

Advanced Non-Destructive Inspection and Integrity Assurance of Offshore and Marine Pipelines for Critical Energy and Water Infrastructure in Saudi Arabia.

Abstract

Offshore pipelines connect hydrocarbon production, coastal industrial operations and seawater-dependent water systems, yet their integrity cannot be inferred from occasional inspection results alone. Saudi Arabia presents a demanding case because high-consequence energy assets coexist with seawater intakes, desalination facilities and transmission networks serving arid regions. This critical review evaluates non-destructive inspection technologies reported between 2020 and 2025 and develops an assurance framework that links defect detection, sizing uncertainty, deterioration mechanisms and maintenance decisions. Evidence from ultrasonic testing, guided waves, magnetic flux leakage, acoustic monitoring, distributed fibre sensing, robotic inspection and digital modelling is compared against practical access and validation constraints. The review distinguishes metal loss from cracks, active leakage from latent deterioration, and continuous surveillance from periodic verification. It argues that reliable assurance requires an evidence chain extending from sensor qualification to fitness-for-service assessment, rather than substituting algorithmic predictions for measurements. Two synthesis tables map inspection capabilities to threats and identify the most consequential implementation gaps. A staged Saudi deployment pathway is proposed, prioritising repeatable baselines, representative defect trials, traceable data, cross-disciplinary review and explicit intervention thresholds. The principal conclusion is that multimodal inspection can improve the defensibility of integrity decisions only when environmental interference, detection limits and residual uncertainties are documented. This approach supports safer energy transportation, resilient water supply and the development of specialised national inspection capabilities.

Keywords Offshore pipelines; non-destructive inspection; structural integrity; ultrasonic guided waves; acoustic emission; desalination infrastructure; Saudi Arabia; risk-based inspection.

1. INTRODUCTION

The reliability of an offshore pipeline depends on more than its ability to remain pressure-tight during a scheduled test. A line may satisfy its operating envelope while localised corrosion consumes a narrow ligament, an undetected weld imperfection extends under cyclic

stress, or an unsupported span develops fatigue damage. Leakage represents the end of a sequence of deterioration and imperfect decisions, not necessarily the first detectable sign. Current integrity practice therefore needs inspection strategies that identify credible precursors, quantify their severity and communicate uncertainty before the opportunity for controlled intervention disappears [1–3].

For Saudi Arabia, these questions extend across connected but technically different infrastructures. Offshore oil and gas networks carry fluids with changing compositions, pressures and temperatures, while marine seawater systems supply cooling and desalination processes. Treated-water transmission lines subsequently face different water chemistry, material interfaces and service demands. The national water strategy identifies supply continuity, cost effectiveness, environmental protection and local technical capability as linked policy aims. A pipeline failure can accordingly create consequences beyond direct repair expenditure: production interruption, reduced water availability, marine contamination and costly emergency logistics. These consequences justify greater scrutiny of inspection selection and the confidence attached to reported findings.

Non-destructive inspection is often described as a collection of competing instruments. That framing is incomplete. Guided-wave systems may screen relatively long sections but cannot always size an individual flaw adequately; a high-resolution ultrasonic survey can quantify local wall loss yet cover only the accessed surface; an acoustic alarm indicates an event but does not automatically establish remaining strength. In-line instruments encounter geometric and operational constraints, while external surveys depend on access, positioning and marine conditions. The central engineering problem is the coordination of imperfect evidence into a decision that can withstand audit [4–6].

The aim of this review is to establish a technically defensible architecture for advanced non-destructive inspection and integrity assurance of Saudi offshore and marine pipelines. Its distinct objectives are to identify dominant damage pathways across energy and water services; assess the strengths and limits of established and emerging inspection modalities; examine how environmental noise and measurement uncertainty affect defect characterisation; and translate the evidence into a risk-based deployment and validation pathway. The contribution is deliberately integrative. It does not claim a new sensor, field trial or measured reduction in failure frequency. Instead, it specifies how different forms of evidence should complement one another and where further Saudi-specific qualification is most valuable.

