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Real-Time Leak Monitoring and Loss Prevention during Commissioning and Start-Up of Oil and Gas Infrastructure in Saudi Arabia

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Abstract- Commissioning and start-up are unusually vulnerable phases in oil and gas projects because containment is being proven under changing pressure, temperature, composition, flow regime and control configuration while construction handovers, temporary systems and simultaneous operations may still be active. This review evaluates how real-time leak monitoring can be integrated with loss-prevention controls during hydrocarbon introduction and early operation in Saudi Arabia. An integrative review of peer-reviewed literature published principally between 2020 and 2025 was undertaken across Scopus-indexed and major publisher databases, emphasizing pipeline leak detection, continuous methane monitoring, acoustic and optical sensing, computational pipeline monitoring, digital twins, process safety and pre-start-up safety review. The evidence shows that no single technique offers dependable coverage across commissioning transients. Mass-balance and model-based systems provide continuous process-wide surveillance but can be destabilized by inventory changes and valve sequencing; acoustic, negative-pressure-wave and distributed fiber sensing provide fast local signatures but are installation- and noise-sensitive; optical gas imaging and continuous methane sensors independently confirm atmospheric releases but depend on meteorology, geometry and detection thresholds. The review therefore proposes a layered Saudi commissioning framework that links readiness assurance, dynamic baseline management, multi-sensor confirmation, alarm governance, escalation logic and post-start-up learning. Its central contribution is to treat leak monitoring not as a stand-alone instrument function but as a time-dependent barrier system whose configuration must change as the facility progresses from inert condition to line packing, first hydrocarbons, stabilization and performance testing. The framework supports faster detection, fewer nuisance alarms, disciplined isolation and evidence-based loss prevention without claiming that monitoring can replace mechanical integrity or safe commissioning practice.

Keywords: commissioning; start-up; leak detection; loss prevention; oil and gas; methane monitoring; Saudi Arabia; digital twin

I. INTRODUCTION

Saudi Arabia is expanding, upgrading and integrating complex upstream, midstream, gas-processing, refining and petrochemical infrastructure while simultaneously increasing expectations for operational reliability, emissions control and digitalization. The commissioning boundary between completed construction and routine operation is therefore strategically important. During this period, new piping is pressurized for the first time, valves and control loops are exercised under live process conditions, rotating equipment moves through transient operating envelopes, temporary blinds and bypasses are removed, and inventories accumulate in vessels and lines. The attached structural reference correctly treats commissioning as a transition in which phased execution, operational readiness, communication and digital tools must work together; however, the present review narrows that logic to containment assurance and loss prevention during first hydrocarbon introduction and start-up.

Leak risk during start-up differs from steady-state risk. A stable operating plant can establish expected correlations between inlet and outlet flow, pressure, temperature and inventory. During line filling, recycle establishment, compressor loading or separator stabilization, those relationships move deliberately. A conventional alarm may therefore interpret planned transients as leakage, while aggressive filtering intended to suppress nuisance alarms may conceal a small real release. Reviews of oil and gas leak detection consistently conclude that performance depends on leak size, fluid properties, topology, sensor spacing and operating state, and that hybrid methods are generally more robust than single-method solutions (Lu et al., 2020; Zaman et al., 2020; Korlapati et al., 2022; Yuan et al., 2023). This is

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especially relevant to commissioning, where the baseline itself is nonstationary.

Loss prevention also extends beyond detecting a leak. The useful safety outcome is the time from release initiation to recognition, confirmation, localization, isolation, depressurization and recovery. A sensitive detector that produces frequent false alarms can erode operator trust; a highly specific detector that responds too slowly can allow a small loss of containment to become a fire, vapor-cloud or environmental event. Continuous methane-monitoring trials likewise show that detection probability and quantification uncertainty vary materially among technologies and meteorological conditions (Chen et al., 2023; Bell et al., 2023; Ilonze et al., 2024). Consequently, monitoring architecture must be designed with explicit decision thresholds, redundancy and response responsibilities rather than evaluated only through laboratory accuracy.

