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A Systematic Literature Review (SLR) on Degradation Mechanism in Mechanical Components of CCS Facilities in Malaysian marine environment

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Abstract
Malaysia has committed to achieving net-zero emissions by 2050, with Carbon Capture and Storage (CCS) identified as a key strategy. However, CCS infrastructure faces heightened risks of corrosion and material degradation under the tropical marine environment. This review synthesises recent studies on degradation mechanisms, including corrosion, stress corrosion cracking, and fatigue in CCS components. Findings reveal accelerated deterioration of carbon steels, improved resistance of chromium-enriched alloys, and critical impacts of impurities in s-CO_2. Research gaps include limited tropical field data, underdeveloped predictive models, and the absence of Malaysia-specific guidelines. Addressing these issues is vital for a sustainable CCS deployment.

Keywords: Mechanical Components; Carbon Capture and Storage; Corrosion; Malaysian Marine Environment

1.0 Introduction

Malaysia has set a target to achieve net-zero Carbon emissions by 2050. It is one of the commitments outlined in the 12th Malaysia Plan (RMK-12) and reinforced by the National Energy Transition Roadmap (NTER). In Malaysia, large-scale industrial activities such as oil and gas processing and fossil-fuel power generation plants are significant contributors of carbon dioxide (CO_2). Hence, Carbon Capture and Storage (CCS) has been recognised as a critical technology for reducing emissions and contributing to the decarbonisation of the energy sector. CCS is a chain of processes in which CO_2 is captured, transported, and injected into suitable underground facilities for permanent storage (Nasir & Go, 2024). The deployment of the CCS project is anticipated to substantially reduce environmental impacts by storing an estimated 1,646 tonnes of CO_2 per day (Sukor et al., 2020). Successful implementation of this technology does not only depend on policy support and technological readiness, but also on the long-term durability of infrastructure materials exposed to harsh operating environments.

1.1 Material Degradation and Corrosion Failure

Among the primary engineering concerns in CCS systems are material degradation and corrosion-related failures. Components such as pipelines, compressors, pressure vessels, and heat exchangers are subjected to repeated thermal and mechanical loading, as well as exposure to wet CO_2 conditions and traces of impurities. These combinations can accelerate low-temperature cracking, ductile fracture, CO2 corrosion, stress corrosion cracking (SCC), and fatigue failure (Sonke et al., 2022; Pfennig et al., 2021). Recent research on galvanic corrosion in the tropical marine atmospheric environment, focusing on corrosion and failure mechanisms of galvanised steel pipe (Liu, et al., 2025). The International Energy Agency (IEA) also established guidelines for the material selection of CCS equipment in standard operating environments (International Energy Agency, 2010). However, there is limited literature that focuses specifically on the material degradation and failure of mechanical components of CCS facilities in tropical environments, particularly Malaysia. This gap indicates the need for a focused review of material behaviour, failure mechanisms, and protection strategies tailored to the Malaysian context. This paper aims to review and analyse the degradation mechanisms affecting mechanical components in Carbon Capture and Storage (CCS) facilities in the Malaysian marine environment, with particular attention to corrosion behaviour, material performance, and the need for localised engineering guidelines. The objectives of this review are: - (i) to identify types of degradation mechanisms (corrosion, stress corrosion cracking & fatigue failure), (ii) to determine how tropical environmental factors such as humidity, salinity and temperature affect the material degradation, (iii) to compare the performance of commonly used steel materials under s-CO_2 and marine conditions and (iv) to recommend the monitoring strategies and mitigation practices necessary for enhancing long-term reliability and supporting sustainable CCS operation in Malaysia.

2.0 Literature Review

2.1 Carbon Capture Storage in Malaysia

According to the National Energy Transition Roadmap (NETR), Malaysia is targeting net-zero emissions by 2050, and CCS technologies have been formally recognised as a core pillar of this transition, particularly in high-emission sectors such as power, cement, and oil & gas. Key milestones include large-scale initiatives, such as the Kasawari CCS project located offshore Sarawak, which is forecast to start up by the end of 2025 and is expected to capture an estimated 3.7 million metric tonnes of CO_2 annually (Rizal et al., 2025). Malaysia's CCUS Act, the Carbon Capture, Utilisation and Storage Bill, the recently passed legislation in 2025, has formalised the regulatory framework for licensing, monitoring, and cross-border storage infrastructure (MyCCUS, 2024). Together, these developments emphasise the strategic importance of CCS in Malaysia's decarbonisation roadmap and thus, robust mechanical system design and materials durability under tropical climate conditions are important.