2. REVIEW APPROACH AND EVIDENCE BOUNDARIES

A structured critical narrative review was undertaken using literature published from 2020 through 2025. The supplied technical review informed the organisation of damage mechanisms and acoustic inspection issues, while targeted checks of journal records and their digital identifiers supplied the substantive evidence base. Search concepts combined subsea or offshore pipeline with corrosion, leak detection, ultrasonic inspection, guided waves, in-line inspection, acoustic sensing, robotics, remaining life and digital twins. Water-sector terms included seawater, desalination, pipe materials and corrosion. References were retained when their stated methods or findings could inform inspection capability, integrity interpretation or deployment constraints.

The unit of synthesis was an engineering claim, not a simple count of favourable papers. Review studies were used to establish the breadth of known methods; experimental articles informed sensor behaviour under defined conditions; and probabilistic or digital models informed the logic of decision support. A laboratory classification score was not treated as an offshore probability of detection, and a numerical failure-pressure estimate was not equated with an independently verified field measurement. The review also separated defect detection, defect sizing, leak localisation and remaining-life prediction, because success in one task gives no automatic proof of success in another [7–10].

This approach is reproducible at the level of the cited evidence and its thematic eligibility, but it is not a claim of exhaustive database coverage or statistical pooling. Search-return totals, formal exclusion counts and pooled effect sizes have not been invented. The thirty referenced journal contributions were checked against publisher, scholarly repository or bibliographic records for title, publication year and DOI. Their heterogeneous materials, failure mechanisms and test environments prohibit meaningful pooled accuracy estimates without the original datasets. Conclusions are therefore expressed as conditional engineering inferences, with recommendations clearly distinguished from demonstrated field performance.

A further appraisal rule concerns the maturity of each proposed technique. Demonstration on a clean laboratory specimen establishes physical feasibility, whereas deployment on an operational pipeline additionally requires documented calibration, environmental compensation, repeatable positioning and acceptance by the asset owner. Evidence was interpreted conservatively when authors reported improvements against narrow algorithmic benchmarks rather than against independently measured defects. This distinction is particularly important for automated classification, where dataset imbalance and repeated

measurements of the same specimen can inflate apparent generalisation. The review consequently gives stronger practical weight to studies explaining validation boundaries than to unsupported claims of universal superiority.

3. ENVIRONMENTAL EXPOSURE AND DAMAGE PATHWAYS

3.1. External and internal deterioration

Marine immersion couples chloride-bearing electrolytes, coating imperfections, oxygen gradients, deposits and electrical protection systems. Localised corrosion may concentrate at coating holidays, clamps, supports, weld interfaces and regions where shielding complicates cathodic protection. Internal degradation follows a different causal route: produced water, carbon dioxide, hydrogen sulphide, deposits, microbial activity and stratified multiphase flow can create severe local conditions even when average corrosion rates appear modest. Reviews of metallic-pipeline damage emphasise that mitigation is mechanism-specific and that corrosion-control measures do not eliminate the need for independent condition assessment [2,12,13].

The difference between general thinning and deep pitting is consequential. An average wall-thickness trend can remain apparently stable while a small, aggressive pit governs the local failure margin. Conversely, a shallow, extensive region may influence collapse or buckling differently from an isolated cavity. Recent subsea corrosion research has therefore moved towards spatially resolved assessment, dynamic deterioration models and interacting-defect analysis [16,22,25–27]. Inspection plans should specify the defect dimensions relevant to each limit state rather than pursuing a single generic indication threshold.

3.2. Structural loading and geometric discontinuities

Pressure cycles, wave-induced motion, free spans, thermal expansion, seabed movement and installation residual stresses provide mechanisms for fatigue or deformation. Weld toes and girth-weld heat-affected zones can act as local stress raisers. Marine pipelines may also experience external impact from dropped objects or equipment interaction, which changes both the immediate defect geometry and the subsequent corrosion response. Recent competing-failure modelling illustrates why treating impact and corrosion as independent threats can underestimate interacting pathways [16,27].

