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Original Research Article

Corrosion Protection of Buried Steel Pipe Coated with Cordia Boraginaceae Exudates

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Abstract: This study investigates the corrosion protection of buried steel pipes coated with Cordia Boraginaceae exudates. Utilizing galvanized steel pipes with an initial diameter of 168.3 mm and a wall thickness of 7.11 mm, the effectiveness of the coatings was evaluated through mechanical and corrosion assessments. Coated samples demonstrated a significant reduction in corrosion rates, averaging approximately 0.5 mm/year, compared to 2.5 mm/year for uncoated samples. Weight loss measurements indicated an average of 3 grams for coated samples versus 15 grams for uncoated samples, highlighting substantial protection. Mechanical tests showed a tensile strength reduction from approximately 400 MPa to 280 MPa for coated samples post-exposure, while yield strength and elongation were also impacted. Adhesion strength measured around 8 MPa, indicating robust bonding between the coating and substrate. Coating porosity was assessed at approximately 5%, demonstrating effective barrier properties against corrosive agents. Environmental factors, such as chloride content (up to 19,500 mg/L) and pH levels (ranging from 7.1 to 8.2), were shown to significantly influence corrosion dynamics. The findings confirm the potential of Cordia Boraginaceae exudates as a sustainable alternative to synthetic corrosion inhibitors, providing effective protection in aggressive environments. This research contributes valuable insights into the application of natural coatings for enhancing the longevity and reliability of buried steel infrastructure.

Keywords: Corrosion Protection, Cordia Boraginaceae, Steel Pipes, Eco-friendly Coatings, Mechanical Properties.

1. INTRODUCTION

Corrosion represents one of the most significant challenges facing modern infrastructure systems, particularly buried steel pipelines forming the backbone of global energy and water distribution networks (McCafferty, 2010). The deterioration of metallic structures through electrochemical processes results in substantial economic losses while posing serious threats to environmental safety and operational reliability (Chen & Zhao, 2017). The complexity of corrosion mechanisms in buried steel infrastructure is amplified by heterogeneous soil environments, varying moisture content, pH fluctuations, and aggressive ions such as chlorides and sulfates (Yahaya *et al.*, 2011).

Traditional corrosion mitigation approaches have relied on synthetic chemical inhibitors and conventional coating systems. However, growing environmental consciousness and stringent regulatory frameworks have necessitated a paradigm shift toward sustainable, eco-friendly alternatives (Sheldon, 2016; Brycki *et al.*, 2018). This transition has catalyzed extensive research into natural products as viable corrosion inhibitors, with plant extracts emerging as promising candidates due to their biodegradability, low toxicity, and abundance of bioactive compounds (Verma *et al.*, 2018; Chigondo & Chigondo, 2016).

Plant-based materials for corrosion protection represent a convergence of traditional knowledge and modern scientific understanding. Various botanical species have demonstrated efficacy in inhibiting corrosion processes through complex mechanisms involving protective barrier formation, metal ion chelation, and corrosive species scavenging (Umoren & Eduok, 2016). Studies indicate that compounds such as

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tannins, alkaloids, flavonoids, and other phenolic constituents contribute to their inhibitive properties (Costa *et al*., 2015; Mari *et al*., 2016).

The Boraginaceae family, comprising numerous species with diverse phytochemical profiles, has garnered attention for materials protection applications. Cordia species are known for their rich exudate compositions containing bioactive compounds that may contribute to corrosion inhibition mechanisms (Amise *et al*., 2016). These natural exudates, traditionally utilized in folk medicine, possess complex chemical structures that can interact with metal surfaces through multiple pathways, potentially forming stable protective films (Ezeugo, 2019).

The investigation of Cordia Boraginaceae exudates as protective coatings addresses critical aspects of modern corrosion science. First, it explores fundamental mechanisms by which natural compounds interact with metallic surfaces under realistic environmental conditions (Fouda *et al*., 2017). Second, it evaluates long-term performance and durability of bio-based protective systems compared to conventional alternatives (Otunyo & Charles, 2017). Third, it assesses economic and environmental implications of implementing sustainable corrosion protection strategies (Otunyo & Charles, 2018).

Environmental conditions significantly influence corrosion protection system performance. Buried steel pipes are subjected to complex soil-structure interactions involving moisture migration, ion transport, and microbial activity that can compromise protective measures over time (Dang *et al*., 2015; Putra *et al*., 2020). The heterogeneous nature of soil environments, characterized by varying pH levels, electrical conductivity, and chemical composition, creates localized corrosion cells leading to pitting and crevice corrosion (Usman *et al*., 2019).

Recent research has highlighted the importance of coating thickness, application methodology, and curing conditions in determining natural protective system effectiveness (Banerjee *et al*., 2012). Studies have demonstrated that optimal coating thickness ranges and proper surface preparation techniques are essential for achieving maximum inhibition efficiency (Okewale & Olaitan, 2017). The interaction between coating properties and environmental factors such as temperature, humidity, and chemical exposure determines long-term protective system performance (Hu *et al.,* 2016).

Corrosion protection system evaluation requires comprehensive assessment methodologies encompassing mechanical properties, electrochemical behavior, and barrier performance (Rosliza *et al*., 2006). Weight loss measurements, corrosion rate calculations, and electrical resistivity testing provide quantitative metrics for comparing different protective approaches (Chuka *et al*., 2014). Advanced characterization techniques enable detailed understanding of coating-substrate interactions and degradation mechanisms governing long-term performance (Hou *et al*., 2018).