2.2 Materials Selection for Carbon Capture Storage Facilities

Based on a study conducted by J. Sonke et al., there are a few key factors that have been summarised to select the material in the design of CCS infrastructure. First, the material selection must ensure that any degradation processes can be controlled and detected, while avoiding rapid deterioration mechanisms. Second, to establish and clearly define the operating envelope, including potential process upsets such as sudden pressure reductions. This is essential, as these conditions may induce the condensation of water and other corrosive liquids or cause abrupt temperature drops. Third, it is also important to determine the CO_2 stream specification, with strict limits on allowable impurities. Fourth, there should also be stringent control over CO_2 specifications, as impurities such as strong acids and elemental sulphur dropouts can cause corrosion. Fifth, corrosion-resistant alloys (CRA) materials for injection wells require special attention, particularly when oxygen is present at elevated temperatures or when injection occurs in highly saline reservoirs where brine backflow is possible. Lastly, specific attention is also required for polymer materials in contact with CO_2, as they are susceptible to rapid gas decompression and may be further compromised by impurity interactions. These factors underscore the need for stringent materials engineering practices to ensure the long-term integrity of CCS facilities (J. Sonke et al., 2022)

2.3 Degradation Mechanism of Mechanical Components in Tropical Environment

Mechanical equipment in CCS systems, such as high-pressure compressors, transport pipelines, pressure vessels, and absorption column must withstand supercritical CO_2 environments, often combined with moisture and contaminants like SO_2 and H_2S (Sukor et al., 2020). These conditions will accelerate corrosion, stress-corrosion cracking (SCC), and fatigue failures if not adequately addressed. A study conducted by Abubakar et al. (Abubakar et al., 2023) demonstrated that carbon steel pipelines exposed to CO_2 in simulated marine environments show an increasing corrosion rate as the solution temperature increases. Besides, in a warmer marine environment, the localised corrosion penetration can reach up to 30 times greater than general corrosion (Laleh, et al., 2024). This condition indicates that dissolved CO_2 will significantly worsen mechanical degradation under humid coastal conditions, which is a scenario highly relevant to Malaysia's CCS facilities.

2.4 Economic and Energy Implications of Corrosion

Corrosion is not only about the technical challenge, but also an economic burden for the energy sector. The estimated cost of corrosion is approximately 3 to 4% of global gross domestic product (GDP). Beyond economics, corrosion contributes to additional CO_2 emissions from frequent repair and replacement of materials. Iannuzzi et al. quantified the carbon footprint of steel corrosion and emphasised its indirect role in climate change (Iannuzzi et al., 2022). These findings suggest that corrosion management in CCS facilities is important not only for safety but also for ensuring sustainable energy operations.

3.0 Methodology

This study was carried out through a structured review of published research and review articles relevant to Carbon Capture and Storage (CCS) facilities operating under tropical environmental conditions. Selected articles were screened for relevance based on their focus on material degradation, corrosion mechanisms, and environmental influences on mechanical components in CCS or CO_2 service systems. The structured review method was selected because it enables consistent comparison across studies and facilitates identification of common degradation patterns and influencing factors.

3.1 Literature Search Strategy
Journals from Elsevier and MDPI were searched using targeted keywords, including *"Carbon Capture and Storage (CCS), Carbon Capture Utilisation and Storage (CCUS), material degradation, corrosion, and tropical climate."* Keywords were applied individually and in combination to ensure broad coverage. Articles published between the year 2021 and 2025 were prioritised to reflect the most recent developments related to this study. This selection strategy ensures that the review incorporates both global and region-specific insights essential for understanding CCS material challenges in the tropical marine environment.

3.2 Limitations
The analysis is limited to the scope of available published works and does not include experimental validation. Nonetheless, the structured review of existing studies provides valuable insights into material performance in CCS facilities and tropical environments, and highlights research gaps requiring further investigation.

4.0 Findings

Studies on Material Degradation of Mechanical Components in CCS/CCUS Facility in Tropical Environment are tabulated in Table 1. Focus Area, Data Collection Methods, Components, Environment Studied, Results and Key Findings are established based on the selected journal articles as reference.