Saudi operating environments add practical considerations. Large asset footprints, hot and dusty conditions, remote rights-of-way, dense process units, offshore facilities, sour-service applications and high-throughput gas systems create heterogeneous sensing problems. Regional methane studies also demonstrate the value of measurement-based verification and independent top-down observations in Middle Eastern hydrocarbon systems (Chen et al., 2023a; Shen et al., 2023). These observations do not directly measure commissioning leaks, but they reinforce the need to combine facility-level monitoring with broader emissions assurance. The central question is therefore how technologies with different physical principles and failure modes can be orchestrated as a commissioning barrier rather than purchased as isolated devices.

This review develops that orchestration. It synthesizes evidence on computational, acoustic, fiber-optic, imaging, continuous methane and digital-twin approaches; examines start-up-specific limitations; and converts the synthesis into a staged framework for Saudi projects. The emphasis is on technical and managerial integration: verified readiness before hydrocarbons, dynamic baselines during transients, rapid multi-sensor confirmation, pre-agreed escalation and isolation, and structured learning after stabilization. The objective is not to prescribe a single vendor solution, but to define the architecture and evidence requirements by which project teams can select, test and govern leak-monitoring barriers.

II. AIM OF THE STUDY

The aim of this review is to develop an evidence-based framework for real-time leak monitoring and loss prevention during commissioning and start-up of Saudi Arabian oil and gas infrastructure. It specifically examines how sensing technologies, process analytics, operational-readiness controls and response governance can be combined across changing start-up states so that leak detection remains timely and credible without allowing nuisance alarms, transient process behavior or fragmented handover responsibilities to weaken containment assurance.

III. RESEARCH OBJECTIVES

The review pursues five objectives. First, it evaluates the strengths and limitations of major real-time leak-detection families under commissioning transients rather than only steady-state operation. Second, it identifies how pre-start-up safety review, mechanical-completion evidence and barrier verification should condition the activation of monitoring systems before hydrocarbon introduction. Third, it compares the roles of process-based, acoustic, fiber-optic, optical, methane-sensing and data-driven methods in detection, confirmation, localization and quantification. Fourth, it develops a staged multi-layer monitoring and escalation framework suitable for Saudi oil and gas projects. Fifth, it identifies research, validation and governance gaps that must be addressed before digital leak-monitoring performance can be treated as a dependable safety and loss-prevention barrier.

IV. RESEARCH QUESTIONS

RQ1: Which real-time leak-monitoring methods provide the most credible detection and localization capability during nonstationary commissioning and start-up conditions? RQ2: How should computational process monitoring be combined with independent field sensing to reduce both missed leaks and nuisance

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alarms? RQ3: What readiness, alarm-management and response controls are required to convert a detection signal into effective loss prevention? RQ4: How should monitoring architecture change between inert testing, line packing, first hydrocarbons, stabilization and performance testing? RQ5: What evidence gaps limit confident deployment of these approaches in Saudi Arabian operating environments?

V. REVIEW METHODOLOGY

An integrative review design was selected because the research problem crosses process safety, instrumentation, pipeline engineering, methane measurement, machine learning and commissioning management. A narrowly defined systematic review of one sensor class would not answer the implementation question, while an unstructured narrative review would make technology comparison difficult. The method therefore combined a transparent structured search with critical thematic synthesis. The attached commissioning article was used only as a structural reference for organizing discussion around readiness, phased execution, communication and outcomes; its claims and reference list were not adopted as evidence. Searches were designed around Scopus-indexed literature and publisher databases including ScienceDirect, SpringerLink, Wiley Online Library, ACS Publications, IEEE Xplore and MDPI. Search strings combined terms such as “oil gas pipeline leak detection,” “real-time leak monitoring,” “commissioning start-up process safety,” “pre-start-up safety review,” “acoustic emission pipeline,” “negative pressure wave,” “distributed acoustic sensing,” “optical gas imaging methane,” “continuous methane monitoring,” “digital twin leak detection,” “machine learning pipeline leakage,” and “Saudi methane emissions.” The principal evidence window was 2020-2025, with older literature considered only when it provided foundational context that remained technically relevant. The final reference set was intentionally limited to 30 peer-reviewed journal papers whose bibliographic records and DOI links were checked against publisher or DOI metadata.

