Global Scientific JOURNALS
GSJ: Volume 12, Issue 4, April 2024, Online: ISSN 2320-9186
www.globalscientificjournal.com

Application of Artificial Intelligence and Internet of Things for Corrosion Mitigation in Chemical Engineering Processes

ODUOLA Koyejo[1], **NWAKIRI** Ifeakachukwu[2]
[1]Department of Chemical Engineering, [2]Centre for Information & Telecommunications Engineering,
University of Port Harcourt, Port Harcourt, Nigeria
koyejo.oduola@uniport.edu.ng; ifeaka@yahoo.com

Abstract
This chapter delves into the transformative integration of Artificial Intelligence (AI) and the Internet of Things (IoT) to revolutionize corrosion mitigation strategies in Chemical Engineering Processes. The significance of effective corrosion control is emphasized, addressing challenges such as material degradation, safety risks, and increased maintenance costs. This necessitates innovative, proactive, and data-driven solutions. The chapter provides a comprehensive overview of AI and IoT applications, highlighting their real-time monitoring, predictive analytics, and adaptive control capabilities. The impact of corrosion on various components and systems within chemical engineering processes is explored, emphasizing the economic and environmental consequences, including maintenance costs, energy inefficiency, and material waste. The synergies between AI and IoT enable not only continuous monitoring but also early detection and prediction of corrosion trends. The adaptive learning mechanisms of AI are discussed, showcasing how these technologies optimize maintenance schedules and contribute to the development of customized corrosion prevention strategies. Specific AI applications, such as machine learning models for corrosion prediction and anomaly detection, are elucidated with real-world examples from diverse industries, including oil and gas, chemical processing, and renewable energy. IoT devices in corrosion monitoring, coupled with advanced sensor technologies for real-time data collection, enhance the granularity and accuracy of corrosion-related information. Challenges associated with data security, interoperability, and sensor reliability have been discussed, while presenting avenues for addressing these concerns. It also points toward ongoing research in advanced sensor technologies, explainable AI, and the potential use of quantum computing for corrosion modeling. In conclusion, the chapter underscores the transformative potential of leveraging AI and IoT for effective corrosion mitigation in Chemical Engineering processes. The proactive, real-time, and data-driven nature of these technologies not only ensures the longevity and safety of critical infrastructure but also aligns with broader sustainability goals.

Keywords: Corrosion Mitigation; Artificial Intelligence (AI); Internet of Things (IoT); Environmental Sustainability; Predictive Maintenance.

1. INTRODUCTION

In the field of Chemical Engineering, corrosion poses a significant challenge with far-reaching implications for both industrial processes and environmental sustainability. Corrosion, the gradual deterioration of materials due to chemical reactions with the environment, can lead to structural failures, increased maintenance costs, and energy inefficiencies. In Chemical Engineering context, where intricate systems and specialized materials are commonplace, corrosion can compromise the integrity of equipment, pipelines, and vessels, affecting the reliability and safety of processes (Rane et al., 2023).

Environmental sustainability is intrinsically linked to corrosion mitigation in Chemical Engineering. The repercussions of corrosion include the release of pollutants, degradation of materials, and increased resource consumption for repairs and replacements. By addressing corrosion, Chemical Engineers contribute to minimizing the environmental impact of industrial activities. Sustainable practices in corrosion mitigation not only enhance the longevity and efficiency of equipment but also align with broader efforts to reduce waste, conserve resources, and promote responsible industrial practices.

In the pursuit of environmentally conscious engineering solutions, the development and application of advanced technologies, such as Artificial Intelligence (AI) and the Internet of Things (IoT), play a pivotal role (Ang et al., 2022). These technologies offer innovative means to monitor, predict, and mitigate corrosion in real time, enabling proactive strategies that enhance both the economic viability and environmental sustainability of Chemical Engineering processes. The intersection of corrosion mitigation, chemical engineering, and environmental sustainability underscores the importance of seeking holistic and technologically driven approaches to address challenges and promote a more sustainable future (Pankaj , 2023; Prabhakar et al. 2023**;** Khayatazad et al., 2020).

1.1 Challenges Posed by Corrosion in Industrial Processes:

Corrosion represents a formidable obstacle in industrial processes, presenting multifaceted challenges that extend beyond mere material degradation. Recognizing and addressing these challenges is crucial for ensuring the longevity, efficiency, and safety of industrial operations. Key challenges include:

Safety Risks: Corrosion compromises the structural integrity of equipment and infrastructure, elevating the risk of catastrophic failures. In industries such as petrochemicals and oil refining, where corrosive environments are prevalent, safety hazards escalate with the potential for leaks, spills, and accidents (Aba et al., 2020).

Economic Implications: The financial burden of corrosion is substantial, encompassing repair costs, maintenance expenses, and production downtime. Unplanned shutdowns for repairs not only disrupt operations but also lead to revenue losses, making corrosion a significant economic concern for industries reliant on continuous processes (Pankaj , 2023; Olabi, 2019, NACE, 2016).

Energy Inefficiency: Corroded surfaces often result in increased friction and reduced heat transfer efficiency. This inefficiency demands higher energy inputs to maintain optimal operational temperatures, contributing to elevated energy consumption, increased greenhouse gas emissions, and lowered overall energy efficiency.

Environmental Impact: Corrosion-related failures can release harmful substances into the environment, posing environmental risks and necessitating costly cleanup efforts. The environmental impact extends to resource depletion as frequent replacements and repairs contribute to increased material consumption and waste generation (Ahmed et al., 2020; Ahmed et al., 2021; Ahmed et al., 2022).

1.2 The Need for Innovative Solutions:

Addressing the challenges posed by corrosion requires a proactive and innovative approach. Traditional mitigation methods are often reactive and costly, emphasizing the urgency of embracing innovative solutions. Some key imperatives include:

Predictive Technologies: Implementing advanced predictive technologies, such as AI and machine learning (ML), enables the early detection of corrosion precursors. By analyzing historical data and monitoring corrosion parameters in real time, these technologies empower industries to forecast potential issues and proactively schedule maintenance (Akhtar & Moridpour, 2021).

Corrosion-Resistant Materials: Investing in the research and development of corrosion-resistant materials contributes to the long-term durability of equipment and infrastructure. Innovations in material science can lead to the creation of alloys and coatings that withstand corrosive environments, reducing the frequency of replacements and repairs.

IoT-Enabled Monitoring: Leveraging the IoT allows for continuous and remote monitoring of corrosion-related factors. IoT sensors provide real-time data on temperature, humidity, and corrosive agents, enabling swift responses to changing conditions and facilitating condition-based maintenance.

Green Corrosion Inhibitors: Exploring environmentally friendly corrosion inhibitors aligns with sustainable practices. Research into inhibitors that are both effective and environmentally benign contributes to minimizing the ecological footprint associated with corrosion mitigation.

In summary, the challenges presented by corrosion in industrial processes necessitate a paradigm shift towards innovative, proactive, and sustainable solutions. Embracing cutting-edge technologies and materials, coupled with a commitment to environmental responsibility, can mitigate the adverse impacts of corrosion, promoting safer, more efficient, and economically viable industrial operations (Liu and Pang, 2019, Ahmed et al., 2022).

1.3. Overview of AI and IoT Applications in Addressing Corrosion-Related Issues:

In recent years, the integration of AI and IoT has revolutionized the approach to corrosion mitigation in industrial settings. By combining advanced data analytics, real-time monitoring, and predictive capabilities, AI and IoT offer innovative solutions to address corrosion-related challenges. Some related applications are discussed below:

Predictive Analytics:

Data Analysis for Corrosion Prediction are attainable with the aid of AI algorithms analyzing historical and real-time data, identifying patterns and correlations associated with corrosion. This enables the prediction of potential corrosion events before they manifest, allowing for timely intervention and maintenance. In addition to this, ML models can be trained on diverse datasets, incorporating factors such as temperature, humidity, chemical exposure, and material properties. These models learn and adapt over time, improving their accuracy in forecasting corrosion risks.