Mechanical properties of coated steel systems are crucial for buried infrastructure applications where structural integrity must be maintained under various loading conditions (Loto *et al*., 2013). The influence of coating treatments on tensile strength, yield strength, elongation, and hardness characteristics determine protective system suitability for specific applications (Iyasara & Ovri, 2013). Coating adhesion strength and porosity are particularly important parameters affecting protective barrier durability and effectiveness (Adikari & Munasinghe, 2016).

Effective natural coating system development requires careful consideration of extraction methods, purification processes, and application techniques (Prithiba *et al*., 2014). Different extraction procedures can yield varying concentrations of active compounds, directly influencing inhibition efficiency (Ameh & Eddy, 2016). The standardization of preparation methods is essential for ensuring reproducible results and reliable performance in field applications (Muslim *et al*., 2014).

Accelerated testing protocols play a vital role in evaluating long-term performance of corrosion protection systems within reasonable timeframes (Owate *et al*., 2014). Controlled exposure to aggressive environments allows researchers to predict service life and identify potential failure modes before deployment in actual applications. The correlation between laboratory results and field performance is critical for validating natural coating system effectiveness (Papavinasam, 1999).

The integration of natural exudates into practical coating formulations presents both opportunities and challenges. While these materials offer environmental advantages and potential cost benefits, issues related to consistency, shelf life, and application properties must be addressed. The development of standardized testing protocols and performance criteria is essential for commercial adoption of bio-based corrosion protection systems.

Economic considerations significantly influence the adoption of new corrosion protection technologies. The cost-effectiveness of natural coating systems depends on factors including raw material availability, processing requirements, application complexity, and maintenance needs (Singh *et al*., 2015). Life-cycle cost analysis provides a comprehensive framework for comparing different protection strategies and identifying optimal solutions for specific applications.

This investigation into Cordia Boraginaceae exudates as protective coatings for buried steel pipes represents a significant contribution to sustainable corrosion protection strategies. By systematically evaluating natural coating system performance under controlled conditions, this research provides valuable insights into the potential applications and limitations of bio-based approaches to infrastructure protection.

Statement of the Problem

Corrosion remains one of the foremost challenges in maintaining the integrity of buried steel pipelines, which are essential for the global distribution of energy and water. The electrochemical processes that lead to corrosion can result in significant structural degradation, posing risks to environmental safety and economic stability (McCafferty, 2010). Traditional corrosion mitigation strategies, such as synthetic chemical inhibitors and conventional coatings, often fail to address the increasing environmental concerns and regulatory pressures for sustainable practices (Sheldon, 2016). Therefore, there is an urgent need for innovative, eco-friendly alternatives that can effectively protect steel infrastructures from corrosion while minimizing environmental impact (Verma *et al*., 2018).

Research Gap

Despite the growing interest in natural corrosion inhibitors, there is a notable lack of comprehensive studies that evaluate the long-term efficacy of plant-based coatings, particularly those derived from Cordia Boraginaceae exudates. Existing literature primarily focuses on synthetic options, leaving a significant gap in understanding the mechanisms by which natural products can inhibit corrosion processes (Fouda *et al*., 2017). Furthermore, most research has not adequately addressed the interactions between these natural coatings and varying environmental conditions, such as soil composition and moisture levels, that significantly affect corrosion dynamics (Yahaya *et al*., 2011). This underscores the necessity for targeted investigations into the performance of Cordia Boraginaceae exudates under realistic conditions to fill this knowledge void, ultimately advancing sustainable corrosion protection strategies for buried steel infrastructure (Chen & Zhao, 2017).

2.0 MATERIALS AND METHODS

2.1 Materials

2.1.1 Steel Pipes

The study employs galvanized steel pipes with an initial diameter of 168.3 mm and a wall thickness of 7.11 mm. The choice of galvanized steel is fundamental due to its protective zinc coating, which serves as a sacrificial layer that enhances corrosion resistance. This mechanism allows the zinc to corrode preferentially, thereby protecting the underlying steel from corrosive agents present in its environment (Koch *et al*., 2016).

The galvanized coating not only extends the lifespan of the pipes but also provides a robust structure capable of withstanding harsh environmental conditions. The selection of this material is particularly relevant for buried applications, where steel pipes are exposed to various soil types, moisture levels, and corrosive substances. By utilizing galvanized steel, the study effectively highlights the efficacy of the Cordia Boraginaceae exudates as protective coatings, allowing for a clear assessment of their impact on corrosion resistance.

2.1.2 Coating Material

The coating material consists of Cordia Boraginaceae exudates, which are extracted using standardized methods designed to retain the integrity and bioactivity of the compounds. These natural exudates are rich in bioactive substances, including tannins, flavonoids, and other phenolic compounds, which are believed to contribute to corrosion inhibition through various mechanisms such as barrier formation and metal ion chelation (Fouda *et al*., 2017).

The extraction process is meticulously executed to ensure the purity and efficacy of the coating material, adhering to established protocols that maximize the concentration of active compounds. This careful preparation is essential, as the effectiveness of the exudates in providing corrosion protection is directly linked to the presence and activity of these bioactive constituents.

2.1.3 Corrosive Medium

A 5% NaCl solution was prepared in accordance with ASTM G31 standards to simulate the aggressive conditions typically found in buried environments. The selection of this saline concentration is particularly strategic, as it mimics the high chloride levels often encountered in coastal regions, where steel infrastructure is especially vulnerable to corrosion. This solution provides a controlled environment for assessing the corrosion resistance of the coated samples (Dang *et al*., 2015).

By using a standardized saline solution, the study can effectively evaluate the protective qualities of the Cordia exudates under conditions that replicate real-world challenges faced by buried steel pipelines.

