

Multi-Barrier Preservation Systems for Corrosion Prevention in Offshore Wellhead Platforms: A Systematic Review of Current Practices and Future Perspectives

Sukanta Sembiring

Mechanical Engineering, Faculty of Engineering, Universitas Riau Kepulauan, Batam, Indonesia

E-mail: sukanta.sembiring@gmail.com

Received: June 25, 2026

Revision: September 19, 2026

Accepted: September 22, 2026

Abstract: Maintaining the integrity and operational readiness of offshore wellhead-platform equipment during storage, construction delays, pre-commissioning, temporary shutdowns, and extended inactivity remains challenging because corrosion and mechanical degradation can continue in the absence of normal operating loads. This study systematically reviews preservation strategies and integrates the available evidence into an equipment-specific multi-barrier framework. A systematic literature review was conducted using six scientific information sources and reported with reference to PRISMA 2020. Publications from 2015 to 2025 were considered; 178 records were identified, 149 unique records were screened, 68 full-text publications were assessed, and 43 studies were included in the qualitative synthesis. The evidence was analyzed according to degradation mechanism, preservation function, equipment applicability, verification requirement, and implementation limitation. The findings show that no single preservation barrier addresses all degradation risks. Protective coatings and cathodic protection primarily control external and electrochemical corrosion; nitrogen or inert-atmosphere preservation limits internal oxygen exposure; corrosion inhibitors and VpCI provide chemical protection; humidity-control measures reduce condensation risk; and lubrication protects contacting and moving components. Inspection, condition monitoring, and digital technologies provide complementary verification and decision-support functions. Based on the synthesis, this review proposes a decision-oriented framework linking degradation mechanism, preservation barrier, condition verification, and maintenance response. The evidence also reveals limited long-term offshore validation of integrated preservation, particularly for nitrogen blanketing, humidity control, lubrication-based preservation, and combined barriers. Future research should emphasize field validation, standardized preservation-performance indicators, and condition-based preservation strategies to support reliable return-to-service decisions.

Keywords: offshore preservation, wellhead platform, corrosion prevention, multi-barrier preservation, asset integrity, condition monitoring, systematic literature review.

Abstrak: Mempertahankan integritas dan kesiapan operasi peralatan anjungan kepala sumur lepas pantai selama penyimpanan, keterlambatan konstruksi, pre-commissioning, temporary shutdown, dan periode tidak beroperasi yang panjang merupakan tantangan karena korosi dan degradasi mekanis tetap dapat berlangsung tanpa adanya beban operasi normal. Penelitian ini meninjau secara sistematis strategi preservasi dan mengintegrasikan bukti yang tersedia ke dalam kerangka preservasi multi-barrier yang spesifik terhadap jenis peralatan. Tinjauan literatur sistematis dilakukan menggunakan enam sumber informasi ilmiah dan dilaporkan dengan mengacu pada PRISMA 2020. Publikasi tahun 2015–2025 dipertimbangkan; sebanyak 178 rekaman teridentifikasi, 149 rekaman unik disaring, 68 publikasi full-text dinilai kelayakannya, dan 43 studi dimasukkan dalam sintesis kualitatif. Bukti dianalisis berdasarkan mekanisme degradasi, fungsi preservasi, penerapan pada peralatan, kebutuhan verifikasi, dan keterbatasan implementasi. Hasil menunjukkan bahwa tidak ada satu barrier preservasi yang mampu mengatasi seluruh risiko degradasi. Pelapis protektif dan proteksi katodik terutama mengendalikan korosi eksternal dan elektrokimia; nitrogen atau atmosfer inert membatasi paparan oksigen internal; inhibitor korosi dan VpCI memberikan proteksi kimia; pengendalian kelembapan mengurangi risiko kondensasi; sedangkan pelumasan melindungi komponen yang berkontak dan bergerak. Inspeksi, pemantauan kondisi, dan teknologi digital berfungsi sebagai lapisan verifikasi dan pendukung keputusan. Berdasarkan sintesis, penelitian ini mengusulkan kerangka yang menghubungkan mekanisme degradasi, barrier preservasi, verifikasi kondisi, dan respons pemeliharaan. Bukti juga menunjukkan masih terbatasnya validasi lepas pantai jangka panjang terhadap preservasi terintegrasi. Penelitian selanjutnya perlu menekankan validasi lapangan, indikator kinerja preservasi yang terstandar, dan strategi preservasi berbasis kondisi untuk mendukung keputusan return-to-service yang andal.

Kata kunci: *preservasi lepas pantai, anjungan kepala sumur, pencegahan korosi, preservasi multi-barrier, integritas aset, pemantauan kondisi, tinjauan literatur sistematis.*

INTRODUCTION

Offshore oil and gas facilities operate in aggressive marine environments characterized by high humidity, chloride deposition, seawater exposure, temperature variation, and atmospheric contaminants. These conditions promote electrochemical corrosion, coating deterioration, and progressive degradation of metallic equipment. Piping, pressure-containing equipment, valves, rotating machinery, wire ropes, electrical equipment, and instrumentation on wellhead platforms therefore remain vulnerable throughout their service life [1]–[7].

Degradation can also continue when equipment is temporarily inactive. Storage, construction delays, pre-commissioning, temporary shutdowns, and prolonged idle periods may expose equipment to moisture accumulation, condensation, oxygen ingress, chloride contamination, lubricant degradation, coating damage, and loss of enclosure integrity. Corrosion may interact with friction and wear in contacting components, while enclosed equipment may experience condensation-related deterioration [8]–[13]. Consequently, mechanically inactive equipment may still lose integrity and readiness for service.

Preservation is intended to control these degradation processes during periods when equipment is not operating normally. Conventional preservation practices include cleaning, drying, protective coatings, corrosion inhibitors, vapor-phase corrosion inhibitors (VpCI), nitrogen or inert-atmosphere preservation, lubrication, desiccant or dehumidification, sealing, and periodic inspection. The appropriate method depends on equipment configuration, degradation mechanism, environmental exposure, accessibility, criticality, and expected preservation duration [8]–[17].

The current literature demonstrates substantial development in individual corrosion-control technologies. Protective coatings and cathodic protection have been extensively investigated for offshore structures [1]–[7], while corrosion inhibitors have received considerable attention in offshore and oil-and-gas systems [14]–[17]. Temporary corrosion-protection methods, including VpCI and rust-preventive systems, have also been investigated for equipment during storage and transportation [8]–[10], [18]. Experimental evidence further demonstrates the importance of lubrication in combined corrosion-friction-wear behavior [11], as well as the role of humidity and anti-condensation control in enclosed equipment [12], [13].

In parallel, offshore asset-integrity management has increasingly incorporated risk-based inspection, condition monitoring, structural-health monitoring, predictive maintenance, and digital technologies. Risk-based methods provide a basis for linking equipment criticality with inspection and maintenance requirements [19]–[21]. Offshore monitoring technologies enable continuous or periodic assessment of equipment and structural condition [22]–[30], while recent developments in digital twins and predictive models provide additional opportunities for condition forecasting and maintenance decision support [31]–[36].

Despite these developments, the available evidence remains fragmented across individual technologies and engineering disciplines. Studies on coatings generally focus on external corrosion protection; inhibitor studies focus predominantly on internal corrosion; monitoring literature focuses on condition assessment; and digital-twin studies largely address structural damage prediction and maintenance. Fewer studies consider how these technologies should operate together as a coordinated preservation system during equipment inactivity.

