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Comparative Review of Cathodic Protection Studies in Nigerian Soil and Marine Environments: Towards Defining Effective Voltage Ranges

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Abstract

Corrosion of buried and submerged steel infrastructure is a critical challenge in Nigeria's oil, gas, and water industries, resulting in significant economic losses and environmental risks. Cathodic protection (CP) is widely adopted to mitigate corrosion, yet studies conducted in Nigerian environments—such as swampy soils, loamy soils, and saline seawater—report varying levels of effectiveness without defining a clear operational voltage range. This paper reviews and compares three notable CP studies: swampy soil environments (Ekott et al., 2013), buried steel pipelines in the Niger Delta (Ekott et al., 2014), and seawater immersion (Ekott&Etukudo, 2016). Findings reveal that protection efficiencies ranged from 53% in saline media to over 90% in soil environments, but the applied CP voltages were not systematically correlated with current density or long-term corrosion behaviour. This gap highlights the need for controlled, multi-environment experimentation aimed at defining effective CP voltage windows. The paper proposes a conceptual framework for future research to address this gap and outlines how low-cost data acquisition and monitoring innovations can enhance future CP studies and field practices in Nigeria.

Keywords: *Cathodic protection, corrosion, pipeline integrity, corrosion monitoring, oil and gas.*

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I. INTRODUCTION

CORROSION is a major challenge affecting metallic infrastructure worldwide and remains one of the leading causes of deterioration in pipelines, storage tanks, marine facilities, and other critical engineering assets [1]. Its impact is particularly significant in the oil- and gas-producing Niger Delta region of Nigeria, where buried and submerged steel structures are continuously exposed to aggressive electrolytic environments. Waterlogged soils, swampy terrains, and saline marine conditions accelerate corrosion processes, leading to pipeline failures, environmental pollution, production losses, and increased maintenance costs [2]. Studies have reported that corrosion contributes significantly to pipeline failures in the region, highlighting the need for effective and sustainable corrosion control strategies [3].

Cathodic protection (CP) is one of the most widely adopted techniques for mitigating corrosion in buried and submerged metallic structures. By shifting the electrochemical potential of a metal surface to a protected state, CP suppresses anodic dissolution and reduces the corrosion rate [4]. The two principal CP methods are sacrificial anode cathodic protection and impressed current cathodic protection. Although these techniques have demonstrated effectiveness in diverse environments, their performance is influenced by several factors, including electrolyte resistivity, salinity, pH, coating condition, protection potential, and current density [5].

In addition to proper system design, continuous monitoring and performance evaluation are essential for effective cathodic protection. Recent advances in Industry 4.0 have expanded the scope of cathodic protection beyond conventional corrosion prevention to intelligent asset management. The integration of Internet of Things (IoT) technologies, wireless communication, remote monitoring, predictive analytics, and automated system control has significantly enhanced cathodic protection monitoring by enabling the real-time acquisition, transmission, and visualization of protection data. These technologies facilitate continuous assessment of protection performance, early fault detection, improved operational reliability, and optimised corrosion management for critical infrastructure [6]. Nevertheless, protection effectiveness continues to be evaluated using established criteria based on potential measurements and related electrochemical monitoring techniques, which remain fundamental for assessing the performance of cathodic protection systems [7].

These developments improve operational reliability, reduce the need for frequent field inspections, and provide opportunities for predictive maintenance and intelligent asset management. However, environmental variations can significantly affect CP performance, making it difficult to apply a single protection criterion across different operating conditions. Consequently, understanding the relationship between protection potential, current density, and environmental characteristics remains an important engineering challenge.

Several studies have investigated the application of cathodic protection in Nigerian environments. Ekott et al. reported protection efficiencies of up to 90% in swampy soil conditions [8]. Ekott, Akpabio, and Etukudo examined corrosion challenges associated with buried steel oil pipelines in the Niger Delta [3], while Ekott and Etukudo evaluated CP performance in seawater environments and reported lower protection efficiency due to the influence of high salinity [8]. Collectively, these studies demonstrate the benefits of cathodic protection under local environmental conditions and provide valuable insight into the influence of soil and marine characteristics on protection effectiveness.

Despite these contributions, important gaps remain. Existing studies primarily focused on demonstrating CP effectiveness within specific environments and did not establish a defined relationship between protection potential, current density, and protection performance across multiple electrolytic conditions. Consequently, CP system design often relies on generalized standards or empirical practices that may not adequately reflect local environmental characteristics. Furthermore, comparative evaluation of CP behaviour across soil and marine environments remains limited.