Real-Time Monitoring with IoT:

IoT devices, equipped with various sensors, can be strategically placed in industrial environments to continuously monitor conditions relevant to corrosion. Parameters such as temperature, humidity, pH levels, and corrosive agents can be tracked in real time. The IoT allows for remote monitoring of corrosion-prone assets. This capability is particularly valuable for assets in challenging or hazardous environments, enabling timely responses to evolving corrosion conditions without the need for physical presence.

Condition-Based Maintenance:

Proactive Maintenance Strategies are achievable with AI and IoT facilitating the shift from scheduled maintenance to condition-based maintenance. By continuously monitoring the condition of equipment, these technologies enable maintenance interventions precisely when needed, optimizing operational efficiency and reducing downtime. AI algorithms can also assess the risk of corrosion based on current and predicted environmental conditions. This risk assessment guides decision-making regarding maintenance priorities, resource allocation, and the implementation of corrosion prevention measures.

Corrosion Modeling and Simulation:

AI-driven modeling and simulation tools can create virtual environments to simulate and predict corrosion processes. This allows engineers to test various scenarios and assess the effectiveness of corrosion mitigation strategies without physical experimentation. Similarly, AI optimization algorithms can analyze vast datasets to identify the most effective corrosion mitigation strategies. This includes optimizing the selection of materials, coatings, and inhibitors based on real-time and historical performance data.

Early Detection and Alert Systems:

AI algorithms can identify anomalies in corrosion-related data, signaling potential issues at an early stage. This early detection capability enables proactive measures to be taken before significant damage occurs. Integrated with IoT sensor networks, AI-driven alert systems can provide instant notifications when abnormal corrosion-related conditions are detected, enabling rapid response and intervention.

Decision Support Systems:

AI provides decision support systems that leverage data analysis to guide corrosion management decisions. This includes recommending optimal maintenance schedules, selecting suitable corrosion prevention measures, and assessing the cost-effectiveness of different strategies.

2. CORROSION IN CHEMICAL ENGINEERING PROCESSES

2.1 Impact of Corrosion on Various Components and Systems in Chemical Engineering Processes:

Corrosion, a pervasive and insidious process, exerts a wide-ranging impact on diverse components and systems within chemical engineering processes. Its effects extend beyond mere material degradation, encompassing safety hazards, operational inefficiencies, and economic consequences. Let us look into the specific impact of corrosion on certain elements of chemical engineering processes:

Pipelines and Transportation Systems:

Corrosion compromises the integrity of pipelines, leading to material degradation and the formation of weak spots. This can result in leaks, spills, and ruptures, posing safety risks and environmental hazards.

Accumulation of corrosion by-products on pipeline walls can impede the flow of fluids, reducing the efficiency of transportation systems and requiring increased energy inputs (Ding, 2022; Ding et al., 2022).

Vessels and Reactors:

Corrosion weakens the structural integrity of vessels and reactors, increasing the risk of catastrophic failures. This is particularly critical in processes involving high pressure and temperature conditions. Besides, corrosion by-products can contaminate chemical products, affecting their quality and purity. This is especially problematic in industries where precise product specifications are crucial (Elechi et al., 2020).

Heat Exchangers and Cooling Systems:

On heat exchange surfaces the presence of corrosion leads to heat transfer efficiency. This requires higher energy inputs to maintain optimal temperatures, leading to increased operational costs and energy consumption. Corrosion products contribute to fouling and scaling in cooling systems, further impairing heat exchange performance and necessitating more frequent maintenance (Elsisi et al.2021).

Storage Tanks and Containers:

Leakage and Spillage Risks: Corrosion weakens the structural integrity of storage tanks, elevating the risk of leaks and spillage. This poses safety hazards to personnel, compromises environmental integrity, and may lead to regulatory non-compliance. Corrosion-induced breaches in containment systems can result in the loss of valuable chemicals, leading to economic losses and potential environmental contamination.

Instrumentation and Control Systems:

Corrosion can impair the functionality of sensors and instruments critical for monitoring and control. This compromises the accuracy of process measurements and may lead to suboptimal control of chemical processes. Corrosion-related damage to data transmission systems can also result in unreliable data, hindering the effectiveness of control systems and decision-making processes.

Pumps and Valves:

Reduced Operational Lifespan: Corrosion affects the operational lifespan of pumps and valves, leading to increased maintenance and replacement costs. Corrosion-induced deposits on valve bonnet/trim can disrupt fluid flow, affecting the efficiency and reliability of control mechanisms.

Structural Components and Supports:

Corrosion weakens structural components and supports, jeopardizing the stability of infrastructure. This is particularly critical in the design and maintenance of platforms, walkways, and supporting structures.

Environmental and Regulatory Implications:

Corrosion-related failures may release hazardous chemicals into the environment, posing risks to ecosystems and public health. Non-compliance with environmental regulations may result from corrosion-related incidents, leading to legal consequences and reputational damage.

It is therefore noteworthy that the impact of corrosion within chemical engineering processes is broad and multifaceted. From safety and environmental considerations to operational and economic implications, the mitigation of corrosion becomes imperative for ensuring the sustainability and reliability of chemical processes. Proactive strategies, such as leveraging AI and IoT for monitoring and prediction, are crucial for minimizing the adverse effects of corrosion on these critical components and systems.

2.2. Economic and Environmental Consequences of Corrosion:

Corrosion in industrial processes exacts a substantial toll on both economic resources and environmental sustainability. The consequences extend across various facets, including maintenance costs, energy efficiency, and material waste.

Maintenance Costs:

Corrosion necessitates unplanned maintenance and repairs, leading to downtime in industrial processes. The costs associated with emergency repairs, equipment replacement, and production interruptions can be considerable. Industries grappling with corrosion often incur additional expenses for frequent inspections and monitoring to detect and address corrosion-related issues promptly (Zinno et al., 2022).

Energy Inefficiency:

Heat transfer efficiency is reduced as a result of corrosion and increased friction is observed in equipment. Consequently, more energy is required to maintain optimal temperatures and operational conditions, leading to higher energy consumption. Corrosion-induced fouling and scaling in heat exchangers and other equipment further exacerbate operational inefficiencies, requiring increased energy inputs for processes to compensate.

Material Waste:

Corrosion accelerates the degradation of materials, necessitating premature replacements of components such as pipes, vessels, and structural elements. This leads to significant material waste and adds to the environmental burden associated with resource extraction and manufacturing. The disposal of corroded materials poses environmental challenges, especially if the materials contain hazardous substances. Proper disposal methods are often required to mitigate the environmental impact.

Resource Consumption:

Frequent corrosion-induced replacements lead to increased consumption of raw materials and energy for manufacturing new components. This contributes to resource depletion and places additional stress on ecosystems. Corrosion mitigation measures, such as chemical treatments and coatings, may require additional water and chemicals, impacting both resource usage and potential environmental consequences.

Environmental Contamination:

Corrosion-related failures can result in the release of hazardous chemicals into the environment, posing risks to ecosystems and water sources. Environmental contamination may lead to long-term ecological damage and the need for remediation efforts. Industries may incur costs related to regulatory compliance and environmental remediation in the aftermath of corrosion-related incidents, including fines and legal expenses (Jahanshahi, & Masri, 2013).

Impact on Product Quality:

Corrosion by-products can contaminate chemical products, affecting their quality and purity. This may result in the loss of marketable products, additional quality control measures, and potential reputational damage.

Safety Risks:

The need for enhanced safety measures and protocols to address corrosion-related risks can incur additional costs for training, safety equipment, and emergency response preparedness.

It is therefore evident that the economic and environmental consequences of corrosion are intertwined and extensive. Mitigating these impacts requires a holistic approach that encompasses not only reactive measures but also proactive strategies, such as leveraging advanced technologies like AI and IoT for predictive maintenance and corrosion prevention. By addressing corrosion comprehensively, industries can reduce costs, enhance operational efficiency, and contribute to a more sustainable and environmentally responsible approach to chemical engineering processes.