The distribution of available evidence is also uneven. Protective coatings, corrosion inhibitors, integrity assessment, and monitoring technologies are supported by a relatively broad literature base, whereas fewer independent investigations directly evaluate nitrogen blanketing, humidity-control strategies, lubrication-based preservation, and other temporary preservation measures under prolonged offshore inactivity. Moreover, much of the available evidence originates from offshore structures, pipelines, marine equipment, and related oil-and-gas applications rather than specifically from offshore wellhead-platform equipment.

These limitations indicate a need for an integrated engineering perspective that links preservation measures directly to the degradation mechanisms they are intended to control.

Accordingly, the novelty of this review lies in integrating previously fragmented evidence on physical, environmental, chemical, inspection, and digital preservation measures into an equipment-specific and decision-

oriented multi-barrier preservation framework for offshore wellhead platforms during periods of inactivity. Rather than considering preservation methods as independent treatments, the proposed framework links the dominant degradation mechanism with the appropriate preservation barrier, measurable condition-verification parameter, and corresponding maintenance response.

The review addresses the following research questions:

- RQ1: What degradation mechanisms affect offshore wellhead-platform equipment during storage, pre-commissioning, shutdown, and other periods of inactivity?
- RQ2: What preservation technologies are reported for mitigating corrosion and mechanical degradation of offshore equipment?
- RQ3: How can individual preservation measures be integrated within a multi-barrier preservation strategy?
- RQ4: What inspection, monitoring, and verification parameters are used to assess preservation effectiveness?
- RQ5: What limitations, research gaps, and future opportunities remain for preservation management in offshore wellhead platforms?

The objectives of this review are therefore to synthesize current preservation practices, compare the functions and limitations of individual preservation barriers, identify equipment-specific preservation and verification requirements, develop an integrated multi-barrier preservation framework, and identify research priorities for condition-based and digitally supported preservation management.

METHODS

Research Design and Review Questions

This study employed a systematic literature review (SLR) to identify, evaluate, and synthesize current knowledge regarding corrosion prevention and equipment preservation in offshore wellhead platforms. The review focused particularly on preservation during storage, construction delays, pre-commissioning, commissioning, temporary shutdowns, and extended periods of inactivity. The review process was organized with reference to the PRISMA 2020 reporting framework [37] to provide a transparent structure for literature identification, screening, eligibility assessment, and study selection.

The five research questions defined in the Introduction guided the literature search, evidence classification, thematic synthesis, comparative assessment, and development of the proposed multi-barrier preservation framework.

Information Sources and Search Strategy

A structured literature search was conducted using six scientific information sources: Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. The search was designed to identify publications related to offshore preservation, corrosion prevention, equipment integrity, and associated preservation technologies.

The principal search terms included offshore preservation, wellhead platform preservation, equipment preservation, corrosion prevention, asset integrity management, multi-barrier corrosion protection, nitrogen blanketing, corrosion inhibitor, vapor-phase corrosion inhibitor, cathodic protection, protective coating, lubrication, humidity control, digital monitoring, predictive maintenance, and digital twin. These terms were combined using Boolean operators such as AND and OR and adapted to the syntax of each information source.

The eligibility period was 2015–2025 to capture contemporary preservation practices and technological developments. Publication-year filters were applied where supported by the information source; any out-of-range records remaining in the retrieved results were removed during screening. Earlier publications, engineering handbooks, and recognized standards were retained only when required to support fundamental corrosion mechanisms, engineering interpretation, or established industrial practice and were not counted as part of the primary systematic evidence set. Additional relevant publications were identified through backward and forward citation tracking of highly relevant studies.

Eligibility Criteria

Studies were considered eligible for the primary systematic synthesis when they: (1) were published between 2015 and 2025; (2) were available in English; (3) were peer-reviewed journal articles, review articles, or

eligible full-text technical studies; (4) addressed corrosion prevention, preservation, equipment integrity, reliability, monitoring, or related degradation mechanisms; (5) concerned offshore, marine, oil-and-gas, or technically comparable equipment where the preservation mechanism was applicable to offshore wellhead-platform equipment; (6) evaluated or discussed one or more relevant preservation approaches; and (7) provided sufficient technical or methodological information to support qualitative analysis.

Studies were excluded when they were unrelated to the preservation objectives of this review, focused on applications without technically transferable degradation or protection mechanisms, were duplicate records, consisted only of conference abstracts without accessible full text, lacked sufficient technical information, or represented promotional and non-technical material.

Study Selection Process

The literature-selection process followed the PRISMA 2020 framework [37]. The initial search identified 178 records. Following removal of 29 duplicate records, 149 unique records remained for title and abstract screening. During screening, 81 records were excluded because they did not satisfy the predefined relevance, publication-period, language, or subject-scope requirements. This resulted in 68 publications being retained for full-text eligibility assessment. A further 25 publications were excluded during full-text assessment because they did not provide sufficient technical information, were outside the relevant preservation scope, focused on non-transferable applications, or otherwise failed to satisfy the eligibility requirements. A total of 43 scientific and technical publications were included in the final qualitative synthesis. The study-selection process is summarized in Figure 1.

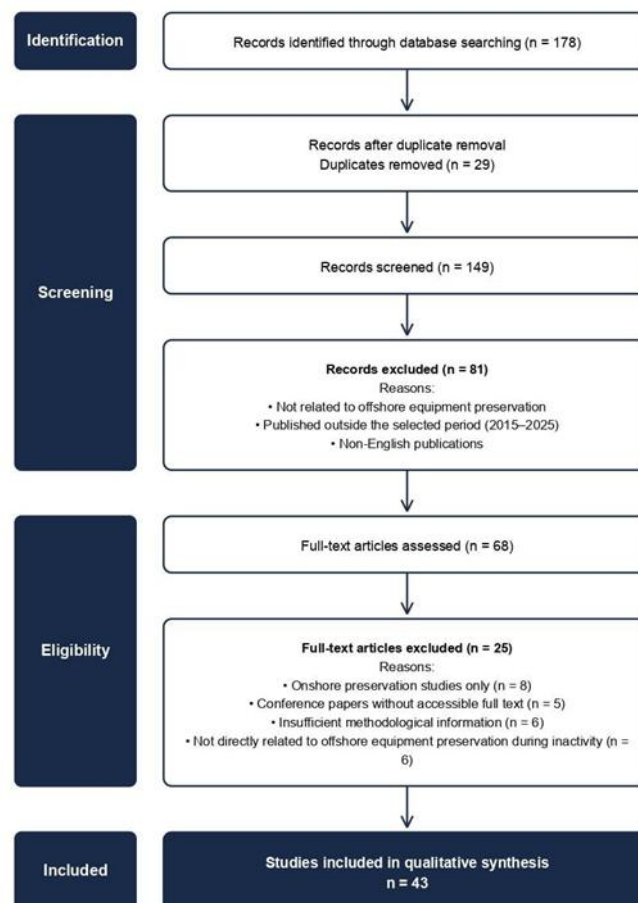


Figure 1. Literature Selection Process Based on the PRISMA Framework

Data Extraction

A structured data-extraction framework was used to organize information from the included publications. Extracted variables included author and publication year, publication source, study and application context, equipment or system investigated, dominant degradation mechanism, preservation technology or integrity strategy, protection mechanism, preservation or exposure duration when reported, inspection and monitoring method, preservation-verification parameter, reported advantages and limitations, and implications for equipment integrity, reliability, and readiness for service.