Table 1. Summary of Studies on Material Degradation in Tropical Environments and CCS-Related Conditions

No.	Author(s), (Ref)	Focus Area	Data Collection Method	Components	Environment Studied	Results	Key Findings
1	Luo et al. (Luo, Wang, Zhou, Liu, & Wang, 2022)	Corrosion behavior of aluminum alloy structural materials under the combined effects of atmospheric corrosion of thin electrolyte layer and elastic cyclic stress	• Field exposure test • Electrochemical measurement • Corrosion morphology • Mechanical properties measurement	Superstructure marine equipment (7A09 Aluminum Alloy)	Tropical coastal atmosphere	• Elastic cyclic stress accelerates corrosion process of alloy • Stressed surface with shorter period exposure in tropical coastal atmosphere show larger losses in mechanical properties compared to unstressed surface after 12 months exposure	Corrosion products found on the stressed sample such as Cl, S come from the atmosphere such as rainwater, deposition of seal salt and acid rain.
2	Pfennig et al. (Pfennig, Wolf, & Kranzmann, 2021)	Steels used as pipes for CO2 transportation or injection into CCS site are prone to CO2-corrosion affected by: • Temperature and partial pressure • composition and contamination of alloy and corrosive media • flow conditions and injection pressure • protective corrosion scales	• Static corrosion experiments • Corrosion fatigue experiments	Mild steel, martensitic steel & duplex stainless steel	• Carbon capture and storage at ambient and high pressure (100 bar) • Geothermal energy production (aquifer water)	• Corrosion rates are influenced by pressure and atmosphere (vapor phase / liquid phase) • Fatigue strength failure of steels in CCS environments is mainly due to corrosion caused by carbonic acid formation instead of mechanical loading	Steel material with higher chromium (Cr) content has higher corrosion resistance.
3	Sun et al. (Du, Liu, Liu, Li, & Wu, 2021)	Traditional weathering steel undergoes significant corrosion and fails to develop a stable, protective rust	• Dry/wet cyclic test • Element composition analysis of rust layers • Electrochemical measurements	Weathering steel	Simulated tropical marine atmosphere (temperature: 40 ±1°C, humidity: 90 %)	Significant reduction in steel weight loss and rust layers with addition of Cr in the steel	Cr-containing weathering steel exhibit excellent corrosion resistance, as compactness and stability of

		layer in the harsh conditions of tropical marine atmospheres characterized by high humidity, temperature, and salinity.					rust layer are significantly improved by Cr
4	Zhang et al. (Zhang, et al., 2024)	Corrosion damage of 17-4 PH martensitic stainless steel (MSS) reached the highest level specified by ISO 9223 in tropical marine environment	• Weight change and corrosion rate • Macroscopic morphology and corrosion products analysis • Electrochemical properties of corrosion products	17-4 PH martensitic stainless steel	Tropical marine environment (average annual temp: 27 deg C; relative humidity: 82%; annual rainfall: 1600mm/year; average salt spray deposition: 3.5 mg/m2h; annual radiation: 6850 MJ/m2)	• Corrosion rate of 17-4 PH MSS peaked at the start of exposure and gradually declined over time • Corrosion processes divided into three stages: i) rapid formation and shedding of corrosion products ii) adhesion and transformation iii) significant improvement in protective properties	17-4 PH MSS exhibits superior corrosion resistance compared to conventional low-carbon steel in tropical marine environments.
5	Sun et al. (Sun, Wang, Zeng, & Liu, 2023)	Corrosion in s-CO2 transportation, storage and utilization systems.	Impurity types and contents	CO_2 transportation pipeline	Supercritical CO_2 (s-CO_2)	• In s-CO_2-rich phase, carbon steel (CS) is highly susceptible to corrosion if water and impurity levels are not strictly controlled. • Corrosivity of impurities decreases in the order: $NO_x > SO_2 > H_2S > O_2$. Oxygen significantly contributes to synergistic corrosion effects in CO_2–H_2O–O_2–SO_2–H_2S systems; therefore, its concentration should be maintained below 1000 ppm, while other impurities should remain under 100 ppm.	Opportunity for research collaboration to develop dependable machine learning model to study steels corrosion in s-CO_2 environments.
6	Craig et al. (Craig, et al., 2023)	Lack of comprehensive guidelines for the selection of suitable corrosion resistant alloys (CRAs) for CCS and CCUS projects.	• Industrial data on CRAs performance • Factors impacting CRA selection	Injection wells	Supercritical CO_2	Material of construction for the wellhead should be Class HH (CRA on fluid-wetted surfaces), for design life greater than 20 years and in the presence of impurities	• Without any impurities , S13Cr alloy was corrosion resistant. • In presence of O_2, 25Cr SDSS was preferred compared to S13Cr.
7	Tagliari et al. (Craidy, Borges, Tagliari, & Fonseca, 2021)	Stress corrosion cracking (SCC) in CO_2/H_2O environment	• Failure cases on CO_2/H_2O system • Parameters affecting CO_2 stress corrosion cracking	Carbon steels	CO_2/H_2O systems	Presence of superficial layer of corrosion products is a contributing factor to the occurrence of SCC caused by CO_2 in carbon steel.	SCC can also be influenced by high CO_2 partial pressure and presence of contaminants (H2S, CO & O2)