3. FUNDAMENTALS OF AI AND IoT

3.1 Artificial Intelligence (AI):

Artificial Intelligence refers to the development of computer systems that can perform tasks that usually require human intelligence. It encompasses a range of techniques and technologies designed to enable machines to simulate human cognition, learning, problem-solving, and decision-making.

Key Components of AI include:

Machine Learning (ML): ML is a subset of AI that focuses on creating algorithms and models that enable computers to learn from data. It includes supervised learning, unsupervised learning, and reinforcement learning, allowing systems to improve their performance over time without explicit programming (Figure 1).

Deep Learning: Deep learning is a type of ML that involves neural networks with multiple layers (deep neural networks). It has been particularly successful in tasks such as image and speech recognition, natural language processing, and complex pattern recognition.

Natural Language Processing (NLP): NLP enables machines to understand, interpret, and generate human language. It plays a crucial role in applications like chatbots, language translation, sentiment analysis, and voice recognition.

Computer Vision: Computer vision involves teaching machines to interpret and make decisions based on visual data. Applications include image and video analysis, facial recognition, object detection, and autonomous vehicles (Howard et al., 2017).

Expert Systems: Expert systems use rule-based reasoning to emulate the decision-making abilities of a human expert in a specific domain. They are used in fields where expertise is crucial, such as medical diagnosis or financial analysis (van Smeden et al., 2022).

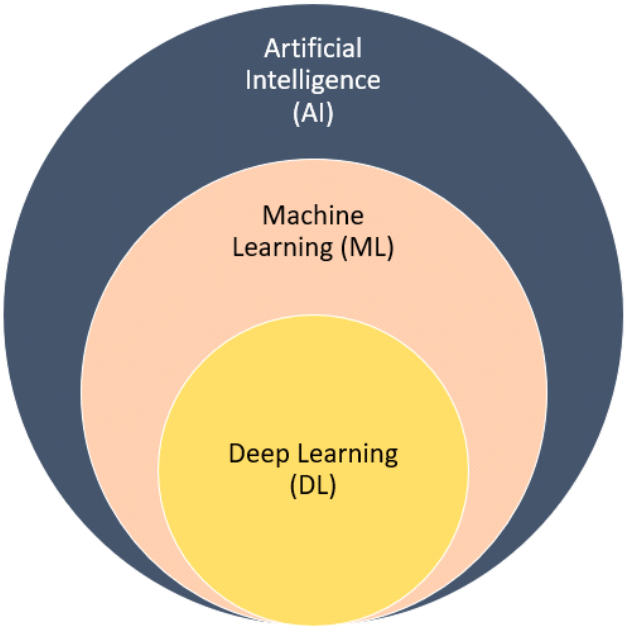

Figure 1: Venn diagram of artificial intelligence (Matthaiou, 2021).

AI is widely applied in Healthcare (diagnostics, personalized medicine, drug discovery); Finance (fraud detection, algorithmic trading, customer service: chatbots, virtual assistants, sentiment analysis); Manufacturing (predictive maintenance, quality control, supply chain optimization); Autonomous Systems (Self-driving cars, drones, robotics) (Zhang et al., 2021; Zhang & Cheng, 2022; van Smeden et al., 2022). There are inherent challenges including ethical concerns (bias in algorithms, job displacement, privacy issues), data quality and security and complexity - the "black box" nature of some AI models can make it challenging to understand their decision-making processes.

3.2 Internet of Things (IoT):

The Internet of Things refers to the network of interconnected devices embedded with sensors, software, and other technologies to collect and exchange data. These devices, often everyday objects, can communicate and make intelligent decisions without direct human intervention.

The key components are:

Sensors and Actuators: Devices in the IoT are equipped with sensors to gather data from the environment, and actuators to perform actions or make changes based on that data. IoT devices are equipped with various sensors (e.g., temperature, humidity, pressure, motion, chemical) that continuously monitor and collect data from the surrounding environment.

Connectivity: IoT devices rely on various communication protocols, such as Wi-Fi, Bluetooth, Zigbee, or cellular networks, to connect and exchange data.

Cloud Computing: The data collected by IoT devices is often processed and stored in the cloud, allowing for centralized management, analysis, and access from anywhere. Data is often sent to cloud servers for more extensive processing. Cloud platforms provide scalability and the computational power needed for complex analytics (Beach, 2013;).

Edge Computing: In some IoT applications, data processing occurs closer to the source (at the edge of the network) to reduce latency and enhance real-time decision-making. IoT devices with processing capabilities can perform initial data processing locally. This involves filtering, aggregating, or preprocessing data before transmitting it to a central system.

Applications of IoT include smart homes (connected thermostats, security systems, and appliances), industrial IoT (IIoT), e.g. predictive maintenance, supply chain optimization, asset tracking; healthcare: remote patient monitoring, smart medical devices; smart cities: traffic management, waste management, environmental monitoring; agriculture: precision farming, crop monitoring, livestock tracking (Tian et al., 2019, Song & Liang, 2022, Niyonambaza et al., 2020; Mohamed et al., 2023; Lin et al., 2020). IoT devices can, however, be vulnerable to cyber-attacks, posing risks to privacy and data integrity. Another challenge here is in ensuring seamless communication and compatibility among diverse IoT devices and platforms. As the number of connected devices grows, scalability becomes a critical consideration. Collecting and handling sensitive data raises concerns about privacy and consent (Mao & Zhang, 2021, Luo, 2022).

In summary, both AI and IoT represent transformative technologies with applications across various industries, and their convergence is driving advancements in areas such as predictive maintenance, intelligent decision-making, and real-time data analytics.

AI models deployed in IoT systems can be designed for continuous learning. They adapt to changing conditions and learn from new data, ensuring that the system remains effective over time. Data generated from the system's actions can be fed back into the learning process, improving the accuracy and relevance of future predictions and decisions. AI-driven insights can be integrated into decision support systems. These systems provide actionable recommendations to users based on real-time data analysis. AI algorithms can trigger automated responses or actions through IoT devices based on predefined rules. For example, adjusting equipment settings, sending alerts, or initiating preventive maintenance (Wu, 2022; Yang et al., 2023).

3.3. Potential of AI and IoT in Transforming Corrosion Monitoring and Mitigation Strategies:

The integration of AI and IoT technologies into corrosion monitoring and mitigation strategies represents a paradigm shift, offering a dynamic, data-driven, and proactive approach. This transformation not only enhances the reliability and safety of industrial processes but also contributes to cost savings, sustainability, and improved overall operational efficiency (). This can be illustrated in Table 1 below upon comparing the advantages the traditional approaches in conventional process engineering activities. Early detection, prediction and monitoring are easily achieved by employing the advantages of the AI and IoT transformation.

Table 1. Highlights of the key advantages of AI and IoT transformation for corrosion monitoring/prevention in chemical processes.