Evidence Classification and Critical Appraisal

Because the available literature varied in its proximity to offshore wellhead-platform applications, evidence was classified according to application context. Direct offshore-platform evidence included studies conducted specifically on offshore platforms, offshore oil-and-gas facilities, or associated equipment. Transferable offshore evidence included studies involving other offshore or marine structures for which the environmental exposure, degradation mechanism, or preservation technology was directly applicable to wellhead-platform equipment. Transferable oil-and-gas or mechanical evidence included studies addressing pipelines, pressure-containing equipment, wire ropes, enclosed metallic equipment, or other technically comparable systems.

The methodological relevance of the selected evidence was critically appraised according to methodological clarity, relevance to corrosion prevention or preservation, strength of the reported evidence, applicability to offshore equipment, and contribution to the thematic synthesis. The appraisal was used to determine the relative interpretive weight of individual studies rather than as a numerical score or standalone exclusion criterion. Greater interpretive weight was given to studies with clearly described methods, experimental or field data, direct offshore applicability, and measurable preservation or integrity outcomes.

Data Synthesis and Comparative Analysis

The selected studies were analyzed using qualitative thematic synthesis. Evidence was grouped according to the principal preservation and integrity themes: protective coatings; cathodic protection; nitrogen or inert-atmosphere preservation; conventional corrosion inhibitors; VpCI/VCI and temporary preservation; environmental and humidity control; lubrication; asset-integrity and risk-based inspection; condition and corrosion monitoring; and digital or predictive technologies. Within each theme, evidence was analyzed according to the sequence: degradation mechanism → preservation function → equipment applicability → verification requirement → implementation limitation. This technology-oriented synthesis formed the basis of the comparative assessment in Table 2.

The evidence was subsequently reorganized according to equipment type using the sequence: equipment category → dominant degradation mechanism → primary preservation barrier → complementary verification → critical condition parameter. This equipment-oriented synthesis formed the basis for the proposed integrated preservation framework in Table 3.

Development of the Multi-Barrier Preservation Framework

The integrated multi-barrier framework was developed from the combined findings of the reviewed evidence rather than being reproduced from a single publication. Multi-barrier preservation was not interpreted as the simultaneous application of as many protection methods as possible. Instead, individual measures were considered complementary when they addressed different degradation mechanisms or provided different protection and verification functions. The framework therefore integrates four principal elements: degradation mechanism → preservation barrier → condition verification → maintenance response.

Supporting Engineering References

Industry standards and recommended practices, including API RP 686, ISO 12944-9, ISO 55000, NORSOK Z-015, and DNV-RP-F115, were used as supporting engineering references to interpret machinery, coating, asset-management, temporary-equipment, and pre-commissioning practices [38]–[42]. These documents were not counted among the 43 scientific and technical publications included in the qualitative synthesis.

Review Validity and Limitations

The credibility of the review was supported through multiple scientific information sources, predefined eligibility criteria, systematic screening, evidence classification, structured data extraction, and thematic comparison. Evidence from direct offshore applications was distinguished from technically transferable studies to avoid interpreting all reviewed publications as having the same application context.

Several limitations should nevertheless be acknowledged. Direct studies specifically investigating long-duration preservation of offshore wellhead-platform equipment remain relatively limited. Consequently, technically transferable evidence from related offshore, marine, oil-and-gas, and mechanical applications was required for several preservation mechanisms. The studies were also heterogeneous in equipment type, environmental conditions, preservation duration, test methodology, and reported performance parameters. Quantitative meta-analysis was therefore not considered appropriate, and the findings were synthesized qualitatively.

RESULTS AND DISCUSSION

The systematic synthesis indicates that preservation of offshore wellhead-platform equipment is closely associated with mechanical integrity, equipment reliability, and readiness for commissioning or return to service. Equipment may continue to deteriorate during storage, construction delays, pre-commissioning, temporary shutdowns, and other extended periods of inactivity even in the absence of normal operating loads. Moisture, oxygen, chloride-containing contaminants, temperature fluctuations, coating deterioration, lubricant degradation, and loss of enclosure integrity represent important degradation drivers under these conditions.

The reviewed evidence also indicates that preservation effectiveness depends not simply on applying a protective treatment, but on matching the preservation barrier to the dominant degradation mechanism and subsequently verifying that the barrier remains effective. Accordingly, the findings are discussed in terms of degradation mechanisms, equipment-specific preservation requirements, comparative barrier performance, verification methods, implementation constraints, and opportunities for digital integration.

Degradation Mechanisms During Equipment Inactivity

Mechanical equipment remains susceptible to degradation even when it is not operating. In offshore environments, prolonged inactivity does not eliminate exposure to moisture, oxygen, chlorides, temperature variations, and atmospheric contaminants. These factors may promote corrosion on exposed metallic surfaces and condensation within enclosed equipment.

For contacting and moving components, degradation may involve both corrosion and tribological processes. Experimental evidence on lubricated wire ropes shows that corrosive environments can deteriorate the protective performance of grease or oil and modify friction and wear behavior [11]. This interaction indicates that corrosion and mechanical surface degradation should not always be evaluated independently.

Moisture-related deterioration represents another important mechanism during inactivity. High relative humidity and temperature variation can promote condensation within enclosed equipment. Experimental investigation of desiccant-coated metallic cabinets demonstrated that moisture-control measures can delay condensation under the investigated conditions [12]. Anti-condensation control of non-operating cabinets provides complementary evidence that dew-point management is relevant to humidity-sensitive enclosed equipment [13].

These findings suggest that preservation planning should begin with identification of the dominant degradation mechanism and equipment vulnerability. This provides a stronger engineering basis for preservation selection than applying a uniform preservation procedure across different equipment categories.

Preservation of Mechanical and Rotating Equipment

Mechanical and rotating equipment require preservation measures that maintain both material condition and functional readiness. Components such as wire ropes, bearings, shafts, gears, and other contacting surfaces may deteriorate through the combined effects of corrosion, lubricant degradation, friction, and wear.

Lubrication constitutes an important preservation barrier because it reduces direct surface interaction and limits friction and wear. However, experimental evidence indicates that lubricant performance may deteriorate under corrosive exposure [11]. Water ingress, corrosive species, particulate contamination, and prolonged environmental exposure can therefore reduce the ability of a lubricant to provide adequate protection.

Preservation of these components should consequently include cleaning, drying, lubricant application, and periodic condition verification rather than lubrication alone. For wire ropes, relevant inspection locations include strands, terminations, sheaves, and contact zones. For other rotating components, lubricant condition, seal integrity, evidence of moisture ingress, surface condition, and extended standstill should also be considered. Thus, lubrication should be treated as part of a broader preservation process in which the condition of the lubricant and the protected component are periodically verified.

Environmental and Humidity Control as Supporting Preservation Barriers

Environmental control provides an important supporting preservation function because relative humidity, temperature variation, and condensation directly influence moisture accumulation within enclosed mechanical, electrical, and instrumentation equipment. When surface temperature falls below the dew-point temperature, moisture may condense on metallic or electrical surfaces and promote corrosion, insulation deterioration, and loss of equipment reliability.

