International Journal of Multidisciplinary and Innovative Research

ISSN(print): 3050-6883, ISSN(online): 3050-6891

Volume 03 Issue 08 August 2026

DOI: 10.58806/ijmir.2026.v3i8n08

Page No: 698-709

Study of Corrosion Deterioration in Industrial Machinery and Equipment: A Comprehensive Review

T. M. S. A. Hossain[1], A. K. Saad[2], I. M. Santo[3], M. Hossain[4], M. S. Islam[5]

[1]Department of Automobile Engineering (AE), World University of Bangladesh (WUB), Dhaka-1230, Bangladesh

[2,3,4,5]Department of Mechanical Engineering (ME), World University of Bangladesh (WUB), Dhaka-1230, Bangladesh

ABSTRACT

Corrosion deterioration is one of the most significant challenges affecting the reliability, safety, and service life of industrial machinery and equipment. It causes gradual degradation of metallic materials through chemical and electrochemical reactions with the surrounding environment, leading to equipment failure, production losses, increased maintenance costs, and safety hazards. Corrosion affects a wide range of industries, including manufacturing, oil and gas, power generation, chemical processing, marine engineering, mining, transportation, and infrastructure. Traditional corrosion management relies on periodic inspections, protective coatings, cathodic protection, and corrosion inhibitors. However, the emergence of Industry 4.0 technologies has introduced intelligent corrosion monitoring systems that integrate sensors, the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), Digital Twins, robotics, and predictive analytics for real-time corrosion assessment and maintenance planning. This review comprehensively discusses corrosion mechanisms, types of corrosion, influencing factors, conventional corrosion assessment techniques, modern monitoring technologies, corrosion prevention and control strategies, industrial applications, current challenges, and future research directions. The review highlights the importance of integrating advanced sensing technologies with intelligent maintenance systems to improve equipment reliability, reduce operational costs, and achieve sustainable industrial asset management.

KEYWORDS: Corrosion, Industrial Machinery, Corrosion Monitoring, Predictive Maintenance, Industry 4.0, IoT, Artificial Intelligence, Digital Twin, Corrosion Protection, Structural Health Monitoring.

ARTICLE DETAILS

Published On:
21 August 2026

Available on:
https://ijmir.com

1. INTRODUCTION

Corrosion is one of the most serious forms of material deterioration affecting industrial machinery, equipment, and infrastructure worldwide. It is a naturally occurring electrochemical or chemical process through which metals and alloys gradually degrade when exposed to aggressive environmental conditions such as moisture, oxygen, salts, acids, alkalis, and industrial pollutants [1-4]. This degradation reduces the mechanical strength, structural integrity, and operational efficiency of industrial components, often leading to equipment failure, production interruptions, environmental contamination, and safety hazards [2], [3]. Corrosion is particularly prevalent in industries such as oil and gas, chemical processing, manufacturing, power generation, marine engineering, mining, transportation, aerospace, and water treatment, where equipment operates under harsh environmental and operating conditions [1], [4], [5]. Consequently, effective corrosion management has become a critical aspect of industrial asset integrity, maintenance engineering, and occupational safety [5], [6].

1.1 Background of Industrial Corrosion: Industrial corrosion is the gradual deterioration of metallic materials caused by chemical or electrochemical reactions between the material and its surrounding environment [1], [2]. Unlike mechanical wear, corrosion progressively weakens the internal and external surfaces of components, reducing their load-bearing capacity and service life. The corrosion process is influenced by several factors, including humidity, temperature, pH, dissolved oxygen, chloride ions, chemical contaminants, mechanical stress, and microbial activity [2], [4]. Depending on environmental conditions and material composition, corrosion may occur uniformly across a surface or locally in highly concentrated areas, resulting in severe damage that may remain undetected until catastrophic failure occurs. Industrial machinery and equipment are continuously exposed to corrosive environments. Pipelines transport corrosive fluids and gases under high pressure, boilers and heat exchangers operate at elevated temperatures, offshore structures remain exposed to seawater, and manufacturing equipment encounters moisture, lubricants, and industrial chemicals. These operating conditions accelerate corrosion processes and increase maintenance requirements. Therefore, understanding corrosion mechanisms and implementing effective monitoring and protection strategies are essential for maintaining equipment reliability and ensuring uninterrupted industrial operations [3], [5], [7].

1.2 Global Economic Impact of Corrosion: Corrosion imposes a substantial economic burden on industries and national economies. According to the World Corrosion Organization (WCO) and studies conducted by NACE International (now AMPP), the global cost of corrosion is estimated to exceed US$2.5 trillion annually, representing approximately 3–4% of the world's Gross Domestic Product (GDP) [6], [8]. These costs include direct expenses such as equipment replacement, maintenance, protective coatings, corrosion inhibitors, and inspection, as well as indirect losses resulting from production downtime, environmental remediation, reduced operational efficiency, energy losses, and accident-related damages. Many corrosion-related failures are preventable through appropriate design, material selection, preventive maintenance, and corrosion monitoring. Studies suggest that implementing effective corrosion management strategies can reduce corrosion-related costs by 15–35%, generating significant economic benefits while improving equipment reliability and sustainability [6], [8]. As industrial systems become increasingly complex, minimizing corrosion-related losses has become a major priority for asset management and maintenance engineers.

1.3 Corrosion-Related Equipment Failures: Corrosion is one of the leading causes of equipment deterioration and unexpected failures in industrial facilities [1], [3]. Continuous corrosion weakens structural components, reduces wall thickness, initiates cracks, and accelerates fatigue damage, eventually leading to leakage, rupture, collapse, or complete equipment failure [2], [5]. Corrosion-related failures have been responsible for numerous industrial accidents involving pipelines, pressure vessels, storage tanks, offshore platforms, bridges, boilers, and heat exchangers [4], [7]. In the oil and gas industry, internal corrosion can cause pipeline leaks, resulting in hydrocarbon spills, environmental pollution, and fire hazards. In power plants, corrosion of boilers, condensers, and steam turbines reduces thermal efficiency and increases maintenance frequency. Chemical processing plants frequently experience corrosion of reactors, valves, and piping systems due to exposure to aggressive chemicals. Similarly, marine structures are highly susceptible to seawater corrosion, while automotive and aerospace components may experience corrosion fatigue that compromises structural integrity and passenger safety [3], [5], [9]. Beyond economic losses, corrosion-related failures may endanger human life, damage ecosystems, interrupt industrial production, and reduce the overall reliability of critical infrastructure. Consequently, early detection and effective corrosion control are essential for ensuring safe and sustainable industrial operations [6], [10].1.4 Need for Corrosion Monitoring: Traditional corrosion management has primarily relied on periodic visual inspections, thickness measurements, corrosion coupons, and non-destructive testing (NDT) techniques. Although these approaches remain widely used, they are often labor-intensive, time-consuming, and incapable of providing continuous information about corrosion progression. Since corrosion develops gradually and often occurs in inaccessible locations, periodic inspections may fail to identify deterioration before significant damage has occurred.

