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Risk-Based Integrity Management of CO₂ Pipelines in CCUS: Integration of Failure Mechanisms, Risk Assessment, and Inspection Strategies—A Review

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Abstract: The rapid deployment of Carbon Capture, Utilization, and Storage (CCUS) systems has significantly increased the demand for safe and reliable CO₂ transportation infrastructure. Pipelines are widely recognized as the most economical and technically feasible option for large-scale CO₂ transport. However, the thermodynamic behavior of dense-phase CO₂, coupled with impurity interactions, rapid decompression, and environmentally assisted degradation, introduces integrity challenges that differ substantially from those encountered in conventional hydrocarbon pipelines. This review aims to integrate current knowledge on CO₂ pipeline failure mechanisms, probabilistic risk assessment approaches, and inspection strategies into a comprehensive Risk-Based Inspection (RBI) framework for CCUS applications. A structured literature review was conducted using peer-reviewed publications retrieved from the Scopus and Web of Science databases, complemented by internationally recognized engineering standards, including API 580, API 581, API 579-1/ASME FFS-1, and DNV recommended practices. The selected studies were systematically analyzed according to degradation mechanisms, probabilistic risk assessment methodologies, uncertainty treatment, and inspection and monitoring technologies. The review indicates that internal corrosion, impurity-induced degradation, and running fracture remain the dominant threats to CO₂ pipeline integrity, while probabilistic approaches, particularly Bayesian networks and reliability-based models, provide superior capability for representing operational uncertainty compared with conventional deterministic methods. Nevertheless, existing studies remain fragmented, with degradation assessment, probabilistic risk modeling, and inspection optimization frequently addressed as separate research topics. To overcome this limitation, this paper proposes a Dynamic Risk-Based Inspection (D-RBI) framework that integrates CO₂-specific degradation mechanisms, Bayesian risk updating, real-time monitoring, and adaptive inspection scheduling into a unified integrity management strategy. The proposed framework provides a conceptual foundation for developing adaptive, data-driven, and risk-informed integrity management systems capable of supporting the long-term safety and reliability of future CCUS pipeline networks.

Citation: Risdianto., Soedarsono, J. W., Pratesa, Y. (2026). Risk-Based Integrity Management of CO₂ Pipelines in CCUS: Integration of Failure Mechanisms, Risk Assessment, and Inspection Strategies—A Review. *Recent in Engineering Science and Technology*, 4(4), 185–208. Retrieved from <https://www.mbi-journals.com/index.php/riestech/article/view/167>.

Academic Editor: Yudhi Ariadi

Received: 21 June 2026

Accepted: 27 July 2026

Published: 11 October 2026

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Keywords: CO₂ pipeline; Carbon Capture, Utilization and Storage; Risk-Based Inspection; integrity management; Bayesian network; corrosion; fracture propagation.

1. Introduction

Global efforts to achieve carbon neutrality and mitigate greenhouse gas emissions have accelerated the deployment of Carbon Capture, Utilization, and Storage (CCUS) technologies as one of the principal decarbonization strategies for hard-to-abate industrial sectors. The International Energy Agency (IEA) identifies CCUS as an essential technology for achieving global net-zero emission targets because it enables substantial reductions in carbon emissions from cement, steel, petrochemical, refining, and fossil-fuel power generation facilities [1].

A critical component of any CCUS system is the transportation network responsible for transferring captured carbon dioxide from emission sources to geological storage sites or utilization facilities. Among the available transportation alternatives, pipelines remain the most technically mature and economically attractive solution for continuous, large-capacity CO₂ transport over long distances [2]. To maximize transport efficiency, CO₂ pipelines are commonly operated under dense-phase or supercritical conditions, where fluid properties become highly sensitive to pressure, temperature, and impurity composition [3].

Unlike conventional natural gas transmission systems, captured CO₂ streams frequently contain impurities such as water (H₂O), hydrogen sulfide (H₂S), sulfur dioxide (SO₂), oxygen (O₂), and nitrogen oxides (NO_x). These impurities influence phase stability, electrochemical behavior, corrosion kinetics, fracture propagation, and decompression characteristics, thereby introducing degradation mechanisms that are fundamentally different from those encountered in hydrocarbon pipelines [4,5]. Internal corrosion caused by free water and acidic contaminants remains one of the most critical threats to pipeline integrity [6]. Furthermore, rapid decompression during accidental rupture can significantly accelerate crack propagation and reduce crack-arrest capability, increasing the likelihood of high-consequence failures [7]. Additional degradation mechanisms, including stress corrosion cracking (SCC), sulfide stress cracking (SSC), hydrogen-induced cracking (HIC), and impurity-assisted localized corrosion, have also been reported under specific operating conditions [8].

Risk-Based Inspection (RBI) has become a widely accepted methodology for optimizing inspection planning and maintenance strategies in the oil and gas industry. By integrating the Probability of Failure (PoF), Consequence of Failure (CoF), degradation mechanisms, and inspection effectiveness, RBI enables inspection resources to be allocated according to risk rather than fixed inspection intervals [9,10]. However, current RBI methodologies were primarily developed for conventional hydrocarbon facilities and do not explicitly consider the unique thermodynamic behavior, impurity effects, decompression characteristics, and environmentally assisted degradation mechanisms associated with dense-phase CO₂ transportation.

Although substantial progress has been made in understanding individual aspects of CO₂ pipeline integrity, existing research remains highly fragmented. Numerous studies investigate corrosion mechanisms, fracture mechanics, probabilistic reliability analysis, inspection technologies, or digital monitoring independently, with relatively limited efforts devoted to integrating these disciplines into a unified integrity management framework. This fragmentation has important practical consequences. In the absence of an integrated framework, degradation mechanisms may be evaluated independently from inspection planning, resulting in overly conservative inspection intervals, insufficient inspection coverage for emerging degradation mechanisms, inefficient allocation of maintenance resources, and an increased likelihood of undetected failures under variable operating conditions. Consequently, operators may either incur unnecessary inspection costs or underestimate evolving integrity risks, particularly in large-scale CCUS transportation networks.

Several review papers have discussed corrosion mechanisms, fracture control, or pipeline reliability individually. However, few studies have systematically integrate CO₂-specific degradation mechanisms, probabilistic risk assessment, uncertainty management, and inspection optimization into a single Risk-Based Inspection framework. Accordingly, the primary novelty of this review lies in proposing an integrated Dynamic Risk-Based Inspection (D-RBI) framework that combines CO₂-specific degradation mechanisms, Bayesian probabilistic updating, real-time monitoring, and adaptive inspection planning

within a unified integrity management concept. Unlike previous reviews, this study emphasizes the interaction between degradation assessment, uncertainty quantification, and inspection decision-making to support future digitalized CCUS infrastructure.

Therefore, this review aims to synthesize current knowledge on CO₂ pipeline failure mechanisms, probabilistic risk assessment methodologies, inspection technologies, and uncertainty treatment, and subsequently integrate these elements into a conceptual Dynamic Risk-Based Inspection framework suitable for future CCUS applications. The guiding research question addressed in this review is : *How can CO₂-specific degradation mechanisms, probabilistic risk assessment, uncertainty management, and inspection strategies be integrated to establish an adaptive Risk-Based Inspection framework for ensuring the long-term integrity of CO₂ transportation pipelines?*

Table 1. Comparative analysis of key literature and identified research gaps.

Author and Year	Main Paper Title	Core Methodology	Primary Contributions	Limitations / Gaps
Yarveisy et al. (2020) [11]	Dynamic risk assessment of corrosion in CO ₂ transportation pipelines...	Probabilistic modeling & dynamic risk assessment	Established dynamic risk model integrating transient operations with probabilistic corrosion growth.	Limited to corrosion; not translated into tactile inspection scheduling or fracture control.
Khan et al. (2021) [12]	Risk-based pipeline integrity management: A road map for resilient pipelines	Conceptual framework & reliability analysis	Provided a roadmap for digital transformation of conventional RBI toward predictive analytics.	Generalized for conventional hydrocarbon; dense-phase CO ₂ multi-impurity effects unaddressed.
Li et al. (2018) [5]	Corrosion behavior of carbon steel in dense-phase CO ₂ pipelines...	Experimental laboratory investigation	Delivered electrochemical data on impurity effects (SO ₂ , H ₂ S, O ₂ , NO _x) on pitting initiation.	Focused on lab-scale mechanisms without probabilistic risk modeling or field optimization.
Zhu and Wang (2023) [13]	Data-driven RBI framework for carbon transport infrastructure	Machine learning & data-driven RBI	Used operational data to forecast wall-thickness degradation and optimize inspection intervals.	Black-box statistical correlations were not sufficiently constrained by metallurgy or fracture limits.
Zheng et al. (2022) [14]	Integrity management of CCUS pipelines under uncertainty	Uncertainty quantification & simulation	Quantified epistemic and aleatory uncertainties under supply fluctuations from capture facilities.	Inspection optimization remained largely static rather than adaptively updated via sensors.