A defect register must consequently describe location, orientation, length, depth, material and operating history together. A crack-like indication at a loaded weld has different significance from the same signal at an unloaded location, while a dent near a weld demands different

verification from isolated corrosion. Periodic pressure testing provides system-level information but is not an adequate substitute for identifying a subcritical defect and evaluating its likely growth. It may also introduce operational disruption or test-related risk that needs explicit justification.

3.3. Seawater and desalinated-water services

Water infrastructure cannot simply inherit the corrosion assumptions used for hydrocarbon transport. Seawater intake and cooling lines encounter fouling, sediments, aeration changes and biological deposits; internal surfaces may include metals, cementitious linings and polymers. At the other end of the chain, low-alkalinity desalinated water can be chemically aggressive unless conditioned for distribution. Shokri and Sanavi Fard examined corrosion management in desalination, while Cai and colleagues demonstrated that pipe material selection affects desalinated-water stability and microbiological behaviour [12,17].

These findings imply service-specific inspection objectives. A marine intake may require evidence on erosion, blockage, coating loss and external exposure; a treated-water pipeline may require attention to lining condition, joints, leakage and interactions between transported water and material. Hydraulic observations can reveal anomalies, but they cannot by themselves identify the metallurgical cause of a local defect. The recommended inspection programme should therefore map water quality, material compatibility and geometry before specifying instrumentation, avoiding false equivalence between water and oil-and-gas failure modes.

Water-system integrity also requires careful separation of pressure containment from hygienic performance. A pipe may retain adequate mechanical strength while lining deterioration changes water quality; conversely, a minor leak can threaten service continuity without implying imminent structural rupture. For intake lines, inspection plans should record whether biofouling or sediment accumulation alters acoustic transmission and the ability of tools to pass through the bore. For desalinated-water networks, the relevant intervention may be lining rehabilitation or joint replacement rather than the steel-wall repair typical of hydrocarbon facilities. Consequently, inspection acceptance criteria should be approved jointly by asset integrity and water-quality specialists.

4. INSPECTION TECHNOLOGIES: CAPABILITY AND LIMITS

4.1. Ultrasonic methods and guided-wave screening

Conventional ultrasonic thickness measurement yields local wall dimensions when coupling, calibration, surface preparation and temperature compensation are controlled. Encoded scans and phased-array examinations provide denser maps and more informative weld interrogation than isolated spot readings. Their strength is geometrical detail at accessible locations; their weakness is incomplete coverage when access is restricted by burial, insulation, coatings, clamps or subsea intervention limits. A scan should be judged by its demonstrated coverage and sizing accuracy rather than by nominal equipment resolution.

Ultrasonic guided waves address the coverage problem differently. Excitation from an accessible ring or transducer arrangement propagates selected wave modes along the pipe, with reflections indicating changes in geometry or material response. Zang and colleagues review the theory, mode selection, signal interpretation and environmental sensitivity of pipeline guided waves; Cawley similarly emphasises the value of long-range screening alongside its practical constraints [14,20]. Flanges, bends, supports, coatings and contents change attenuation and scattering, making interpretation site-dependent. A screening indication needs targeted follow-up before a remaining-wall claim is accepted.

The choice of wave mode and inspection frequency should also be linked to the smallest consequential flaw. Increased attenuation can reduce test range, particularly where protective layers or contact conditions absorb mechanical energy. Similarly, an apparent change in reflection amplitude may be caused by temperature variation rather than progression of corrosion. Reference baselines are useful only when operating conditions are sufficiently comparable or an experimentally justified compensation method is available. Reporting the effective inspection range together with unexamined zones prevents a nominal coverage percentage from overstating actual assurance.

The essential trade-off is between spatial reach and characterisation fidelity. Lower-frequency screening may detect a significant cross-sectional change over a substantial distance but miss a small localised pit. Higher-resolution examination shortens the inspected footprint and increases access demands. An effective campaign therefore defines detection classes in advance: broad metal loss, isolated pitting, crack-like flaws and geometric anomalies do not share one optimum inspection setting. For each class, calibration artefacts and representative defects should reflect the pipe diameter, thickness, material, coating and service environment actually being inspected.