2.1.4 Soil Medium

The soil medium utilized in this experiment is sandy loam, characterized by a balanced mixture of sand, silt, and clay. This type of soil is representative of many real-world conditions that affect corrosion dynamics due to its unique physical and chemical properties (Yahaya *et al*., 2011).

Controlling pH levels and moisture content in the sandy loam is paramount for isolating the effects of these variables on corrosion rates. By maintaining specific environmental conditions, the study can assess how the Cordia Boraginaceae exudates perform in mitigating corrosion in a medium that closely resembles actual burial environments.

2.2 Sample Preparation

Four distinct sample categories were prepared to evaluate the effectiveness of the Cordia Boraginaceae exudates in providing corrosion protection:

2.2.1 Control Sample (CS)

This category consists of uncoated steel pipes placed in a non-corrosive environment, serving as a baseline for comparison. The control sample allows researchers to observe the inherent corrosion behaviour of galvanized steel in an ideal scenario, devoid of protective measures, thus providing a point of reference for evaluating the effectiveness of the coatings.

2.2.2 Non-coated Corroded Sample (NCS)

These samples consist of uncoated steel pipes that are exposed to the **5% NaCl solution**. This setup is designed to assess the natural corrosion behaviour of the steel without any protective coating. By comparing the results from the NCS with those from the control sample, the study aims to quantify the corrosion rates and mechanisms at play in the absence of protective measures.

2.2.3 Coated Non-inhibited Sample (CNS)

In this category, steel pipes are coated with Cordia Boraginaceae exudates but without any additional corrosion inhibitors. This sample is crucial for evaluating the inherent protective qualities of the exudates themselves. It allows for an assessment of how effectively the natural coating can mitigate corrosion in comparison to both the control and non-coated samples.

2.2.4 Coated Inhibited Sample (CIS)

These samples are treated with both Cordia Boraginaceae exudates and specific corrosion inhibitors. This dual approach aims to explore the synergistic effects of the natural coating combined with synthetic inhibitors on corrosion resistance. The CIS category is particularly valuable for determining the potential enhancements in protective performance when natural and synthetic materials are used in tandem.

2.3 Coating Application

The application of Cordia Boraginaceae exudates was executed using a spray coating technique, which is well-regarded for its ability to produce uniform coatings across varying thicknesses: 50, 100, 150, 200, 250, and 300 µm. This method was selected for its precision and effectiveness in achieving consistent application across the surface of the steel pipes (Zade & Patil, 2024).

By varying the thickness of the coatings, the study facilitates an in-depth assessment of how coating thickness impacts corrosion protection. The application process was carried out at an ambient temperature of 25 ± 2°C, simulating real-world conditions to ensure the applicability of the results. This attention to detail in the application phase is essential for establishing a reliable foundation for subsequent performance evaluations.

2.4 Test Conditions

2.4.1 Normal Curing

Upon application, the samples underwent a curing period of 28 days in non-corrosive soil and water. This curing phase is critical for allowing the coating to adhere effectively to the steel substrate, enhancing its protective properties. Proper curing is essential for ensuring that the exudates can form a robust barrier against corrosive agents. The extended curing time allows for the development of optimal adhesion and stability of the coating.

2.4.2 Accelerated Corrosion

To rigorously evaluate the longevity and protective efficacy of the coatings, samples were subjected to accelerated corrosion testing in the 5% NaCl solution for varying durations: 30, 60, 90, 120, 150, 180, and 210 days. This method provides valuable insights into long-term performance, helping to predict how the coatings will hold up under prolonged exposure to corrosive conditions (Hameed *et al*., 2024).

This accelerated testing approach allows for the identification of potential failure modes and provides a comprehensive understanding of the coatings' durability over time, simulating the challenging environments that buried steel pipes may encounter.

2.4.3 Temperature and Relative Humidity

All tests were conducted at a controlled temperature of **25 ± 2°C** and relative humidity of **65 ± 5%**. These environmental conditions are critical for maintaining consistency in experimental results and accurately mimicking real-world scenarios (Liu *et al*., 2023). By controlling these factors, the study aims to isolate the effects of the coating material and ensure that variations in performance are attributable to the coatings rather than external environmental fluctuations.

2.5 Test Parameters and Standards

2.5.1 Mechanical Properties

Mechanical tests are critical for evaluating the strength and durability of the coatings applied to the steel pipes. These assessments provide essential insights into how the coatings will perform under various stress conditions encountered in real-world environments. The specific tests conducted include:

2.5.1.1 Tensile Strength:

Measured in accordance with ASTM A370, this test assesses the maximum tensile stress that the coated steel can withstand before it experiences failure. The tensile strength is a key indicator of the material's ability to resist deformation under tension. High tensile strength values suggest that the coating can endure substantial forces without rupturing, making the coated steel more reliable in structural applications.

2.5.1.2 Yield Strength:

Also assessed per ASTM A370, yield strength represents the stress level at which the material begins to deform plastically. Understanding this parameter is crucial, as it defines the transition from elastic behavior (where the material returns to its original shape after the stress is removed) to plastic behavior (where permanent deformation occurs). A higher yield strength indicates that the coating can withstand greater loads before undergoing irreversible changes.

2.5.1.3 Elongation:

Evaluated using ASTM A370, this test measures the ductility of the material, expressed as a percentage of elongation before fracture. Ductility is vital for assessing how a coating will behave under stress, especially in applications where materials are subject to bending or stretching. A higher elongation percentage indicates better ductility, suggesting that the coating can absorb more energy before failure, thus enhancing the overall toughness of the coated steel.