2. Review Methodology

This study was conducted as a structured literature review to critically evaluate recent developments in CO₂ pipeline integrity management for Carbon Capture, Utilization, and Storage (CCUS) systems. The review focused on integrating knowledge from degradation mechanisms, probabilistic risk assessment, inspection technologies, uncertainty analysis,

and integrity management frameworks to establish a comprehensive understanding of Risk-Based Inspection (RBI) implementation for CO₂ transportation infrastructure.

A systematic literature search was performed using the Scopus and Web of Science databases because of their extensive coverage of high-quality peer-reviewed engineering literature. The search strategy employed combinations of Boolean operators using keywords including "CO₂ pipeline", "CCUS", "carbon capture and storage", "pipeline integrity", "Risk-Based Inspection", "corrosion", "fracture propagation", "dense-phase CO₂", "Bayesian network", "probabilistic risk assessment", "inspection optimization", and "integrity management". In addition to journal articles, internationally recognized engineering standards and recommended practices, including API 580, API 581, API 579-1/ASME FFS-1, DNV-RP-F104, and DNV-ST-F101, were reviewed to provide industrial context and current engineering practice.

Publications were screened according to predefined inclusion criteria. Studies were retained when they discussed at least one of the following topics:

1. CO₂-specific degradation mechanisms, including corrosion, fracture, and environmentally assisted cracking;
2. Probabilistic, reliability-based, or uncertainty-based risk assessment methodologies;
3. Inspection, monitoring, or integrity management technologies applicable to CO₂ pipelines; or
4. Conceptual or practical Risk-Based Inspection (RBI) frameworks.

Studies unrelated to CO₂ transportation, duplicate publications, papers lacking sufficient technical information, and articles focusing exclusively on non-pipeline CCS components were excluded. Following the screening process, 78 publications were selected for detailed review and classified into four categories: numerical/simulation studies, experimental investigations, field applications, and conceptual or framework-oriented studies.

The selected publications were subsequently analyzed using a qualitative thematic synthesis approach. Each study was evaluated according to four analytical dimensions: (i) degradation mechanisms, (ii) probabilistic risk assessment methodology, (iii) inspection and monitoring technology, and (iv) integrity management strategy. Comparative analysis of these themes enabled the identification of current research trends, methodological limitations, and remaining knowledge gaps. The synthesized findings formed the scientific basis for developing the *Dynamic Risk-Based Inspection (D-RBI) framework* proposed in this review.

Although this review does not constitute a formal meta-analysis, the structured search strategy, predefined selection criteria, and thematic synthesis methodology provide a transparent and reproducible approach for identifying current advances and future research directions in CO₂ pipeline integrity management.

3. Results and Discussion

3.1. Overview of Selected Studies

The reviewed literature demonstrates a marked increase in research activity on CO₂ pipeline integrity following 2018, coinciding with the rapid global expansion of Carbon Capture, Utilization, and Storage (CCUS) initiatives and increasing international commitments toward carbon neutrality. This growing research interest reflects the recognition that CO₂ transportation infrastructure represents one of the most critical components determining the technical feasibility and long-term reliability of large-scale CCUS deployment. As investment in carbon transportation networks continues to increase, ensuring pipeline integrity has become an important multidisciplinary research topic

encompassing metallurgy, corrosion engineering, fracture mechanics, probabilistic reliability, structural health monitoring, and risk-informed decision making.

Analysis of the selected publications indicates that the majority of existing studies focus on individual technical aspects of pipeline integrity rather than on integrated integrity management. Corrosion mechanisms, fracture propagation, probabilistic reliability assessment, and monitoring technologies have all received considerable attention; however, relatively few publications attempt to establish systematic relationships among these disciplines within a unified Risk-Based Inspection (RBI) framework. Consequently, current knowledge remains compartmentalized, making it difficult to translate scientific findings into practical inspection and maintenance strategies for future CO₂ transportation systems.

The classification of the selected studies further illustrates this imbalance. As summarized in Table 2, numerical and simulation-based investigations account for approximately 41% of the reviewed publications, followed by experimental and laboratory investigations (29%), field studies (20%), and conceptual or framework-oriented studies (9%). The predominance of simulation-based research indicates that considerable effort has been devoted to modeling corrosion growth, fracture propagation, decompression behavior, and probabilistic reliability under controlled assumptions. Nevertheless, relatively limited validation has been conducted using operational pipeline data, particularly for dense-phase CO₂ transportation systems where long-term industrial experience remains scarce.

Table 2. Distribution of selected studies according to research category.

Category	Number	Percentage
Numerical/Simulation	32	41%
Experimental/Laboratory	23	29%
Field Study	16	20%
Conceptual/Framework	7	9%
Total	78	100%

The relatively small proportion of conceptual studies is particularly noteworthy because it indicates that, despite significant advances in individual research domains, comparatively little attention has been devoted to developing comprehensive integrity management methodologies specifically tailored to CO₂ transportation pipelines. Existing studies generally concentrate on solving isolated engineering problems, such as predicting corrosion rates, evaluating fracture resistance, or improving monitoring technologies, without adequately considering how these findings should collectively support inspection planning and operational decision-making. This observation directly supports the research gap identified in the Introduction. As CCUS infrastructure evolves toward large-scale interconnected pipeline networks, integrity management will increasingly require multidisciplinary approaches capable of integrating degradation assessment, uncertainty quantification, inspection effectiveness, and operational monitoring into a single decision-support framework. Therefore, the current literature suggests that future research should move beyond isolated degradation studies toward integrated integrity management methodologies that continuously incorporate operational information into adaptive inspection planning.

3.2. CO₂ Pipeline Operational Characteristics

The operational characteristics of CO₂ transportation pipelines differ fundamentally from those of conventional hydrocarbon transmission systems because of the unique thermodynamic behavior of carbon dioxide under dense-phase and supercritical operating conditions. To maximize transportation efficiency while minimizing compression costs, CO₂ is typically transported at pressures above its critical pressure (7.38 MPa) and temperatures near or above its critical temperature (31.1 °C), where relatively small variations in operating conditions may produce substantial changes in fluid density, compressibility, and phase stability [3]. Unlike natural gas pipelines, the physical behavior of dense-phase CO₂ is highly sensitive not only to pressure and temperature but also to the presence of impurities originating from different carbon capture processes. Depending on the capture technology and emission source, transported CO₂ streams may contain varying concentrations of water (H₂O), hydrogen sulfide (H₂S), sulfur dioxide (SO₂), oxygen (O₂), nitrogen oxides (NO_x), methane (CH₄), nitrogen (N₂), hydrogen (H₂), and other trace components. Even relatively small impurity concentrations may significantly alter phase equilibrium, decompression characteristics, and electrochemical behavior, thereby influencing both operational safety and long-term material degradation [4,5].

Among these impurities, water represents one of the most critical parameters controlling pipeline integrity. Under dry conditions, carbon steel generally exhibits excellent compatibility with dense-phase CO₂. However, when free water is present, dissolved CO₂ readily forms carbonic acid (H₂CO₃), initiating electrochemical reactions that may result in generalized corrosion, localized pitting, or under-deposit corrosion. The presence of acidic contaminants such as SO₂ and NO_x further decreases solution pH and accelerates corrosion kinetics, while H₂S may promote sulfide stress cracking and hydrogen-assisted degradation in susceptible pipeline steels [4–6]. Consequently, strict impurity control should be regarded not only as a process requirement but also as a fundamental component of integrity management for CO₂ transportation systems.