4.2. Magnetic and electromagnetic inspection

Magnetic flux leakage can identify ferromagnetic wall-loss features through perturbations in a magnetised pipe wall. Its effectiveness depends on magnetisation, lift-off, sensor orientation, velocity and flaw geometry. Crack detection and precise depth sizing are not interchangeable outcomes, and signals near welds or geometric transitions require specialised interpretation. Electromagnetic acoustic approaches reduce dependence on a liquid couplant but introduce their own sensitivity to material properties, stand-off and electromagnetic interference. These technologies are attractive for in-line systems because measurement can be acquired over long distances without exposing the external pipe surface directly.

Instrument selection still begins with the material and threat. Magnetic methods are unsuitable for some non-ferromagnetic structures and do not resolve the integrity of polymeric water lines merely because a device can traverse their bore. The resulting dataset must be supported by positional registration, tool calibration, velocity records and an agreed defect taxonomy.

Tool passage itself introduces a separate chain of operational assurance. Gauge velocity excursions, excessive debris, poor cleaning, instrument saturation or incomplete sensor contact may produce portions of data that are technically recorded but unsuitable for characterisation. Operators should specify a minimum acceptable data-quality threshold for each pipe section and a recovery action for sections falling below it. Repeat runs should not be regarded as identical observations unless chainage alignment, operating conditions and processing settings are reconciled. A documented unusable-data segment is preferable to a falsely reassuring blank inspection map. A high count of classified indications should not be confused with high-quality sizing. Where the mechanism is crack growth rather than metal loss, an additional sensor or independent confirmation is needed before assigning a fitness-for-service conclusion.

4.3. Acoustic emission, leak monitoring and fibre sensing

Acoustic techniques listen for transient energy associated with leakage, mechanical activity or propagating damage. Diao and colleagues combined acoustic information with guided-wave interpretation to localise leaks in flanged pipes [6]. Studies on gas and water lines show how leak apertures, flow conditions and sensor placement influence recorded signatures [7,8]. Subsea acoustic studies likewise indicate that a small leak cannot be inferred reliably from amplitude alone when the fluid regime, background vibration and propagation path are changing [10,18,23].

Noise rejection is therefore a safety function, not a cosmetic improvement to plots. Kousiopoulos and colleagues tested time-frequency segmentation and arrival-time methods in noisy conditions [11]. Yan and colleagues investigated learning-based detection and localisation [19]. Such results demonstrate analytical possibilities but cannot establish site-wide accuracy without independent, representative offshore testing. Pump transients, valve operations, flow-regime changes, vessel activity and acoustic reflections may mimic fault signatures. Alarm design should describe false-positive rates, missed-event consequences and conditions where confidence collapses.

Distributed fibre sensing extends the measurement footprint by using optical responses along installed cable. Peng and colleagues combined distributed acoustic measurements with learning algorithms for intrusion and corrosion-related discrimination, indicating the promise of distributed surveillance [4]. However, fibre location, cable coupling and installation geometry determine what can be observed; a fibre near a pipeline is not equivalent to continuous proof of wall integrity. Continuous sensing should trigger or prioritise local examination, while periodic high-resolution measurements establish defect dimensions and material condition. Figure 1 summarises that division of responsibility.