8	Abubakar et al. (Abubakar, Mori, & Sumner, 2023)	Corrosion behavior of pipeline steels under applied stress prior to failure in CO_2-saturated marine environments	• C-Ring Loading Test • Exposure Analysis	API 5L X70 & X100 Carbon steel	Saltwater with saturated CO2	• Corrosion rates increase along the increase in temperature • Alloy with higher tensile strength (X100) has faster corrosion rate	Solution temperature, carbon steel microstructure, trace gases, and applied stress levels directly influence the corrosion morphology and initiation of cracks in exposed carbon steel.
9	Pongsaksawad et al. (Pongsaksawad , et al., 2021)	Accuracy of corrosion rate prediction along coastal area based on factors influencing chloride distribution	• Chloride ion deposition rate monitoring • Wind data • GIS corrosion map	AS11 column	Coastal area in Thailand	Rate of chloride deposition declines exponentially as the distance from the coastline increases, with sea winds significantly contributing to the inland transport of chloride.	Relationship between chloride deposition rate and run of wind can be utilized to estimate chloride deposition rate at seashore.
10	Yang et al. (Yang, et al., 2025)	Limitations of current atmospheric corrosion classification approaches, stem from their dependence on long-term averages and static datasets.	• Dynamic evaluation by Pearson correlation coefficient • Machine learning	Carbon steel	Marine atmospheric environment in China	• Temperature, humidity, wind speed, and wind direction are recognized as primary factors influencing corrosion severity. • Humidity being the most significant, which elevated humidity levels are essential for increased corrosion intensity	The proposed dynamic classification method effectively tracks changes in corrosion levels and differentiates environmental corrosivity between various locations

5.0 Discussion

The studies reviewed demonstrate that material degradation in CCS facilities is not the result of a single factor, but a complex interaction influenced by environmental conditions, material composition, and operational parameters. Although most of the existing research focuses on general corrosion and stress corrosion cracking in marine or CO_2-rich systems, the findings collectively revealed critical implications regarding infrastructure exposure in tropical climates.

5.1 Corrosion in Marine and Tropical Environments

Mechanical components fabricated from carbon steels and conventional alloys are highly susceptible to corrosion when exposed to tropical marine environments. Elevated temperatures, high humidity, and chloride-rich coastal atmosphere significantly accelerate corrosion rates, often resulting in rapid deterioration of protective oxide films, particularly in steels with lower chromium content. Steels with higher chromium content display superior resistance, as confirmed by Pfennig et al. and Sun et al., who reported that chromium-enriched weathering steels offer better protection through more stable and compact rust layers (Pfennig et al., 2021; Sun et al., 2023). This suggests that while conventional steels may remain viable in temperate climates, they are less suitable for tropical CCS infrastructure, reinforcing the application of alloy material in high-chloride and high-humidity regions.