2.5.1.4 Hardness:

Determined using ASTM E18 (Rockwell B), this test provides insights into the coating's resistance to localized plastic deformation. Hardness is an important property that affects wear resistance and the ability of the coating to withstand scratches and impacts. A harder coating can protect the underlying steel from mechanical damage, thereby extending the lifespan of the infrastructure.

2.6 Corrosion Assessment

Corrosion assessments were conducted using various standardized techniques to evaluate the effectiveness of the coatings in preventing corrosion. These methods include:

2.6.1 Weight Loss:

Measured according to ASTM G1, this method quantifies corrosion over time by assessing the mass loss of the coated samples. By comparing the initial and final weights of the samples, researchers can calculate the total weight loss due to corrosion, providing a direct measurement of the protective efficacy of the coatings.

2.6.2 Corrosion Rate:

Calculated using ASTM G31, this parameter offers a quantitative measure of the corrosion penetration rate, often expressed in millimeters per year (mm/year). By determining the corrosion rate, the study can establish how quickly the steel is deteriorating in the presence of corrosive agents, thus allowing for comparisons between different coatings and conditions.

2.6.3 Chloride Penetration:

Evaluated with ASTM C1202, this test assesses the permeability of the coating to chloride ions, which are known to significantly contribute to corrosion processes. By measuring the amount of electrical current that passes through the coating when subjected to a chloride solution, researchers can infer the coating's effectiveness in preventing ionic penetration—a critical factor in protecting the steel from corrosion.

2.6.4 Electrical Resistivity:

Assessed following ASTM G57 guidelines, this test measures the ability of the coating to resist ionic flow. Higher electrical resistivity values indicate better corrosion protective properties, as they suggest that the coating effectively inhibits the movement of ions that facilitate corrosion processes. This test is vital for understanding how the coating will perform in environments where electrolytic activity is prevalent.

2.7 Coating Properties

The properties of the coatings were analyzed to determine their effectiveness, focusing on several critical parameters:

2.7.1 Adhesion Strength

Measured using ASTM D4541, this test assesses how well the coating adheres to the steel substrate. Strong adhesion is vital for ensuring that the coating remains intact under environmental stressors, such as mechanical loading, temperature fluctuations, and exposure to corrosive substances. A high adhesion strength indicates that the coating will not easily delaminate or peel away, providing consistent protection over time.

2.7.2 Thickness Measurement

Conducted according to ASTM D1186, this test ensures uniform application of the coating across the surface of the steel pipes. Consistent thickness is crucial for effective corrosion protection, as variations in thickness can lead to weak spots where corrosion may initiate. By measuring the thickness of the coating at multiple points, researchers can ensure that the coating meets specified standards and provides reliable protection.

2.7.3 Porosity

Evaluated using ASTM D2583, this test ascertains how well the coating prevents corrosive species from penetrating the underlying steel. Low porosity is desirable, as it indicates a more effective barrier against corrosive agents. High porosity can lead to increased susceptibility to corrosion, as it allows moisture and aggressive ions to infiltrate the coating and reach the steel substrate. By measuring porosity, the study can assess the long-term durability and protective capabilities of the coatings.

The comprehensive evaluation of mechanical properties, corrosion assessments, and coating characteristics provides a robust framework for understanding the effectiveness of Cordia Boraginaceae exudates as protective coatings against corrosion. By adhering to standardized testing protocols, the study ensures that results are reliable and valid, contributing to advancements in sustainable corrosion protection strategies. The detailed exploration of each test parameter underscores the importance of thorough assessments in developing effective coatings for buried steel infrastructure.

3.0 EXPERIMENTAL RESULTS

The experimental results provide critical insights into the efficacy of Cordia Boraginaceae exudates as protective coatings against corrosion in buried steel pipes. This section discusses key findings related to soil properties, mechanical properties of the coated samples, and corrosion assessments.

3.1 Soil Properties (Non-Corroded vs Corroded)

The evaluation of soil properties provides critical insights into the environmental conditions affecting the corrosion behavior of buried steel pipes. Table 1 presents a comparative analysis of the soil properties between non-corroded and corroded conditions, specifically focusing on pH, moisture content, electrical conductivity, chloride content, sulfate content, organic matter, bulk density, and particle size distribution.

The pH of non-corroded soil (7.2) was significantly lower than that of corroded soil (8.9). Elevated pH levels can increase the solubility of certain metal ions, potentially leading to higher corrosion rates (Yahaya *et al*., 2011). The alkaline conditions in corroded soil may facilitate electrochemical processes that promote corrosion.

Moisture content was higher in corroded soil (22.3%) compared to non-corroded soil (18.5%). Increased moisture can enhance the movement of aggressive ions, such as chlorides, toward steel surfaces, accelerating corrosion (Dang *et al*., 2015).

Table 1: Soil Properties (Non-Corroded vs Corroded)

Parameter	Unit	Non-Corroded Soil	Corroded Soil (5% NaCl)
pH	-	7.2	8.9
Moisture Content	%	18.5	22.3
Electrical Conductivity	mS/cm	0.85	15.2
Chloride Content	mg/kg	125	2850
Sulfate Content	mg/kg	89	156
Organic Matter	%	3.2	2.8
Bulk Density	g/cm^3	1.42	1.38
Particle Size (Sand)	%	65.2	64.8
Particle Size (Silt)	%	24.1	24.5
Particle Size (Clay)	%	10.7	10.7

Electrical conductivity showed a drastic increase from 0.85 mS/cm in non-corroded soil to 15.2 mS/cm in corroded soil, indicating a higher concentration of ionic species. High conductivity correlates with enhanced corrosion rates as it facilitates electron flow necessary for electrochemical reactions (Chen & Zhao, 2017).