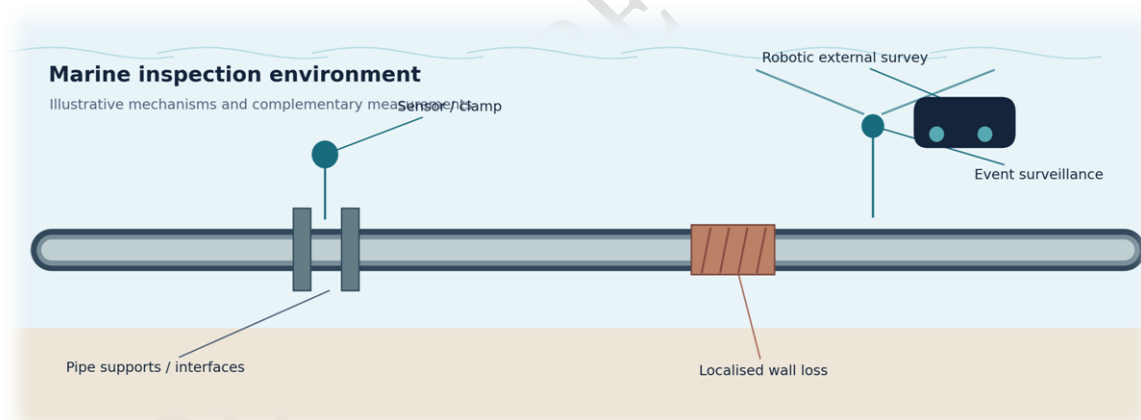


Figure 1. Illustrative offshore pipeline exposure and complementary monitoring activities; schematic is conceptual and not drawn to scale.

4.4. In-line inspection and access limitations

Instrumented gauges can collect consistent circumferential measurements across extensive pipe lengths, but successful deployment depends on launch and recovery facilities, bend radius, internal restrictions, flow control and the management of stuck-tool risk. Acoustic tracking of inspection gauges has been demonstrated by Bernasconi and Giunta and provides a useful operational assurance layer [5]. Pigging feasibility should be determined before the

inspection specification is finalised, not treated as an implementation detail after procurement.

When a line is not practically piggable, alternative access strategies include externally mounted probes, robotic crawlers, diver or remotely operated vehicle intervention and permanent monitoring. The decision turns on seabed exposure, intervention window, water depth, visibility, current, coating condition and acceptable downtime. A hybrid campaign can use a long-range screening instrument to select segments for local, higher-resolution surveys. Importantly, inaccessible spans remain a documented evidence gap; they should not be silently classified as defect-free.

5. UNDERWATER ROBOTICS AND DATA INTEGRATION

Remotely operated platforms can bring visual, sonar and contact sensors to locations that are dangerous or uneconomic for divers. Autonomous systems promise broader repeat coverage, but positioning drift, power consumption and reliable contact with curved structures remain important practical constraints. Nauert and Kampmann identify the technological gap between underwater inspection and fully autonomous intervention, while Kasparavičiūtė and colleagues address energy-efficient route planning for resident inspection vehicles [15,24]. Vehicle autonomy must not be interpreted as autonomous engineering acceptance of defect measurements.

An offshore robotic survey contains at least three separable products: navigation evidence establishing where the vehicle travelled, inspection evidence describing what the sensor observed, and interpretative evidence explaining whether the observed condition threatens serviceability. Sonar may document burial and free spans without quantifying remaining wall; visual imaging may identify coating anomalies without measuring corrosion depth; contact ultrasonics may size exposed metal loss but require stable probe placement. Reliable asset records align all three products within a common pipeline chainage and coordinate reference.

The water and energy sectors also differ in acceptable inspection disruption. A process pipeline might have a planned maintenance outage or controlled flow window, whereas a water intake supporting desalination may have stricter continuity requirements. Risk-based work packaging should therefore include the consequence of taking a line out of service as well as the consequence of leaving a defect unexamined. The strongest technology portfolio may be a modest combination of repeatable sensors rather than one highly sophisticated platform with limited deployability.

6. FROM DETECTION TO QUANTIFIED INTEGRITY

Detection is only the first link in the assurance chain. Integrity evaluation needs an estimate of defect size and location, a description of measurement error, an appropriate limit-state model and the operating scenarios over which the conclusion holds. Work on pipeline failure prediction has highlighted variation in model assumptions and input quality [1]. More recent subsea studies apply dynamic Bayesian representations, interacting-defect simulations and data-driven remaining-life methods, demonstrating increasingly sophisticated ways to represent time-dependent risk [16,22,25–27]. Complexity, however, does not guarantee better decisions.