1.4 Need for Corrosion Monitoring: Continuous corrosion monitoring provides real-time information regarding corrosion rates, environmental conditions, material degradation, and structural health. Modern monitoring systems utilize electrochemical sensors, ultrasonic sensors, fiber-optic sensors, wireless sensor networks, and environmental monitoring devices to detect early signs of corrosion [11]–[15]. These systems enable maintenance personnel to identify potential failures before they become critical, allowing preventive maintenance to be scheduled efficiently. Effective corrosion monitoring offers several important advantages, including [12], [16]:

1. Early detection of corrosion damage.
2. Improved equipment reliability and operational safety.
3. Reduced maintenance and repair costs.
4. Extended service life of industrial assets.
5. Prevention of catastrophic failures and environmental pollution.
6. Support for predictive maintenance and asset integrity management.
7. Improved regulatory compliance and workplace safety.

As industries increasingly adopt predictive maintenance strategies, corrosion monitoring has become an essential component of intelligent industrial maintenance systems [13], [17].

1.5 Industry 4.0 and Smart Maintenance: The emergence of Industry 4.0 has fundamentally transformed corrosion monitoring and maintenance practices by integrating digital technologies with industrial equipment. Industry 4.0 incorporates Cyber-Physical Systems (CPS), the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), cloud computing, edge computing, Digital Twins, robotics, and advanced sensor technologies to create intelligent maintenance systems capable of continuously monitoring equipment health [18-22]. IoT-enabled corrosion sensors continuously collect data related to temperature, humidity, pH, chloride concentration, corrosion potential, wall thickness, and structural vibration. These data are transmitted through industrial communication networks to cloud or edge computing platforms, where AI and machine learning algorithms analyze equipment conditions and predict future corrosion progression [13], [18], [20]. Computer vision systems inspect structural surfaces using cameras and deep learning models, while drones and autonomous robots inspect hazardous or inaccessible locations without interrupting industrial operations [21], [23].

Digital Twin technology further enhances corrosion management by creating virtual replicas of industrial equipment that continuously synchronize with real-world operating conditions. Engineers can simulate corrosion behavior, evaluate maintenance strategies, estimate Remaining Useful Life (RUL), and optimize inspection intervals without affecting actual production processes [19], [22], [24].

The integration of Industry 4.0 technologies enables industries to transition from traditional time-based maintenance toward Condition-Based Maintenance (CBM) and Predictive Maintenance (PdM), significantly improving equipment availability, reducing operational costs, and enhancing industrial safety [9], [18], [24].

1.6 Scope and Objectives of the Review: This review provides a comprehensive overview of corrosion deterioration in industrial machinery and equipment by examining conventional corrosion mechanisms, modern monitoring technologies, prevention strategies, and emerging research trends. The review covers the major types of corrosion affecting industrial equipment, factors influencing corrosion behavior, conventional inspection methods, intelligent corrosion monitoring technologies, predictive maintenance approaches, industrial applications, current challenges, and future research directions [1], [3], [11], [20]. The primary objectives of this review are to:

1. Explain the fundamental mechanisms and types of industrial corrosion.
2. Review conventional corrosion inspection and assessment techniques.
3. Discuss recent advances in IoT-, AI-, and Digital Twin-based corrosion monitoring systems.
4. Evaluate corrosion prevention and protection technologies.
5. Examine predictive maintenance strategies for corrosion management.
6. Summarize industrial applications across multiple engineering sectors.
7. Identify current research challenges and technological limitations.
8. Highlight future research opportunities for intelligent, autonomous, and sustainable corrosion management systems.

By integrating knowledge from corrosion science, materials engineering, industrial automation, artificial intelligence, and predictive maintenance, this review aims to provide researchers, engineers, asset managers, and industry professionals with a comprehensive understanding of modern corrosion management technologies and their role in improving equipment reliability, operational safety, and sustainable industrial development [9], [18-24].

2. FUNDAMENTALS OF CORROSION

Corrosion is the gradual deterioration of metals and alloys caused by chemical or electrochemical reactions with the surrounding environment. It is a major cause of equipment degradation, structural failure, increased maintenance costs, production downtime, and safety risks in industries such as manufacturing, oil and gas, power generation, chemical processing, marine engineering, and mining [1-4]. Understanding the basic principles of corrosion is essential for effective material selection, corrosion prevention, condition monitoring, and maintenance planning [2], [5].

2.1 Definition of Corrosion: Corrosion is the natural process by which metals deteriorate when exposed to environmental factors such as moisture, oxygen, chemicals, and pollutants. It reduces the mechanical strength, durability, and service life of industrial machinery, equipment, and infrastructure, resulting in economic losses and increased safety risks [1], [2], [6].

2.2 Electrochemical Mechanism of Corrosion: Most corrosion occurs through electrochemical reactions involving anodic oxidation and cathodic reduction. At the anode, metal atoms lose electrons and dissolve into the surrounding environment, while reduction reactions occur at the cathode. The presence of an electrolyte and an electrical pathway allows these reactions to continue, leading to the formation of corrosion products such as rust on steel surfaces [2], [3], [7]. The rate of corrosion depends on factors including electrolyte conductivity, oxygen concentration, temperature, and the electrochemical properties of the metal [1], [4].

2.3 Corrosion Cell Formation: A corrosion cell consists of four essential components: an anode, where metal dissolution occurs; a cathode, where reduction reactions take place; an electrolyte, which enables ion movement; and an electrical path, which allows electron flow between anodic and cathodic regions. The interaction of these components drives the continuous corrosion process and determines the corrosion rate under different environmental conditions [2], [5], [8].

2.4 Factors Affecting Corrosion

1. Several environmental and operational factors significantly influence corrosion rates and mechanisms [1], [4], [9]:
2. Moisture: Provides the electrolyte required for electrochemical reactions.
3. Oxygen: Accelerates oxidation and rust formation on metal surfaces.
4. Temperature: Higher temperatures generally increase corrosion rates by accelerating chemical reactions.

5. pH: Acidic environments promote faster metal dissolution and increase corrosion severity.
6. Salinity: Chloride ions increase electrical conductivity and promote localized corrosion such as pitting.
7. Mechanical Stress: Contributes to stress corrosion cracking (SCC) and corrosion fatigue.
8. Pollutants: Industrial gases and chemicals, such as sulfur dioxide and carbon dioxide, accelerate material degradation.
9. Microorganisms: Certain bacteria and fungi cause Microbiologically Influenced Corrosion (MIC), particularly in pipelines, storage tanks, and marine environments [3], [10].