Experimental investigation of desiccant-coated metallic cabinets demonstrated that moisture adsorption can delay condensation compared with unprotected metallic surfaces [12]. Complementary evidence from control cabinets further demonstrates that anti-condensation control is particularly relevant during non-operating periods under high-temperature and high-humidity conditions [13]. Although these studies were not conducted

specifically on offshore wellhead platforms, their underlying mechanisms are transferable to humidity-sensitive enclosed equipment in marine environments.

Environmental preservation should therefore focus not only on the presence of desiccant or heating devices but also on measurable conditions such as relative humidity, internal temperature, dew point, and enclosure integrity. When the required environmental condition is no longer maintained, corrective actions may include desiccant replacement, drying, enclosure repair, restoration of anti-condensation heating, or further inspection.

Protective Coatings and Cathodic Protection

Protective coatings constitute a primary barrier against atmospheric and splash-zone corrosion by limiting direct contact between metallic substrates and moisture, oxygen, chlorides, and other aggressive species. Long-term offshore exposure studies demonstrate that coating performance is influenced by mechanical damage, coating integrity, adhesion, structural details, and exposure zone [1], [2], [5]–[7]. Mechanical damage can initiate coating delamination and expose the underlying steel to localized corrosion [5]. Abrasive loading may also progressively reduce coating thickness and protective capability, indicating that mechanical degradation should be considered together with electrochemical corrosion [43].

Cathodic protection provides a complementary electrochemical protection mechanism for submerged or continuously wetted steel. Offshore evidence indicates that biofouling and corrosion products can influence protection-current demand [3]. Accordingly, coating condition, protection potential, current demand, environmental exposure, and accessibility should be considered together when these barriers are applied. ISO 12944-9 provides additional engineering context for protective paint systems used on offshore and related structures [39].

Nitrogen Blanketing and Internal Preservation

Internal surfaces of piping, pressure vessels, and other pressure-containing equipment may remain susceptible to corrosion during prolonged inactivity when residual oxygen and moisture are present. Nitrogen blanketing provides an oxygen-exclusion strategy by replacing or diluting the internal atmosphere with nitrogen, thereby reducing the availability of oxygen required for corrosion reactions.

Experimental evidence from oil-and-gas casing systems demonstrates that corrosion rate decreases as the nitrogen concentration of the protected environment increases [44]. Although the study was conducted in a salt-cavern gas-storage application rather than an offshore wellhead platform [45], the underlying oxygen-exclusion mechanism provides transferable evidence for internal preservation of enclosed steel systems [46], [47].

The effectiveness of nitrogen preservation depends on maintaining the intended internal atmosphere. Leakage through valves, flanges, seals, temporary connections, or other pressure boundaries may allow atmospheric air and moisture to enter the system. Nitrogen blanketing should therefore be implemented together with drying [48], isolation control, and pressure-boundary verification. Pressure stability provides a practical indication of preservation integrity, while oxygen concentration, relative humidity, or dew point may provide additional verification where appropriate instrumentation is available.

Table 1. Equipment-Specific Degradation Mechanisms and Preservation Requirements Identified from the Reviewed Evidence

Equipment category	Dominant degradation	Main contributing factors	Preservation requirement	Verification focus	Reference
Wire ropes and contacting components	Corrosion, friction, and wear	Corrosive environment, moisture, lubricant deterioration	Cleaning, drying, and appropriate lubrication	Lubricant condition, strands, terminations, contact zones, wear	[11]
Externally exposed piping and metallic surfaces	Atmospheric corrosion and coating degradation	Marine atmosphere, moisture, chloride deposition, coating defects, mechanical damage	Protective coating and localized repair where required	Coating condition, defects, surface condition, wall thickness where applicable	[1], [2], [5]–[7], [43], [48]
Submerged or continuously wetted metallic components	Electrochemical corrosion	Seawater exposure, biofouling, corrosion products, surface condition	Cathodic protection supplemented by coating where applicable	Protection potential, current demand, coating condition	[1], [3], [4]

Equipment category	Dominant degradation	Main contributing factors	Preservation requirement	Verification focus	Reference
Internal piping and pressure-containing equipment	Internal corrosion	Residual oxygen, moisture, deposits, leakage, loss of isolation	Drying, inhibitor treatment and/or inert-atmosphere preservation	Pressure stability, leakage, O ₂ /RH or dew point, internal condition	[14]–[17], [44]
Humidity-sensitive electrical/instrumentation equipment	Condensation and moisture-related deterioration	High RH, temperature variation, surface temperature below dew point, enclosure leakage	Desiccant/dehumidification and/or anti-condensation control	RH, temperature, dew point, condensation, enclosure condition	[12], [13]
Enclosed metallic cavities and assemblies	Corrosion of inaccessible internal surfaces	Moisture, confined atmosphere, limited surface accessibility	VpCI/VCI where applicable	Enclosure integrity, inhibitor condition, leakage, ventilation	[8]–[10], [18]

Table 1 demonstrates that preservation requirements differ according to equipment configuration and dominant degradation mechanism. No single preservation measure addresses corrosion, moisture-related degradation, and tribological deterioration simultaneously. The results therefore support a mechanism-based preservation approach in which equipment vulnerability, preservation method, and condition-verification parameter are considered together.

Corrosion Inhibitors, VpCI, and Temporary Corrosion Protection

Corrosion inhibitors provide chemical protection by reducing anodic, cathodic, or combined electrochemical reactions at metallic surfaces. In offshore oil-and-gas production facilities, organic inhibitors are widely applied for control of internal corrosion in pipelines, storage systems, and other metallic equipment [14]–[17]. Film-forming inhibitors provide protection through adsorption and formation of a protective layer on the metallic surface [16].

VpCI/VCI represents a more specific temporary preservation approach for enclosed or difficult-to-access metallic surfaces. Vapor-phase inhibitors can migrate through the atmosphere within an enclosed space and interact with metallic surfaces that may not be directly accessible [8]–[10], [18]. Temporary rust-preventive systems are also widely discussed for protection during manufacturing, storage, transportation, and other non-operating periods [8], [9].

The effectiveness of VpCI depends strongly on maintaining the required enclosure condition. Excessive ventilation, enclosure leakage, loss of inhibitor availability, or prolonged storage without verification may reduce protection. VpCI should therefore be regarded as a complementary preservation barrier rather than as a universal replacement for coatings, lubrication, drying, or humidity control.

Comparative Assessment of Preservation Technologies

The reviewed evidence indicates that preservation technologies should not be evaluated according to a single universal ranking. Each barrier addresses a different degradation pathway and operates through a different physical, chemical, electrochemical, or verification mechanism. Accordingly, preservation technologies are more appropriately compared in terms of their primary degradation target, protective function, verification requirement, and implementation limitation.