An uncertainty register should distinguish sensor repeatability, systematic sizing bias, incomplete surface coverage, uncertain defect growth and model-form error. These terms matter differently. A repeatable but biased instrument can consistently understate corrosion depth; a correct local reading can miss a more severe defect outside the scanned area; a sound present-day size estimate can still lead to poor maintenance timing when growth conditions change. Assigning a single confidence score without identifying its underlying contributors conceals these distinctions.

Inspection qualification should therefore employ representative flaws with independently measured truth dimensions, including difficult orientations and features near welds. Probability of detection, false-call performance and sizing error must be reported against defect type and size, not merely as one headline classification percentage. Blind trials prevent operators or algorithms from exploiting knowledge of the test specimen. For field campaigns, matched reinspection locations can reveal sensor drift and distinguish true growth from inconsistent scanning. These arrangements are especially important where inaccessible subsea sections make repeat measurement expensive.

Digital twins can organise the evidence but cannot repair weak inputs. Wang and colleagues integrated physical sensing, modelling and probabilistic updating into a pipeline digital-twin case study [21]. Yu and colleagues used multi-fidelity monitoring and transfer-oriented modelling in deep-sea contexts [28,29]. The practical lesson is to preserve the distinction between observation, model estimate and forecast. Predictions should carry uncertainty bounds, explain their domain of validity and be revised when new measurements contradict expected deterioration. A model trained on clean laboratory signals must remain provisional when deployed on acoustically complex offshore assets.

7. A RISK-BASED ASSURANCE FRAMEWORK FOR SAUDI ARABIA

The proposed framework begins with functional criticality and plausible damage, not with a catalogue of available inspection tools. Operators first divide a network into segments with coherent pipe material, diameter, service, protection system, seabed condition and operating history. Each segment receives a threat statement that identifies the expected defect morphology and associated failure mode. The inspection question can then be expressed precisely: for example, whether an exposed bend contains external wall loss exceeding an assessment threshold, or whether a welded transition has developed a crack-like defect under cyclic loading.

A second stage assigns sensing roles rather than assuming every measurement supports every decision. Long-range techniques screen for abnormal regions, acoustic systems monitor events, high-resolution examinations size discrete flaws, and environmental measurements inform likely deterioration drivers. If several independent modalities agree, confidence may improve; if they disagree, the contradiction triggers technical review rather than averaging incompatible readings. Figure 2 presents this decision architecture, from threat definition through verified intervention.

Closed-loop pipeline integrity assurance

Each hand-off requires traceable evidence; model estimates do not replace qualified measurements.

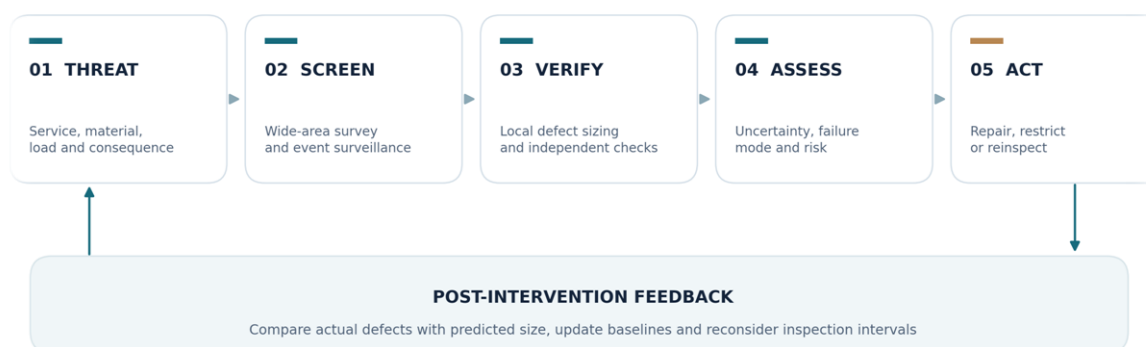


Figure 2. Proposed assurance workflow showing qualification, intervention and feedback as connected decision stages.