Inclusion required direct relevance to at least one of four analytical domains: leak detection or localization in oil/gas or analogous pressurized pipelines; continuous or optical methane detection at oil and gas facilities; data-driven or digital-twin fault detection; or process-safety/readiness control applicable to start-up. Studies had to provide enough methodological detail to assess sensing principle, operating assumptions, performance limitations or implementation implications. Purely promotional material, patents, non-peer-reviewed vendor claims, unrelated corrosion studies, and papers whose contribution could not be connected to real-time monitoring or start-up risk were excluded. Saudi-specific peer-reviewed evidence was retained when it informed regional emissions verification or implementation context, but the review did not treat data from another operating phase or country as direct evidence of Saudi commissioning performance.

Screening was qualitative and relevance-led; no article-count flow numbers are reported because the search was iterative across engineering subfields and the review did not maintain a prospectively registered screening log. This avoids the false precision of reconstructing PRISMA-style counts after the fact. Quality appraisal considered peer-review status, experimental or field basis, transparency of detection conditions, treatment of false alarms and uncertainty, external validation, and transferability to transient operations. Controlled-release studies were weighted strongly for detection-performance claims because they expose practical detection limits and false-positive behavior. Simulation and machine-learning studies were used to explain emerging capabilities but were interpreted cautiously where training data, leak classes or operating regimes were narrower than real commissioning conditions.

The synthesis proceeded in four stages. First, technologies were grouped by the physical information they observe: hydraulic/process imbalance, propagating acoustic or pressure disturbances, distributed strain/temperature/vibration, direct optical visualization, atmospheric methane concentration, and model-data residuals. Second, each group was assessed against start-up requirements: speed, localization, small-leak sensitivity, transient tolerance, retrofitability, coverage and interpretability. Third, evidence was mapped to commissioning stages and response decisions. Fourth, recurring limitations were converted into design principles for a layered architecture. Because heterogeneous studies report accuracy, probability of detection, localization error and detection limits under different conditions, no statistical meta-analysis was attempted. The method instead emphasizes mechanistic comparison and bounded inference, which is more appropriate for translating diverse evidence into a commissioning framework.

Table 1. Comparative role of major leak-monitoring approaches during commissioning

Method	Primary signal	Commissioning strength	Key weakness	Best role	Typical evidence
Computational / mass balance	Pressure, flow, temperature, inventory	Continuous plant-wide context	Transient baseline and model uncertainty	Screening and segment diagnosis	SCADA/model residual
Acoustic / pressure wave	Leak-generated vibration or transient	Fast event response and localization	Noise, coupling, valve/pump interference	Rapid independent confirmation	Wave arrival / spectral signature
Distributed fiber sensing	Spatial vibration/strain/temperature	Long linear coverage	Installation and coupling dependence	Pipeline/route localization	Distributed event location
Fixed methane sensing	Atmospheric CH4 concentration	Continuous release confirmation	Wind and placement dependence	Independent atmospheric layer	Concentration/plume interception
Optical gas imaging	Infrared hydrocarbon plume	Component-level visual localization	Not inherently continuous; line-of-sight	Targeted first-fill walkdown	Visible plume at source
Digital twin / ML	Data-driven residual or class	Pattern recognition and sensor fusion	Domain shift and training bias	Correlation and decision support	Multi-variable anomaly score

VI. THEMATIC LITERATURE REVIEW AND CRITICAL ANALYSIS

6.1. Commissioning transients as a distinct leak-detection problem

Start-up creates intentional disturbances that resemble faults. Valve stroking, pump starts, compressor loading, line packing, recycle changes and controller tuning produce pressure and flow signatures that can trigger methods calibrated on steady operation. Vaughen (2020) showed more broadly that transient operations are disproportionately vulnerable when engineering and administrative controls do not behave as expected. Di Vito (2020) and Abu Bakar and Aziz (2024) similarly position pre-start-up safety review as the point at which safety-critical systems, procedures, actions and readiness evidence are confirmed before hazardous material is introduced. For leak monitoring, this means sensors must not merely be installed; their ranges, timestamps, communications, alarm routing, cause-and-effect logic and baseline assumptions must be tested as part of readiness.

A commissioning leak-detection philosophy should therefore define state-dependent expectations. During nitrogen circulation or hydrotest recovery, atmospheric hydrocarbon sensors may provide little information while pressure-decay or tightness testing dominates. During initial gas-in, a mass-balance residual may be meaningless until line inventory and compressibility are reconciled. During stabilized circulation, the same residual can become powerful. Treating one alarm threshold as valid throughout these states creates avoidable conflict between sensitivity and nuisance-alarm control.