In addition to corrosion-related challenges, dense-phase CO₂ pipelines exhibit decompression behavior that differs significantly from conventional gas transmission pipelines. During accidental rupture, rapid depressurization may induce substantial Joule–Thomson cooling, phase transformation, and two-phase flow, resulting in decompression wave velocities that strongly influence crack propagation and crack-arrest capability [7]. These thermodynamic phenomena complicate fracture control because traditional design criteria developed for natural gas pipelines may underestimate fracture propagation risks under dense-phase CO₂ conditions.

The combined effects of thermodynamic behavior, impurity chemistry, and fracture mechanics create complex interactions among operating parameters, degradation mechanisms, and structural integrity. Variations in operating pressure, temperature, flow rate, or impurity concentration may simultaneously influence corrosion susceptibility, crack initiation, and fracture propagation, producing dynamic changes in pipeline risk throughout the operational life cycle. Therefore, integrity management for CO₂ transportation systems cannot rely solely on deterministic design margins or fixed inspection intervals but should incorporate continuous monitoring, probabilistic risk assessment, and adaptive inspection planning capable of responding to changing operating conditions.

These operational characteristics distinguish CO₂ transportation pipelines from conventional hydrocarbon systems and provide the technical justification for developing CO₂-specific Risk-Based Inspection methodologies. Rather than treating degradation mechanisms independently, future integrity management strategies should integrate thermodynamic behavior, material degradation, operational uncertainty, and inspection

effectiveness within a unified framework capable of supporting predictive and adaptive decision-making for large-scale CCUS infrastructure.

3.3. Failure Mechanisms in CO₂ Pipelines

The integrity of CO₂ transportation pipelines is governed by a complex interaction between environmental conditions, material properties, operating parameters, and fluid chemistry. Unlike conventional hydrocarbon pipelines, degradation in dense-phase CO₂ systems is influenced not only by mechanical loading but also by thermodynamic instability and impurity-induced electrochemical reactions. Consequently, pipeline failures generally originate from multiple interacting degradation mechanisms rather than a single isolated defect.

The reviewed literature indicates that corrosion-related degradation and fracture propagation represent the two dominant integrity threats for dense-phase CO₂ transportation pipelines. These mechanisms are closely interconnected because corrosion defects frequently serve as crack initiation sites, while fracture propagation is strongly influenced by material degradation, residual strength, and operating pressure. Therefore, understanding the interaction between corrosion and fracture is essential for developing effective Risk-Based Inspection (RBI) strategies capable of predicting failure probability under variable operating conditions.

Table 3. Synthesis of degradation mechanisms in CO₂ Pipelines

Degradation Mechanisms	Key Drivers / Contributing Factors	Main Effects on Pipeline Integrity	Typical Locations / Conditions	Indicators / Observable Signs	Key References
General CO ₂ Corrosion	Presence of free water, carbonic acid formation, low pH, temperature, partial pressure of CO ₂	Uniform wall thinning, loss of load-bearing capacity	Low points, water accumulation zones	Metal loss (wt%), corrosion rate increase	[4], [6], [18], [34]
Localised Corrosion (Pitting)	Chlorides, deposits, differential aeration cells, flow disturbances	Pit initiation and growth, potential perforation	Under deposits, welds, coating holidays	Pit depth, pit density, ILI anomaly	[4], [5], [6], [8], [34]
Erosion–Corrosion	High velocity, sand/solid particles, two-phase flow, impingement	Accelerated metal loss, grooving, coating damage	Bends, reducers, elbows, tees	Wall thinning pattern, groove formation	[6], [18], [29], [35]
Sulfide Stress Cracking (SSC)	H ₂ S presence, high strength steel, tensile stress, high pCO ₂	Crack initiation and propagation, brittle failure	High strength pipe, HAZ, girth weld	Crack indications (ILI/UT), pressure/deformation drop	[6], [15], [18], [33]
Hydrogen-Induced Cracking (HIC)	Cathodic protection, high strength steel, moist CO ₂ environment	Internal crack growth parallel to metal surface	High strength steel, coated/CP areas	Blistering, stepwise crack growth	[6], [15], [18], [33]
Decompression Fatigue (DCF)	Rapid depressurization, trapped gas, high stress, material toughness	Crack nucleation and propagation under decompression	Compressor stations, shutdown events	Axial crack, brittle fracture features	[15], [18], [33], [36]

Thermodynamic Phase Transition Effects	Pressure/temperature fluctuations, proximity to critical point, Joule–Thomson cooling	Two-phase flow, slugging, accelerated corrosion/erosion	Near critical region, valves, control points	Temperature drop, slug flow, corrosion spikes	[18], [19], [35], [37]
External Corrosion	Soil resistivity, MIC, coating damage, CP failure, water retention	External metal loss, coating disbondment	Buried sections, coating defects	CIS survey, coating holiday, current density change	[7], [18], [28]

3.3.1. Corrosion

Corrosion was identified as the most extensively investigated degradation mechanism in the reviewed literature, with approximately 87% of the selected publications discussing corrosion behavior under dense-phase CO₂ conditions. This predominance reflects the critical role of internal corrosion in determining the long-term structural integrity and service life of carbon steel pipelines used for CO₂ transportation. Unlike dry CO₂, which is generally considered non-corrosive to carbon steel, the presence of free water fundamentally changes the electrochemical environment. Once water condenses within the pipeline, dissolved CO₂ reacts to form carbonic acid (H₂CO₃), initiating electrochemical dissolution of iron according to well-established sweet corrosion mechanisms [6]. Depending on operating conditions, corrosion may occur as uniform wall thinning, localized pitting, mesa attack, or under-deposit corrosion, each of which contributes differently to structural degradation and remaining strength. The severity of corrosion is strongly influenced by impurity composition. Laboratory investigations have consistently demonstrated that impurities such as SO₂, NO_x, H₂S, and O₂ significantly modify corrosion kinetics and corrosion product stability [4,5]. Sulfur dioxide and nitrogen oxides reduce local solution pH, destabilize protective corrosion films, and promote localized corrosion, while hydrogen sulfide may facilitate hydrogen absorption into the steel substrate, increasing susceptibility to sulfide stress cracking (SSC) and hydrogen-induced cracking (HIC). Even trace concentrations of oxygen can accelerate cathodic reactions and increase general corrosion rates under moist conditions.

An important characteristic of dense-phase CO₂ transportation systems is that corrosion behavior is governed by the combined interaction between thermodynamic conditions and fluid chemistry rather than by individual parameters alone. Variations in operating pressure, temperature, impurity concentration, and water content may significantly alter phase equilibrium, resulting in intermittent condensation of aqueous phases that locally accelerate corrosion processes. Consequently, degradation rates cannot be represented accurately using deterministic corrosion allowances alone but require continuous monitoring and probabilistic assessment capable of accounting for operational variability. From an integrity management perspective, corrosion represents considerably more than a wall-thinning mechanism. Progressive metal loss reduces pipeline burst strength, decreases fracture resistance, and creates geometric discontinuities that significantly increase local stress concentration. Localized corrosion pits frequently act as preferential sites for crack initiation, particularly under cyclic loading or environmentally assisted degradation. Therefore, corrosion assessment should not be treated independently from fracture mechanics but rather as an integral component of structural reliability evaluation.

These observations suggest that upstream impurity control should be regarded as a primary integrity barrier rather than merely a process-quality requirement. Maintaining water content below the CO₂ solubility limit, controlling acidic impurities, and continuously monitoring corrosion activity represent essential preventive measures for minimizing degradation and extending pipeline service life.

3.3.2. Fracture and Cracking

Fracture propagation constitutes the second major integrity threat identified in the reviewed literature, with approximately 49% of the selected studies addressing ductile fracture, brittle fracture, or running fracture behavior. Compared with conventional natural gas pipelines, fracture control in dense-phase CO₂ transportation systems is considerably more challenging because decompression behavior strongly influences crack propagation characteristics following accidental rupture.

During pipeline failure, rapid depressurization generates a decompression wave accompanied by substantial Joule–Thomson cooling and phase transformation. Unlike methane pipelines, where decompression generally follows predictable gas expansion, dense-phase CO₂ undergoes complex thermodynamic changes involving liquid, gaseous, and solid phases. These phenomena reduce crack-arrest capability and may substantially increase the likelihood of unstable running fracture over long pipeline distances [7].