Table 2. Functional Comparison of Preservation Barriers Identified from the Reviewed Evidence

Preservation barrier	Primary degradation addressed	Preservation function	Verification parameter	Principal limitation	Reference
Protective coating	External/atmospheric corrosion	Physical barrier between metal and corrosive environment	Coating condition, defects, adhesion, thickness where applicable	Aging, mechanical damage, disbondment, localized failure	[1], [2], [4]–[7], [43], [48]
Cathodic protection	Electrochemical corrosion of submerged/wetted steel	Electrochemical protection of applicable steel surfaces	Protection potential and current demand	Requires appropriate design; affected by surface/environmental conditions	[1], [3], [4]

Preservation barrier	Primary degradation addressed	Preservation function	Verification parameter	Principal limitation	Reference
Nitrogen/inert-atmosphere preservation	Internal oxygen- and moisture-related corrosion	Reduces oxygen exposure and atmospheric ingress	Pressure stability, leakage, O ₂ /RH or dew point where applicable	Leakage can compromise protected atmosphere	[44]
Conventional corrosion inhibitors	Internal corrosion	Adsorption/film formation reduces corrosion reactions	Inhibitor concentration, fluid condition, corrosion trend	Effectiveness depends on chemistry, transport, dosage, surface condition	[14]–[17]
VpCI/VCI and temporary protection	Corrosion of enclosed metallic surfaces	Volatile inhibitor provides protection within confined spaces	Enclosure integrity, inhibitor condition	Ventilation/leakage reduce inhibitor effectiveness	[8]–[10], [18]
Desiccant/dehumidification and anti-condensation	Condensation and high relative humidity	Reduces moisture accumulation and/or maintains temperature above dew point	RH, temperature, dew point, desiccant condition	Saturation, enclosure leakage, power/control dependency	[12], [13]
Lubrication	Friction, wear, and corrosion of contacting components	Reduces direct surface interaction and limits friction/wear	Lubricant and component condition	Contamination and corrosive exposure can degrade lubricant performance	[11]
Condition/digital monitoring	Undetected loss of preservation effectiveness	Supports condition verification, trend analysis, maintenance decisions	Sensor validity, data continuity, condition trends	Calibration, reliability, communication, data quality	[22]–[30]
Predictive/digital-twin assessment	Progressive degradation requiring prediction	Combines monitoring/model information for predictive assessment	Model validity, sensor input quality, degradation trend	Requires reliable data, validated models, interoperability	[31]–[36]

The comparison in Table 2 shows that the barriers are functionally complementary rather than interchangeable. Protective coatings and cathodic protection primarily address external and electrochemical corrosion, whereas nitrogen preservation addresses internal oxygen and moisture exposure. VpCI and environmental-control measures are particularly relevant to enclosed environments, while lubrication primarily addresses contacting and moving surfaces. Digital monitoring differs from physical and chemical preservation barriers because it does not directly prevent deterioration; instead, it provides a condition-verification and decision-support function. A multi-barrier preservation system should therefore combine barriers that address different but relevant degradation pathways rather than simply maximizing the number of protection methods applied.

Wellhead-Platform-Specific Preservation Challenges

Wellhead platforms present particular preservation challenges because offshore access, available deck space, personnel availability, inspection opportunities, and logistics may be more constrained than at larger processing facilities. Construction delays, phased development, extended storage, and prolonged pre-commissioning may increase the period during which equipment remains inactive. Under these conditions, a preservation technique that is technically effective but requires frequent offshore intervention may become difficult to maintain.

The preservation challenge is particularly relevant to mature offshore fields where installed infrastructure may remain inactive while being retained for possible future use. Evidence from Offshore North West Java describes a large inventory of subsea pipelines with inactive status, including idle or preserved lines [45]. Such conditions reinforce the need for preservation strategies that maintain integrity during non-operating periods while supporting reliable condition assessment before reactivation.

Preservation selection should therefore account for both technical effectiveness and practical maintainability. Externally exposed piping may primarily depend on coating protection; submerged components may require cathodic protection; internal pressure-containing equipment may require dry inert-atmosphere preservation; enclosed components may use VpCI or humidity control; and contacting mechanical components may require lubrication. The appropriate combination depends on equipment criticality, dominant degradation mechanism, accessibility, expected inactivity duration, and the ability to verify preservation condition.

Risk-Based Implementation, Inspection, and Maintainability

Effective preservation requires more than the initial application of a corrosion-control measure. Preservation performance must remain verifiable throughout the inactivity period, and the required level of verification should reflect equipment criticality and degradation risk. Previous studies on offshore-platform asset integrity management demonstrate that risk identification and quantitative risk assessment can support maintenance prioritization and integrity decision-making [19], [20]. Risk-based structural integrity approaches further demonstrate that inspection intervals and requirements can be adjusted according to equipment or structural risk rather than being determined solely by fixed schedules [21].

These principles are directly relevant to preservation management. Equipment with greater safety, reliability, or production consequences should require a higher level of preservation assurance and condition verification. Preservation management can therefore be structured through five interconnected steps: (1) identify the dominant degradation mechanism; (2) determine equipment criticality and vulnerability; (3) select the primary and complementary preservation barriers; (4) define measurable verification parameters and inspection intervals; and (5) establish corrective actions when preservation effectiveness deteriorates.

For example, coating deterioration may trigger localized repair or additional wall-thickness assessment; loss of pressure in a nitrogen-preserved system may require leakage investigation and restoration of the inert atmosphere; degradation of lubricant condition may require cleaning and re-lubrication; and excessive relative humidity may require drying, desiccant replacement, or enclosure repair. Maintainability is particularly important for offshore wellhead platforms because inspection frequency may be constrained by personnel availability, access, weather, and offshore logistics.

Digital Monitoring and Predictive Preservation

The reviewed literature indicates progressive development from conventional condition sensing toward integrated monitoring and predictive digital assessment. Corrosion-monitoring technologies include conventional coupons and electrical-resistance probes as well as electrochemical, ultrasonic, magnetic, optical-fiber, and wireless sensing systems [22]–[24]. At the system level, condition-monitoring and structural-health-monitoring architectures have been demonstrated for FPSO systems and offshore jacket platforms [25]–[30].

More recent developments extend this capability through digital-twin and artificial-intelligence approaches. Digital-twin frameworks have been used for offshore-platform damage identification, optimal sensor placement, fatigue prediction, and predictive maintenance [31]–[34], [36], while AI-based corrosion-monitoring research indicates opportunities for improved data interpretation and corrosion prediction in oil-and-gas applications [35].

These technologies nevertheless remain supporting layers within a preservation system. Their function is to provide measurable information on equipment condition and barrier deterioration rather than to replace the physical, chemical, or electrochemical barrier itself. Data quality, sensor reliability, calibration, model validity, communication integrity, and interoperability therefore become important considerations in digital preservation management.

Integrated Decision-Oriented Multi-Barrier Preservation Framework

The overall synthesis supports an integrated preservation framework in which preservation decisions are linked to equipment condition, dominant degradation mechanism, preservation barrier, verification requirement, and corrective maintenance response. The proposed framework does not represent a preservation procedure reproduced from a single publication; rather, it represents a synthesis of the evidence reviewed in this study.