3. CORROSION DETERIORATION IN INDUSTRIAL MACHINERY

Corrosion deterioration is a major cause of reduced performance, equipment failure, increased maintenance costs, and safety hazards across various industrial sectors. Continuous exposure to moisture, chemicals, high temperatures, abrasive materials, and corrosive environments accelerates the degradation of industrial machinery and components. Different industries experience distinct corrosion mechanisms depending on their operating conditions, materials, and environmental exposure [1-4]. Understanding corrosion behavior in different industrial applications is essential for implementing effective inspection, monitoring, and protection strategies that improve equipment reliability and service life [5], [6].

3.1 Manufacturing Equipment: Manufacturing equipment such as Computer Numerical Control (CNC) machines, hydraulic presses, and conveyor systems is exposed to lubricants, coolants, humidity, and metallic particles that promote corrosion [2], [7]. Corrosion can reduce machining accuracy, damage structural components, increase friction, and shorten equipment life. Components such as machine beds, guide rails, bearings, and conveyor rollers are particularly vulnerable to moisture-induced corrosion. Regular lubrication, corrosion-resistant coatings, scheduled maintenance, and condition monitoring systems help minimize corrosion-related failures and improve manufacturing efficiency [7], [8].

3.2 Oil and Gas Equipment: The oil and gas industry are highly susceptible to corrosion due to exposure to water, carbon dioxide (CO_2), hydrogen sulfide (H_2S), chlorides, high-pressure fluids, and harsh offshore environments [3], [9].

1. Pipelines: Internal and external corrosion may cause leaks, ruptures, environmental pollution, and significant economic losses.
2. Pressure Vessels: Corrosion reduces wall thickness and structural integrity, increasing the risk of catastrophic failure.
3. Storage Tanks: Corrosion affects tank bottoms, roofs, and sidewalls, resulting in product leakage and contamination.
4. Offshore Platforms: Continuous exposure to seawater, salt spray, and marine atmospheres accelerates corrosion of structural components.
5. To mitigate these risks, industries employ corrosion monitoring systems, cathodic protection, corrosion inhibitors, and protective coatings to extend equipment life and maintain asset integrity [9-11].

3.3 Power Plants: Power generation equipment operates under high temperatures and pressures, making corrosion one of the major maintenance challenges [2], [12].

1. Boilers: High-temperature oxidation, water-side corrosion, and scaling reduce thermal efficiency.
2. Heat Exchangers: Corrosion and fouling decrease heat transfer performance and increase energy consumption.
3. Steam Turbines: Moisture, dissolved oxygen, and steam impurities cause corrosion and erosion of turbine blades.
4. Cooling Towers: Continuous water circulation promotes scaling, microbiological growth, and corrosion.
5. Advanced water treatment, corrosion inhibitors, and online corrosion monitoring systems improve equipment reliability, operational efficiency, and plant safety [12], [13].

3.4 Chemical Industries: Chemical processing equipment is continuously exposed to aggressive acids, alkalis, solvents, oxidizing agents, and other reactive chemicals, making corrosion a major operational concern [1], [5].

1. Reactors: Corrosion reduces process efficiency, contaminates products, and weakens structural integrity.
2. Pumps: Chemical attack causes impeller degradation, seal failures, and reduced pumping efficiency.
3. Valves: Corrosion results in leakage, poor flow control, and increased maintenance requirements.
4. The use of corrosion-resistant alloys, protective linings, corrosion inhibitors, and continuous monitoring systems is essential for ensuring safe and reliable operation in chemical industries [5], [14].

3.5 Marine Industry: Marine environments are among the most corrosive due to continuous exposure to seawater, high humidity, dissolved oxygen, and chloride ions [2], [15].

1. Ships: Hull corrosion increases maintenance costs, structural deterioration, and fuel consumption.
2. Propellers: Cavitation and seawater corrosion reduce propulsion efficiency and component lifespan.
3. Offshore Structures: Long-term marine exposure weakens structural members and shortens service life.
4. Protective coatings, cathodic protection systems, corrosion-resistant alloys, and regular underwater inspections are widely used to mitigate marine corrosion [15], [16].

3.6 Mining Equipment: Mining machinery operates under highly abrasive, humid, and chemically aggressive conditions that accelerate corrosion and wear [4], [17].

1. Crushers: Simultaneous abrasion and corrosion reduce equipment durability.
2. Excavators: Structural components experience corrosion due to moisture, mud, and harsh environmental conditions.
3. Slurry Pipelines: Corrosive slurry combined with erosion accelerates pipeline degradation and increases maintenance costs.
4. Regular inspections, wear-resistant materials, protective coatings, and corrosion protection systems improve equipment longevity and operational reliability [17], [18].

3.7 Automotive Industry: Automotive components are exposed to moisture, road salts, pollutants, temperature variations, and atmospheric contaminants that promote corrosion throughout their service life [2], [19].

1. Engines: Cooling systems and engine components may corrode because of coolant degradation and chemical reactions.
2. Chassis: Continuous exposure to water and de-icing salts causes structural corrosion.
3. Brake Systems: Corrosion affects brake discs, calipers, and hydraulic components, reducing braking performance and safety.
4. Exhaust Systems: High temperatures and corrosive exhaust gases accelerate oxidation and material deterioration.
5. To improve vehicle durability, manufacturers widely employ galvanized steel, stainless steel, corrosion-resistant alloys, advanced surface coatings, and cathodic electrocoating technologies [19], [20].

4. CONVENTIONAL CORROSION INSPECTION TECHNIQUES

Conventional corrosion inspection techniques are widely used to detect, evaluate, and monitor corrosion damage in industrial machinery and equipment. These methods help assess material degradation, ensure structural integrity, and support preventive maintenance. Although modern smart monitoring technologies provide continuous condition assessment, conventional inspection methods remain essential for routine maintenance, regulatory compliance, and non-destructive testing (NDT) [1-3]. Each inspection technique has specific advantages and limitations depending on the type of material, corrosion mechanism, and operating environment [4], [5].

4.1 Visual Inspection: Visual inspection is the simplest and most commonly used method for identifying visible signs of corrosion, including rust, pitting, discoloration, coating deterioration, cracks, and leakage [2], [6]. It is inexpensive, easy to perform, and suitable for routine maintenance inspections without requiring sophisticated equipment. However, visual inspection is limited to surface observations and cannot detect hidden, internal, or subsurface corrosion, making it necessary to combine it with other non-destructive testing methods for comprehensive assessment [5], [7].

4.2 Ultrasonic Testing (UT): Ultrasonic Testing (UT) uses high-frequency sound waves to measure material thickness and detect internal corrosion, wall thinning, cracks, and other structural defects [3], [8]. The reflected ultrasonic waves are analyzed to determine the remaining wall thickness and identify areas affected by corrosion. UT is widely used for inspecting pipelines, pressure vessels, storage tanks, boilers, and heat exchangers because of its high accuracy, rapid measurement capability, and non-destructive nature [8], [9].