This paper presents a comparative analysis of selected cathodic protection studies conducted in Nigerian soil and marine environments. The study reviews their methodologies, findings, and limitations, identifies key knowledge gaps relating to protection potential and current density, and highlights the need for controlled multi-environment investigations. In addition, recent advances in intelligent cathodic protection monitoring are examined to demonstrate how modern sensing, remote monitoring, and digital data acquisition technologies can support improved corrosion management. The ultimate objective is to provide a foundation for future research aimed at establishing environment-specific cathodic protection voltage ranges while supporting the development of intelligent and remotely monitored cathodic protection systems for critical infrastructure.

II. BACKGROUND ON CATHODIC PROTECTION

A. Principles of Corrosion and Cathodic Protection

Corrosion of steel in soil and aqueous environments is an electrochemical process involving simultaneous anodic and cathodic reactions [1]. At anodic regions, iron dissolves into the electrolyte, while reduction reactions occur at cathodic sites. If left uncontrolled, these reactions result in continuous metal loss, deterioration of mechanical integrity, and eventual structural failure. Cathodic protection (CP) mitigates corrosion by shifting the electrochemical potential of the steel surface to a protected state, causing the structure to function as the cathode of an electrochemical cell [1], [4]. By supplying external electrons, anodic dissolution is suppressed and corrosion rates are significantly reduced [1], [10].

B. Cathodic Protection Methods

Two principal methods of cathodic protection are widely used in engineering practice [4], [11]:

• Sacrificial Anode Cathodic Protection (SACP)

In this method, a more active metal such as zinc, magnesium, or aluminium is electrically connected to the steel structure. The sacrificial anode corrodes preferentially and supplies protective current to the structure. SACP systems are simple, self-regulating, and require no external power source. However, their effectiveness is limited by the finite life and current output capability of the sacrificial anodes.

• Impressed Current Cathodic Protection (ICCP)

In ICCP systems, protective current is supplied by an external DC power source through inert or semi-inert anodes such as graphite, mixed metal oxide, or high-silicon cast iron. ICCP systems provide greater flexibility in controlling protection potential and current density, making them suitable for large structures and long pipelines [11]. However, improper operation may result in overprotection, coating disbondment, or hydrogen-related effects, necessitating proper monitoring and control.

C. Role of Protection Potential and Current Density

The effectiveness of cathodic protection depends on both protection potential and current density. Industry standards commonly adopt a protection criterion of approximately –850 mV with respect to a $Cu/CuSO_4$ reference electrode for buried steel structures [4], [7]. Achieving and maintaining this protection level requires the application of sufficient protective current to polarize the structure.

Current density represents the amount of protective current supplied per unit surface area of the structure and is a critical design parameter in CP systems [10], [11], [12]. Required current density varies significantly with coating condition, environmental resistivity, and electrolyte composition. Well-coated structures generally require lower protective current densities than bare or deteriorated structures. Similarly, different environments demand different current densities to achieve effective protection. Consequently, protection potential alone may not fully describe CP performance without considering the associated current density requirements.

D. Environmental Factors Affecting CP Performance

The performance of CP systems is strongly influenced by environmental conditions [5], [10], [11].

• Loamy and swampy soils often exhibit relatively low resistivity, enabling efficient current distribution and improved protection performance.

• Seawater possesses high conductivity and salinity, which can accelerate corrosion processes and increase protection demands.

• Acidic environments may promote hydrogen evolution and require tighter control of protection potential and current density.

• Coating degradation, moisture content, temperature, and electrolyte chemistry also influence the amount of protective current required.

These variations demonstrate that CP parameters established for one environment may not necessarily provide optimum performance in another.

E. Monitoring and Performance Evaluation

Effective cathodic protection requires continuous monitoring and performance evaluation to ensure that protection criteria are achieved and maintained [7], [11]. Conventional monitoring techniques commonly employed in CP systems include:

- Weight-loss measurements for estimating corrosion rates.
- Pipe-to-soil or structure-to-electrolyte potential measurements using stable reference electrodes such as $Cu/CuSO_4$ or Ag/AgCl.
- Current monitoring using shunt resistors, current probes, or data acquisition systems.
- Close Interval Potential Surveys (CIPS) and On/Off potential measurements for field assessment of pipeline protection performance.