The third stage establishes acceptance rules before data collection. A condition assessment should state the governing assessment method, conservative material parameters, operating envelope, corrosion allowance where relevant, and criteria for repair, pressure restriction or shorter inspection intervals. The rule set should distinguish measured defects from assumed defects and include escalation for inadequate coverage. Risk ranking may consider failure

likelihood and consequence, but neither dimension should be reduced to a single opaque machine-learning output. In particular, the consequences of a release in sensitive coastal waters differ from those of lost water transmission, even when the defect geometry is similar.

A fourth stage converts inspection results into a traceable decision record. Raw readings, calibration records, survey coordinates, analyst interpretations, models and final dispositions should be linked to the same asset identifier. Changes in chainage conventions or sensor processing versions can otherwise create artificial trends. Strong data governance also allows a later reviewer to distinguish an asset that was thoroughly examined from one that simply produced few alarms. The result is a defensible basis for life-extension decisions and more transparent procurement of specialist inspection services.

The fifth stage establishes a feedback loop from repair and excavation findings. Actual defects discovered during intervention should be compared with inspection estimates, allowing operators to identify systematic bias and refine inspection thresholds. Failure to examine false negatives is particularly damaging because an apparently clean dataset can progressively strengthen unjustified confidence. After maintenance, the verified condition becomes the new baseline and the next inspection interval is reconsidered using updated deterioration evidence, access costs and the consequence of service interruption [1,22,25].

Table 1 distinguishes what each modality can reasonably establish. Table 2 translates the resulting gaps into validation questions and ownership responsibilities. The emphasis is not on adding sensors indefinitely; it is on ensuring that each consequential decision has an evidence source capable of answering the right question. Where no method has adequate capability, the management choice must be explicit: accept a documented residual risk, introduce an additional inspection access point, impose an operating restriction or replace the affected segment.

Table 1. Threat-oriented use of non-destructive inspection methods and their decision limits.

Threat service	Screening approach	Local confirmation	Principal uncertainty	Decision supported
External steel corrosion	Guided waves; magnetic inspection	Encoded ultrasonic mapping	Coatings, supports; pit shape	Remaining wall and reassessment
Weld or fatigue	Targeted ultrasonics;	Phased-array / specialist flaw	Orientation; crack-tip	Repair or interval adjustment

cracking	surveillance	sizing	detection	
Active hydrocarbon leak	Acoustic / fibre monitoring	Local leak survey; pressure review	Multiphase flow and background noise	Isolation and response
Marine intake deterioration	Hydraulic trend; visual / sonar	Local UT; material / lining check	Fouling, sediment, access	Cleaning, lining or repair
Unpiggable subsea segment	Robot and external screening	Contact UT / targeted intervention	Location uncertainty and contact	Risk acceptance or access improvement

Table 2. Priority qualification gaps for a Saudi field implementation programme.

Gap	Verification evidence	Responsible team	Decision gate
Environmental noise	Blind alarm tests across loads and flow states	Monitoring and operations	Acceptable alarm / miss performance
Hidden or inaccessible wall	Measured coverage and documented blind zones	Inspection engineering	Additional access or controlled risk
Defect sizing bias	Independent true dimensions and repeat trials	NDT qualification lead	Fitness-for-service input limits
Model domain shift	Cross-asset tests and uncertainty calibration	Integrity / data science	Provisional or approved forecast
Water-service differences	Chemistry, material and lining benchmarks	Water-quality / asset teams	Service-specific intervention criteria

8. IMPLEMENTATION PATHWAY AND RESEARCH PRIORITIES

A staged Saudi programme should begin with a small number of contrasting pilot assets: an accessible offshore steel line, a difficult-to-access marine segment and a seawater or desalinated-water system. This selection allows a common assurance process to be tested without pretending that sensor physics or failure mechanisms are identical. Baseline work

would reconcile drawings, material records, historical inspection data, protection performance and operational transients. It should also document where existing records cannot establish whether a pipe section has ever been examined adequately.