Key advantage	Traditional Approach	Transformation with AI and IoT
Condition-Based Maintenance	Scheduled maintenance based on fixed intervals	Continuous monitoring by IoT devices, coupled with AI analytics, enables condition-based maintenance.
Real-Time Corrosion Monitoring	Periodic inspections and manual measurements	real-time monitoring enhances responsiveness and allows for immediate corrective actions
Data-Driven Decision Support	relies on experience and historical data analysis	data-driven approach enhances the precision and efficiency of decision-making processes.
Customized Corrosion Solutions	Insensitive to specific environmental conditions or variations in equipment	customization of corrosion mitigation strategies, improving effectiveness
Integration of Monitoring Systems:	operate in isolation	Integration of multiple IoT devices and monitoring systems
Reduced Maintenance Costs	higher costs associated with emergency repairs and component replacements	Proactive, condition-based maintenance reduces the frequency of emergency interventions, minimizing overall maintenance costs
Environmental Impact Reduction	Environmental contamination and increased resource consumption.	Timely identification and mitigation of corrosion; optimized maintenance and material usage
Continuous Learning	Not easy to learn from experience	iterative learning process improved accuracy and adaptability

4. AI and IoT TECHNOLOGIES APPLICATIONS IN CORROSION MITIGATION

There are diverse applications of AI in corrosion control, ranging from predictive maintenance and monitoring to smart coating selection and decision support systems. The integration of AI and IoT technologies continues to revolutionize how industries approach corrosion prevention and mitigation, leading to more efficient and cost-effective strategies. Internet of Things (IoT) devices play a pivotal role in modernizing corrosion monitoring and data acquisition processes. These connected devices enable continuous, real-time monitoring of environmental conditions and corrosion-related parameters, providing valuable insights for proactive corrosion control. Chemical processing plants have adopted AI-driven smart corrosion monitoring systems. IoT sensors continuously measure corrosion-related parameters, and machine learning models analyze the data for early detection of corrosion (Simonyan & Zisserman, 2014; Schneller et al., 2022; Thibbotuwa et al., 2022). The system provides real-time insights into corrosion trends, allowing for timely preventive measures (Nwakiri et al., 2023).

Application examples include cathodic protection systems in pipelines enhanced with AI for optimal performance. AI algorithms adjust the parameters of cathodic protection systems based on real-time corrosion data. This adaptive control ensures efficient protection against corrosion, especially in challenging environments. Industries employ AI-driven decision support systems for corrosion management. These systems integrate data from various sources, including IoT sensors, laboratory tests, and historical records.

The neural network model here proposed integrates geometrical characteristics of a pipeline (an application case is considered), corrosion deterministic models and simulations of multiphase flow velocity and transport, as schematized in Figure 2 (De-Masi et al., 2014).

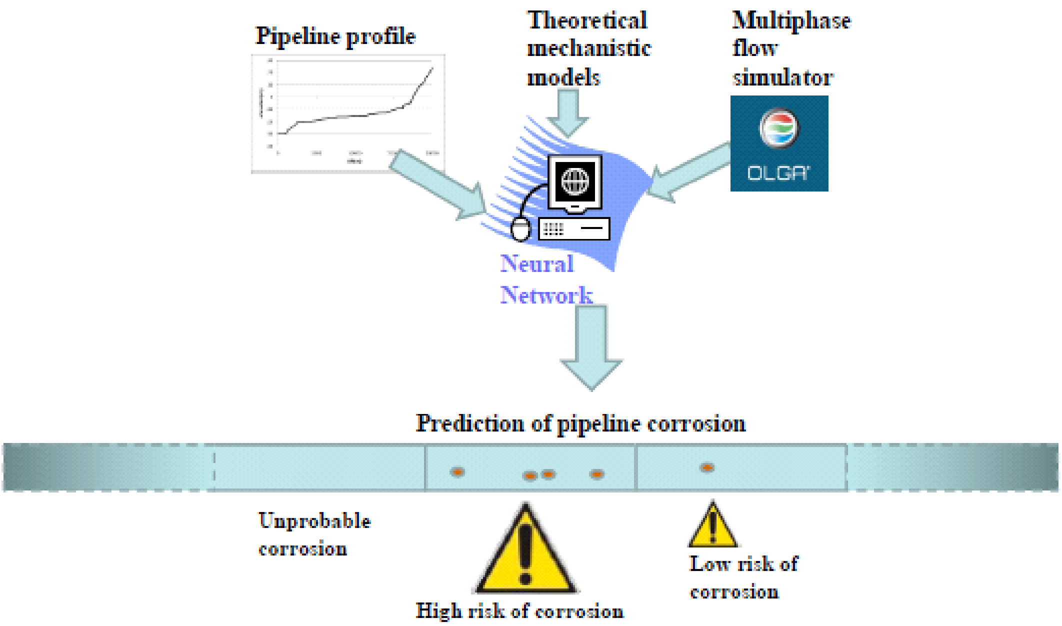

Figure 2: Scheme of artificial intelligence model (De-Masi et al., 2014).

AI algorithms provide actionable insights, assisting in the development of effective corrosion prevention strategies and resource allocation. AI-Integrated Corrosion Inspection Drones equipped with AI technology are used for aerial corrosion inspections. Drones capture high-resolution images and data from structures, and AI algorithms analyze this information to identify signs of corrosion. This approach improves the efficiency of inspections and reduces the need for manual labor in challenging environments. Integration of these sensor technologies in Internet of Things (IoT) platforms allows for comprehensive, real-time corrosion monitoring and data acquisition. By leveraging these sensors, industries can implement proactive corrosion control strategies, optimize maintenance schedules, and prevent costly damage to infrastructure and equipment (Kor et al., 2023; Liang & Xu, 2021, Garlik, 2022).

Case Studies

Shell's Pipeline Corrosion Monitoring (Nigeria):

Shell implemented IoT sensors along pipelines in Nigeria to monitor corrosion conditions. Real-time data from the sensors enabled proactive maintenance and corrosion mitigation strategies. By predicting potential corrosion events, Shell reduced the risk of pipeline failures, minimizing environmental impact and operational disruption (Honeywell International Inc. 2023; Safuriyawu Ahmed, 2022)

Chevron's Smart Oil Fields (California, USA):

Chevron implemented IoT devices and sensors in their oil fields to monitor equipment health and corrosion. Real-time data on corrosion rates and environmental conditions allowed Chevron to optimize maintenance schedules and implement targeted corrosion prevention measures. This resulted in increased operational efficiency and reduced downtime (Khan et al., 2017).

Siemens' Smart Cathodic Protection Systems:

Siemens developed smart cathodic protection systems for pipelines and storage tanks, integrating IoT sensors and communication modules. The system continuously monitors the effectiveness of cathodic protection, adapting parameters based on real-time corrosion data. This approach optimizes corrosion prevention, extending the lifespan of infrastructure and reducing maintenance costs (Safuriyawu, 2022).

IoT-Based Corrosion Monitoring in Offshore Wind Farms (North Sea):

Offshore wind farms in the North Sea utilize IoT sensors to monitor corrosion on wind turbine structures. The continuous monitoring of corrosion conditions allows for early detection and timely maintenance. This proactive approach ensures the integrity of the infrastructure, minimizing the risk of structural failures in challenging marine environments (Thibbotuwa et al., 2022).

Automated Corrosion Monitoring in Chemical Plants (Europe):

Chemical plants in Europe have implemented automated corrosion monitoring systems using IoT devices. Real-time data on corrosion rates and environmental conditions enable predictive maintenance and optimization of corrosion prevention strategies. This has led to improved safety, reduced unplanned shutdowns, and enhanced operational efficiency.

These examples highlight how IoT technologies contribute to effective corrosion mitigation strategies across diverse industries. The integration of real-time data and predictive analytics enables proactive decision-making, reducing maintenance costs, improving safety, and extending the lifespan of critical assets.

5. INTEGRATED AI-IOT SOLUTIONS

The synergies between Artificial Intelligence (AI) and the Internet of Things (IoT) play a crucial role in creating comprehensive corrosion mitigation strategies. This collaboration enhances the capabilities of corrosion monitoring, prediction, and prevention, leading to more efficient and proactive approaches. Here are key aspects of the synergies between AI and IoT in the context of corrosion mitigation:

Real-Time Monitoring and Data Acquisition:

IoT devices equipped with sensors continuously collect real-time data on environmental conditions, corrosion-related parameters, and equipment health. AI algorithms process the massive amounts of data generated by IoT devices in real-time. This integration allows for immediate analysis and identification of corrosion trends, anomalies, or potential issues (Figure 3).

