of inaccessible zones make the resulting risk assessment more credible. A useful review meeting should therefore include operations, inspection, corrosion engineering, maintenance planning and emergency response representatives. Together they can examine whether the assumed release pathway remains credible, whether the forecast reflects recent changes in product handling, and whether the proposed action can be completed before the available safety margin is exhausted. The signed decision record should identify a responsible owner, completion deadline and explicit trigger for reopening the assessment. These records support accountable decisions. Independent reviewers should examine unscanned regions, forecast uncertainty, repair readiness, and protection-system evidence before endorsing any extended inspection horizon for continued service. Where necessary, the review should explicitly.

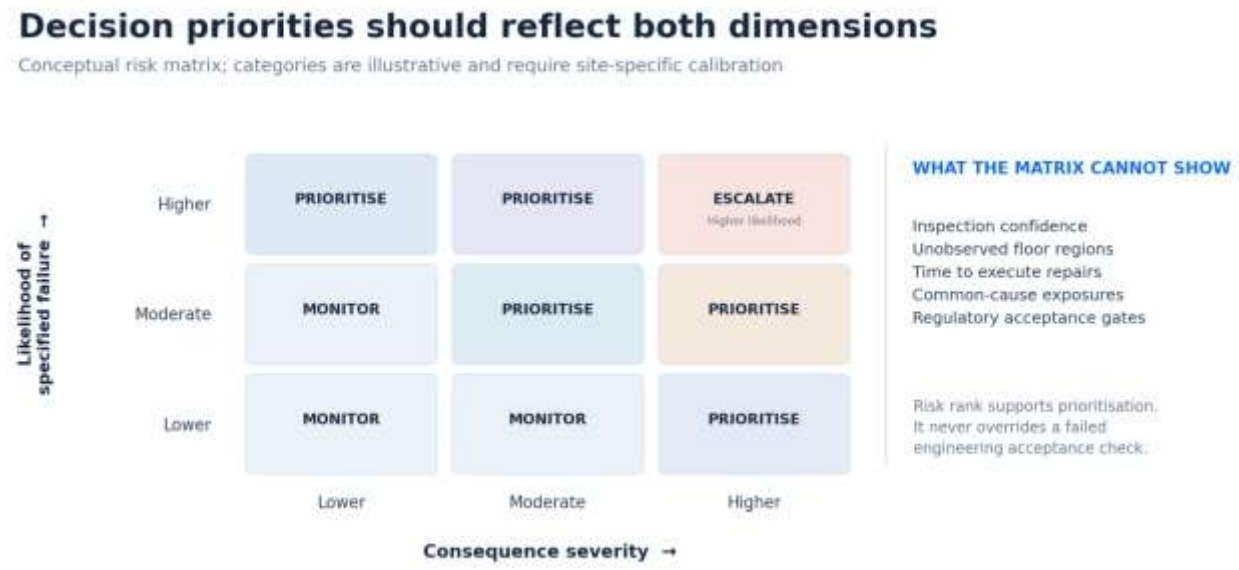


Figure 2. Conceptual likelihood–consequence prioritisation matrix. Coloured categories are illustrative and do not prescribe API thresholds or inspection intervals.

Table 2. Decision gates linking assessment outcomes with risk-based maintenance actions.

Decision state	Evidence threshold	Primary action	Control against inappropriate extension
Unacceptable condition	Applicable acceptance criterion not satisfied	Restrict service; repair, replace or retire	Engineering approval and required testing
High credible risk	Severe consequence or likely deterioration	Expedite targeted inspection and prevention	Independent review of scenario and uncertainty
Uncertain hidden damage	Inadequate coverage or conflicting results	Acquire targeted NDE; revise probability	Record detection limits and missed areas
Manageable degradation	Acceptable condition and supported forecast	Plan mitigation, inspection and outage	Apply code limits and conservative margin
Verified low exposure	Strong monitoring and protection evidence	Continue justified surveillance	Reassess after changes or new indications

Implementation under Vision 2030:-

A Saudi operator could introduce the framework in three maturity stages. The initial stage standardises tank registers, component-level criticality, current compliance assessments and defect nomenclature across terminals. The second stage introduces common corrosion maps, assured inspection coverage, protection-system performance data and risk-ranked work orders. The third stage tests probabilistic forecasting and remote surveillance against subsequent actual inspections, measuring missed defects and calibration drift before granting the models wider influence. Progress depends on maintenance leadership, independent inspection competence, reliable contractor data transfer and budgeting for corrective work as well as software.