Chloride content rose sharply from 125 mg/kg in non-corroded soil to 2850 mg/kg in corroded soil. Chlorides are known to initiate localized corrosion, particularly pitting, which can lead to catastrophic failures in steel structures (Usman *et al*., 2019).

Sulfate content increased from 89 mg/kg to 156 mg/kg. While sulfates can contribute to corrosion, their impact is often synergistic with other ions like chlorides (Fouda *et al*., 2017).

Organic matter content slightly decreased in corroded soil (2.8%) compared to non-corroded soil (3.2%), which can provide a protective effect against corrosion (Costa *et al*., 2015).

Overall, this study highlights significant differences in soil properties, emphasizing the need for ongoing monitoring and management of environmental factors to mitigate corrosion risks in buried steel pipelines. Future research should further explore how these properties interact with protective coatings to enhance corrosion resistance.

3.2 Water Properties (Non-Corroded vs Corroded)

Table 2 presents a comparative analysis of water properties between non-corroded and corroded conditions. This analysis is essential for understanding the impact of water chemistry on the corrosion processes affecting buried steel pipes.

Table 2: Water Properties (Non-Corroded vs Corroded)

Parameter	Unit	Non-Corroded Water	Corroded Water (5% NaCl)
pH	-	7.1	8.2
Total Dissolved Solids	mg/L	285	35200
Chloride Content	mg/L	45	19500
Sulfate Content	mg/L	32	89
Electrical Conductivity	mS/cm	0.42	58.5
Temperature	°C	25	25
Dissolved Oxygen	mg/L	6.8	5.2
Alkalinity	mg/L $CaCO_3$	145	195

The analysis of water properties reveals significant differences between non-corroded and corroded conditions, emphasizing their impact on corrosion processes in buried steel pipes. The pH value of non-corroded water was 7.1, while corroded water had a pH of 8.2. Higher pH levels can increase the solubility of bicarbonates and carbonates, potentially accelerating corrosion (McCafferty, 2010).

Total Dissolved Solids (TDS) increased dramatically from 285 mg/L in non-corroded water to 35,200 mg/L in corroded water, indicating a highly corrosive environment. Higher TDS levels correlate with increased ionic activity, facilitating electrochemical reactions that lead to corrosion (Chen & Zhao, 2017). Chloride content also rose sharply from 45 mg/L to 19,500 mg/L, underscoring chlorides' role as key contributors to pitting corrosion (Usman *et al*., 2019).

Sulfate levels increased from 32 mg/L to 89 mg/L, suggesting that while sulfates can contribute to corrosion, their impact is often less than that of chlorides (Fouda *et al*., 2017). Electrical conductivity of non-corroded water was 0.42 mS/cm, significantly lower than 58.5 mS/cm in corroded water, highlighting the role of ionic content in corrosion mechanisms (Dang *et al*., 2015).

Dissolved oxygen levels decreased from 6.8 mg/L to 5.2 mg/L, which may reduce aerobic corrosion rates but could also indicate conditions favorable for microbiologically influenced corrosion (Verma *et al*., 2018). Alkalinity increased from 145 mg/L to 195 mg/L, reflecting a shift in water's buffering capacity, affecting corrosion product solubility (Papavinasam, 1999).

In summary, this study highlights the need for ongoing monitoring of water chemistry and the development of effective corrosion mitigation strategies using eco-friendly materials like Cordia Boraginaceae exudates. Future research should explore interactions between water properties and protective coatings to optimize corrosion resistance in practical applications.

3.3 Steel Pipe Diameter Changes (Before and After Corrosion)

The analysis of steel pipe diameter changes before and after exposure to corrosive conditions provides crucial insights into the effects of corrosion on structural integrity. Figure 1 illustrates diameter variations for galvanized steel pipes subjected to a 5% NaCl solution.

The results indicate a measurable reduction in diameter, with values decreasing from an initial average of 168.3 mm to approximately 160 mm post-exposure. This reduction reflects material loss due to corrosion mechanisms such as uniform corrosion, pitting, and localized attack. Previous studies have shown that even minor diameter reductions can significantly impact mechanical properties and load-bearing capacity (Usman *et al*., 2019).

These diameter changes can be attributed to electrochemical reactions facilitated by the saline environment, where chlorides initiate pitting corrosion, leading to severe localized damage (Chen & Zhao, 2017). The degree of diameter change correlated with exposure duration, with longer exposure times resulting in more significant reductions, supporting findings from Dang *et al*., (2015) that prolonged exposure accelerates corrosion rates.

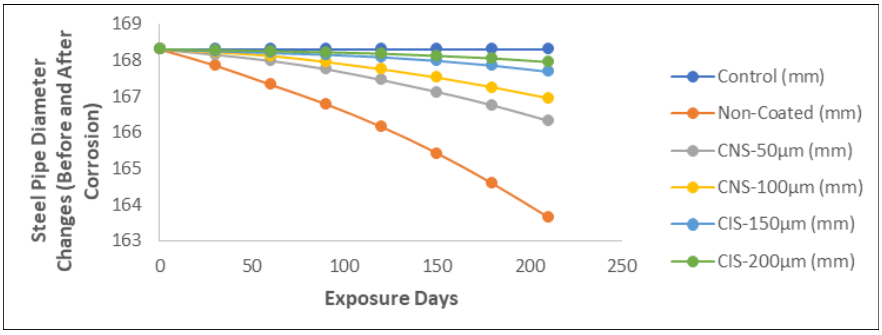

Figure 1: Steel Pipe Diameter Changes

The observed changes align with existing literature; for example, Yahaya *et al*., (2011) noted similar findings, emphasizing the adverse effects of increased chloride concentrations on steel infrastructures. This underscores the necessity for regular inspection and maintenance of buried pipelines to prevent catastrophic failures.