Fracture resistance depends on multiple interacting parameters, including operating pressure, pipe diameter, wall thickness, material toughness, fracture toughness, crack geometry, and decompression wave velocity [15]. Consequently, fracture assessment for CO₂ pipelines requires consideration of both structural mechanics and fluid thermodynamics. Conventional fracture-control methodologies developed for hydrocarbon pipelines may therefore underestimate fracture propagation risks when applied directly to dense-phase CO₂ transportation systems. In addition to rapid fracture propagation, environmentally assisted cracking mechanisms have received increasing attention in recent years. Approximately 31% of the reviewed studies discussed degradation mechanisms including Stress Corrosion Cracking (SCC), Sulfide Stress Cracking (SSC), Hydrogen-Induced Cracking (HIC), and Hydrogen-Assisted Cracking (HAC). These mechanisms generally develop through the combined effects of tensile stress, susceptible microstructures, and aggressive chemical environments. Their occurrence is particularly significant in high-strength low-alloy steels exposed to impurity-containing CO₂ streams.

Corrosion and fracture should not be considered independent degradation mechanisms because they frequently interact throughout the pipeline life cycle. Corrosion defects create localized stress concentration, while fracture processes accelerate once crack initiation has occurred at corrosion sites. Similarly, hydrogen generated during corrosion reactions may diffuse into the steel matrix, reducing ductility and fracture toughness and promoting environmentally assisted cracking. This interaction significantly increases failure probability compared with isolated corrosion or fracture mechanisms.

The literature therefore suggests that effective integrity management should evaluate fracture susceptibility using integrated approaches that simultaneously consider corrosion growth, material degradation, operational loading, and fracture mechanics. Such multidisciplinary assessment is particularly important for Risk-Based Inspection because inspection priorities should reflect not only defect size but also the potential interaction between degradation mechanisms that may substantially increase the Probability of Failure (PoF).

Table 4. Frequency of failure mechanisms discussed in the reviewed literature.

Failure Mechanism	Number of Studies	Percentage*
CO ₂ (sweet) corrosion	54	87%
Impurity-induced corrosion	34	44%
SCC / cracking	24	31%
Fracture (ductile/brittle)	38	49%
Running fracture	12	15%
Other degradation mechanisms	16	21%

*Note: Percentage is based on reviewed studies discussing the corresponding mechanisms.

3.4. Risk Assessment Approaches

Risk assessment forms the foundation of modern pipeline integrity management because it provides a systematic framework for evaluating the likelihood and consequences of pipeline failure under uncertain operating conditions. In conventional pipeline systems, risk assessment has traditionally been based on deterministic engineering approaches that employ conservative safety factors, predefined inspection intervals, and fixed acceptance criteria. Although these approaches have demonstrated satisfactory performance in hydrocarbon transportation systems, they often fail to adequately represent the complex degradation behavior and operational uncertainty associated with dense-phase CO₂ pipelines.

Table 5. Methods for risk Assessment of CO₂ Pipelines

Risk Assessment Method	Purpose / Application	Key Inputs	Key Outputs	Advantages	Limitations	Key References
Deterministic Assessment (Code-Based)	Check compliance with design codes and standards	Material properties, design pressure, minimum wall thickness, operating conditions	Safety factor, utilization ratio	Simple, straightforward, widely accepted	Does not account for uncertainty and variability	[9], [10], [18]
Reliability-Based Assessment (RBA)	Quantify probability of failure from structural reliability	Limit state functions, statistics of material/loads, degradation data	Probability of Failure (PoF), reliability index (β)	Considers variability and uncertainty	Requires statistical data and modeling expertise	[10], [16], [17], [24]
Risk-Based Inspection (RBI)	Prioritize inspection based on risk (PoF $\times$ CoF)	PoF, Consequence of Failure (CoF), inspection data	Risk ranking, inspection priority, inspection interval	Optimizes resources, industry standardized (API 580/581)	Static decision between inspection cycles	[9], [10], [12]
Bayesian Network (BN)	Model causal relationships and update risk dynamically	Operational data, degradation model,	Updated PoF (posterior), uncertainty reduction	Captures dependencies, updates with new data	Requires sufficient data and expert knowledge	[11], [14], [16], [24]

		inspection evidence, expert judgment (prior probabilities)				
Monte Carlo Simulation (MCS)	Quantify uncertainty through random sampling	Probability distributions of loads, material properties, corrosion rate, model parameters	PoF distribution, confidence interval	Flexible, handles complex problems	Computationally intensive	[16], [17], [24]
Digital Twin-Based Assessment	Real-time prediction using virtual pipeline model	Real-time sensor data, physics-based models, historical data	Real-time risk, RUL, what-if analysis	Real-time monitoring and scenario analysis	High data and model requirements	[12], [18], [42]

The reviewed literature indicates a clear transition from deterministic methodologies toward probabilistic and reliability-based risk assessment approaches. Approximately half of the selected studies employ probabilistic techniques to quantify the uncertainty associated with corrosion growth, fracture initiation, inspection accuracy, material properties, and operational variability. This transition reflects the increasing recognition that pipeline degradation is inherently stochastic and cannot be represented accurately by single deterministic values. Among the available probabilistic approaches, *Monte Carlo Simulation (MCS)* remains one of the most widely adopted techniques for propagating uncertainty through degradation models. MCS enables statistical evaluation of multiple uncertain variables simultaneously, including corrosion rate, wall-thickness loss, material strength, operating pressure, and inspection uncertainty. Consequently, Monte Carlo methods provide probability distributions for failure events rather than single conservative estimates, thereby supporting more realistic integrity assessment.

Reliability-based approaches have also gained considerable attention because they explicitly quantify structural safety using probabilistic limit-state functions and reliability indices. Instead of relying solely on safety margins, reliability analysis evaluates the probability that structural resistance becomes lower than operational loading during service. Such methodologies provide a rational basis for estimating Probability of Failure (PoF) while accounting for uncertainties associated with material properties, manufacturing tolerances, degradation mechanisms, and inspection effectiveness.

Recent studies increasingly utilize *Bayesian Networks (BNs)* to represent complex dependency relationships among degradation mechanisms, operational conditions, and inspection outcomes. Unlike conventional probabilistic models, Bayesian Networks allow causal relationships among multiple variables to be represented explicitly within a probabilistic graphical model. Parent nodes typically represent operational parameters, including pressure, temperature, water content, impurity concentration, and material properties, whereas intermediate nodes describe degradation processes such as corrosion rate, crack initiation, hydrogen embrittlement, and fracture susceptibility. Leaf nodes subsequently estimate the Probability of Failure associated with different integrity limit states. One of the principal advantages of Bayesian Networks is their capability to update failure probability continuously as new operational evidence becomes available. Inspection findings, corrosion monitoring data, fiber-optic sensing measurements, or operational transients may be incorporated through Bayesian updating, allowing posterior probabilities to evolve dynamically throughout the operational life of the pipeline. This adaptive capability makes Bayesian Networks particularly attractive for supporting Risk-

Based Inspection (RBI) in emerging CCUS infrastructure, where operating conditions and impurity compositions may vary considerably over time.

The establishment of Bayesian Network models generally involves two complementary processes. First, prior probabilities are derived from historical inspection records, published reliability data, laboratory investigations, or expert judgement where field observations remain limited. Second, Conditional Probability Tables (CPTs) are constructed using a combination of statistical analysis, physics-based degradation models, experimental observations, and engineering expertise to quantify probabilistic relationships between parent and child nodes. As additional monitoring information becomes available, Bayesian inference updates posterior probabilities according to Bayes' theorem, thereby reducing epistemic uncertainty and improving prediction accuracy throughout pipeline operation. Despite these significant advances, the reviewed literature indicates that most probabilistic studies remain focused primarily on failure prediction rather than inspection optimization. Risk models frequently terminate at Probability of Failure estimation without explicitly translating updated risk information into inspection intervals, maintenance prioritization, or resource allocation. Consequently, substantial opportunities remain for integrating probabilistic risk assessment with adaptive inspection planning, thereby enabling risk-informed decision-making that continuously reflects actual pipeline operating conditions.