Table 3. Proposed Equipment-Based Multi-Barrier Preservation Framework Synthesized from the Reviewed Evidence

Equipment category	Degradation / exposure	Primary preservation barrier	Supporting measure	Verification parameter	Reference
Externally exposed piping and metallic surfaces	Marine atmosphere, moisture, chloride deposition, coating deterioration	Protective coating	Visual inspection and corrosion/thickness monitoring	Coating integrity, visible defects, wall thickness	[1], [2], [5], [43], [48]
Submerged or continuously wetted metallic structures	Seawater-driven electrochemical corrosion	Cathodic protection	Protective coating and electrical monitoring	Protection potential and current demand	[1], [3]
Internal piping and pressure-containing equipment	Internal oxygen and moisture exposure	Drying plus inhibitor and/or nitrogen/inert-atmosphere preservation	Isolation, pressure, and internal-condition verification	Pressure stability, leakage, O ₂ /RH or dew point	[14]–[17], [44]

Equipment category	Degradation / exposure	Primary preservation barrier	Supporting measure	Verification parameter	Reference
Wire ropes and contacting components	Corrosion, friction, and wear	Lubrication	Cleaning and periodic condition inspection	Lubricant condition, strands, terminations, contact zones, wear	[11]
Enclosed valves and metallic assemblies	Moisture-related corrosion of inaccessible surfaces	VpCI/VCI	Enclosure-condition verification	Enclosure integrity, ventilation/leakage, inhibitor condition	[8]–[10], [18]
Humidity-sensitive electrical/instrumentation enclosures	Condensation, high RH, moisture-related deterioration	Desiccant/dehumidification or anti-condensation control	Environmental monitoring and enclosure inspection	RH, temperature, dew point, condensation, enclosure integrity	[12], [13]
High-criticality or difficult-to-access equipment	Undetected loss of preservation effectiveness	Applicable physical/chemical preservation barrier	Digital condition monitoring	Sensor reliability, data continuity, preservation-condition trend	[22]–[30]
Equipment requiring predictive assessment	Progressive degradation requiring forecast	Applicable preservation and inspection strategy	Digital-twin/predictive assessment	Data quality, model validity, degradation trend	[31]–[36]

Table 3 highlights three important elements of the proposed framework. First, preservation selection is degradation-mechanism driven: the barrier should be selected according to the relevant deterioration pathway rather than according to a standardized treatment applied indiscriminately to all assets. Second, preservation requires measurable verification. Coating condition, wall thickness, cathodic-protection potential, pressure stability, relative humidity, lubricant condition, enclosure integrity, and monitoring trends represent different forms of evidence that a preservation barrier remains functional. Third, verification must be connected to maintenance action. Deviations from the required preservation condition should lead to defined responses such as coating repair, drying, re-lubrication, inhibitor replacement, leakage repair, restoration of an inert atmosphere, or further integrity assessment.

Accordingly, preservation can be interpreted as a condition-based integrity-management activity that connects degradation mechanism → preservation barrier → condition verification → maintenance response. This relationship represents the central synthesis of the review.

Research Gaps and Future Directions

The literature reviewed in this study demonstrates substantial research activity in offshore coatings, cathodic protection, corrosion inhibitors, temporary rust preventives, VpCI, condition monitoring, structural-health monitoring, asset-integrity management, and digital-twin technologies. However, these research domains remain largely fragmented. Studies addressing temporary preservation typically focus on individual protection mechanisms or specific equipment classes, whereas offshore integrity studies predominantly address operating structures, pipelines, or structural degradation.

Table 4. Thematic Evidence Map and Role of Reviewed Studies

Evidence theme	Main contribution to the synthesis	Reference
Protective coatings	External corrosion prevention, coating deterioration, adhesion, mechanical damage	[1], [2], [4]–[7], [43], [46], [48], [49]
Cathodic protection	Electrochemical protection of submerged or wetted metallic structures	[1], [3], [4]
Nitrogen/inert preservation	Reduction of internal oxygen exposure	[44]
Conventional corrosion inhibitors	Internal corrosion mitigation and surface-film protection	[14]–[17], [28]
VpCI and temporary preservation	Protection during storage, transportation, and inactivity	[8]–[10], [18]
Environmental/humidity control	Condensation prevention and preservation of enclosed equipment	[12], [13]
Lubrication/tribological preservation	Protection against friction, wear, and corrosion of contacting surfaces	[11]
Asset integrity and risk assessment	Equipment criticality, inspection prioritization, risk-based decisions	[19]–[21]
Condition/corrosion monitoring	Verification of equipment and preservation condition	[22]–[30]

Evidence theme	Main contribution to the synthesis	Reference
Digital twin and predictive technologies	Predictive condition assessment and future digital preservation integration	[31]–[36]
Inactive/preserved offshore infrastructure	Integrity management of non-operating offshore assets	[45]

Table 4 illustrates the thematic concentration of the reviewed evidence. Protective coatings, corrosion inhibitors, integrity assessment, and condition-monitoring technologies are represented by a broader body of reviewed literature, whereas nitrogen blanketing, humidity-control strategies, lubrication-based preservation, and preservation of inactive offshore equipment are represented by comparatively fewer studies. This pattern indicates that several widely applied preservation practices rely more heavily on engineering practice and transferable evidence than on extensive long-term offshore field validation.

Another important observation is the fragmentation of the available evidence. Most studies investigate individual corrosion-control technologies, monitoring systems, or integrity-management approaches independently. Relatively few studies examine how physical, environmental, chemical, inspection, and digital measures can be coordinated as a single equipment-specific preservation strategy during prolonged inactivity. This fragmentation provides the principal basis for the multi-barrier framework proposed in this review.

Future research should experimentally and operationally evaluate combined preservation strategies under realistic storage, pre-commissioning, shutdown, and extended-idle conditions, with particular attention to measurable performance indicators such as relative humidity, dew point, oxygen concentration, pressure stability, coating condition, corrosion rate, lubricant condition, and equipment readiness for return to service. Recent marine and offshore reviews further emphasize the continuing need to integrate corrosion protection with monitoring and lifecycle management [46]–[49]. Digital twins and AI-based approaches may support predictive preservation, but their implementation requires validated models, reliable sensor data, and interoperability [32], [35], [36].

CONCLUSIONS

This systematic review examined corrosion-prevention and preservation strategies for offshore wellhead-platform equipment during storage, construction delays, pre-commissioning, temporary shutdowns, and other extended periods of inactivity. The findings show that degradation during inactivity results from multiple mechanisms, including atmospheric and electrochemical corrosion, oxygen and moisture exposure, condensation, lubricant deterioration, friction, and wear. Accordingly, no single preservation method can address all degradation risks. Protective coatings, cathodic protection, nitrogen or inert-atmosphere preservation, corrosion inhibitors, VpCI, environmental control, and lubrication provide complementary protection according to equipment type and degradation mechanism.

A key finding is that preservation effectiveness depends not only on applying an appropriate protection method but also on verifying that the preservation barrier remains functional throughout the inactivity period. Based on the reviewed evidence, this study proposes an equipment-specific and decision-oriented multi-barrier framework linking four elements: degradation mechanism → preservation barrier → condition verification → maintenance response. Digital monitoring, prognostics, and digital-twin technologies can strengthen this framework by supporting condition assessment and maintenance decisions, but they should complement rather than replace physical, chemical, or electrochemical preservation barriers.

The review also identifies uneven evidence across preservation technologies. Protective coatings, corrosion inhibitors, integrity assessment, and monitoring systems are relatively well represented, whereas fewer studies address nitrogen blanketing, humidity control, lubrication-based preservation, and integrated multi-barrier strategies under prolonged offshore inactivity. Future research should therefore emphasize long-term field validation, standardized preservation-performance indicators, quantitative condition monitoring, and risk-based approaches that support the transition from calendar-based preservation toward condition-based and predictive preservation management.

ACKNOWLEDGEMENT

The author would like to thank colleagues and reviewers for their valuable comments, suggestions, and academic support during preparation of this manuscript. Their contributions helped improve the quality and clarity of this review.