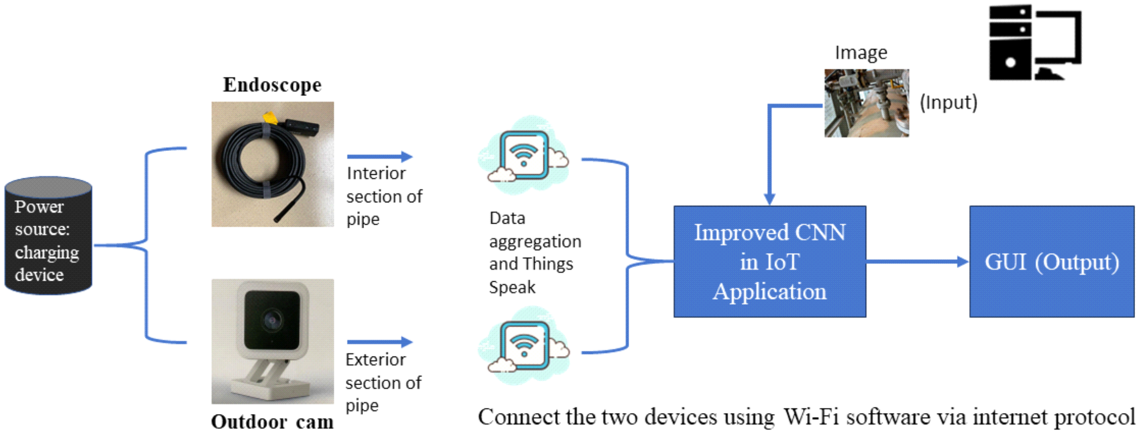

Figure 3: Proposed IoT system adopted for real-time corrosion monitoring (Nwakiri et al., 2023)

Early Detection and Prediction:

IoT sensors provide continuous monitoring, offering a detailed view of corrosion-related parameters. Changes in these parameters can be indicative of early-stage corrosion. AI algorithms, particularly machine learning models, analyze historical and real-time data to identify patterns and predict potential corrosion events. Early detection through AI enables timely intervention and preventive measures.

Predictive Maintenance Optimization:

IoT devices contribute to the collection of data related to equipment health, corrosion rates, and environmental conditions. AI models analyze this data to predict when equipment is likely to require maintenance due to corrosion. Predictive maintenance schedules are optimized, reducing downtime and minimizing the economic impact of unplanned maintenance (Jiang et al., 2023).

Adaptive Learning and Continuous Improvement:

IoT devices continuously collect data from the operational environment and corrosion sensors. AI algorithms, particularly those based on machine learning, adapt and improve over time by learning from new data and feedback from maintenance actions. This adaptive learning process enhances the accuracy of corrosion predictions and mitigation strategies (Jing et al., 2022; Jingyi et al., 2020).

Integration of Multi-Sensor Networks:

IoT facilitates the deployment of diverse sensor networks, capturing various corrosion-related parameters. AI algorithms integrate data from multiple sensors (sensor fusion), providing a comprehensive understanding of the corrosion environment. This holistic approach enhances the accuracy of corrosion assessments.

Decision Support Systems:

IoT devices generate vast amounts of data, including corrosion rates, environmental conditions, and equipment status. AI-driven decision support systems process this data to provide actionable insights. These insights guide operators and engineers in making informed decisions related to corrosion prevention, maintenance planning, and resource allocation (Figure 4).

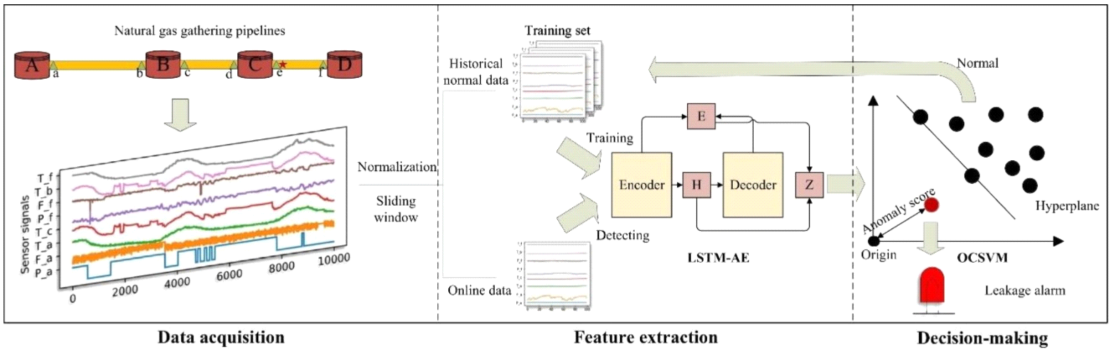

Figure 4. The framework proposed by Mazumder et al. for failure risk analysis (Mazumder et al., 2021).

Customized Corrosion Solutions:

IoT devices collect data on a wide range of parameters, including temperature, humidity, chemical exposure, and material conditions. AI algorithms analyze diverse datasets to customize corrosion mitigation strategies based on specific environmental conditions. This tailored approach improves the effectiveness of corrosion prevention measures. A typical procedure for implementing a CNN model is presented in Figure 5.

Anomaly Detection and Alerts:

IoT sensors continuously monitor corrosion-related parameters and equipment conditions. AI algorithms, especially those focused on anomaly detection, analyze incoming data to identify deviations from expected patterns. Alerts and notifications are generated in real-time, allowing for immediate response to potential corrosion threats (Fortino et al., 2014).

Optimized Cathodic Protection Systems:

IoT devices monitor the performance of cathodic protection systems in real-time. AI algorithms optimize cathodic protection parameters based on continuous data analysis. This adaptive control ensures efficient corrosion prevention, especially in dynamic environmental conditions.

Data-Driven Corrosion Modeling:

IoT devices provide data on corrosion rates, environmental conditions, and material properties. AI models simulate corrosion processes, predict material behavior, and model the impact of various environmental factors on corrosion. This data-driven approach aids in designing corrosion-resistant systems.

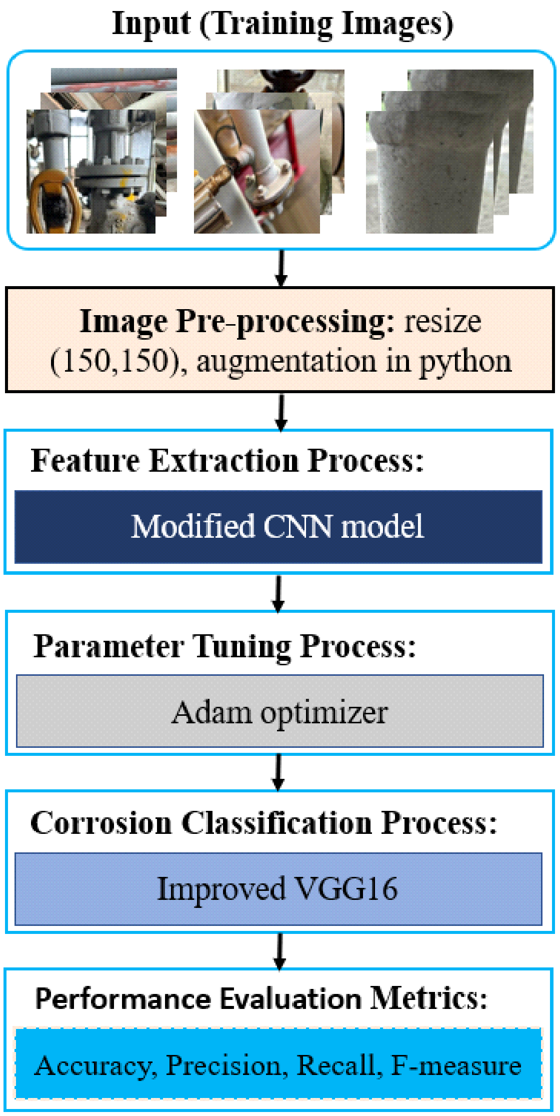

Figure 5: Procedure for implementation of CNN model

The synergy between AI and IoT transforms corrosion mitigation from a reactive to a proactive and data-driven process. By combining the real-time monitoring capabilities of IoT with the analytical power of AI, industries can enhance the reliability, safety, and sustainability of their operations while minimizing the economic and environmental impact of corrosion-related issues.