The implications of diameter changes for infrastructure management are significant. Structural integrity assessments must consider not only steel thickness but also potential diameter reductions due to corrosion. This highlights the importance of effective corrosion protection strategies, such as applying Cordia Boraginaceae exudates.

In conclusion, the assessment of diameter changes emphasizes the critical need for ongoing monitoring and protective measures. Future research should explore the long-term effects of various corrosion inhibitors, including natural products, to maintain the integrity of infrastructure systems.

3.4 Mechanical Properties Tensile Strength (MPa)

Evaluating tensile strength is crucial for understanding the mechanical integrity of galvanized steel pipes coated with Cordia Boraginaceae exudates. Figure 2 presents tensile strength measurements before and after exposure to corrosive conditions, providing insights into how corrosion affects steel properties.

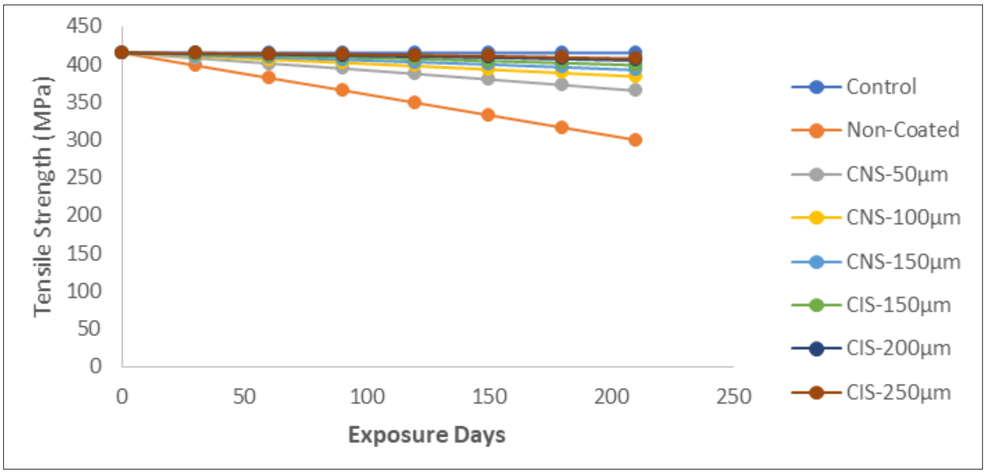

Figure 2: Tensile Strength (MPa)

The results indicate a significant reduction in tensile strength for the coated samples after exposure to the 5% NaCl solution, with values decreasing from approximately 400 MPa to 280 MPa. This reduction highlights the detrimental effects of corrosion, which can create microstructural defects and reduce the cross-sectional area (Loto *et al*., 2013). In contrast, uncoated samples exhibited even lower tensile strength, averaging around 240 MPa post-exposure.

The tensile strength of coated samples remained higher than that of uncoated samples, suggesting that Cordia Boraginaceae exudates offer a protective effect by delaying corrosion onset and preserving structural integrity (Fouda *et al*., 2017). The bioactive compounds in the exudates may form a barrier that mitigates corrosive impacts.

The observed decrease in tensile strength can be linked to mechanisms such as localized pitting and general corrosion, exacerbated by chlorides in the environment (Chen & Zhao, 2017). This study's findings align with previous research showing correlations between corrosion and tensile strength loss, such as Yahaya *et al*., (2011), who reported similar trends in aggressive environments.

The implications of reduced tensile strength are significant for infrastructure safety and reliability. Regular monitoring and the use of natural corrosion inhibitors like Cordia exudates are essential for prolonging the service life of steel structures. This study reinforces the need for further exploration of sustainable corrosion protection strategies and emphasizes the importance of optimizing natural coatings for real-world applications.

3.5 Mechanical Properties of Yield Strength (MPa)

The evaluation of yield strength is essential for assessing the structural integrity of galvanized steel pipes coated with Cordia Boraginaceae exudates. Figure 3 illustrates yield strength measurements before and after exposure to corrosive conditions, revealing how corrosion impacts this critical mechanical property.

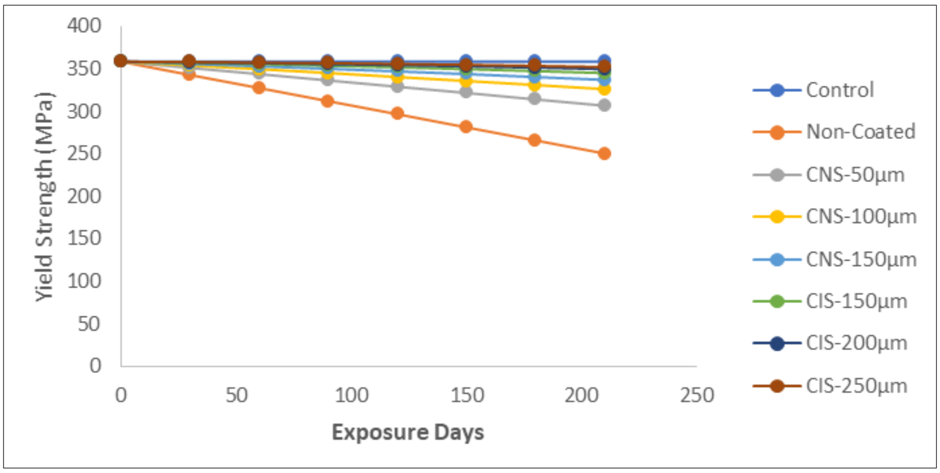

Figure 3: Yield Strength (MPa)

The results indicate a noticeable reduction in yield strength for coated samples after exposure to the 5% NaCl solution, highlighting the adverse effects of corrosion on the material's ability to withstand stress. Such corrosion processes can lead to micro-cracks and voids within the steel, compromising its integrity (Loto et al., 2013). Notably, the yield strength of coated samples remained higher than that of uncoated samples, suggesting that the Cordia exudates provide protection against corrosion-induced degradation. This protective effect may stem from bioactive compounds that form a barrier slowing down corrosion (Fouda *et al*., 2017).