In practice, automated interrupters are frequently employed to temporarily disconnect the protective current, allowing more accurate potential measurements by minimizing IR-drop effects [7]. These conventional techniques remain fundamental for evaluating CP performance and verifying compliance with established protection criteria.

Recent advances in sensing, communication, and digital technologies have significantly transformed cathodic protection monitoring. Modern CP systems increasingly incorporate Internet of Things (IoT) devices, wireless sensors, cloud-based data acquisition, and remote monitoring platforms to enable continuous real-time assessment of protection potentials, current densities, and system health [6]. The integration of Industry 4.0 technologies, including smart sensors, automated data logging, cloud computing, and digital communication, provide improved operational reliability, facilitate predictive maintenance, and reduce the need for frequent field inspections [6].

Emerging Industry 4.0 technologies are also creating opportunities for autonomous cathodic protection systems capable of predictive maintenance, intelligent decision support, and real-time remote monitoring. Recent studies have demonstrated the feasibility of transmitting protection data to centralized monitoring stations for continuous analysis and decision-making [6], [13]

III. REVIEW OF CATHODIC PROTECTION STUDIES IN NIGERIAN ENVIRONMENTS

A. Cathodic Protection Performance in Swampy Soil Environments

1. Background

Swampy soils are common within the Niger Delta region and are characterized by high moisture content and relatively low resistivity. While these conditions facilitate current distribution in cathodic protection systems, they also create an aggressive environment for buried steel structures. A study conducted in swampy soil conditions investigated the effectiveness of impressed current cathodic protection (ICCP) under representative Niger Delta conditions [8].

2. Methodology

• Steel coupons were buried in swampy soil samples contained in experimental test tanks.
• A 12 V DC source supplied impressed current through zinc and aluminium anodes.
• Corrosion performance was evaluated using weight-loss measurements over an extended exposure period [8].

3. Results and Discussion

• Protection efficiencies exceeding 90% were reported.
• The high conductivity of the swampy soil promoted effective current distribution and improved protection performance.
• The results demonstrated that CP can significantly reduce corrosion in waterlogged soil environments [8].

4. Limitations

• Only a single soil type was investigated.
• The relationship between applied voltage, current density, and protection effectiveness was not established.
• Performance evaluation relied primarily on weight-loss measurements, without continuous monitoring or electrochemical potential measurements.

These limitations indicate the need for more comprehensive investigations involving multiple environmental conditions and operational parameters.

B. Cathodic Protection of Buried Oil Pipelines in the Niger Delta

1. Background

Buried oil and gas pipelines in the Niger Delta traverse environments with varying soil resistivity, moisture content, and chemical composition. These variations influence both corrosion behaviour and cathodic protection effectiveness. A field-based study examined pipeline failures and CP practices in operational pipeline systems within the region [3].

2. Methodology

• Field observations were conducted on operating buried pipeline networks.
• Maintenance records, failure statistics, and CP operational data were reviewed.
• The study considered pipelines transporting crude oil, natural gas, and refined petroleum products [3].

3. Results and Discussion

• Corrosion was identified as a significant contributor to pipeline failures, accounting for approximately 18% of reported failures.
• Cathodic protection was confirmed as an essential corrosion mitigation strategy.
• Variations in soil conditions and maintenance practices influenced CP effectiveness.
• The findings highlighted the importance of monitoring, inspection, and maintenance in sustaining pipeline integrity [3], [7].

4. Limitations

• The investigation was largely observational.
• Controlled laboratory measurements were not performed.
• No systematic analysis of protection potential, current density, or voltage optimisation was undertaken.
• The study focused primarily on failure assessment rather than electrochemical performance evaluation.

Consequently, the study provided valuable operational insight but offered limited information regarding optimum CP operating conditions.

C. Cathodic Protection Performance in Seawater Environments

1. Background

Marine structures and offshore facilities operate in highly conductive saline environments where corrosion rates can be significantly higher than those encountered in most soils. A study conducted using seawater obtained from the Qua Iboe coastal area investigated the effectiveness of ICCP under saline conditions [9].

2. Methodology

• Steel specimens were immersed in seawater with a salinity of approximately 32.47 ppt.
• ICCP was applied using a 12 V DC source and zinc anode.
• Corrosion behaviour was assessed using periodic weight-loss measurements over a 70-day exposure period [9].

3. Results and Discussion

• Unprotected specimens experienced substantially higher material loss than protected specimens.
• A protection efficiency of approximately 53% was achieved.
• Protection effectiveness was significantly lower than values reported for swampy and loamy soil environments.
• The results suggest that high salinity increases corrosion severity and may require different operating conditions to achieve effective protection [9].