The integration of AI-driven analytics and IoT sensor networks holds immense potential for ushering in proactive and adaptive corrosion control measures. This synergistic approach transforms traditional corrosion management strategies by providing real-time insights, predictive capabilities, and adaptive interventions.

By integrating AI-driven analytics with IoT sensor networks, industries can proactively address corrosion challenges by predicting issues before they escalate and adapting control measures in real time. This holistic and data-driven approach not only improves the reliability and safety of operations but also contributes to cost savings and sustainability goals.

6. CHALLENGES AND FUTURE DIRECTIONS

6.1 Challenges associated with AI and IoT applications for corrosion mitigation

While the integration of AI and IoT in corrosion mitigation offers significant advantages, there are several challenges and limitations that need to be considered. Addressing these issues is crucial to ensuring the effectiveness, reliability, and safety of corrosion control strategies (Turner et al., 2023; Jan et al., 2023; Arun Kumar et al. 2023). Here are some key challenges associated with the application of AI and IoT in corrosion mitigation and ways of resolving them (Table 2):

Table 2: Challenges associated with AI and IoT applications for corrosion mitigation

Issues	Challenges	Mitigation
Data Security and Privacy	Collecting and transmitting sensitive corrosion data	Implement robust security measures to protect data. Adhere to privacy regulations and standards, responsible handling of sensitive information
Interoperability	IoT devices and AI systems from different manufacturers	Standardize communication protocols to enhance interoperability.
Reliability of Sensor Data	IoT sensor data affected by sensor drift, calibration errors, or environmental interferences	Implement regular calibration and maintenance procedures for sensors. Employ data validation techniques to identify and correct anomalies.
Energy Consumption and Battery Life	frequent data transmission or processing by AI algorithms lead to increased energy consumption and reduced battery life	Optimize data transmission intervals and implement energy-efficient IoT sensors. Explore alternative power sources, such as energy harvesting technologies, to extend battery life.
Scalability Issues	managing and processing large volumes of data.	Use cloud-based platforms capable of accommodating increased data volumes.
Cost of Implementation	can be substantial	Conduct a cost-benefit analysis to demonstrate the long-term advantages of corrosion mitigation
Standardization	may hinder seamless integration	Participate in industry-wide standardization efforts to establish common protocols
AI Models	Complex	Promote transparency in AI algorithms, providing explanations of model decisions
Environmental Conditions	Could be harsh	Select sensors that are designed for specific environmental conditions
Regulatory Compliance	Meeting regulatory requirements	Stay informed about relevant regulations and ensure that AI and IoT implementations comply with industry standards and legal requirements

Addressing these challenges requires a holistic and multidisciplinary approach involving experts in AI, IoT, corrosion science, and cybersecurity. Continuous monitoring, regular updates, and collaboration within the industry are essential to overcome these limitations and ensure the successful application of AI and IoT in corrosion mitigation.

6.2. Future trends in the field of corrosion mitigation with AI and IoT

Ongoing research in the field of corrosion mitigation with AI and IoT is dynamic and continuously evolving. Researchers are exploring various avenues to enhance the capabilities of these technologies for more effective and sustainable corrosion control. Here are some potential future developments and ongoing research areas:

Advanced Sensor Technologies:

Researchers are developing advanced sensor technologies with improved accuracy, durability, and sensitivity to capture nuanced corrosion-related data. Innovations include nanoscale sensors, smart coatings, and wireless sensors with extended battery life.

Edge Computing for Real-Time Processing:

Edge computing is gaining attention for its potential to process data closer to the source, reducing latency and improving real-time analytics. Future developments may involve integrating edge computing solutions to enhance the efficiency of AI-driven corrosion monitoring.

Machine Learning Model Interpretability:

Enhancing the interpretability of machine learning models is a focus of research. Researchers are working on methods to make AI models more transparent, understandable, and interpretable, especially in critical applications like corrosion prediction and prevention.

Explainable AI in Corrosion Mitigation:

Explainable AI (XAI) research aims to make AI algorithms more transparent and interpretable. This is particularly important in corrosion mitigation, where operators and engineers need to understand the basis of AI-driven recommendations and decisions (Giannotti et al., 2023).

AI-Integrated Robotic Inspection Systems:

Research is exploring the integration of AI with robotic inspection systems for autonomous corrosion detection and monitoring. This involves the development of AI-driven robotic platforms capable of navigating complex industrial environments and conducting corrosion inspections.

Smart Coatings with Embedded Sensors:

The development of smart coatings with embedded IoT sensors is an area of ongoing research. These coatings can provide real-time feedback on corrosion conditions, enabling early detection and targeted maintenance.

Multi-Modal Data Fusion:

Researchers are exploring the integration of data from multiple sources, such as visual inspection, ultrasonic testing, and IoT sensors, for comprehensive corrosion assessment. Multi-modal data fusion aims to provide a more holistic understanding of corrosion processes (Beach, 2013).

Digital Twins for Corrosion Prediction:

Digital twins, virtual replicas of physical systems, are being used for corrosion prediction and monitoring. Future developments may involve refining digital twin models to simulate corrosion processes accurately and predict material degradation in real-time (Boje et al. 2020).

Blockchain for Data Integrity:

Research is examining the application of blockchain technology to ensure the integrity and security of corrosion-related data. Blockchain can provide a tamper-proof and transparent record of data collected by IoT sensors.

Quantum Computing for Corrosion Modeling:

The potential use of quantum computing in corrosion modeling is a frontier area of research. Quantum computing's capacity for processing complex calculations may offer new insights into corrosion mechanisms and accelerate the development of corrosion-resistant materials.

Human-in-the-Loop Systems:

Human-in-the-loop systems involve the collaboration between AI algorithms and human experts. Ongoing research explores how human expertise can complement AI in corrosion mitigation, especially in interpreting complex data patterns and making informed decisions (Chen et al., 2023).

Climate-Adaptive Corrosion Strategies:

Researchers are investigating the impact of climate change on corrosion and developing adaptive strategies. This includes studying the correlation between changing environmental conditions and corrosion rates, leading to the development of climate-resilient corrosion control measures.

Standardization and Industry Collaboration:

Ongoing efforts involve standardizing protocols, communication formats, and data exchange mechanisms in the AI and IoT corrosion mitigation landscape. Collaboration within industries and standardization bodies helps establish best practices and interoperability.

Lifecycle Assessment of Corrosion Control Measures:

Researchers are increasingly focusing on the lifecycle assessment of corrosion control measures, considering environmental and economic sustainability. This involves evaluating the long-term impact and effectiveness of different corrosion prevention strategies.

Social and Ethical Implications:

As AI and IoT play a more significant role in corrosion mitigation, researchers are exploring the social and ethical implications. This includes addressing issues related to bias in AI models, privacy concerns, and the responsible use of technology in sensitive industrial applications (Chen, 2023).

Ongoing research is expected to contribute to the refinement and advancement of AI and IoT technologies in corrosion mitigation, ultimately improving the resilience and sustainability of infrastructure across various industries.

7. CONCLUSIONS

The chapter on "Application of AI and IoT for Corrosion Mitigation in Chemical Engineering Processes" underscores the critical role that the integration of Artificial Intelligence (AI) and the Internet of Things (IoT) plays in revolutionizing corrosion mitigation strategies. It has been established that corrosion poses significant challenges in chemical engineering processes, leading to maintenance issues, energy inefficiency, environmental concerns, safety risks, and increased maintenance costs. Environmental implications include the release of harmful substances and the depletion of resources, emphasizing the need for sustainable corrosion control. AI and IoT technologies offer real-time monitoring, predictive analytics, and adaptive control strategies for corrosion mitigation.