6.2. Process and computational pipeline monitoring

Computational pipeline monitoring uses measured pressure, flow, temperature and sometimes composition to infer abnormal losses. Model-based sensor fusion can estimate leak magnitude and location, as demonstrated by Doshmanziari et al. (2020), while inverse transient analysis can support real-time localization in oil systems (Malekpour & She, 2021). Reviews by Korlapati et al. (2022), Yuan et al. (2023) and the computational comparison by Sekhavati et al. (2022) converge on an important point: process-based methods provide continuous coverage without requiring direct access to every component, but their reliability depends on model fidelity, instrumentation quality and knowledge of operating state.

Machine-learning methods expand the ability to recognize complex signatures. Banjara et al. (2020) combined acoustic emission with learning algorithms; Wang et al. (2020) used representation learning and ensemble classification; Li et al. (2022) combined a convolutional network with optimization for negative-pressure-wave data; and Wang et al. (2023) addressed small-sample transfer from offline to online detection. Miao et al. (2023) is particularly relevant to commissioning because unsupervised learning reduces dependence on large labeled leak datasets. Yet these studies also reveal the central deployment gap: high classification accuracy on experimental or historical datasets does not guarantee dependable performance during first-fill transients that were absent from training.

Digital twins offer a potential bridge. Liang et al. (2023) proposed a data-driven twin that learns normal pipeline behavior and updates with operational data. Such adaptation is attractive during stabilization, but it creates a governance question: a model that continuously learns may also learn abnormal behavior if the validation boundary is weak. In commissioning, adaptive models should therefore use frozen acceptance baselines at critical hold points, with controlled retraining only after operations confirm that the process state is healthy.

6.3. Acoustic, pressure-wave and distributed sensing

Acoustic emission and pressure-wave approaches can respond rapidly because a leak creates a propagating disturbance. Ullah et al. (2023) demonstrated high experimental classification performance using acoustic emission features, while Rai et al. (2021) used distributional comparison of acoustic features to distinguish leak states. Yan et al. (2023) showed that deep one-dimensional acoustic models can jointly support detection and localization. These methods are attractive for first hydrocarbons because they can identify fast-developing releases before a plant-wide material balance settles.

Their weakness is context sensitivity. Pumps, control valves, relief events, steam blows, rotating equipment and construction activity generate broadband noise. Start-up therefore increases precisely the interference that can degrade acoustic discrimination. Distributed sensing can extend coverage along pipelines and rights-of-way, while providing spatially resolved evidence for localization (Ahmed et al., 2023). However, coupling quality, cable placement, soil or support conditions and interrogator settings influence performance. The most defensible role for acoustic or distributed sensing in commissioning is consequently as a rapid independent layer whose events are correlated with process measurements and field confirmation rather than treated as a solitary trip signal.

6.4. Optical gas imaging and continuous methane sensing

Direct methane and hydrocarbon visualization addresses a different question: has material actually escaped into the atmosphere? Optical gas imaging is intuitive for field teams because it localizes visible plumes to components, but controlled testing has shown that detection is affected by release rate, distance, background, operator technique and environmental conditions. Zimmerle et al. (2020) found that realistic field detection limits were less favorable than simplified camera-performance expectations, demonstrating why experienced survey practice and geometry matter. OGI is therefore valuable at targeted flange, valve, seal and connection walkdowns during start-up, but it is not a continuous barrier unless automated imaging is used.

Fixed continuous methane systems fill that temporal gap. Chen et al. (2023) showed through dispersion-based analysis that detection efficiency depends on meteorology, sensor limit, count and placement. Bell et al. (2023) then demonstrated large performance variation among commercial continuous-monitoring solutions under controlled releases, including meaningful false-positive and quantification uncertainty. Ilonze et al. (2024) found improving performance in a later single-blind campaign, but still emphasized solution-specific detection limits. Daniels et al. (2024) further showed that nondetect periods caused by unfavorable wind direction can bias inferred emission duration. These findings are directly relevant to Saudi plants: continuous sensors should be laid out using site wind statistics and release scenarios, while alarm logic should distinguish "no plume intercepted" from "no release exists."