5.2 Corrosion and Stress Corrosion Cracking in CO_2 Systems

Stress corrosion cracking (SCC) is one of the critical degradation mechanisms in CO_2 transport and storage systems. A study by Tagliari et al. and Abubakar et al. demonstrates that SCC initiation and propagation depend strongly on microstructural features of carbon steel, applied or residual stress, and solution temperature. These studies highlight that the risk is magnified when CO_2 coexists with impurities such as H_2S and O_2 (Craidy et al., 2021; Abubakar et al., 2023). The presence of H_2S and O_2 compounds will cause acid corrosion and sour corrosion (Asmara & Ma'arof, 2022). In s-CO_2 transport systems, impurity control is important. Sun et al. showed that impurity concentration exceeding 100 ppm can significantly reduce the service life of carbon steels in s-CO_2 environments (Sun et al., 2023). Taken together, these results emphasise that strict impurity control and stress management are indispensable for the safe operation of Malaysian CCS transport systems, where high ambient temperatures could further amplify SCC susceptibility.

5.3 Environmental Influences and Approaches

Environmental factors play a decisive role in shaping corrosion severity. In a coastal monitoring study conducted by Pongsaksawad et al, chloride deposition rates decrease with distance from the sea, but are strongly influenced by wind direction and speed (Pongsaksawad et al., 2021). From a geographical perspective, in Malaysia, monsoonal wind patterns drive significant chloride transport inland. This has implications for offshore and near-shore CCS infrastructure. Moreover, Yang et al. introduced a dynamic corrosion classification method using machine learning and real-time environmental variables, offering a significant improvement in overcoming limitations of traditional long-term average-based models (Yang et al., 2025). This predictive framework indicates an important step towards integrating predictive maintenance strategies tailored to tropical conditions.

5.4 Unresolved Issues

Despite these valuable insights, the reviewed literature highlights several unresolved issues. First, there are inadequate international guidelines for tropical climates, as the existing ones are mostly based on data from temperate or controlled environments. Second, there are limited numbers of long-term field studies in tropical CCS settings, particularly those examining advanced alloys under combined marine environment and s-CO_2 exposure. Third, predictive models remain underdeveloped, with limited integration of real-time climate variables such as humidity fluctuations, chloride deposition, and monsoonal wind effects. Finally, Malaysia currently lacks localised standards and design practices that consider the unique degradation drivers of its tropical climate. Addressing these gaps will require region-specific corrosion-monitoring frameworks, extended field-exposure programs, and the integration of machine learning with sensor networks to better model and mitigate degradation risks.

6.0 Conclusion & Recommendation

The successful deployment of CCS in Malaysia does not only depends on technological readiness but also on the integrity and durability of its mechanical components under tropical environmental stressors. This review shows that high humidity, saline exposure, and fluctuating temperatures significantly intensify corrosion and degradation processes. While chromium-alloyed steels and stainless steels demonstrate superior resistance, the presence of impurities in s-CO_2 systems must be strictly controlled to mitigate stress corrosion cracking and accelerated corrosion. There is a concerning need for Malaysia-specific guidelines for material selection, corrosion monitoring, and maintenance strategies. In addition, predictive models that integrate environmental dynamics with machine learning hold great potential to extend component lifecycles and enhance infrastructure reliability. Advancing these areas through targeted research and policy will be essential to ensure safe and long-term deployment of CCS and to support Malaysia's broader transition to a low-carbon future. Future research should focus on conducting long-term field studies under Malaysia's tropical marine conditions to validate material performance data obtained from international sources. Malaysia's first large-scale offshore development, the Kasawari CCS project, presents a valuable opportunity to serve as a pilot site for such field-based investigations. The integration of real-time corrosion monitoring and machine learning techniques within this operational environment is also recommended to improve predictive accuracy. Furthermore, developing Malaysia-specific standards and design guidelines based on findings from the Kasawari CCS pilot study will strengthen the reliability and applicability of future CCS infrastructure in Malaysia. These directions will serve as a foundation for future interdisciplinary research that combines materials engineering, data science, and environmental studies to advance Malaysia's CCS reliability and sustainability.

Paper Contribution to Related Field of Study

This paper contributes to the field of environmental energy and materials engineering by consolidating current knowledge on degradation mechanisms in CCS infrastructure under tropical climatic conditions representative of Malaysia. Although limited local data are available, the tropical marine parameters investigated in regional and international studies, such as high humidity, salinity, and temperature fluctuations, closely resemble those of Malaysia's coastal environment. By synthesising these comparable findings, this paper provides insights that are directly applicable to Malaysia's emerging CCS projects, including the Kasawari CCS development. The study therefore establishes a valuable foundation for developing Malaysia specific guidelines, predictive models, and durability standards, supporting the nation's transition toward sustainable energy and its net-zero emissions goal.

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