AI involves advanced algorithms and machine learning models that can analyze data and make predictions, while IoT comprises interconnected devices equipped with sensors, enabling real-time data collection and communication. AI algorithms and IoT devices collaboratively collect, process, and analyze corrosion-related data in real-time. This real-time capability allows for immediate detection of corrosion trends, anomalies, and potential issues. The synergies between AI and IoT enable proactive corrosion control measures by predicting potential issues before significant damage occurs. Adaptive learning and continuous improvement mechanisms enhance the accuracy and effectiveness of corrosion mitigation strategies over time.

Case studies considered demonstrate successful implementations of AI in corrosion control in industries such as oil and gas, chemical processing, and renewable energy. These implementations highlight the tangible benefits of AI in reducing downtime, improving safety, and optimizing maintenance. Ongoing research explores advanced sensor technologies, edge computing, explainable AI, and quantum computing for corrosion mitigation.

Addressing data security and privacy concerns, ensuring interoperability, and managing the reliability of sensor data are challenges associated with AI and IoT in corrosion mitigation. Cost considerations, standardization issues, and the need for human-in-the-loop systems are also important aspects to be addressed.

In conclusion, the application of AI and IoT in corrosion mitigation represents a paradigm shift in how industries approach the challenges posed by corrosion. Leveraging these technologies enables a holistic, data-driven, and proactive approach that not only preserves critical infrastructure but also aligns with broader environmental and economic sustainability goals in chemical engineering processes.

8. REFERENCES

Aba, E. N., Olugboji, O. A., Nasir, A., Olutoye, M. A., & Adedipe, O. (2020) Development of a petroleum pipeline monitoring system for characterization of damages using a Fourier transform. Niger J Technol (NIJOTECH) 39(2), 442–451. https ://doi.org/10.4314/njt. v39i2.14

Ahmed S., F. Le Mou¨el, N. Stouls, and Jilles Dibangoye, "R-MDP: A Game Theory Approach for Fault-Tolerant Data and Service Management in Crude Oil Pipeline Monitoring System," in Proceedings of the 19th International Conference on Mobile and Ubiquitous Systems (MobiQuitous). Springer, Nov. 2022.

Ahmed S., Fr´ed´eric Le Mou¨el, and N. Stouls, "Resilient IoT-based Monitoring System for Crude Oil Pipelines," in Proceedings of the 7th International Conference on Internet of Things: Systems, Management and Security (IOTSMS). IEEE, Dec. 2020.

Ahmed S., Fr´ed´eric Le Mou¨el, N. Stouls, and G. L. Kouyi, "HyDiLLEch: a WSN-based Distributed Leak Detection and Localisation in Crude Oil Pipelines," in Proceedings of the 35th International Conference on Advanced Information Networking and Applications (AINA-2021). Springer, May 2021.

Akhtar, M., & Moridpour, S. (2021). A Review of Traffic Congestion Prediction Using Artificial Intelligence. In Journal of Advanced Transportation (Vol. 2021). https://doi.org/10.1155/2021/8878011

Ang, L. M., Seng, K. P., & Wachowicz, M. (2022). Embedded intelligence and the data-driven future of application-specific Internet of Things for smart environments. In International Journal of Distributed Sensor Networks (Vol. 18, Issue 6). https://doi.org/10.1177/15501329221102371 Electronic copy available at: https://ssrn.com/abstract=4642197

Arun Kumar, G. S., Roy, A., Singh, R., Gehlot, A., Iqbal, M. I., & Akram, S. V. (2023). A Comprehensive Approach to Real-time Site Monitoring and Risk Assessment in Construction Settings using Internet of Things and Artificial Intelligence. SSRG International Journal of Electronics and Communication Engineering, 10(8). https://doi.org/10.14445/23488379/IJEEE-V10I8P111

Beach, T. H., Rana, O. F., Rezgui, Y. Y., & Parashar, M. (2013). Cloud computing for the architecture, engineering & construction sector: Requirements, prototype & experience. Journal of Cloud Computing, 2(1). https://doi.org/10.1186/2192-113X-2-8

Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. In Automation in Construction (Vol. 114). https://doi.org/10.1016/j.autcon.2020.103179

Chen X., Wang X & Qu Y. (2023) Constructing Ethical AI Based on the "Human-in-the-Loop" System, Systems, 11(11), 548; https://doi.org/10.3390/systems11110548

Chen, X. **(2023)** Ethical Governance of AI: An Integrated Approach via Human-in-the-Loop Machine Learning. *Comput. Sci. Math. Forum.*, *8*, 29.

De Masi, G., Vichi, R., Gentile, M., Bruschi, R., Gabetta, G., (2014). A neural network predictive model of pipeline internal corrosion profile. In: Proceedings of the 1st International Conference on Systems Informatics, Modeling and Simulation. pp. 18–23.

Ding, J. (2022). Construction of a Safety Management System for University Laboratories Based on Artificial Intelligence and IoT Technology. In International Transactions on Electrical Energy Systems (Vol. 2022). https://doi.org/10.1155/2022/7914454

Ding, Z., Jiang, S., Xu, X., & Han, Y. (2022). An Internet of Things based scalable framework for disaster data management. Journal of Safety Science and Resilience, 3(2). https://doi.org/10.1016/j.jnlssr.2021.10.005

Elechi, P., Orike, S., & Douglas, H. I. (2020). Predictive Model for Corrosion Control in Crude Oil and Gas Production Facilities, International Journal of Analytical and Applied Chemistry, 6(2), 2582 – 5933.

Elsisi, M., Tran, M. Q., Mahmoud, K., Lehtonen, M., & Darwish, M. M. F. (2021). Deep learning-based industry 4.0 and internet of things towards effective energy management for smart buildings. Sensors (Switzerland), 21(4). https://doi.org/10.3390/s21041038

Fortino, G., Guerrieri, A., Russo, W., Savaglio, C. (2014). Middlewares for Smart Objects and Smart Environments: Overview and Comparison. In: Fortino, G., Trunfio, P. (eds) Internet of Things Based on Smart Objects. Internet of Things. Springer, Cham. URL: https://doi.org/10.1007/978-3-319-00491-4_1 (accessed 26.04.2022).

Giannotti F., Naretto F., Bodria F. (2023) Explainable for Trustworthy AI, In book: Human-Centered Artificial Intelligence, DOI:10.1007/978-3-031-24349-3_10

Garlik B. (2022). Energy Centers in a Smart City as a Platform for the Application of Artificial Intelligence and the Internet of Things. Applied Sciences (Switzerland), 12(7). https://doi.org/10.3390/app12073386

Honeywell International Inc. Predict®-RT: Real Time Corrosion Prediction and Management; Product Information Note. Available from: https://www.honeywellforge.ai/us/en/products/industrial-operations/predict-corrosion-suite, accessed Dec. 11, 2023

Howard, A. G., Zhu, M., Chen, B., Kalenichenko, D., Wang, W., Weyand, T., Andreetto, M., & Adam, H. (2017). Mobilenets: Efficient convolutional neural networks for mobile vision applications, arXiv preprint arXiv:1704.04861.

Jahanshahi, M. R., & Masri, S. F. (2013). Parametric performance evaluation of wavelet-based corrosion detection algorithms for condition assessment of civil infrastructure systems. *J Comput Civil Eng.,* 27(4), 345–357.