Top-down systems add periodic independent verification. Tyner and Johnson (2021) used airborne LiDAR to identify concentrated emissions, Cusworth et al. (2021) demonstrated multisatellite characterization of a major blowout, and Irakulis-Loitxate et al. (2022) showed that satellite observations can find large, abatable oil-sector sources. Chen et al. (2023a) and Shen et al. (2023) extended satellite-based quantification to national and Middle Eastern oil-gas contexts. These platforms are not substitutes for second-by-second commissioning detection, but they support later assurance, emissions reconciliation and identification of persistent sources that local routines may miss.

6.5. From detection to loss prevention

A monitoring architecture prevents loss only when it is connected to action. The practical chain is detection, validation, localization, hazard assessment, isolation, depressurization, repair and controlled restart. A process alarm that cannot identify a likely segment may delay field response; a local methane alarm without process context may not indicate whether inventory is increasing or already isolated. The literature therefore supports complementary layers rather than technology competition. Process analytics provide system context, acoustic or distributed sensing provides rapid spatial evidence, local gas sensing confirms release, and field imaging supports component-level verification.

During commissioning, the response logic should also reflect escalation asymmetry. A high-confidence multi-sensor event near an ignition source should trigger conservative isolation even if the release rate is uncertain. By contrast, a single low-level concentration alarm under shifting winds may justify verification before trip action. This requires predefined alarm classes, minimum confirmation rules and authority matrices. It also requires synchronized time bases: without common timestamps, teams cannot reliably determine whether pressure, acoustic and gas events describe the same physical incident.

The synthesis thus supports a state-aware barrier model. Monitoring should be commissioned before the process is commissioned, then reconfigured as process states change. A technology that is weak during line packing may become strong after stabilization; a portable OGI camera that is insufficient for unattended monitoring may be highly effective during a controlled flange-by-flange first-fill walkdown. The key design variable is not the nominal accuracy of a device, but whether the right combination of sensors and response rules is active for the hazard state.

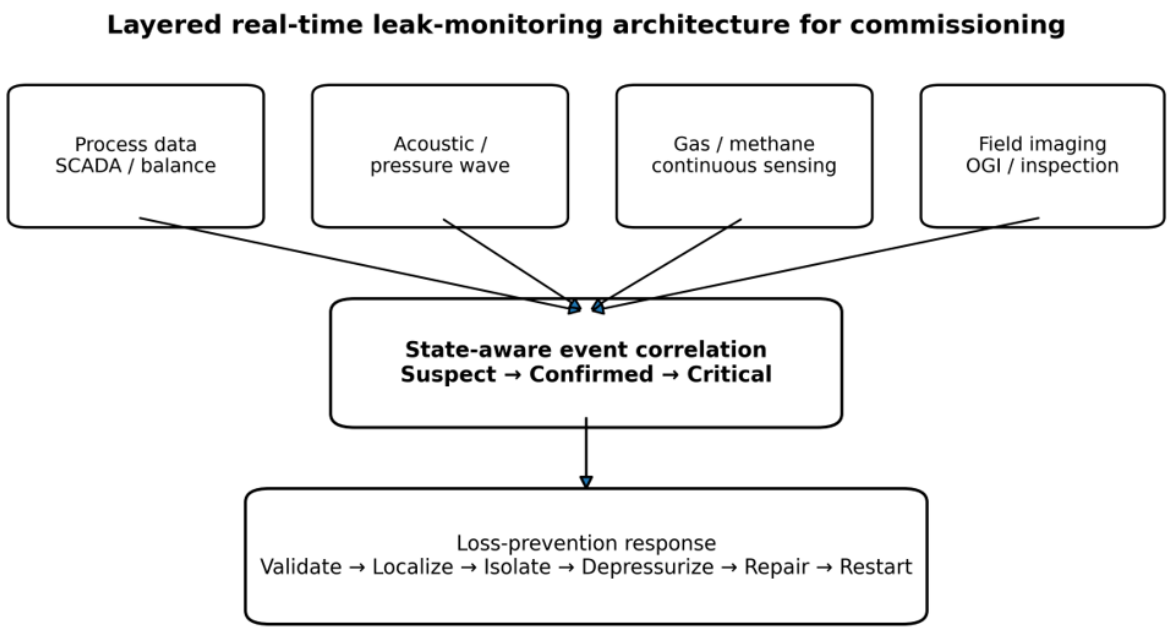

Figure 1. Layered real-time leak-monitoring architecture for commissioning

Figure 1 shows that independent sensing modalities should converge through state-aware correlation before escalation to loss-prevention actions; the architecture deliberately separates detection from confirmation and response.