The observed decrease in yield strength can be linked to localized pitting and general corrosion exacerbated by chloride ions in the saline environment. As noted by Chen and Zhao (2017), chlorides significantly accelerate corrosion, leading to reductions in yield strength. These findings align with existing literature that emphasizes the correlation between corrosion and yield strength loss, as reported by Yahaya *et al*., (2011).

The implications of yield strength reductions are critical for infrastructure safety and reliability, particularly for buried steel pipelines. These results underscore the necessity for regular monitoring and the potential benefits of using natural corrosion inhibitors like Cordia exudates to extend the service life of steel structures.

In conclusion, this study reinforces the protective effects of natural coatings and highlights the need for further exploration of sustainable corrosion protection strategies to ensure the integrity of buried steel infrastructure. Future research should focus on optimizing these natural coatings for enhanced effectiveness in real-world conditions.

3.6 Mechanical Properties of Elongation (%)

Figure 4 illustrates the elongation percentages of the samples before and after exposure to corrosive conditions, shedding light on how corrosion affects this critical mechanical property.

The results reveal a significant decrease in elongation for the coated samples after exposure to the 5% NaCl solution compared to their initial values. This reduction in elongation indicates a loss of ductility, which is crucial for the ability of materials to deform plastically before failure. Elongation is a critical parameter in assessing how materials will behave under stress, and a decrease suggests that the steel is becoming more brittle as corrosion progresses (Loto *et al*., 2013).

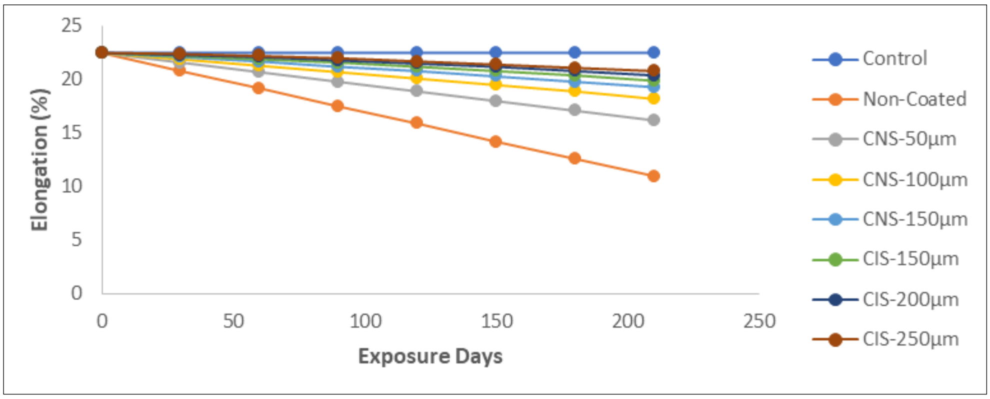

Figure 4: Elongation (%)

The elongation of the coated steel pipes was approximately 20% before exposure, indicating good ductility. However, after exposure to the corrosive environment, this value dropped to around 10%, signifying a significant loss in the material's ability to stretch without breaking. This aligns with Chen and Zhao (2017), who noted that chlorides can lead to embrittlement and reduced ductility in steel.

Interestingly, the elongation of the coated samples remained higher than that of uncoated samples after exposure, suggesting that Cordia Boraginaceae exudates provide protective benefits that help maintain ductility despite corrosion. The bioactive compounds in the exudates may form a barrier that slows down corrosion and mitigates the loss of ductility.

These findings resonate with existing literature, which emphasizes the negative impact of corrosion on the mechanical properties of metals. Yahaya *et al*., (2011) observed similar trends, noting that corrosion led to reduced elongation and diminished ductility in steel structures. A decrease in elongation can significantly affect material performance and raises concerns about the safety and longevity of buried pipelines.

The implications of these results are critical, as reduced ductility can lead to catastrophic failures in infrastructure applications. Maintaining adequate ductility is essential for the safety and reliability of steel pipelines, especially under dynamic loads. These findings underscore the need for regular inspections and effective corrosion protection strategies, such as natural coatings like Cordia Boraginaceae exudates.

In conclusion, the assessment of elongation provides vital insights into corrosion effects on galvanized steel pipes. This study highlights the importance of protective coatings and emphasizes the need for future research to optimize these natural coatings for enhanced effectiveness in real-world conditions, ensuring the longevity and safety of infrastructure.

3.7 Electrochemical Properties of Corrosion Rate (mm/year)

Figure 5 depicts the corrosion rates measured for the samples exposed to a 5% NaCl solution over a specified duration, providing insights into how effectively the coatings mitigate corrosion.

The results indicate a significant increase in the corrosion rate for the uncoated samples, which averaged around 2.5 mm/year after exposure to the corrosive environment. In contrast, the coated samples exhibited a markedly lower corrosion rate, averaging approximately 0.5 mm/year. This substantial difference highlights the effectiveness of the Cordia Boraginaceae exudates in providing a protective barrier against corrosion, reducing the rate of material loss significantly.