Jan, Z., Ahamed, F., Mayer, W., Patel, N., Grossmann, G., Stumptner, M., & Kuusk, A. (2023). Artificial intelligence for industry 4.0: Systematic review of applications, challenges, and opportunities. Expert Systems with Applications, 216. https://doi.org/10.1016/j.eswa.2022.119456

Jiang, Y., Yu, Y., Kong, M., Mei, Y., Yuan, L., Huang, Z., Kuang, K., Wang, Z., Yao, H., Zou, J., Coley, C. W., & Wei, Y. (2023). Artificial Intelligence for Retrosynthesis Prediction. In Engineering. https://doi.org/10.1016/j.eng.2022.04.021

Jing, X., Zhu, R., Lin, J., Yu, B., & Lu, M. (2022). Education Sustainability for Intelligent Manufacturing in the Context of the New Generation of Artificial Intelligence. Sustainability (Switzerland), 14(21). https://doi.org/10.3390/su142114148

Jingyi, Q., Hua, L., Xiu, C., & Wen, F. (2020). Explore and practice of china's intelligent "new engineering" — based on the grounded theory. International Journal of Information and Education Technology, 10(8). https://doi.org/10.18178/ijiet.2020.10.8.1436

Khan, W. Z., Aalsalem, M. Y., Khan, M. K., Hossain, M. S., & Atiquzzaman, M. (2017). A reliable Internet of Things based architecture for oil and gas industry. International Conference on Advanced Communication Technology, ICACT, (pp. 705–710). IEEE. 10.23919/ICACT.2017.7890184

Khayatazad, M., De-Pue, L., & De-Waele, W. (2020). Detection of corrosion on steel structures using automated image processing. *Developments in the Built Environment*, 3, 100022.

Kor, M., Yitmen, I., & Alizadehsalehi, S. (2023). An investigation for integration of deep learning and digital twins towards Construction 4.0. Smart and Sustainable Built Environment, 12(3). https://doi.org/10.1108/SASBE-08-2021-0148

Liang, X. L., & Xu, J. (2021). Biased ReLU neural networks. Neurocomputing 423, 71–79. doi: 10.1016/j.neucom.2020.09.050

Lin, G., Tang, Y., Zou, X., Xiong, J. & Fang, Y. (2020).``Color-, depth-, and shape-based 3D fruit detection,'' *Precis. Agricult.*, vol. 21, no. 1, pp. 1 – 17, Feb. 2020.

Liu, C., & Peng, Z. (2019). A review on the application of internet of things in oil and gas industry. Journal of Natural Gas Science and Engineering, 66, 36-46.

Luo, J. (2022). A Bibliometric Review on Artificial Intelligence for Smart Buildings. In Sustainability (Switzerland) (Vol. 14, Issue 16). https://doi.org/10.3390/su141610230

Mao, Y., & Zhang, L. (2021). Optimization of the Medical Service Consultation System Based on the Artificial Intelligence of the Internet of Things. IEEE Access, 9. https://doi.org/10.1109/ACCESS.2021.3096188

Mazumder R.K., Salman A.M., Li Y. (2021) Failure risk analysis of pipelines using data-driven machine learning algorithms. Struct. Saf., 89 , Article 102047

Mohamed El Abd, N. (2023). Smart monitoring solution through internet of things utilization to achieve resilient preservation. Ain Shams Engineering Journal, 14(6). https://doi.org/10.1016/j.asej.2023.102176

NACE International. (2016). Corrosion Costs and Preventive Strategies in the United States. Retrieved from https://impact.nace.org/Cost-of-Corrosion.aspx

Niyonambaza, I., Zennaro, M., & Uwitonze, A. (2020). Predictive maintenance (Pdm) structure using internet of things (iot) for mechanical equipment used into hospitals in Rwanda. Future Internet, 12(12). https://doi.org/10.3390/fi12120224

Nwakiri. I, Oduola K., Matthew E., Real-time artificial intelligent based corrosion mitigation model for oil and gas facilities, 6th International Midstream/Downstream Oil & Gas Conference, PH, NLNG_CGRP/NSChE, Sept. 2023.

Oduola, M.K. Engineering Practice in the Era of Digital Technological Advances, Engineering Week Lecture, NSE Bonny Branch, Bonny, Rivers, Nov. 2023.

Olabi, A. G., & Wilberforce, T. (2019). A review on the corrosion of metals in petroleum industry. Journal of Natural Gas Science and Engineering, 70, 102923.

Pankaj Mohindru (2023) A review on smart sensors used in chemical industry 4.0 Journal of Data Acquisition and Processing Vol. 38 (2), 1172-1188.

Prabhakar, V., Belarmin Xavier, C. S., & Abubeker, K. M. (2023). A Review on Challenges and Solutions in the Implementation of Ai, IoT and Blockchain in Construction Industry. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2023.03.535

Rane, Nitin and Choudhary, Saurabh and Rane, Jayesh (2023) Artificial Intelligence (AI) and Internet of Things (IoT) - based sensors for monitoring and controlling in architecture, engineering, and construction: applications, challenges, and opportunities. http://dx.doi.org/10.2139/ssrn.4642197

Safuriyawu Ahmed. Resilient IoT-based monitoring system for the Nigerian oil and gas industry. Networking and Internet Architecture [cs.NI]. INSA de Lyon, 2022. English. ffNNT : 2022ISAL0120ff. fftel-04107131

Schneller, W., Leitner, M., Maier, B., Grün, F., Jantschner, O., Leuders, S., & Pfeifer, T. (2022). Artificial intelligence assisted fatigue failure prediction. International Journal of Fatigue, 155. https://doi.org/10.1016/j.ijfatigue.2021.106580

Simonyan, K., & Zisserman, A. (2014). Very deep convolutional networks for Large-scale image Recognition[C]//computer vision and pattern recognition. 1–14.

Song, J., & Liang, J. (2022). Agricultural Internet of Things Application in the Construction of Regional Smart Cities. Mobile Information Systems, 2022. https://doi.org/10.1155/2022/2644867

Thibbotuwa, U.C.; Cortés, A.; Irizar, A. (2022) Ultrasound-Based Smart Corrosion Monitoring System for Offshore Wind Turbines. Appl. Sci. 12, 808. https://doi.org/10.3390/app12020808.

Tian, Y., Yang, G., Wang, Z., Wang, H., Li, E., & Liang, Z. (2019).``Apple detection during different growth stages in orchards using the improved YOLO-V3 model," *Comput. Electron. Agricult.*, 157, 417 – 426, doi: 10.1016/j.compag.2019.01.012.

Turner, C. J., Oyekan, J., Stergioulas, L., & Griffin, D. (2021). Utilizing Industry 4.0 on the Construction Site: Challenges and Opportunities. IEEE Transactions on Industrial Informatics, 17(2). https://doi.org/10.1109/TII.2020.3002197

van Smeden, M., Heinze, G., van Calster, B., Asselbergs, F. W., Vardas, P. E., Bruining, N., de Jaegere, P., Moore, J. H., Denaxas, S., Boulesteix, A. L., & Moons, K. G. M. (2022). Critical appraisal of artificial intelligence-based prediction models for cardiovascular disease. European Heart Journal, 43 (31). https://doi.org/10.1093/eurheartj/ehac238

Wang, M., Wang, C. C., Sepasgozar, S., & Zlatanova, S. (2020). A systematic review of digital technology adoption in off-site construction: Current status and future direction towards industry 4.0. In Buildings (Vol. 10, Issue 11). https://doi.org/10.3390/buildings10110204

Wu, H. te. (2022). The internet-of-vehicle traffic condition system developed by artificial intelligence of things. Journal of Supercomputing, 78(2). https://doi.org/10.1007/s11227-021-03969-0

Yang, D., Zhang, X., Zhou, T., Wang, T., & Li, J. (2023). A Novel Pipeline Corrosion Monitoring Method Based on Piezoelectric Active Sensing and CNN. Sensors 2023, 23, 855. https://doi.org/10.3390/s23020855

Zhang, H., & Cheng, S. (2022). Application of Internet of Things Technology Based on Artificial Intelligence in Electronic Information Engineering. Mobile Information Systems, 2022. https://doi.org/10.1155/2022/2888925

Zhang, Y., Geng, P., Sivaparthipan, C. B., & Muthu, B. A. (2021). Big data and artificial intelligence based early risk warning system of fire hazard for smart cities. Sustainable Energy Technologies and Assessments, 45. https://doi.org/10.1016/j.seta.2020.100986

Zinno, R., Haghshenas, S. S., Guido, G., & Vitale, A. (2022). Artificial Intelligence and Structural Health Monitoring of Bridges: A Review of the State-of-the-Art. In IEEE Access (Vol. 10). https://doi.org/10.1109/ACCESS.2022.3199443