4. Limitations

• Only a single operating voltage was investigated.
• Potential measurements and current density assessments were not reported.
• Corrosion evaluation relied solely on weight-loss analysis.
• The influence of varying protection potentials and current densities was not examined.

These observations suggest that fixed-voltage operation may not provide optimum protection in highly saline environments and reinforce the need for systematic voltage-current density investigations.

D. Comparative Observations

The reviewed studies collectively demonstrate that cathodic protection is effective in reducing corrosion across Nigerian soil and marine environments. However, protection performance varied considerably with environmental conditions. Swampy soil environments exhibited the highest reported protection efficiencies, whereas seawater environments showed substantially lower performance under similar operating conditions [8]–[9].

A common limitation across the reviewed studies is the absence of systematic evaluation of protection potential and current density. Although CP effectiveness was demonstrated, the studies did not establish optimum operating ranges or voltage-current relationships for different environments. Furthermore, monitoring approaches were generally limited, with little use of continuous potential measurement, current logging, or advanced performance assessment techniques [7].

These findings highlight the need for controlled multi-environment investigations aimed at defining effective protection voltage ranges and current density requirements for Nigerian operating conditions.

IV. COMPARATIVE ANALYSIS AND IDENTIFICATION OF RESEARCH GAPS

A. Comparative Analysis

TABLE I
COMPARATIVE ANALYSIS OF CATHODIC PROTECTION STUDIES IN NIGERIAN ENVIRONMENTS

Environment / Study	CP Approach	Monitoring Method	Protection Performance	Key Observation	Major Limitation
Swampy Soil [8]	ICCP (Zn/Al anodes)	Weight-loss measurement	~90% efficiency	High soil conductivity improved current distribution and CP effectiveness.	No potential monitoring; voltage-current density relationship not established.
Buried Oil Pipelines [3]	Operational field CP systems	Field observations and maintenance records	Not quantified	CP was essential for pipeline integrity; corrosion contributed significantly to failures.	No controlled voltage or current density evaluation; observational study only.
Seawater [9]	ICCP (Zn anode)	Weight-loss measurement	53% efficiency	High salinity increased corrosion severity and reduced protection effectiveness.	Fixed-voltage operation; no potential or current density measurements.
Nigeria CP Monitoring Study [7]	Operational CP systems	Pipe-to-soil potential measurements, CIPS, On/Off surveys	Site dependent	Monitoring and performance assessment are critical for effective CP operation.	Did not establish optimum protection voltage-current operating windows.
Industry 4.0 Monitoring Review [14]	Smart CP monitoring systems	Smart sensors, IoT platforms, cloud computing, remote monitoring	Conceptual review	Modern CP systems increasingly depend on continuous monitoring and automation.	Limited experimental validation of protection voltage optimisation.

The reviewed studies collectively demonstrate that cathodic protection can significantly reduce corrosion in both soil and marine environments. However, protection effectiveness varies considerably with environmental conditions and operational practices. Swampy soil environments exhibited the highest reported protection efficiencies, while seawater environments showed substantially lower performance under similar operating conditions [8]–[9].

A common observation across the reviewed studies is the importance of monitoring and performance evaluation. Field investigations and recent monitoring-oriented studies indicate that effective cathodic protection depends not only on the application of protective current but also on continuous assessment of protection potentials and system performance [7], [14].

Despite their contributions, none of the reviewed studies established a quantitative relationship between protection potential, current density, and corrosion protection effectiveness across multiple environments. Consequently, the optimum operating window for cathodic protection under Nigerian conditions remains undefined.

B. Identified Research Gaps

Despite demonstrating the effectiveness of cathodic protection under Nigerian conditions, the reviewed studies reveal several limitations that restrict their application to CP system optimization and design.

i. Absence of Defined Protection Voltage Ranges

The reviewed investigations generally employed fixed operating voltages without systematic variation. Consequently, neither the minimum effective protection voltage nor the optimum operating range for different environments was established. This limitation hinders the development of environment-specific CP design criteria.

ii. Lack of Voltage–Current Density Relationships

None of the studies quantified the relationship between applied voltage, resulting current density, and corrosion protection effectiveness. Since current density is a critical parameter in cathodic protection design, the absence of such data limits the ability to optimize CP performance under Nigerian operating conditions.