Overall, the literature demonstrates that probabilistic methodologies provide a substantially more realistic representation of CO₂ pipeline integrity than deterministic approaches because they explicitly account for uncertainty, operational variability, and continuous learning. These characteristics provide the theoretical foundation for the Dynamic Risk-Based Inspection (D-RBI) framework proposed in this study, where Bayesian updating continuously links operational monitoring with inspection planning.

3.5. Inspection and Monitoring Strategies

Inspection and monitoring constitute essential components of pipeline integrity management because they provide the operational information required to identify degradation before structural failure occurs. Within the Risk-Based Inspection (RBI) philosophy, inspection should not merely detect existing defects but should also reduce uncertainty associated with degradation mechanisms and improve confidence in subsequent risk assessment. Consequently, inspection effectiveness directly influences the reliability of Probability of Failure estimation and the optimization of maintenance strategies.

Table 6. Inspection Technologies and strategies for CO₂ Pipelines

Inspection Technology / Strategy	Type	Detectable Features	Best Application / Location	Advantages	Limitations	Key References
Inline Inspection (ILI)	In-line (Smart PIG)	Metal loss, pitting, cracks, deformation, geometry	Long-distance pipelines, mainline	High coverage, accurate sizing, minimal downtime	High cost, requires launcher/receiver	[9], [10], [39], [40]
Corrosion Monitoring Probes	Online Monitoring	Corrosion rate (uniform/local), environmental parameters	High risk locations, corrosion loops	Real-time data, early warning	Limited to local area	[18], [28], [41]

Distributed Fiber Optic Sensing (DFOS)	Continuous Monitoring	Temperature, strain, vibration, acoustic signals	Long-distance, remote pipelines	Distributed, real-time, long range	High installation complexity and cost	[12], [18], [29]
Direct Assessment (DA)	In-situ	Wall thickness, crack sizing, mechanical properties	High risk spots, anomaly verification	High accuracy	Requires shutdown, labor intensive	[9], [10], [30]
External Corrosion Survey (CIS)	External Inspection	Coating condition, corrosion rate, CP effectiveness	Buried pipelines	Detects external corrosion, coating defects	Cannot detect internal damage	[7], [28], [31]
Aerial / Satellite Monitoring	Remote Monitoring	Right-of-way, ground movement, third-party interference	Long ROW, remote areas	Large area coverage, low cost per km	Indirect method, lower resolution for defects	[12], [31], [32]
Inspection Strategy (Adaptive Planning)	Management Strategy	Risk-based interval, data fusion, adaptive planning	All pipeline systems	Optimizes resources, adapts to changing risk	Requires dynamic data and advanced analytics	[9], [10], [12], [24]

The reviewed literature indicates that Inline Inspection (ILI) remains the primary inspection technology for long-distance CO₂ transportation pipelines. Modern intelligent pigging systems employ various sensing principles, including Magnetic Flux Leakage (MFL), Ultrasonic Testing (UT), and Electromagnetic Acoustic Transducer (EMAT) technologies to detect internal corrosion, wall-thickness reduction, geometric deformation, longitudinal cracking, and manufacturing defects. Among these techniques, MFL is widely applied for metal-loss assessment, whereas UT generally provides superior sizing accuracy for corrosion defects and crack characterization. EMAT technology has attracted increasing interest because of its capability to detect stress corrosion cracking and other crack-like defects without requiring liquid couplants.

Although periodic Inline Inspection remains indispensable, conventional inspection programs are generally based on predetermined inspection intervals that may not adequately reflect changing operating conditions. Dense-phase CO₂ transportation systems are characterized by continuously varying impurity concentrations, pressure fluctuations, and thermodynamic conditions that may significantly alter degradation rates between scheduled inspections. Consequently, fixed inspection intervals may either result in unnecessary inspection costs or allow critical degradation to develop undetected.

To overcome these limitations, recent studies increasingly emphasize continuous structural health monitoring through permanently installed sensing systems. Distributed Fiber Optic Sensing technologies, including Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing (DAS), provide continuous monitoring over extensive pipeline distances by detecting thermal anomalies, acoustic emissions, mechanical strain, and leak-related disturbances. These technologies enable rapid identification of abnormal operating conditions that may indicate corrosion activity, leakage, or fracture initiation before catastrophic failure occurs.

Additional monitoring technologies, including Linear Polarization Resistance (LPR) probes, Electrical Resistance (ER) sensors, corrosion coupons, acoustic emission monitoring, pressure transient analysis, and wireless sensor networks, have further enhanced the capability for real-time degradation assessment. These monitoring systems provide continuous information regarding corrosion activity, environmental conditions,

and structural response, thereby significantly reducing uncertainty associated with degradation prediction.

Recent advances in digitalization have introduced machine learning and artificial intelligence techniques into pipeline monitoring systems. Data-driven algorithms have demonstrated promising capability for detecting anomalies, forecasting corrosion growth, identifying leakage patterns, and optimizing maintenance scheduling using large operational datasets. Nevertheless, purely data-driven approaches remain limited because statistical correlations alone cannot adequately represent the underlying physical mechanisms governing corrosion, fracture propagation, and thermodynamic behavior. Consequently, increasing attention has shifted toward physics-informed machine learning, which combines physical degradation models with data-driven learning to improve both prediction accuracy and interpretability. From an RBI perspective, the primary objective of inspection extends beyond defect detection. Inspection should function as a mechanism for reducing uncertainty within probabilistic risk models. Each inspection campaign provides new evidence regarding pipeline condition, allowing degradation models and Bayesian Network probabilities to be updated using actual field observations. Consequently, inspection effectiveness should be evaluated according to its ability to reduce uncertainty and improve risk prediction rather than solely according to defect detection capability.

The reviewed literature further indicates that current inspection optimization for CO₂ pipelines remains relatively immature. Most inspection strategies are still developed independently of probabilistic risk assessment and operational monitoring, limiting their ability to respond dynamically to evolving degradation conditions. Future integrity management systems should therefore integrate inspection technologies, continuous monitoring, Bayesian updating, and predictive analytics within a unified decision-support platform capable of continuously adjusting inspection priorities according to changing operational risk.

Such adaptive inspection strategies represent a significant evolution beyond conventional RBI practices and constitute one of the principal components of the Dynamic Risk-Based Inspection (D-RBI) framework proposed in this review. By continuously incorporating monitoring evidence into probabilistic risk assessment, inspection intervals can be optimized according to actual degradation conditions, thereby improving safety while reducing unnecessary inspection and maintenance expenditures.

3.6. Uncertainty Treatment

Uncertainty is one of the fundamental challenges in the integrity management of CO₂ transportation pipelines because degradation mechanisms are governed by complex interactions among operating conditions, material characteristics, environmental exposure, and impurity composition. Compared with conventional hydrocarbon pipelines, dense-phase CO₂ transportation systems are associated with greater uncertainty due to limited long-term operational experience, evolving CCUS infrastructure, and variability in captured CO₂ stream quality. Consequently, uncertainty influences not only degradation prediction but also inspection planning, maintenance optimization, and long-term risk-informed decision making. Zheng et al. [14] emphasized that uncertainty remains one of the principal obstacles to establishing reliable integrity management strategies for future CCUS pipeline networks, while Aven [16] highlighted that uncertainty should be considered an integral component of risk rather than merely a statistical parameter.

From a risk analysis perspective, uncertainty can generally be classified into *aleatory uncertainty* and *epistemic uncertainty*. Aleatory uncertainty represents the inherent variability of physical processes and cannot be eliminated because it originates from natural randomness, such as fluctuations in operating pressure, temperature, flow rate, impurity concentration, and corrosion growth. In contrast, epistemic uncertainty arises

from incomplete knowledge regarding degradation mechanisms, material behavior, inspection effectiveness, and predictive models. Unlike aleatory uncertainty, epistemic uncertainty can be progressively reduced through additional inspection data, laboratory investigations, operational experience, and improved analytical models. The distinction between these two uncertainty types has become a fundamental concept in modern reliability engineering and probabilistic risk assessment because each requires different treatment within integrity management frameworks [16,31,38].