4.3 Radiographic Testing (RT): Radiographic Testing (RT) employs X-rays or gamma rays to examine the internal structure of industrial components and detect hidden corrosion, cracks, voids, and weld defects [2], [5]. The resulting radiographic images provide detailed information about internal damage without dismantling equipment. RT offers high inspection accuracy but requires specialized equipment, trained personnel, and strict radiation safety procedures, making it relatively expensive compared with other inspection techniques [5], [10].

4.4 Eddy Current Testing (ECT): Eddy Current Testing (ECT) is an electromagnetic inspection technique used to identify surface and near-surface defects in electrically conductive materials [4], [9]. Alternating magnetic fields induce eddy currents within the material, and changes in these currents indicate the presence of corrosion, cracks, or material discontinuities. ECT provides rapid, highly sensitive inspections and is widely used in aerospace, power generation, and heat exchanger tube inspections. However, its application is limited to conductive materials [9], [11].

4.5 Magnetic Particle Inspection (MPI): Magnetic Particle Inspection (MPI) detects surface and near-surface cracks in ferromagnetic materials by magnetizing the component and applying fine magnetic particles that accumulate at defect locations [3], [6]. It is particularly effective for inspecting welds, shafts, gears, pipelines, and structural components. MPI is simple, fast, and highly reliable but cannot be used for non-ferromagnetic materials such as aluminum or stainless steel [6], [12].

4.6 Dye Penetrant Testing (DPT): Dye Penetrant Testing (DPT), also known as Liquid Penetrant Testing (LPT), identifies surface-breaking defects by applying a colored or fluorescent liquid penetrant that enters small cracks through capillary action [2], [7]. After removing excess penetrant and applying a developer, defects become clearly visible. DPT is inexpensive, simple, and highly effective for detecting fine surface flaws in metallic and non-metallic materials; however, it cannot detect internal defects [7], [10].

4.7 Electrochemical Testing: Electrochemical testing evaluates corrosion behavior by measuring electrical parameters such as corrosion potential, polarization resistance, electrochemical impedance, and corrosion current density [1], [13]. These techniques provide quantitative information on corrosion rates and the effectiveness of protective coatings, corrosion inhibitors, and cathodic protection systems. Electrochemical testing is widely used in laboratories and industrial corrosion monitoring applications [13], [14].

4.8 Corrosion Coupons: Corrosion coupons are standardized metal specimens placed in corrosive environments to determine corrosion rates through weight-loss measurements after a specified exposure period [4], [14]. They provide reliable long-term corrosion data and are extensively used in pipelines, cooling water systems, offshore facilities, and chemical processing plants. Although corrosion coupons are simple and inexpensive, they do not provide continuous real-time corrosion monitoring [14], [15].

4.9 Thickness Measurement: Thickness measurement employs ultrasonic thickness gauges or similar instruments to monitor wall thinning caused by corrosion and erosion [3], [8]. Periodic thickness measurements help evaluate equipment condition, estimate the remaining service life, identify critical deterioration areas, and support maintenance planning. This technique is widely applied to pipelines, pressure vessels, storage tanks, boilers, and heat exchangers because of its accuracy, portability, and ease of use [8], [15].

5. INTELLIGENT CORROSION MONITORING TECHNOLOGIES

Intelligent corrosion monitoring technologies have transformed corrosion management by enabling continuous monitoring, real-time data acquisition, predictive analysis, and automated maintenance decision-making. Unlike conventional inspection methods, these technologies utilize advanced sensors, communication networks, Artificial Intelligence (AI), Machine Learning (ML), Digital Twins, robotics, and cloud computing to detect corrosion at an early stage, predict future deterioration, and optimize maintenance strategies. They play a vital role in Industry 4.0 by improving equipment reliability, reducing maintenance costs, minimizing downtime, and enhancing industrial safety [16-20].

5.1 Internet of Things (IoT): The Internet of Things (IoT) connects corrosion sensors, industrial equipment, and monitoring systems through wired or wireless communication networks, enabling continuous collection and transmission of corrosion-related data [16], [18]. IoT systems monitor parameters such as temperature, humidity, pH, chloride concentration, corrosion potential, wall thickness, vibration, and environmental conditions in real time. The collected data are transmitted to edge or cloud platforms for analysis, allowing remote supervision, early corrosion detection, and predictive maintenance. IoT-based corrosion monitoring significantly improves asset reliability while reducing inspection frequency and maintenance costs [16], [19], [21].

5.2 Wireless Corrosion Sensors: Wireless corrosion sensors continuously monitor corrosion rates and environmental conditions without requiring extensive wiring or manual inspections [17], [22]. These sensors are widely deployed in pipelines, storage tanks, offshore platforms, bridges, and other remote or inaccessible industrial facilities where conventional inspection is difficult. Wireless monitoring systems offer low installation costs, scalability, and continuous corrosion assessment, making them highly suitable for modern industrial asset management [17], [22].

5.3 Fiber Optic Sensors: Fiber optic sensors detect corrosion-related changes by measuring variations in light transmission caused by strain, temperature, pressure, or chemical exposure [18], [23]. They provide high sensitivity, long-distance monitoring capability, immunity to electromagnetic interference, and excellent durability under harsh industrial conditions. Fiber optic sensing technology is increasingly used for structural health monitoring of pipelines, offshore platforms, bridges, pressure vessels, and other critical infrastructure [18], [23].

5.4 Electrochemical Sensors: Electrochemical sensors measure corrosion potential, corrosion current density, polarization resistance, and other electrochemical parameters to evaluate corrosion activity in real time [13], [24]. These sensors provide quantitative information about corrosion rates and coating performance, making them widely applicable in chemical processing plants, oil and gas facilities, marine structures, and water treatment systems. Continuous electrochemical monitoring enables early identification of corrosion initiation and supports timely maintenance interventions [13], [24].

5.5 Artificial Intelligence (AI): Artificial Intelligence (AI) analyzes large volumes of corrosion data obtained from sensors, inspection reports, and operational databases to identify complex corrosion patterns, predict equipment degradation, and support intelligent maintenance decisions [1], [19], [25]. AI algorithms improve corrosion diagnosis, risk assessment, predictive maintenance, and failure prediction by automating the interpretation of large-scale industrial datasets. The integration of AI significantly enhances maintenance efficiency and reduces unexpected equipment failures [1], [19], [25].