Next, a laboratory and field qualification programme should expose candidate methods to representative conditions. Test pieces require natural or realistically manufactured corrosion, weld features, controlled cracks and geometric discontinuities. Variables should include coating, seawater exposure, temperature, sensor lift-off and background noise. Reference measurements should be completed independently and concealed during blind assessment. A useful qualification report would include coverage achieved, missed indications, false calls, sizing bias and repeatability, with results stratified by defect morphology rather than presented as one overall success rate.

Third, inspection and operations teams should establish a joint data dictionary covering wall thickness, flaw dimensions, location uncertainty, material grade, fluid service, operating pressure and inspection date. Digital platforms can then support controlled comparison between campaigns without erasing original measurements. Emerging sensor-integrated liners illustrate how continuous strain information may be combined with a virtual asset representation, but they remain complementary to validated structural assessment [30]. For legacy offshore assets, improving data provenance may offer earlier gains than immediately deploying complex predictive models.

Finally, a local capability programme should connect operators, universities, inspection contractors and water utilities through shared test specimens and agreed assessment protocols. Priority research questions include acoustic false alarms in real Gulf operating conditions; ultrasonic detectability beneath realistic marine coatings; repeatable robot positioning near supports and bends; and uncertainty propagation from partial inspections to maintenance decisions. Success should be judged by demonstrated inspection coverage, sounder intervention decisions and preserved service continuity, not by the number of deployed devices or the elegance of an analytical dashboard.

9. LIMITATIONS AND FUTURE DIRECTION

The reviewed literature spans laboratory rigs, industrial case studies, model-based assessments and offshore-focused analyses. Their findings cannot be combined into a universal detection probability. Sensor performance changes with geometry, environment, materials, defect distribution and inspection execution. Several methods have credible physical foundations and promising reported demonstrations, yet evidence for sustained,

independently audited deployment on Saudi marine networks is not established by these publications. Recommendations concerning local pilots are consequently prospective rather than descriptions of completed national programmes.

Further work should prioritise datasets containing verified defect truth, operating histories and repeated inspections across seasons. Studies comparing two methods on the same asset should report not only detection but also measurement uncertainty, inspection coverage, cost of access and the maintenance action changed by the result. Field investigations should consider combined deterioration and loading, including pitting near bends, cracking at welded supports, and impact followed by corrosion. For water systems, materials and water chemistry must be retained as explanatory variables rather than treated as background metadata.

Better analytical models will be useful where they expose uncertainty and facilitate audit. An interpretable forecast that openly reports sparse data may be safer than a highly precise numerical output whose training range does not include the asset under review. The most valuable research design would follow a defect from initial screening to independent characterisation, risk assessment, repair decision and post-intervention confirmation. Such longitudinal evidence would test whether advanced inspection actually improves integrity assurance, rather than simply increasing data volume.

Research partnerships should quantify economic consequences of uncertain detections, including missed defects, false calls, vessel mobilisation, downtime and verification, before comparing the value of competing inspection methods.

10. CONCLUSIONS

Advanced non-destructive inspection offers substantial opportunities for managing Saudi offshore and marine pipelines, but inspection capability must be defined against a specific threat and a specific engineering decision. Ultrasonic and electromagnetic methods provide complementary information on material condition; acoustic and distributed sensing support surveillance; and robotic systems extend physical access. None is sufficient, in isolation, to establish integrity across heterogeneous hydrocarbon and water infrastructure.

The review identifies four requirements for defensible assurance: service-specific damage assessment; qualified and independently verified measurements; explicit propagation of uncertainty into fitness-for-service and maintenance decisions; and a traceable feedback loop from field findings to future inspection plans. Saudi adoption should proceed through representative pilots, controlled qualification and shared technical data standards. The

resulting objective is not uninterrupted confidence in digital predictions, but earlier recognition of uncertainty and better-timed interventions that protect energy production, water security and the marine environment.

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