A major source of uncertainty in CO₂ transportation systems is the variability of the transported fluid itself. The composition of captured CO₂ depends strongly on the carbon capture technology and the industrial source, including coal-fired power plants, cement production, steel manufacturing, and petrochemical facilities. As a result, concentrations of impurities such as H₂O, H₂S, SO₂, O₂, and NO_x may vary significantly among projects and even during normal operation. These compositional variations directly affect corrosion kinetics, phase equilibrium, fracture behavior, and thermodynamic stability, leading to substantial uncertainty in degradation prediction. Previous investigations have demonstrated that even trace concentrations of impurities may significantly modify electrochemical reactions and localized corrosion behavior in dense-phase CO₂ environments [4,5,14,34]. Among the various impurities, free water is considered the most influential parameter because it controls the initiation of electrochemical corrosion. Maintaining water content below the CO₂ solubility limit prevents the formation of an aqueous phase and minimizes carbonic acid corrosion. Likewise, acidic impurities such as SO₂ and NO_x reduce local pH and accelerate localized corrosion, whereas H₂S increases susceptibility to sulfide stress cracking (SSC) and hydrogen-induced cracking (HIC) in high-strength pipeline steels. Consequently, impurity specification should be regarded not only as a process requirement but also as a primary integrity control measure for minimizing uncertainty associated with degradation mechanisms [4–6,8].

Additional uncertainty arises from the prediction models used to estimate degradation and structural reliability. Corrosion growth models developed from laboratory experiments frequently differ from field observations because laboratory conditions cannot fully reproduce transient operating conditions, impurity interactions, localized flow characteristics, or environmental fluctuations encountered in service. Similarly, fracture assessment depends on uncertain variables such as fracture toughness, defect geometry, residual stress, and decompression behavior, all of which may vary during pipeline operation. These uncertainties directly affect predictions of Remaining Useful Life (RUL) and Probability of Failure (PoF), indicating that deterministic degradation models alone are insufficient for supporting adaptive integrity management [6,15,16,18].

Inspection activities play a crucial role in reducing epistemic uncertainty because they provide direct evidence of the actual structural condition of the pipeline. Information obtained from inline inspection (ILI), corrosion monitoring systems, non-destructive examination, and field observations continuously improves the understanding of degradation behavior and enables predictive models to be refined. Within the Risk-Based Inspection (RBI) philosophy, inspection should therefore be viewed not only as a defect detection activity but also as a mechanism for uncertainty reduction that increases confidence in subsequent risk assessment and maintenance planning [9,10,12].

Recent developments in probabilistic integrity management have increasingly adopted *Bayesian inference* to manage uncertainty throughout the operational life cycle of pipeline systems. Bayesian methods provide a rigorous mathematical framework for combining prior knowledge derived from historical inspection records, laboratory experiments, published reliability data, and expert judgement with newly acquired operational evidence. In practical applications, prior probabilities are updated as new monitoring information

becomes available, producing posterior probability distributions that continuously improve the estimation of degradation states and Probability of Failure. Han et al. [24] demonstrated that Bayesian Networks are particularly effective for representing causal relationships among operational variables, degradation mechanisms, and failure events, while Yarveisy et al. [11] successfully incorporated Bayesian updating into dynamic corrosion risk assessment for CO₂ transportation pipelines.

Despite these advances, the reviewed literature indicates that uncertainty treatment remains insufficiently integrated with inspection optimization. Most published studies focus on uncertainty quantification or probabilistic failure prediction independently, whereas relatively few explicitly translate uncertainty reduction into adaptive inspection intervals, maintenance prioritization, or inspection resource allocation. Consequently, many existing integrity management systems remain reactive rather than predictive, limiting their capability to respond efficiently to evolving degradation conditions in large-scale CCUS infrastructure [12–14]. Based on the perspective of Risk-Based Inspection, uncertainty should therefore be regarded as a dynamic parameter that evolves continuously throughout the service life of the pipeline. Effective integrity management requires the integration of uncertainty quantification, real-time monitoring, probabilistic risk assessment, and adaptive inspection planning within a unified decision-support framework. Such an approach enables inspection intervals and maintenance priorities to be continuously updated according to the latest operational evidence, thereby reducing both technical uncertainty and unnecessary inspection expenditure while enhancing pipeline safety and reliability [9,11,14,24].

Overall, the literature demonstrates that uncertainty treatment should become a central component of future CO₂ pipeline integrity management rather than a supplementary consideration. Integrating uncertainty quantification with Bayesian updating, continuous monitoring, and Dynamic Risk-Based Inspection (D-RBI) provides a scientifically robust foundation for predictive maintenance and supports the long-term integrity, safety, and economic performance of future CCUS transportation networks.

3.7. Dynamic Risk Based Inspection (D-RBI) Framework for CO₂ Pipelines

The comprehensive review presented in the preceding sections reveals that current integrity management practices for CO₂ transportation pipelines remain largely fragmented. Corrosion studies primarily focus on degradation mechanisms, fracture research emphasizes structural failure behaviour, while probabilistic risk assessment, inspection planning, and uncertainty analysis are generally investigated independently. Although each discipline contributes significantly to pipeline integrity management, limited integration among these approaches restricts the capability of existing Risk-Based Inspection (RBI) systems to respond effectively to continuously evolving operational conditions [9,10,14].

Conventional RBI, as defined in API 580 and API 581, evaluates inspection priorities based on the combination of Probability of Failure (PoF) and Consequence of Failure (CoF) using periodically updated inspection information [9,10]. This methodology has demonstrated considerable success for conventional oil and gas pipelines; however, its application to dense-phase CO₂ transportation systems is challenged by operational variability, impurity-induced degradation, thermodynamic phase transitions, and limited long-term operational experience. DNV-RP-F104 also emphasizes that CO₂ pipeline integrity requires consideration of operating conditions, fluid composition, and material degradation mechanisms that differ substantially from conventional hydrocarbon pipelines [18].