iii. Limited Monitoring and Performance Assessment

Most studies relied primarily on weight-loss measurements or observational data. Continuous monitoring techniques such as reference-electrode potential measurements, current logging, and automated data acquisition were largely absent. As a result, the actual protection potential achieved during operation remains uncertain.

iv. Absence of Multi-Environment Comparative Testing

The reviewed studies investigated individual environments independently. No controlled side-by-side evaluation of cathodic protection performance in soil, seawater, and acidic environments was conducted under standardized operating conditions. Consequently, the development of a reliable voltage-current density operating window applicable to diverse Nigerian environments remains an open research challenge.

v. Limited Integration of Intelligent Monitoring Technologies

Although recent studies have demonstrated the potential of Industry 4.0 technologies, IoT, and digital automation for remote cathodic protection management, their application has largely focused on system monitoring rather than optimisation of protection parameters under varying environmental conditions. Consequently, the integration of intelligent monitoring with environment-specific voltage-current density optimisation remains an important research opportunity [13].

The comparative review presented in the preceding sections highlights significant gaps in the current understanding of cathodic protection performance under different Nigerian operating environments. These observations provide a basis for identifying future research priorities aimed at improving the reliability, optimisation, and monitoring of cathodic protection systems. The conceptual framework shown in Figure 1 summarises the logical progression of this review from the identification of corrosion challenges to the proposed direction for future investigations.

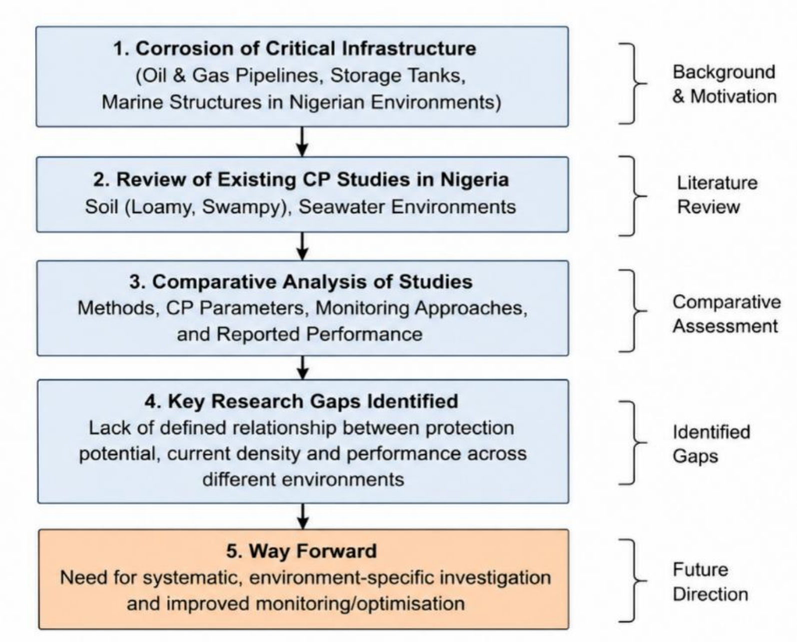

Figure 1. Conceptual framework illustrating the progression from literature review and comparative analysis to the identification of research gaps and future research directions.

V. PROPOSED FRAMEWORK FOR FUTURE RESEARCH

To address the identified research gaps, a structured experimental framework is proposed. The framework combines established cathodic protection principles with modern monitoring and data acquisition techniques to support the development of environment-specific protection criteria for Nigerian operating conditions. The proposed approach is intended to provide both scientific insight and practical engineering guidance for corrosion control applications.

A. Multi-Environment Experimental Design

Future investigations should consider the simultaneous evaluation of cathodic protection performance in representative Nigerian electrolytic environments. These environments may include:

1. Loamy soil
2. Swampy soil
3. Saline seawater
4. Acidic medium

Standardized steel specimens should be exposed under controlled laboratory conditions to enable direct comparison of protection performance across different media.

B. Systematic Voltage and Current Density Evaluation

Unlike previous studies that employed fixed operating conditions, future investigations should systematically vary the applied protection voltage over a controlled range. Corresponding current densities should be monitored continuously to establish voltage-current density-protection relationships for each environment.

Such an approach would facilitate the determination of:

- Minimum effective protection voltage.
- Optimum operating voltage range.
- Current density requirements for different environments.
- Upper operating limits where undesirable effects such as overprotection may occur.