5.6 Machine Learning (ML): Machine Learning (ML) algorithms learn from historical inspection records and real-time operational data to predict corrosion rates, estimate Remaining Useful Life (RUL), and optimize maintenance schedules [2], [20], [26]. ML techniques such as Random Forest, Support Vector Machines (SVM), Artificial Neural Networks (ANN), and XGBoost identify hidden relationships between operating conditions and corrosion behavior, enabling industries to transition from reactive maintenance to predictive maintenance [20], [26].

5.7 Deep Learning: Deep Learning utilizes multi-layer neural networks to automatically extract complex features from corrosion images and sensor data [1], [27]. Convolutional Neural Networks (CNNs) and transformer-based architectures are particularly effective for detecting corrosion defects, classifying corrosion severity, segmenting damaged regions, and analyzing large-scale inspection datasets with high accuracy. Deep learning reduces manual inspection effort while improving inspection consistency and reliability [1], [27].

5.8 Computer Vision: Computer vision combines digital imaging systems with advanced image-processing and deep learning algorithms to automatically detect rust, pitting, cracks, coating degradation, and other surface defects [19], [28]. Object detection models such as YOLO, Faster R-CNN, Mask R-CNN, and SSD enable rapid, accurate, and non-contact corrosion inspection in industrial facilities. Computer vision systems improve inspection efficiency while reducing dependence on manual visual inspections [19], [28].

5.9 Digital Twin: A Digital Twin is a virtual representation of physical equipment that continuously updates using real-time operational and corrosion monitoring data [3], [20], [29]. Digital Twins enable corrosion simulation, structural condition assessment, Remaining Useful Life (RUL) prediction, maintenance optimization, and risk evaluation without interrupting industrial operations. By integrating IoT, AI, and predictive analytics, Digital Twins support intelligent asset management and improve maintenance decision-making [3], [20], [29].

5.10 Robotics and Drones: Autonomous robots and unmanned aerial vehicles (UAVs or drones) perform automated corrosion inspections in hazardous, elevated, underwater, offshore, or confined environments where human access is difficult or unsafe [18], [30]. Equipped with cameras, ultrasonic sensors, thermal imaging systems, LiDAR, and AI-based inspection algorithms, these platforms improve inspection accuracy, reduce worker exposure to hazardous conditions, and significantly increase inspection efficiency [18], [30].

5.11 Edge Computing: Edge computing processes corrosion monitoring data close to the sensor or industrial equipment instead of relying entirely on centralized cloud servers [20], [26]. Local data processing minimizes communication delays, reduces bandwidth requirements, and enables rapid corrosion detection and real-time decision-making for safety-critical industrial applications. Edge AI further enhances corrosion monitoring by supporting intelligent analysis directly at the device level [20], [26].

5.12 Cloud-Based Monitoring: Cloud-based monitoring platforms store, process, and analyze large volumes of corrosion data collected from multiple industrial assets and facilities [16], [21]. These platforms facilitate remote monitoring, predictive analytics, historical data management, digital dashboards, and collaborative decision-making among maintenance engineers and asset managers. Cloud computing provides scalable storage, high computational capability, and seamless integration with AI, IoT, and Digital Twin technologies, making it a key component of smart corrosion management systems [16], [21], [29].

6. CORROSION PREVENTION AND PROTECTION METHODS

Corrosion Prevention and Protection Methods: Corrosion prevention and protection methods are essential for extending the service life of industrial machinery and equipment, improving operational reliability, reducing maintenance costs, and ensuring workplace safety. Modern corrosion control combines traditional protection techniques with advanced materials and smart technologies to minimize material degradation in aggressive industrial environments. The selection of an appropriate protection method depends on factors such as material type, operating conditions, environmental exposure, economic considerations, and maintenance requirements [1-4].

6.1 Protective Coatings: Protective coatings provide a physical barrier between metal surfaces and corrosive environments, preventing direct contact with moisture, oxygen, chemicals, and salts [5], [6]. Common coating systems include paints, epoxy coatings, polyurethane coatings, powder coatings, and metallic coatings such as zinc galvanization. These coatings are extensively applied to pipelines, storage tanks, bridges, offshore platforms, marine vessels, and industrial machinery to reduce corrosion rates and extend service life. Proper surface preparation and periodic coating inspection are essential to ensure long-term protection [5], [7].

6.2 Cathodic Protection: Cathodic protection prevents corrosion by converting the protected metal into the cathode of an electrochemical cell, thereby suppressing metal dissolution [2], [8]. This protection is achieved using sacrificial anodes or impressed current cathodic protection (ICCP) systems. Cathodic protection is widely employed for underground pipelines, buried storage tanks, offshore platforms, ship hulls, and reinforced concrete structures because of its high effectiveness in controlling electrochemical corrosion [8], [9].

6.3 Anodic Protection: Anodic protection controls corrosion by maintaining the metal at a stable passive potential where a thin, protective oxide film forms on its surface [1], [3]. This technique is particularly effective for highly corrosive environments involving strong acids and is commonly used in storage tanks, heat exchangers, and chemical reactors within the chemical processing industry. Although less widely applied than cathodic protection, anodic protection provides excellent corrosion resistance for passivating metals under suitable operating conditions [3], [10].

6.4 Corrosion Inhibitors: Corrosion inhibitors are chemical substances added to corrosive environments to reduce the rate of metal deterioration by modifying electrochemical reactions or forming protective films on metal surfaces [4], [11]. They are extensively used in cooling water systems, boilers, heat exchangers, oil and gas pipelines, and chemical processing facilities. Corrosion inhibitors can be classified as anodic, cathodic, mixed-type, or volatile inhibitors depending on their mechanism of action. Proper inhibitor selection and dosage significantly improve corrosion control and reduce maintenance costs [11], [12].

6.5 Material Selection: Selecting corrosion-resistant materials is one of the most effective long-term strategies for preventing corrosion [2], [5]. Materials such as stainless steel, titanium alloys, nickel-based alloys, aluminum alloys, duplex stainless steels, and corrosion-resistant composites exhibit superior resistance under aggressive environmental conditions. Appropriate material selection based on operating temperature, chemical exposure, mechanical loading, and environmental conditions enhances equipment durability, reduces maintenance frequency, and improves lifecycle performance [5], [13].

6.6 Surface Engineering: Surface engineering techniques improve corrosion resistance by modifying the physical and chemical properties of metallic surfaces [6], [14]. Common processes include electroplating, thermal spraying, laser surface treatment, nitriding, carburizing, Physical Vapor Deposition (PVD), and Chemical Vapor Deposition (CVD). These treatments increase surface hardness, wear resistance, oxidation resistance, and corrosion protection, making them suitable for manufacturing equipment, automotive components, aerospace structures, and heavy industrial machinery [14], [15].