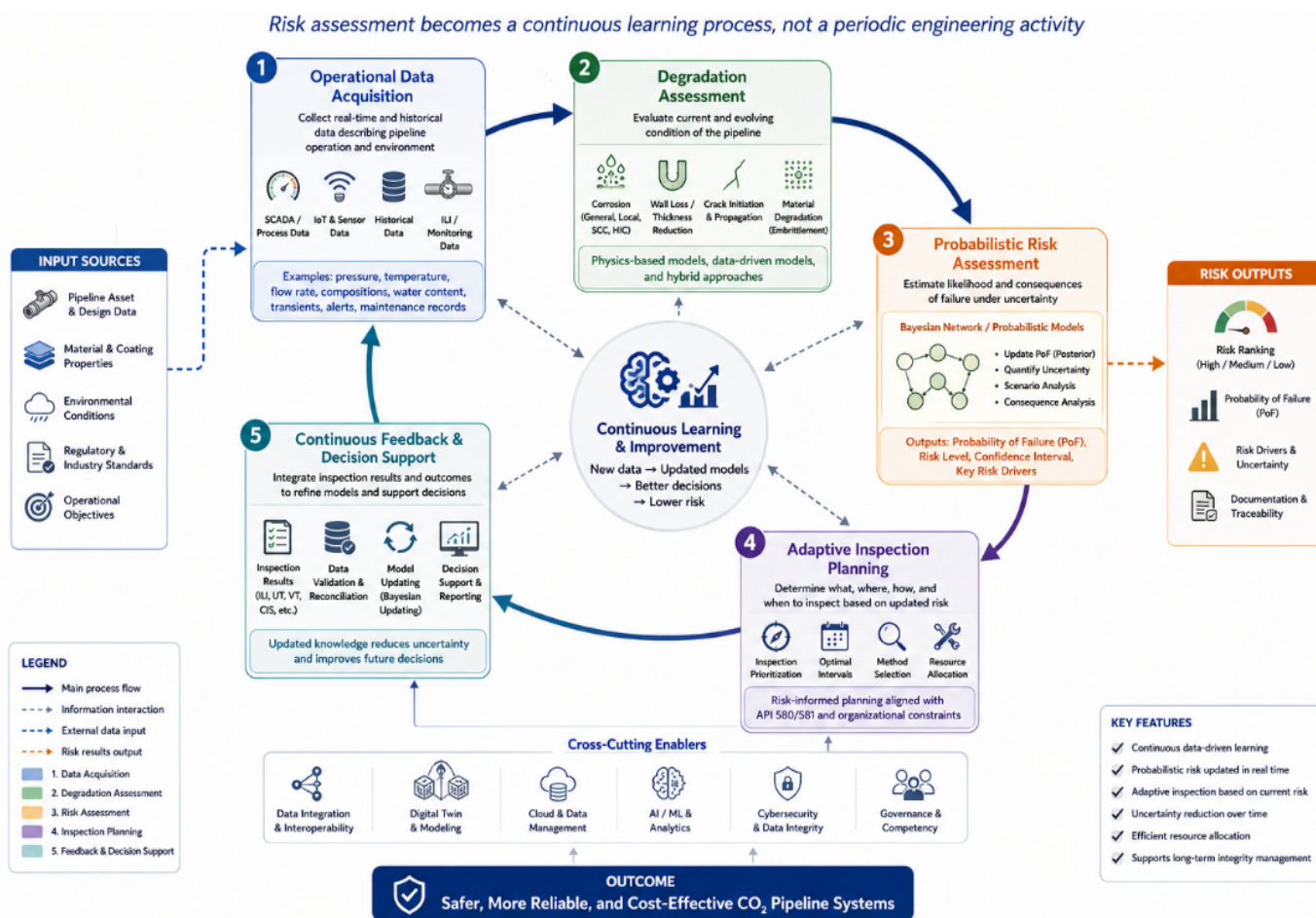


Figure 1. Dynamic Risk-Based Inspection (D-RBI) framework

Based on the reviewed literature, this study proposes an integrated *Dynamic Risk-Based Inspection (D-RBI)* framework in which risk assessment becomes a continuous learning process rather than a periodic engineering activity. As illustrated in Figure 1, the framework integrates five interconnected components: (i) operational data acquisition, (ii) degradation assessment, (iii) probabilistic risk assessment, (iv) adaptive inspection planning, and (v) continuous feedback and decision support. Unlike conventional RBI, which updates inspection plans only after scheduled inspections, D-RBI continuously incorporates operational information obtained from Supervisory Control and Data Acquisition (SCADA), Inline Inspection (ILI), corrosion monitoring systems, Distributed Fiber Optic Sensing (DFOS), and other structural health monitoring technologies [9,12,18].

Within the proposed framework, degradation assessment simultaneously considers corrosion growth, fracture mechanics, material degradation, and structural reliability. Nešić [6] demonstrated that corrosion progressively reduces pipeline structural resistance, whereas Zargarzadeh et al. [15] reported that fracture propagation depends strongly on decompression behaviour, material toughness, and defect geometry. Therefore, corrosion and fracture should not be treated as independent failure mechanisms but as interacting degradation processes that collectively determine structural reliability throughout pipeline operation.

The integration of degradation assessment with probabilistic risk evaluation enables inspection priorities to evolve dynamically according to actual operating conditions rather than predefined inspection intervals. Consequently, pipeline segments experiencing accelerated degradation, increased operational uncertainty, or elevated failure probability

receive higher inspection priority, whereas low-risk sections may safely operate with extended inspection intervals. Such adaptive inspection planning improves maintenance efficiency while maintaining acceptable levels of structural safety and operational reliability [9,10,12]. Overall, the proposed D-RBI framework establishes a conceptual foundation for transitioning from conventional static integrity management toward intelligent, adaptive integrity systems capable of supporting the long-term deployment of CCUS transportation infrastructure.

3.8 Bayesian Network-Based Dynamic Risk Updating

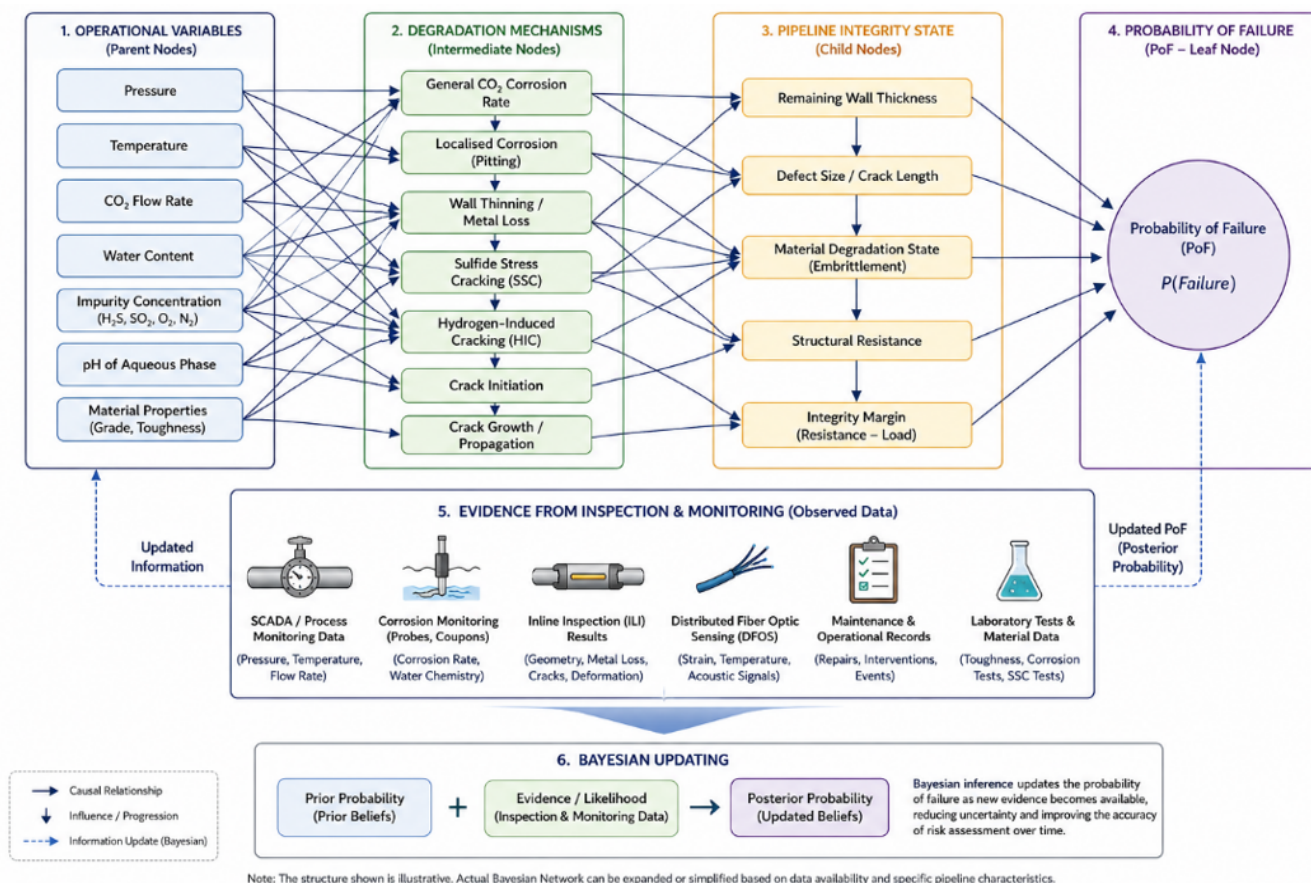


Figure 2. Conceptual Bayesian Network for Dynamic Risk Updating in CO₂ Pipeline Integrity Management.

An essential component of the proposed Dynamic Risk-Based Inspection framework is the application of Bayesian Networks (BNs) for continuously updating pipeline risk throughout the operational life cycle. Compared with conventional deterministic approaches, Bayesian Networks provide a probabilistic graphical framework capable of representing causal relationships among operational conditions, degradation mechanisms, inspection observations, and structural failure events under uncertain environments [11,24].

In Bayesian Networks, operational variables such as pressure, temperature, flow rate, water content, impurity concentration, and material properties are represented as parent nodes, while degradation processes—including corrosion rate, crack initiation, hydrogen-assisted cracking, and fracture susceptibility—are represented as intermediate nodes. The resulting structural condition determines the child node, which estimates the Probability of Failure (PoF). Relationships among these variables are quantified using Conditional

Probability Tables (CPTs) constructed from historical inspection records, laboratory investigations, published reliability data, physics-based degradation models, and expert judgement [11,16,24].