C. Monitoring and Performance Assessment

Performance evaluation should incorporate both conventional and electrochemical monitoring techniques. Recommended assessment methods include:

- Weight-loss measurements for corrosion-rate determination.
- Potential monitoring using appropriate reference electrodes such as $Cu/CuSO_4$ and Ag/AgCl.
- Current density measurements throughout the exposure period.
- Periodic interruption testing to minimize IR-drop effects during potential measurements.

The integration of multiple monitoring techniques would provide a more comprehensive understanding of CP performance than reliance on weight-loss measurements alone.

D. Instrumentation and Data Acquisition

Modern cathodic protection investigations can benefit significantly from intelligent instrumentation, automated monitoring, and digital data acquisition systems capable of continuously recording protection potentials, current densities, operating voltages, environmental parameters, and system status. Compared with conventional manual measurements, continuous monitoring provides more reliable information for evaluating CP performance under varying operating conditions and facilitates early detection of abnormal system behaviour.

A typical experimental setup should incorporate voltage and current sensors, stable reference electrodes, programmable DC power supplies, and a microcontroller-based data acquisition unit capable of recording measurements at predefined intervals. Parameters such as protection potential, output voltage, current density, electrolyte temperature, and environmental conditions should be logged simultaneously to establish the relationship between operating conditions and corrosion protection effectiveness.

Recent developments in Internet of Things (IoT) technologies and Industry 4.0 have further enhanced cathodic protection monitoring by enabling remote acquisition, transmission, storage, and visualization of operational data through cloud-based platforms and wireless communication networks [14]. The integration of smart sensors, wireless communication modules, cloud computing, and real-time dashboards enables continuous system supervision while reducing the need for frequent field inspections. Such technologies also provide opportunities for automated alarm generation, fault diagnosis, predictive maintenance, and long-term performance evaluation.

Furthermore, automated interruption control can be incorporated to minimize IR-drop errors during potential measurements, thereby improving measurement accuracy. Long-term data logging combined with intelligent data processing provides a valuable foundation for developing adaptive cathodic protection systems capable of optimizing protection levels under changing environmental conditions.

The proposed instrumentation framework not only supports the experimental determination of environment-specific voltage-current density operating ranges but also establishes the technological foundation for future intelligent cathodic protection systems incorporating remote monitoring, wireless communication, automated control, and data-driven decision support for critical infrastructure protection.

E. Expected Contributions

Implementation of the proposed framework is expected to generate:

• Environment-specific voltage-current density operating ranges.
• Comparative corrosion-performance data for multiple Nigerian environments.
• Improved understanding of the relationship between protection potential, current density, and protection effectiveness.
• Engineering guidelines for cathodic protection system design and monitoring.
• Foundational data for the development of intelligent and remotely monitored cathodic protection systems.

The resulting knowledge base would contribute toward the establishment of locally relevant cathodic protection criteria and support more reliable corrosion management of critical infrastructure within Nigeria.

VI. CONCLUSION

Cathodic protection remains one of the most effective and widely applied techniques for mitigating corrosion in buried and submerged steel structures. The reviewed studies conducted in Nigerian swampy soil, buried pipeline, and seawater environments demonstrate that CP can significantly reduce corrosion rates, although protection effectiveness varies considerably with environmental conditions. Reported protection efficiencies ranged from approximately 53% in seawater environments to over 90% in swampy soils, highlighting the strong influence of electrolyte characteristics on CP performance.

The comparative analysis revealed several important limitations in the existing body of work. Most studies employed fixed operating conditions and relied primarily on weight-loss measurements, with limited use of continuous monitoring techniques. Furthermore, the relationship between protection potential, current density, and corrosion protection effectiveness remains largely undefined for Nigerian operating environments. As a result, the development of environment-specific cathodic protection criteria remains an unresolved challenge.

To address these limitations, this paper proposed a structured framework for future investigations based on multi-environment testing, systematic voltage variation, current density evaluation, and enhanced monitoring techniques. Such an approach would enable the establishment of environment-specific operating ranges and provide a more comprehensive understanding of CP behaviour under Nigerian conditions.

Beyond conventional corrosion control, future cathodic protection systems should integrate intelligent monitoring, IoT-enabled sensing, cloud computing, predictive analytics, and automated decision support. Such technologies have the potential to facilitate continuous optimisation of protection performance, reduce inspection costs, improve infrastructure reliability, and support the development of intelligent cathodic protection systems for critical oil, gas, marine, and water infrastructure. The proposed framework therefore provides a foundation not only for defining environment-specific voltage-current density operating ranges but also for advancing next-generation intelligent cathodic protection systems based on modern digital monitoring technologies.

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