The relevant performance indicators are not merely numbers of inspections completed. More informative measures include overdue mandatory actions, coverage of critical floor regions, percentage of defects with verified dimensions, rate of repeat corrosion at repaired locations, time from critical finding to intervention, loss-of-containment events and forecast calibration. A decline in reported indications alone would be ambiguous: it might reflect improvement or diminished examination effectiveness. Independent assurance should test both the accuracy of the data and the appropriateness of the decisions derived from them.

Localisation opportunities arise in qualified inspection services, sensor installation, coating application, cathodic protection engineering, corrosion data management and advanced analytical training. Partnerships between operators, technical institutes and universities could create comparable anonymised datasets while protecting commercially sensitive information. A national research programme would be particularly valuable if it covered coastal and inland terminals, different products, roof designs, construction ages and foundation conditions. Such collaboration aligns with domestic capability development, but benefits should be demonstrated through verifiable risk and reliability outcomes rather than assumed from technology deployment.

Research gaps and limitations:-

A persistent weakness is the mismatch between the high spatial variability of corrosion and the sparse, irregular measurements used for forecasting. Future studies should link full-floor maps, local pit statistics, coating condition and environmental exposure, with follow-up inspections sufficient to measure calibration error. Test designs should predefine failure events and distinguish localisation accuracy from severity-estimation accuracy. Studies of smart inspection should report false negatives and inaccessible regions, because impressive aggregate scores may conceal unacceptable critical-defect performance. This applies especially to acoustic, visual and magnetic methods whose signals are influenced by non-corrosion factors [3,22,27].

Another unresolved issue is transfer between apparently similar tanks. Mechanistic variables such as underfloor moisture and water-bottom chemistry are frequently absent from datasets, encouraging models to learn age or site identity as proxies. Multisite validation should therefore reserve entire facilities for external testing and assess whether forecast uncertainty remains meaningful under distribution shift. The role of physical protection requires comparable rigour. Field trials should pair cathodic protection measurements, coating inspections and observed corrosion change instead of assuming that installation guarantees control [20]. Evidence on maintenance economics should include the value of information, shutdown constraints and the social cost of releases.

This review has no access to proprietary Saudi thickness datasets and does not claim observed reductions in failure frequency, inspection cost or emissions. Its approach is interpretive, and the selected literature is heterogeneous in setting and evidential strength. Publication bias, incomplete reporting of negative inspection results and the use of different endpoints limit cross-study comparisons. In addition, some research concerns non-Saudi facilities and extreme accident scenarios, so its relevance is conditional on local engineering screening. These limitations restrict numerical transferability but reinforce the value of a documented, testable implementation framework.

Conclusion:-

Petroleum storage-tank integrity in Saudi Arabia is best managed as a connected assurance problem: establish whether the tank is currently fit for service, determine how and where it is degrading, estimate what may happen before the next intervention, and select actions that reduce credible consequences without breaching inspection obligations. The literature supports complementary nondestructive techniques and explicit modelling of localised corrosion, but no single sensor, risk matrix or forecasting algorithm supplies the complete answer. The distinctive contribution of this review is an ordered decision framework that separates mandatory acceptance, evidence quality, deterioration uncertainty and economic optimisation.

For operators, the immediate priority is dependable component-level data, independently verified inspections and timely action on unacceptable conditions. For researchers, the priority is prospective validation of predictions, intervention effectiveness and lifecycle outcomes across Saudi service environments. Aligning these two agendas can support safer petroleum logistics, fewer avoidable releases and locally developed technical capabilities consistent with Vision 2030. Any claimed performance improvement must ultimately be established through monitored field outcomes, not through the existence of a digital model or a lower calculated risk score.

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