REFERENCES

- [1] S. J. Price and R. B. Figueira, "Corrosion Protection Systems and Fatigue Corrosion in Offshore Wind Structures: Current Status and Future Perspectives," *Coatings*, vol. 7, no. 2, p. 25, 2017. doi: <https://doi.org/10.3390/coatings7020025>.
- [2] A. A. Olajire, "Recent advances on organic coating system technologies for corrosion protection of offshore metallic structures," *J. Mol. Liq.*, vol. 269, pp. 572–606, 2018, doi: <https://doi.org/10.1016/j.molliq.2018.08.053>.
- [3] C. Erdogan and G. Swain, "The Effects of Biofouling and Corrosion Products on Impressed Current Cathodic Protection System Design for Offshore Monopile Foundations," *Journal of Marine Science and Engineering*, vol. 10, no. 11, p. 1670, 2022. doi: <https://doi.org/10.3390/jmse10111670>.
- [4] B. Syrek-Gerstenkorn and S. Paul, "Metallic coatings in offshore wind sector—a mini review," *npj Mater. Degrad.*, vol. 8, no. 1, p. 86, 2024, doi: <https://doi.org/10.1038/s41529-024-00480-8>.
- [5] A. W. Momber, P. Plagemann, and V. Stenzel, "Performance and integrity of protective coating systems for offshore wind power structures after three years under offshore site conditions," *Renew. Energy*, vol. 74, pp. 606–617, 2015, doi: <https://doi.org/10.1016/j.renene.2014.08.047>.
- [6] A. W. Momber, P. Plagemann, and V. Stenzel, "The adhesion of corrosion protection coating systems for offshore wind power constructions after three years under offshore exposure," *Int. J. Adhes. Adhes.*, vol. 65, pp. 96–101, 2016, doi: <https://doi.org/10.1016/j.ijadhadh.2015.11.011>.
- [7] A. W. Momber, M. Irmer, and N. Glück, "Performance characteristics of protective coatings under low-temperature offshore conditions. Part 1: Experimental set-up and corrosion protection performance," *Cold Reg. Sci. Technol.*, vol. 127, pp. 76–82, 2016, doi: <https://doi.org/10.1016/j.coldregions.2016.03.013>.
- [8] Z. Tang, "A review of corrosion inhibitors for rust preventative fluids," *Curr. Opin. Solid State Mater. Sci.*, vol. 23, no. 4, p. 100759, 2019, doi: <https://doi.org/10.1016/j.cossms.2019.06.003>.
- [9] V. S. Saji, "Temporary rust preventives—A retrospective," *Prog. Org. Coatings*, vol. 140, p. 105511, 2020, doi: <https://doi.org/10.1016/j.porgcoat.2019.105511>.
- [10] V. Vorobyova, M. Skiba, and O. Chygyrynets', "A novel eco-friendly vapor phase corrosion inhibitor of mild steel," *Pigment Resin Technol.*, vol. 48, no. 2, pp. 137–147, 2018, doi: <https://doi.org/10.1108/PRT-03-2018-0025>.
- [11] X. Chang *et al.*, "Influence of different corrosive environments on friction and wear characteristics of lubricated wire ropes in a multi-layer winding system," *Eng. Fail. Anal.*, vol. 131, p. 105901, 2022, doi: <https://doi.org/10.1016/j.engfailanal.2021.105901>.
- [12] T. S. Ge, R. Y. Hao, Y. J. Dai, R. Z. Wang, and H. Yan, "Experimental investigation on anti-condensation characteristic of desiccant coated metal cabinet," *Renew. Energy*, vol. 113, pp. 835–845, 2017, doi: <https://doi.org/10.1016/j.renene.2017.06.058>.
- [13] L. Zhao *et al.*, "Performance analysis of a temperature adaptive anti-condensation device in open-plan control cabinets," *Therm. Sci. Eng. Prog.*, vol. 42, p. 101883, 2023, doi: <https://doi.org/10.1016/j.tsep.2023.101883>.
- [14] A. H. Al-Moubaraki and I. B. Obot, "Corrosion challenges in petroleum refinery operations: Sources, mechanisms, mitigation, and future outlook," *J. Saudi Chem. Soc.*, vol. 25, no. 12, p. 101370, 2021, doi: <https://doi.org/10.1016/j.jscs.2021.101370>.
- [15] A. A. Olajire, "Corrosion inhibition of offshore oil and gas production facilities using organic compound inhibitors - A review," *J. Mol. Liq.*, vol. 248, pp. 775–808, 2017, doi: <https://doi.org/10.1016/j.molliq.2017.10.097>.
- [16] M. Askari, M. Aliofkhaeaei, S. Ghaffari, and A. Hajizadeh, "Film former corrosion inhibitors for oil and gas pipelines - A technical review," *J. Nat. Gas Sci. Eng.*, vol. 58, pp. 92–114, 2018, doi: <https://doi.org/10.1016/j.jngse.2018.07.025>.
- [17] A. H. Alamri, "Localized corrosion and mitigation approach of steel materials used in oil and gas pipelines — An overview," *Eng. Fail. Anal.*, vol. 116, p. 104735, Oct. 2020, doi: <https://doi.org/10.1016/j.engfailanal.2020.104735>.
- [18] S. Gangopadhyay and P. A. Mahanwar, "Recent developments in the volatile corrosion inhibitor (VCI) coatings for metal: a review," *J. Coatings Technol. Res.*, vol. 15, no. 4, pp. 789–807, 2018, doi: <https://doi.org/10.1007/s11998-017-0015-6>.
- [19] Y. Tang, J. Yao, G. Wang, Z. Zhang, Y. He, and J. Jing, "Risk Identification and Quantitative Evaluation Method for Asset Integrity Management of Offshore Platform Equipment and Facilities," *Math. Probl. Eng.*, vol. 2019, no. 1, p. 1915842, Jan. 2019, doi: <https://doi.org/10.1155/2019/1915842>.
- [20] S. Ni, Y. Tang, G. Wang, L. Yang, B. Lei, and Z. Zhang, "Risk identification and quantitative assessment method of offshore platform equipment," *Energy Reports*, vol. 8, pp. 7219–7229, 2022, doi: <https://doi.org/10.1016/j.egy.2022.05.159>.
- [21] F. Guédé, "Risk-based structural integrity management for offshore jacket platforms," *Mar. Struct.*, vol. 63, pp. 444–461, 2019, doi: <https://doi.org/10.1016/j.marstruc.2018.04.004>.
- [22] P. Wang, X. Tian, T. Peng, and Y. Luo, "A review of the state-of-the-art developments in the field monitoring of offshore structures," *Ocean Eng.*, vol. 147, pp. 148–164, 2018, doi: <https://doi.org/10.1016/j.oceaneng.2017.10.014>.
- [23] R. Brijder *et al.*, "Review of corrosion monitoring and prognostics in offshore wind turbine structures: Current status and feasible approaches," *Front. Energy Res.*, vol. 10, p. 991343, 2022, doi: <https://doi.org/10.3389/fenrg.2022.991343>.
- [24] R. F. Wright, P. Lu, J. Devkota, F. Lu, M. Ziomek-Moroz, and P. R. Ohodnicki, "Corrosion Sensors for Structural Health Monitoring of Oil and Natural Gas Infrastructure: A Review," *Sensors*, vol. 19, no. 18, p. 3964, 2019, doi: <https://doi.org/10.3390/s19183964>.
- [25] X. Zhang, W. Ni, H. Liao, E. Pohl, P. Xu, and W. Zhang, "Improved condition monitoring for an FPSO system with multiple correlated components," *Measurement*, vol. 166, p. 108223, 2020, doi: <https://doi.org/10.1016/j.measurement.2020.108223>.