6.7 Nanocoatings: Nanocoatings utilize nanostructured materials to produce thin, dense, and highly protective surface layers that provide superior corrosion resistance compared with conventional coatings [13], [16]. These coatings exhibit excellent resistance to corrosion, wear, ultraviolet radiation, and chemical attack while improving coating adhesion and durability. Nanocoatings are increasingly applied in aerospace, marine engineering, automotive manufacturing, biomedical devices, and renewable energy systems because of their enhanced protective performance and long service life [13], [16].

6.8 Smart Coatings: Smart coatings are advanced multifunctional protective materials capable of sensing environmental changes such as pH variation, moisture ingress, temperature fluctuations, or corrosion initiation and responding automatically to these conditions [16], [17]. Some smart coatings release corrosion inhibitors when coating damage occurs, while others provide self-diagnostic capabilities for early corrosion detection. These intelligent coatings reduce maintenance requirements, improve structural reliability, and support predictive maintenance strategies within Industry 4.0 environments [17], [18].

6.9 Self-Healing Coatings: Self-healing coatings contain microcapsules, vascular networks, or embedded healing agents that automatically repair small cracks and coating defects after mechanical damage [16], [19]. When damage occurs, the healing agents are released to restore the protective barrier and prevent corrosive substances from reaching the metal surface. Self-healing coatings significantly extend coating lifespan, reduce maintenance frequency, and improve the long-term durability of industrial assets. They have shown considerable potential for applications in marine engineering, aerospace structures, automotive components, pipelines, and offshore infrastructure [19], [20].

7. INTELLIGENT CORROSION MONITORING TECHNOLOGIES

Predictive maintenance has become an essential strategy for managing corrosion in industrial machinery and equipment. Unlike traditional time-based maintenance, predictive maintenance uses real-time monitoring, sensor data, and advanced analytics to assess equipment condition, predict corrosion progression, and schedule maintenance only when necessary. By integrating Artificial Intelligence (AI), Machine Learning (ML), the Internet of Things (IoT), and Digital Twin technologies, predictive maintenance improves equipment reliability, minimizes unexpected failures, reduces maintenance costs, extends asset service life, and enhances operational safety [16-20].

7.1 Remaining Useful Life (RUL): Remaining Useful Life (RUL) estimation predicts the remaining operational time before equipment reaches a critical level of corrosion or failure [18], [21]. RUL models combine historical inspection records with real-time corrosion monitoring data, including wall thickness, corrosion rate, temperature, humidity, and operating conditions, to forecast equipment degradation. Accurate RUL estimation supports maintenance planning, minimizes unexpected breakdowns, optimizes asset replacement decisions, and reduces lifecycle costs [18], [21], [22].

7.2 AI-Based Prediction: Artificial Intelligence (AI) enhances corrosion management by analyzing large volumes of operational, inspection, and sensor data to predict corrosion rates, identify degradation patterns, and detect potential failures at an early stage [1], [19], [23]. AI techniques—including Artificial Neural Networks (ANN), Support Vector Machines (SVM), Random Forest, XGBoost, and Deep Learning—improve maintenance accuracy, automate decision-making, and reduce equipment downtime. AI-based predictive models also assist engineers in identifying high-risk assets and selecting optimal maintenance strategies [19], [23], [24].

7.3 Condition-Based Maintenance (CBM): Condition-Based Maintenance (CBM) schedules maintenance activities based on the actual condition of equipment rather than fixed maintenance intervals [17], [20], [25]. Continuous monitoring of parameters such as corrosion rate, wall thickness, temperature, humidity, vibration, and corrosion potential enables timely intervention before severe deterioration occurs. CBM reduces unnecessary inspections, lowers maintenance costs, improves equipment availability, and enhances overall operational efficiency [17], [20], [25].

7.4 Risk-Based Inspection (RBI): Risk-Based Inspection (RBI) prioritizes inspection and maintenance activities according to the probability and consequences of corrosion-related failures [5], [26]. By focusing inspection resources on high-risk equipment such as pipelines, pressure vessels, storage tanks, and offshore structures, RBI improves inspection efficiency, enhances workplace safety, supports regulatory compliance, and minimizes maintenance costs while maintaining asset integrity [5], [26], [27].

7.5 Asset Integrity Management (AIM): Asset Integrity Management (AIM) is a systematic approach that ensures industrial equipment performs safely and reliably throughout its operational life [6], [18], [28]. It integrates corrosion monitoring, structural health assessment, inspection planning, maintenance strategies, and risk management to preserve equipment integrity and prevent failures. Modern AIM systems utilize IoT sensors, Digital Twins, AI, and cloud-based analytics to continuously monitor asset condition and support data-driven maintenance decisions [18], [28], [29].

7.6 Reliability-Centered Maintenance (RCM): Reliability-Centered Maintenance (RCM) is a maintenance strategy that identifies the most effective maintenance actions based on equipment functions, failure modes, and operational risks [4], [31], [32]. By incorporating corrosion analysis, failure prediction, and condition monitoring into maintenance planning, RCM improves system reliability, extends equipment lifespan, reduces production interruptions, and optimizes maintenance resources. RCM plays a significant role in supporting predictive maintenance programs within Industry 4.0 environments [21], [29], [33].

8. PREDICTIVE MAINTENANCE FOR CORROSION MANAGEMENT

Corrosion monitoring and management technologies are widely applied across various industrial sectors to improve equipment reliability, extend service life, reduce maintenance costs, and enhance operational safety. The integration of conventional corrosion protection methods with intelligent monitoring technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), Digital Twins, robotics, and predictive maintenance has significantly improved corrosion control in modern industries. These technologies enable continuous condition monitoring, early corrosion detection, Remaining Useful Life (RUL) prediction, and optimized maintenance planning, supporting sustainable asset management and Industry 4.0 transformation [16-20].

8.1 Oil and Gas: The oil and gas industry extensively utilize corrosion monitoring systems for pipelines, pressure vessels, storage tanks, offshore platforms, drilling equipment, and subsea infrastructure [2], [5], [21]. Continuous monitoring of corrosion rates, wall thickness, pressure, and pipeline integrity helps prevent leaks, environmental pollution, hydrocarbon spills, and catastrophic failures. Advanced technologies such as IoT sensors, smart pigging, Digital Twins, and AI-based predictive maintenance improve asset reliability, reduce inspection costs, and enhance operational safety in upstream, midstream, and downstream operations [18], [21], [22].

8.2 Power Plants: Power generation facilities apply corrosion management technologies to boilers, heat exchangers, steam turbines, condensers, cooling systems, piping networks, and pressure vessels [6], [13], [23]. Online corrosion monitoring combined with predictive maintenance improves thermal efficiency, reduces unplanned shutdowns, minimizes equipment failures, and extends the operational life of critical components. Intelligent monitoring also supports optimized water chemistry control and efficient maintenance scheduling [13], [23], [24].