One of the principal advantages of Bayesian Networks lies in their capability to incorporate newly acquired operational evidence through Bayesian updating. Inspection findings, corrosion monitoring results, sensor measurements, pressure transients, and maintenance records are continuously integrated into the probabilistic model, allowing posterior probabilities to replace initial prior estimates. Consequently, epistemic uncertainty decreases progressively as additional operational information becomes available, resulting in increasingly reliable predictions of pipeline degradation and structural integrity [11,16]. Recent studies have demonstrated the effectiveness of Bayesian Networks in supporting pipeline integrity management. Yarveisy et al. [11] successfully integrated corrosion prediction with probabilistic inspection planning using Bayesian inference, while Han et al. [24] showed that Bayesian updating significantly improves failure prediction accuracy by incorporating continuously evolving inspection evidence. Zheng et al. [14] further emphasized that probabilistic learning approaches represent one of the most promising methodologies for supporting integrity management within emerging CCUS infrastructure, where operational uncertainty remains relatively high.

The integration of Bayesian Networks within the D-RBI framework therefore enables continuous updating of both Probability of Failure and inspection priorities. Instead of relying on periodic engineering judgement alone, inspection decisions become data-driven and adaptive, allowing maintenance resources to be directed toward pipeline segments exhibiting the highest updated risk. Such continuous probabilistic learning distinguishes Dynamic RBI from conventional static RBI methodologies and represents a significant advancement in intelligent pipeline integrity management.

3.9. Practical Implications and Future Research Directions

The findings of this review provide several practical implications for pipeline operators, regulators, and researchers involved in the development of Carbon Capture, Utilization, and Storage (CCUS) infrastructure. As commercial deployment of CO₂ transportation networks expands worldwide, maintaining pipeline integrity will become increasingly important for ensuring operational safety, environmental protection, regulatory compliance, and public acceptance. Existing Risk-Based Inspection methodologies described in API 580 and API 581 remain highly relevant; however, they require adaptation to address the operational uncertainty and degradation mechanisms unique to dense-phase CO₂ transportation systems [9,10,18]. From an industrial perspective, the proposed Dynamic Risk-Based Inspection framework offers a systematic strategy for integrating operational monitoring, degradation assessment, Bayesian risk updating, and adaptive inspection planning into a unified asset integrity management system. Continuous evaluation of operational data enables pipeline operators to optimize inspection intervals, improve maintenance prioritization, and reduce unnecessary inspection costs while maintaining acceptable levels of structural reliability [12,14].

The framework also supports ongoing digital transformation within pipeline asset management. Recent developments in SCADA systems, Distributed Fiber Optic Sensing (DFOS), Internet of Things (IoT) technologies, cloud-based asset management platforms, and Digital Twin applications provide unprecedented opportunities for continuously monitoring pipeline condition throughout its operational life cycle. When integrated with Bayesian inference and probabilistic degradation models, these technologies enable near real-time integrity assessment and predictive maintenance, significantly reducing epistemic uncertainty while improving operational decision-making [11,18,24]. Despite these promising developments, several research gaps remain. Long-term field data

describing corrosion evolution, fracture behaviour, and impurity effects under dense-phase CO₂ conditions are still limited, resulting in significant uncertainty within current degradation models [6,14,18]. Furthermore, most existing probabilistic studies focus primarily on estimating Probability of Failure without explicitly integrating inspection optimization, maintenance scheduling, and operational decision support into a unified framework. Consequently, future research should emphasize validation of Dynamic RBI using operational datasets obtained from commercial CO₂ pipeline systems.

Future investigations should also explore the integration of *Digital Twin technology*, *physics-informed machine learning*, and *Bayesian inference* within adaptive integrity management systems. Physics-informed machine learning has the potential to improve degradation prediction while preserving engineering interpretability, whereas Digital Twin technology enables continuous synchronization between virtual pipeline models and field observations. Combined with Bayesian updating, these emerging technologies are expected to provide the foundation for next-generation intelligent integrity management systems capable of supporting autonomous inspection planning and predictive maintenance under uncertain operating environments [12,16,24].

Overall, this review demonstrates that future CO₂ pipeline integrity management should evolve from conventional static inspection practices toward integrated Dynamic Risk-Based Inspection systems that combine engineering mechanics, corrosion science, probabilistic reliability, uncertainty quantification, digital monitoring, and intelligent decision support. Such multidisciplinary integration provides a robust scientific foundation for improving pipeline safety, operational reliability, inspection efficiency, and lifecycle cost performance while supporting the sustainable deployment of global CCUS infrastructure [9,11,14,18,24].

4. Conclusions

This review article critically examined the current state of integrity management for CO₂ transportation pipelines within Carbon Capture, Utilization, and Storage (CCUS) systems by integrating recent advances in degradation mechanisms, probabilistic risk assessment, inspection technologies, uncertainty treatment, and intelligent integrity management. Unlike conventional reviews that address these topics separately, this study synthesized the interrelationships among corrosion, fracture propagation, risk assessment, and inspection planning to establish a comprehensive understanding of CO₂ pipeline integrity.

The literature indicates that corrosion and fracture remain the dominant degradation mechanisms affecting the structural integrity of dense-phase CO₂ pipelines. Their occurrence is strongly influenced by operational parameters, impurity composition, thermodynamic conditions, and material characteristics. These interacting degradation processes increase the complexity of integrity assessment and demonstrate that deterministic approaches based solely on fixed inspection intervals are insufficient for representing the continuously evolving condition of CO₂ transportation systems [6,9,18]. Recent developments in probabilistic risk assessment have significantly improved the capability to quantify uncertainty and predict pipeline failure. Bayesian Networks, reliability-based assessment, and probabilistic degradation models enable continuous updating of the Probability of Failure (PoF) using operational monitoring and inspection evidence, thereby reducing epistemic uncertainty and supporting more reliable decision-making [11,14,16,24]. However, the review also reveals that most existing studies focus primarily on individual degradation mechanisms or probabilistic modelling without fully integrating inspection optimization and real-time operational monitoring.

To address this research gap, this review proposed a *Dynamic Risk-Based Inspection (D-RBI)* framework that integrates operational data acquisition, degradation assessment,

Bayesian risk updating, adaptive inspection planning, and continuous feedback within a unified integrity management cycle. The proposed framework extends conventional Risk-Based Inspection by transforming inspection planning from a periodic activity into a continuous learning process that dynamically responds to changes in operating conditions, degradation behaviour, and inspection findings. Such integration has the potential to improve pipeline safety, optimize maintenance resources, reduce lifecycle costs, and enhance the reliability of future CCUS transportation infrastructure. Despite these advances, several research challenges remain. Long-term field data for dense-phase CO₂ transportation are still limited, and further validation of probabilistic degradation models using operational datasets is required. Future studies should therefore focus on integrating Bayesian inference, Digital Twin technology, physics-informed machine learning, and continuous structural health monitoring to establish intelligent integrity management systems capable of supporting predictive maintenance under uncertain operating environments.

Overall, this review demonstrates that future CO₂ pipeline integrity management should evolve beyond conventional static Risk-Based Inspection toward adaptive, data-driven, and uncertainty-aware integrity management frameworks. The proposed Dynamic Risk-Based Inspection concept provides a practical and scientifically robust foundation for supporting the safe, reliable, and economically sustainable deployment of large-scale CCUS pipeline networks.

Supplementary Materials: Not applicable.

Author Contributions: Conceptualization, Risdianto, J.W.S. and Y.P.; methodology, Risdianto; formal analysis, Risdianto; investigation, Risdianto; writing—original draft preparation, Risdianto; writing—review and editing, J.W.S. and Y.P.; supervision, J.W.S. and Y.P. All authors have read and agreed to the published version of the manuscript.

Funding: This study received no specific funding from government, commercial, or non-profit organizations.

Acknowledgments: The authors acknowledge the Department of Metallurgical and Materials Engineering, Universitas Indonesia, for academic support during preparation of this manuscript. **Conflicts of Interest:** The authors declare no conflict of interest.

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