- <https://doi.org/10.1016/j.measurement.2020.108223>.
- [26] A. Khosravan, B. Asgarian, and H. R. Shokrgozar, "Improved Modal Strain Energy Decomposition Method for damage detection of offshore platforms using data of sensors above the water level," *Ocean Eng.*, vol. 219, p. 108337, 2021, doi: <https://doi.org/10.1016/j.oceaneng.2020.108337>.
- [27] W. Chen, C. Xiong, L. Yu, S. Lian, and Z. Ye, "Dynamic monitoring of an offshore jacket platform based on RTK-GNSS measurement by CF-CEEMDAN method," *Appl. Ocean Res.*, vol. 115, p. 102844, 2021, doi: <https://doi.org/10.1016/j.apor.2021.102844>.
- [28] M. H. Sliem *et al.*, "Monitoring of under deposit corrosion for the oil and gas industry: A review," *J. Pet. Sci. Eng.*, vol. 204, p. 108752, 2021, doi: <https://doi.org/10.1016/j.petrol.2021.108752>.
- [29] H. Ye, C. Jiang, F. Zu, and S. Li, "Design of a Structural Health Monitoring System and Performance Evaluation for a Jacket Offshore Platform in East China Sea," *Applied Sciences*, vol. 12, no. 23. p. 12021, 2022. doi: <https://doi.org/10.3390/app122312021>.
- [30] H. Pezeshki, H. Adeli, D. Pavlou, and S. C. Siriwardane, "State of the art in structural health monitoring of offshore and marine structures," *Proc. Inst. Civ. Eng. - Marit. Eng.*, vol. 176, no. 2, pp. 89–108, 2023, doi: <https://doi.org/10.1680/jmaen.2022.027>.
- [31] X. Fang, H. Wang, W. Li, G. Liu, and B. Cai, "Fatigue crack growth prediction method for offshore platform based on digital twin," *Ocean Eng.*, vol. 244, p. 110320, 2022, doi: <https://doi.org/10.1016/j.oceaneng.2021.110320>.
- [32] J. Sha, J. Leng, H. Mao, J. Pei, and K. Diao, "Research Progress in Predictive Maintenance of Offshore Platform Structures Based on Digital Twin Technology," *J. Mar. Sci. Appl.*, vol. 24, no. 5, pp. 877–899, 2025, doi: <https://doi.org/10.1007/s11804-025-00649-w>.
- [33] M. Wang, A. Incecik, S. Feng, M. K. Gupta, G. Królczyk, and Z. Li, "Damage identification of offshore jacket platforms in a digital twin framework considering optimal sensor placement," *Reliab. Eng. Syst. Saf.*, vol. 237, p. 109336, 2023, doi: <https://doi.org/10.1016/j.ress.2023.109336>.
- [34] A. Haghshenas, A. Hasan, O. Osen, and E. T. Mikalsen, "Predictive digital twin for offshore wind farms," *Energy Informatics*, vol. 6, no. 1, p. 1, 2023, doi: <https://doi.org/10.1186/s42162-023-00257-4>.
- [35] A. Hussein Khalaf *et al.*, "Emerging AI technologies for corrosion monitoring in oil and gas industry: A comprehensive review," *Eng. Fail. Anal.*, vol. 155, p. 107735, 2024, doi: <https://doi.org/10.1016/j.engfailanal.2023.107735>.
- [36] H. Ge, B. Wu, X. Li, Q. Wei, and Y. Jiang, "Enhanced digital twin framework for real-time prediction of fatigue damage on semi-submersible platforms under long-term multi-sea conditions," *Ocean Eng.*, vol. 314, p. 119696, 2024, doi: <https://doi.org/10.1016/j.oceaneng.2024.119696>.
- [37] M. J. Page *et al.*, "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews," *BMJ*, vol. 372, p. n71, Mar. 2021, doi: <https://doi.org/10.1136/bmj.n71>.
- [38] American Petroleum Institute, "API RP 686: Machinery Installation and Installation Design." American Petroleum Institute, Washington, D.C., 2009.
- [39] International Organization for Standardization, "ISO 12944-9:2018, Paints and varnishes - Corrosion protection of steel structures by protective paint systems - Part 9: Protective paint systems and laboratory performance test methods for offshore and related structures." International Organization for Standardization, Geneva, Switzerland, 2018.
- [40] International Organization for Standardization, "ISO 55000:2024, Asset management - Vocabulary, overview and principles." International Organization for Standardization, Geneva, Switzerland, 2024.
- [41] Standards Norway, "NORSOK Z-015:2020, Temporary equipment." Standards Norway, Lysaker, Norway, 2020.
- [42] DNV, "DNV-RP-F115: Pre-commissioning of Submarine Pipelines." DNV, Høvik, Norway, 2025.
- [43] A. W. Momber, M. Irmer, and T. Marquardt, "Effects of polymer hardness on the abrasive wear resistance of thick organic offshore coatings," *Prog. Org. Coatings*, vol. 146, p. 105720, 2020, doi: <https://doi.org/10.1016/j.porgcoat.2020.105720>.
- [44] L. Wan, B. Wang, M. Xie, C. Hu, and Y. Wen, "Prediction of corrosion life of nitrogen blanket casing in salt cavern gas storage," *Energy Sci. Eng.*, vol. 10, no. 8, pp. 3044–3056, Aug. 2022, doi: <https://doi.org/10.1002/ese3.1187>.
- [45] D. Iskandar, I. B. Hartawan, D. Soelistiyono, H. Soetjipto, and F. Irfan, "Pipeline Integrity Management of Unpiggable Pipelines by Corrosion Modelling and Prediction Based on Topside Piping Inspection Data in the Mature Field Offshore North West Java," *SPE Asia Pacific Oil & Gas Conference and Exhibition*. p. D013S101R007, Nov. 17, 2020. doi: 10.2118/202245-MS.
- [46] G. P. V. Dalmora, E. P. Borges Filho, A. A. Maraschin Conterato, W. S. Roso, C. E. Pereira, and A. Dettmer, "Methods of corrosion prevention for steel in marine environments: A review," *Results in Surfaces and Interfaces*, vol. 18, p. 100430, 2025, doi: <https://doi.org/10.1016/j.rsufri.2025.100430>.
- [47] Y. Wu, W. Zhao, and L. Wang, "State of the art and current trends on the metal corrosion and protection strategies in deep sea," *J. Mater. Sci. Technol.*, vol. 215, pp. 192–213, 2025, doi: <https://doi.org/10.1016/j.jmst.2024.07.026>.
- [48] A. O. Ijaola, P. K. Farayibi, and E. Asmatulu, "Superhydrophobic coatings for steel pipeline protection in oil and gas industries: A comprehensive review," *J. Nat. Gas Sci. Eng.*, vol. 83, p. 103544, 2020, doi: <https://doi.org/10.1016/j.jngse.2020.103544>.
- [49] R. Xia, C. Jia, and Y. Garbatov, "Deterioration of marine offshore structures and subsea installations subjected to severely corrosive environment: A review," *Mater. Corros.*, vol. 76, no. 6, pp. 758–775, Jun. 2025, doi: <https://doi.org/10.1002/maco.202314050>.