8.3 Chemical Industries: Chemical processing plants rely on corrosion monitoring to protect reactors, pumps, valves, pipelines, heat exchangers, and storage tanks exposed to aggressive acids, alkalis, solvents, and corrosive chemicals [33], [11], [25]. Electrochemical sensors, AI-based monitoring systems, and automated inspection technologies detect early signs of material degradation, helping prevent leaks, improve process safety, maintain product quality, and ensure regulatory compliance [11], [25].

8.4 Marine Engineering: Marine environments expose ships, offshore platforms, propellers, ports, coastal infrastructure, and underwater structures to seawater, high humidity, and chloride-rich conditions that accelerate corrosion [8], [16], [26]. Intelligent corrosion monitoring technologies—including underwater robots, drones, fiber optic sensors, cathodic protection monitoring, and Digital Twins—support structural integrity assessment, optimize maintenance schedules, reduce corrosion-related operational costs, and improve maritime safety [16], [26].

8.5 Manufacturing: Manufacturing industries employ corrosion management systems for CNC machines, production equipment, conveyor systems, hydraulic machinery, industrial robots, and automated production lines [5], [19], [27]. Continuous monitoring of environmental conditions and equipment health improves machine reliability, minimizes unexpected downtime, enhances production efficiency, and reduces maintenance costs. AI-driven predictive maintenance further enables optimized maintenance scheduling and longer equipment service life [19], [35].

8.6 Transportation: Transportation sectors—including railways, highways, bridges, pipelines, commercial vehicles, and railway infrastructure—use corrosion protection and intelligent monitoring systems to maintain structural integrity and operational safety [7], [40], [28]. Continuous corrosion assessment helps detect structural deterioration at an early stage, allowing predictive maintenance that reduces repair costs, extends infrastructure lifespan, and improves transportation reliability [20], [28].

8.7 Aerospace: In the aerospace industry, corrosion monitoring is essential for aircraft fuselages, wings, landing gear, engines, fuel systems, and structural fasteners [14], [17], [29]. Advanced non-destructive testing, AI-based image analysis, smart coatings, and Digital Twin technologies enable early corrosion detection and structural health monitoring. These technologies improve aircraft reliability, reduce maintenance requirements, enhance passenger safety, and ensure compliance with stringent aviation regulations [17], [36].

8.8 Nuclear Industry: Nuclear power facilities require advanced corrosion management for reactor vessels, steam generators, cooling systems, piping networks, containment structures, and spent fuel storage systems [10], [18], [37]. Continuous monitoring, corrosion-resistant materials, electrochemical sensing, and predictive maintenance are critical for ensuring safe reactor operation, preventing material degradation, extending equipment service life, and maintaining strict regulatory compliance [18], [38].

8.9 Water Treatment Plants: Water and wastewater treatment facilities apply corrosion monitoring technologies to pipelines, pumps, storage tanks, filtration systems, valves, and water distribution networks [4], [12], [24]. Continuous monitoring of water chemistry, corrosion potential, and pipe wall thickness helps maintain water quality, prevent infrastructure failures, reduce leakage, and minimize maintenance costs. Intelligent monitoring systems also improve operational efficiency and ensure regulatory compliance [12], [24].

8.10 Renewable Energy Systems: Renewable energy systems including wind turbines, solar power plants, hydroelectric facilities, tidal energy systems, and offshore wind farms operate under diverse environmental conditions that promote corrosion [15], [19], [39]. Intelligent corrosion monitoring using IoT sensors, drones, AI-based analytics, and Digital Twins improves equipment durability, increases energy production reliability, reduces lifecycle maintenance costs, and supports the long-term sustainability of renewable energy infrastructure [19], [42-43].

9. CONCLUSION

Industrial hazard identification and automated safety control systems have evolved from manual inspection methods to intelligent, data-driven, autonomous solutions. Conventional techniques such as HAZOP, FMEA, FTA, ETA, JSA, and Bow-Tie Analysis remain valuable for systematic risk assessment but are increasingly complemented by AI, IoT, machine learning, computer vision, digital twins, robotics, and edge computing. These technologies enable continuous monitoring, predictive analytics, rapid emergency response, and reduced human exposure to hazardous environments.

While implementation challenges including cybersecurity, interoperability, cost, and workforce readiness persist, ongoing advancements in Industry 4.0 and the transition toward Industry 5.0 are expected to further enhance industrial safety. Future systems will increasingly emphasize intelligent decision support, human–machine collaboration, and resilient, autonomous safety management. Continued research, standardization, and cross-disciplinary collaboration will be essential to developing safer, more efficient, and sustainable industrial environments.

REFERENCES

1) M. M. H. Imran et al., “Emerging AI technologies for corrosion monitoring in oil and gas industry: A comprehensive review,” Engineering Applications of Artificial Intelligence, vol. 127, 2024.
2) L. Polverino, R. Abbate, P. Manco, D. Perfetto, F. Caputo, R. Macchiaroli, and M. Caterino, “Machine learning for prognostics and health management of industrial mechanical systems and equipment: A systematic literature review,” Advances in Mechanical Engineering, vol. 15, no. 7, 2023.