Table 2. Stage-specific monitoring and decision priorities

Commissioning stage	Dominant uncertainty	Priority monitoring	Decision focus	Minimum readiness evidence
Inert / pre-hydrocarbon	Construction status and sensor readiness	Tightness tests, detector proof tests, communications checks	Authorize or block hydrocarbon introduction	Closed punch items, calibrated critical instruments, PSSR actions controlled
Line packing / initial fill	Changing inventory and compressibility	Pressure/flow trends, acoustic layer, field patrol	Differentiate planned inventory change from release	State-specific expected transients and isolation availability
First hydrocarbons	Highest uncertainty and new live joints	Temporary gas sensors, OGI, acoustic, process trends	Rapid confirmation and conservative isolation	Response team deployed, ignition controls, alarm routing tested
Stabilization	Control-loop and equipment transients	Model residuals, fixed gas sensing, targeted imaging	Tune baselines without masking faults	Documented threshold changes and event review
Performance / handover	Longer-term normal variability	Permanent CPM, gas detection, integrity analytics	Establish lifecycle baseline and ownership	Approved baseline, data retention and maintenance plan

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VII. DISCUSSION

The evidence suggests that the most important design decision is architectural rather than algorithmic. Research frequently compares detection methods as alternatives, yet commissioning risk demands overlapping barriers with different failure modes. Hydraulic models can be defeated by uncertain inventory; acoustic systems by noise; methane concentration networks by wind; imaging by line of sight; and machine learning by domain shift. When these technologies are combined, their weaknesses are less correlated. A process residual coincident with an acoustic event and a downwind methane rise has a different decision value from any signal alone.

This layered logic also resolves the tension between sensitivity and alarm burden. Start-up produces many legitimate transients, so setting every detector to maximum sensitivity can overwhelm the control room. Instead, the framework in Figure 1 separates “suspect,” “confirmed” and “critical” states. A single detector may open a diagnostic workflow; two independent modalities may confirm a release; a high-rate or escalating signal may initiate immediate isolation according to pre-approved cause-and-effect logic. Such rules should be rehearsed during commissioning simulations so that operators understand both automated and manual pathways.

Saudi projects can further exploit staged deployment. Portable acoustic instruments, OGI cameras and additional temporary methane sensors can be concentrated around newly introduced systems during first hydrocarbons, then removed or redeployed once stable performance is demonstrated. Permanent computational monitoring and fixed gas detection remain as lifecycle barriers. This avoids the false choice between installing permanent coverage everywhere and accepting weak start-up surveillance. It also aligns resources with the period of highest uncertainty.

Digital twins and machine learning should be used as decision-support technologies until their start-up performance is independently validated. The reviewed algorithms show strong technical promise, but many are trained on controlled leaks and relatively stable operating envelopes. Saudi operators should require testing against realistic sequences: line filling, valve movement, recycle establishment, compressor start, emergency shutdown recovery and sensor dropout. Performance measures should include time-to-detect, false alarms per operating hour, missed-event rate, localization error and recovery behavior after topology changes, not only classification accuracy.

The framework also broadens the meaning of loss prevention. Methane monitoring contributes climate and product-loss information, while process leakage detection protects people, equipment and availability. Combining these objectives can improve investment justification, but safety and emissions metrics should not be conflated. A sensor adequate for quantifying a large methane source may not detect a small hazardous release near personnel quickly enough; conversely, a local combustible-gas detector may protect a module without providing defensible site-wide emissions quantification. Governance should therefore assign each technology a declared safety, operational or emissions function and validate it against that function.

Finally, commissioning data should become part of the asset's integrity baseline. The first stable operating period establishes pressure-flow relationships, background acoustic signatures, normal methane concentrations and sensor-health patterns. Preserving these data creates a reference for later degradation detection and troubleshooting. The commissioning phase thus becomes not only a period to survive safely, but an opportunity to create a high-quality digital baseline for long-term loss prevention.

VIII. RESEARCH GAPS AND FUTURE RESEARCH

Five gaps are particularly important. First, few studies evaluate leak-detection performance through a full commissioning sequence; most use steady-state experiments or simulated leak scenarios. Research should publish controlled datasets that include realistic start-up disturbances and labeled leak events. Second, technology evaluations rarely test integrated multi-modal decision logic. Future trials should measure whether combining process residuals, acoustic signatures and atmospheric sensors reduces false alarms without increasing detection delay.