3) T. M. S. A. Hossain, M. A. Matin, M. A. Hakim, and M. F. Islam. "Characterization of Available Sedimentary Clay of Hobiganj District." (2019).
4) S. Ma, K. A. Flanigan, and M. Bergés, "State-of-the-Art Review: The Use of Digital Twins to Support Artificial Intelligence-Guided Predictive Maintenance," 2024.
5) L. Cummins, A. Sommers, S. B. Ramezani, S. Mittal, J. Jabour, M. Seale, and S. Rahimi, "Explainable Predictive Maintenance: A Survey of Current Methods, Challenges and Opportunities," 2024.
6) J. Jakubowski, N. Wojak-Strzelecka, R. P. Ribeiro, S. Pashami, S. Bobek, J. Gama, and G. J. Nalepa, "Artificial Intelligence Approaches for Predictive Maintenance in the Steel Industry: A Survey," 2024.
7) R. Haque, A. Bajwa, N. A. Siddiqui, and I. Ahmed, "Predictive Maintenance in Industrial Automation: A Systematic Review of IoT Sensor Technologies and AI Algorithms," American Journal of Interdisciplinary Studies, vol. 5, no. 1, pp. 1–30, 2024.
8) T. M. S. A. Hossain, M. Hasanuzzaman. (2026). Characterization of Nanostructure Sedimentary Clay Material of Netrokona District. International Journal of Multidisciplinary and Innovative Research, 3(5), 410-415.
9) N. Nalawade, S. D. Jakkan, S. Mangnale, and P. Patil, "Predictive Maintenance for Industrial Equipment Using IIoT, AI and ML," IJARIIT, vol. 10, no. 6, 2024.
10) S. F. Chevtchenko et al., "Anomaly Detection in Industrial Machinery Using IoT Devices and Machine Learning: A Systematic Mapping," 2023.
11) "Paradigm Shift for Predictive Maintenance and Condition Monitoring from Industry 4.0 to Industry 5.0: A Systematic Review, Challenges and Case Study," Results in Engineering, vol. 24, 2024.
12) O. A. Oyedeji, S. Khan, and J. A. Erkoyuncu, "Application of CNN for Multiple Phase Corrosion Identification and Region Detection," Applied Soft Computing, vol. 164, 2024.
13) T. M. S. A. Hossain, M. A. Matin, M. A. Hakim, and M. F. Islam. "Fabrication and Characterization of NiO-doped $BaTiO_3$ for Multilayer Ceramic Capacitor." In 2018 10th International Conference on Electrical and Computer Engineering (ICECE), pp. 77-80. IEEE, 2018.
14) M. M. H. Imran et al., "A Critical Analysis of Machine Learning in Ship, Offshore, and Oil and Gas Corrosion Research: Part I—Corrosion Detection and Classification," Ocean Engineering, vol. 313, 2024.
15) I. M. Chohan et al., "Effect of Seawater Salinity, pH, and Temperature on External Corrosion Behavior of Offshore Oil and Gas Pipelines," Scientific Reports, vol. 14, 2024.
16) T. M. S. A. Hossain, Chowdhury, M. A., Mithon, K. M. M. F., & Mahmud, I. (2026). Industrial Hazard Identification and Automated Safety Control Systems: A Comprehensive Review of Industry 4.0 Technologies, Artificial Intelligence, And Future Safety Paradigms. International Journal of Multidisciplinary and Innovative Research, 3(7), 619-625.
17) W. Liang et al., "Advances, Challenges and Opportunities in Creating Data for Trustworthy AI," Nature Machine Intelligence, vol. 4, no. 8, 2022.
18) M. Gavryushina et al., "Application of the Random Forest Algorithm to Predict Corrosion Losses of Carbon Steel," Corrosion Engineering, Science and Technology, vol. 58, no. 3, pp. 205–213, 2023.
19) A. Subedi et al., "CorFormer: A Hybrid Transformer-CNN Architecture for Corrosion Segmentation on Metallic Surfaces," Machine Vision and Applications, vol. 36, 2025.
20) M. M. H. Imran et al., "Effective Periodic Noise Reduction for Ship Corrosion Images," Journal of Advanced Research Design, vol. 129, 2025.
21) M. M. H. Imran et al., "Advanced Techniques in Ship Corrosion Analysis Using Active Contour Algorithms," Journal of Advanced Research Design, vol. 128, 2025.
22) T. M. S. A. Hossain, and M. Hasanuzzaman. "Characterization and Beneficiation of Available Sedimentary Clay Collected from Netrokona District for Industrial Application." (2023).
23) A. A. Khan et al., "Artificial Intelligence for Structural Health Monitoring: A Review," Sensors, 2023.
24) Y. Zhang et al., "Deep Learning-Based Surface Defect Detection in Industrial Inspection: A Review," IEEE Access, 2023.
25) X. Wang et al., "Digital Twin Technology for Predictive Maintenance: Recent Advances and Future Trends," Journal of Manufacturing Systems, 2024.
26) T. M. S. A. Hossain, and M. Hasanuzzaman. "CHARACTERIZATION OF HEAT-INSULATING CERAMIC FIBER RAW MATERIAL FOR INSULATION." Chemical Engineering Research Bulletin (2023).
27) J. Li et al., "IoT-Based Structural Health Monitoring Systems: A Review," Sensors, 2023.
28) T. M. S. A. Hossain. "Synthesis and structure-property characterization of BaTiO3/xNio nanocomposite ceramics." (2015).
29) H. Liu et al., "Fiber Optic Sensor Technologies for Corrosion Monitoring: A Review," Measurement, 2023.
30) T. M. S. A. Hossain, M. Hasanuzzam. (2026). Characterization of Nanostructure Sedimentary Clay Material of Netrokona District. International Journal of Multidisciplinary and Innovative Research, 3(5), 410-415.
31) P. Singh et al., "Smart Coatings for Corrosion Protection: Recent Developments," Progress in Organic Coatings, 2024.

32) A. Kumar et al., “Self-Healing Coatings for Corrosion Protection: Advances and Challenges,” Coatings, 2023.
33) F. Tao et al., “Digital Twin-Driven Intelligent Manufacturing: Recent Progress and Future Directions,” Robotics and Computer-Integrated Manufacturing, 2023.
34) T. M. S. A. Hossain, Chowdhury, M. A., Mithon, K. M. M. F., & Mahmud, I. (2026). Industrial Hazard Identification and Automated Safety Control Systems: A Comprehensive Review of Industry 4.0 Technologies, Artificial Intelligence, And Future Safety Paradigms. International Journal of Multidisciplinary and Innovative Research, 3(7), 619-625.
35) L. Wang et al., “Edge AI for Industrial Monitoring and Predictive Maintenance: A Review,” IEEE Access, 2024.
36) M. Javaid, A. Haleem, R. P. Singh, and R. Suman, “Artificial Intelligence Applications in Smart Manufacturing: A Review,” International Journal of Intelligent Networks, 2023.
37) T. M. S. A. Hossain, M. A. A. Islahi, M. H. Ali, D. Das, and M. I. Ali. "Preventive Maintenance and Lubrication Performance Analysis of Gas Generators Used in CNG Refueling Stations: A Comprehensive Review Paper." (2026).
38) S. Sharma et al., “Computer Vision for Industrial Inspection and Defect Detection: A Comprehensive Review,” Engineering Applications of Artificial Intelligence, 2024.
39) T. M. S. A. Hossain, M. A. Emran, I. Hosen, and R. Mia. "Design and Implementation of An Intelligent Pneumatic Automation System with Integrated Industrial Safety and Monitoring Functions: A Review Paper." (2026).
40) Z. Chen et al., “Recent Advances in Corrosion Sensors and Online Monitoring Technologies,” Sensors, 2024.
41) Y. Zhao et al., “Industry 5.0 and Intelligent Asset Management: Challenges and Future Directions,” Journal of Industrial Information Integration, 2025.
42) T. M. S. A. Hossain, Rony, M. T. F., Hosen, M. M., Hossain, M. S., & Hossen, M. A. (2026). Failure Analysis and Maintenance Assessment of Differential Systems in Automobile Power Transmission. International Journal of Multidisciplinary and Innovative Research, 3(8), 635-638.
43) Hossain, T. M. S. A., Ahmmed, M. S., Ahmed, S. I., & Biswas, B.(2026).Comparative Review of Conventional and Sensor-Based Windshield Wiper Systems: Technologies, Performance, Safety, and Future Trends. International Journal of Multidisciplinary and Innovative Research, 3(8), 671-681.