Third, Saudi-specific field evidence is limited. Regional satellite studies provide valuable emissions context, but they do not establish detection limits for desert process plants, sour-gas facilities, long pipelines or offshore start-up. Controlled-release campaigns under Saudi meteorology, dust loading, temperature extremes and equipment density would materially improve design confidence. Fourth, adaptive digital twins need governance research. Methods are required to prevent model drift, preserve auditable baselines and distinguish legitimate process evolution from normalization of a developing fault.

Fifth, human-system integration remains underdeveloped. Detection research often ends at an alarm, whereas loss prevention depends on alarm comprehension, authority, communication and isolation time. Future studies should evaluate operator workload, alarm clustering, handover quality and response performance during simulated first-hydrocarbon scenarios. A useful maturity standard would therefore assess the complete detection-to-isolation chain, not only sensor accuracy.

IX. PRACTICAL, MANAGERIAL AND POLICY IMPLICATIONS

For project teams, leak-monitoring design should begin during commissioning planning rather than after mechanical completion. Each start-up system should have a containment-monitoring plan identifying credible release points, available process measurements, temporary and permanent sensors, expected transient signatures, confirmation methods, escalation thresholds and isolation actions. The plan should be linked to system handover packs and the pre-start-up safety review so that unresolved sensor, communications or alarm defects can block hydrocarbon introduction when they affect a critical barrier.

For operations managers, monitoring should be organized as a layered service with named ownership. Instrument teams maintain detector health; process-control teams manage models and alarm logic; commissioning teams define operating states; HSE teams challenge barrier adequacy; and operations owns the final response. A common event log should synchronize process, acoustic, gas and operator observations. After every start-up stage, nuisance alarms and unexplained anomalies should be reviewed before thresholds are changed. Threshold relaxation without documented cause can silently convert an inconvenient alarm into a weakened barrier.

For Saudi regulators and major operators, policy could encourage performance-based validation rather than prescribing one sensor technology. Acceptance criteria should define minimum detection objectives, test scenarios, data retention, calibration and proof-test expectations while allowing different technical solutions. Commissioning documentation should record which leak-monitoring barriers were active during first hydrocarbons and how they performed. Where continuous methane systems support environmental reporting, their detection limits and meteorological coverage should be disclosed separately from safety-gas detector functions.

Figure 2 translates these implications into a stage-gated deployment model. It shows monitoring intensity peaking during first hydrocarbon introduction and early stabilization, when uncertainty is highest, then transitioning toward optimized permanent coverage. The approach supports Saudi digital-transformation goals while retaining conventional process-safety discipline: digital monitoring strengthens, but does not replace, mechanical integrity, tightness testing, relief protection, isolation design, operating procedures and competent field presence.

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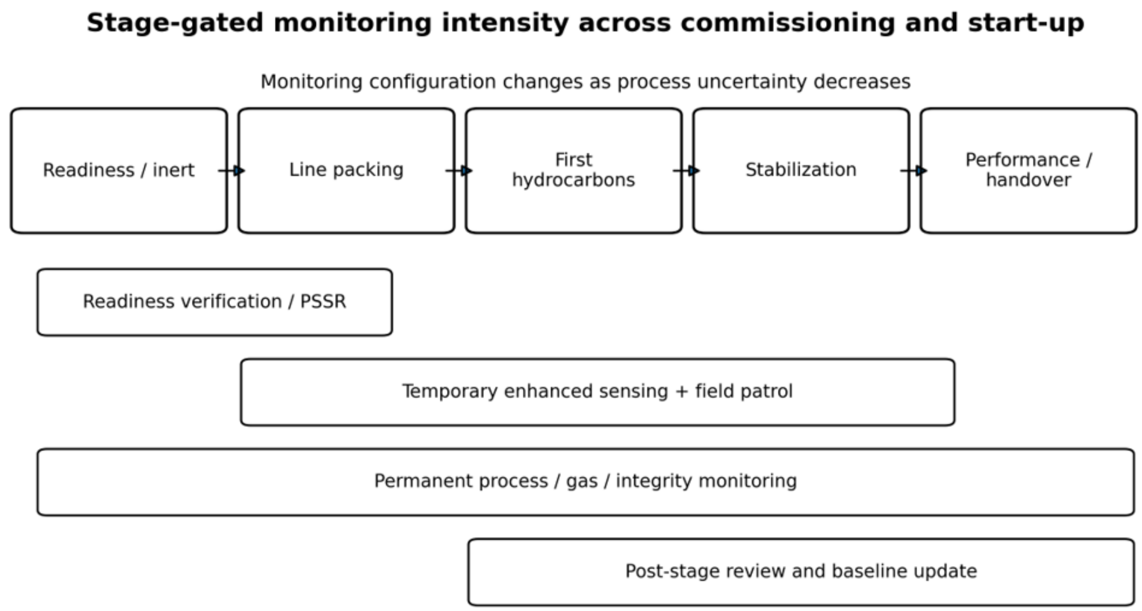

Figure 2. Stage-gated monitoring intensity across commissioning and start-up

Figure 2 emphasizes temporary enhanced coverage during first hydrocarbons, followed by deliberate transition to permanent monitoring after stable baselines and ownership are established.

X. LIMITATIONS

This review has several limitations. It integrates heterogeneous studies whose fluids, pressures, pipe diameters, sensor placements, leak sizes and performance metrics are not directly comparable, so numerical ranking across technologies would be misleading. Much of the machine-learning literature is based on controlled or simulated datasets and may overstate field robustness. Continuous methane studies are concentrated in North American production settings, while Saudi-specific peer-reviewed commissioning trials are scarce. Satellite and airborne studies inform verification and emissions context but operate at temporal and spatial scales different from control-room leak protection.

The search was structured but iterative and did not maintain a prospectively registered screening database; accordingly, the review deliberately avoids fabricated article-flow counts. The 30-reference limit also required prioritization of evidence most directly useful to the framework rather than exhaustive coverage. Finally, the proposed architecture is conceptual. Its thresholds, redundancy and escalation rules must be engineered for each facility through hazard analysis, commissioning procedures, detector specifications and validated cause-and-effect design. Additional validation should distinguish detector availability from detector effectiveness during start-up. A device may be technically sensitive yet temporarily unavailable because of calibration, blocked optics, communications failure, maintenance bypass, power interruption, or missing process data. Commissioning acceptance tests should therefore record both coverage and availability, while any temporary impairment should trigger documented compensating measures such as increased field patrols, portable monitoring, or reduced operating scope. This distinction matters because an absence of alarms can otherwise be misread as evidence of intact containment. It also creates a traceable basis for handover, enabling operations personnel to understand which monitoring barriers were proven, impaired, restored, or still subject to temporary controls before final acceptance. For this reason, final acceptance should verify not merely that each detector can alarm, but that the complete monitoring chain remains available, time-synchronized, actionable, documented, and understood by the personnel responsible for immediate response.

XI. CONCLUSION

Real-time leak monitoring during commissioning and start-up should be treated as a changing barrier system rather than a fixed detector package. The evidence reviewed here shows that commissioning transients undermine the assumptions of many single-method leak-detection approaches: inventories change, hydraulic models are temporarily uncertain, acoustic noise rises, wind controls plume interception and data-driven models encounter states absent from training. No technology therefore provides universally reliable protection.

A stronger approach for Saudi oil and gas infrastructure is layered and stage-aware. Pre-start-up safety review first establishes that containment, instrumentation, communications and response functions are ready. Process and computational monitoring then provide continuous system context; acoustic, pressure-wave or distributed sensing adds rapid independent evidence; local gas sensors and optical imaging confirm atmospheric release; and digital analytics support correlation and learning. Alarm governance converts these observations into suspect, confirmed and critical states tied to predefined authority and isolation actions.

The review's principal contribution is the integration of monitoring technology with commissioning governance. Detection performance matters, but loss prevention depends equally on timing, confirmation, localization, response and safe restart. Saudi operators can strengthen both safety and emissions performance by validating monitoring against realistic start-up sequences, using temporary enhanced coverage during first hydrocarbons, retaining synchronized commissioning data as an integrity baseline, and separating safety functions from emissions-quantification functions. Future work should test this framework through controlled multi-sensor commissioning trials under Saudi environmental and operating conditions. Until such evidence is available, digital methods should be deployed with transparent assumptions and independent confirmation, reinforcing established mechanical-integrity and process-safety controls rather than substituting for them.

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