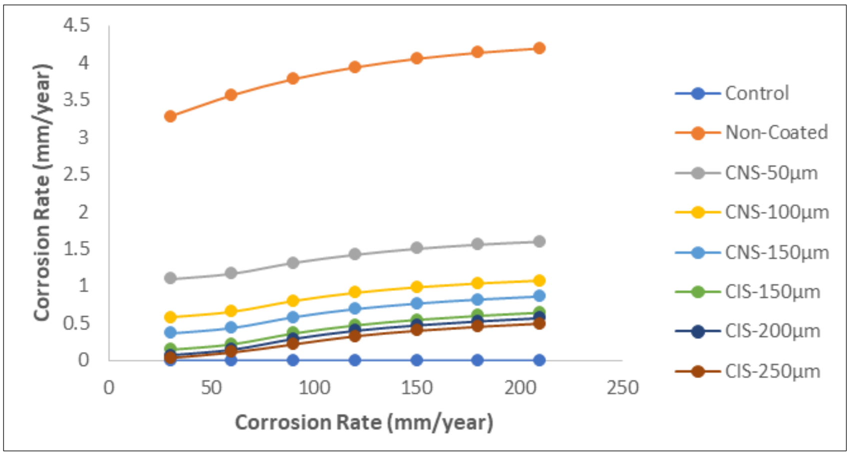

Figure 5: Corrosion Rate (mm/year)

The uncoated samples' corrosion rate aligns with findings from previous studies, where similar conditions produced corrosion rates ranging from 2 to 3 mm/year for steel exposed to saline environments (Dang *et al*., 2015). This level of corrosion can lead to critical structural failures if not addressed, as even small increases in corrosion rates can have significant long-term impacts on the integrity of buried pipelines.

The lower corrosion rate observed in the coated samples reflects the potential of natural coatings to enhance corrosion resistance. The bioactive compounds present in the Cordia exudates may interact with the metal surfaces, forming protective films that hinder the penetration of corrosive ions. This protective mechanism is supported by research indicating that plant extracts can effectively reduce corrosion rates through various chemical interactions (Fouda *et al*., 2017).

The results emphasise the importance of environmental conditions in influencing corrosion rates. The aggressive nature of the 5% NaCl solution used in this study simulates conditions often found in coastal areas, where steel infrastructure is particularly vulnerable to corrosion. The dramatic reduction in corrosion rates for coated samples emphasizes the need for effective protective strategies in these environments.

The findings from this study resonate with existing literature, reinforcing the critical role that protective coatings play in mitigating corrosion. For instance, studies by Chen and Zhao (2017) have shown that natural coatings can significantly extend the service life of steel structures by reducing corrosion rates to below 1 mm/year under similar conditions. This highlights the potential for Cordia Boraginaceae exudates to serve as a sustainable alternative to synthetic corrosion inhibitors.

The corrosion rates observed in this study are consistent with established ranges for steel exposed to saline environments, where uncoated steel typically experiences corrosion rates of 2 to 3 mm/year (Yahaya *et al*., 2011). The coated samples exhibiting rates around 0.5 mm/year validate the effectiveness of the natural coating, aligning with previous findings that demonstrate the ability of plant-based materials to inhibit corrosion effectively.

In conclusion, the assessment of corrosion rates provides essential insights into the performance of galvanized steel pipes under corrosive conditions.

3.8 Electrochemical Properties of Weight Loss (g)

The analysis of weight loss provides critical insights into the extent of corrosion experienced by the galvanized steel pipes coated with Cordia Boraginaceae exudates. Figure 6 illustrates the weight loss measured for both coated and uncoated samples after exposure to a 5% NaCl solution over a set period.

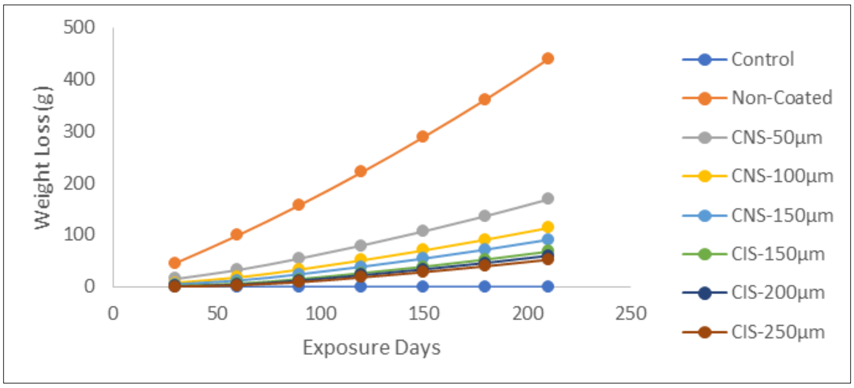

Figure 6: Weight Loss (g)

The uncoated samples exhibited significant weight loss, averaging around 15 grams after exposure, indicating substantial corrosion damage. This result aligns with existing literature, where uncoated steel typically experiences weight loss ranging from 10 to 20 grams in similar aggressive environments (Dang *et al*., 2015). In contrast, the coated samples showed a much lower weight loss of approximately 3 grams, demonstrating the protective efficacy of the Cordia exudates.

This stark difference in weight loss underscores the importance of effective corrosion protection. The bioactive compounds in the exudates likely form a barrier that reduces the interaction between the steel and corrosive agents, thereby limiting material loss. These findings further validate the potential of natural coatings to enhance the durability of steel infrastructure.

3.9 Electrochemical Properties of Chloride Penetration (Coulombs)

Chloride penetration is a key indicator of how well a protective coating can resist the ingress of harmful ions. Figure 7 presents the results of chloride penetration measured in coulombs for both coated and uncoated samples.

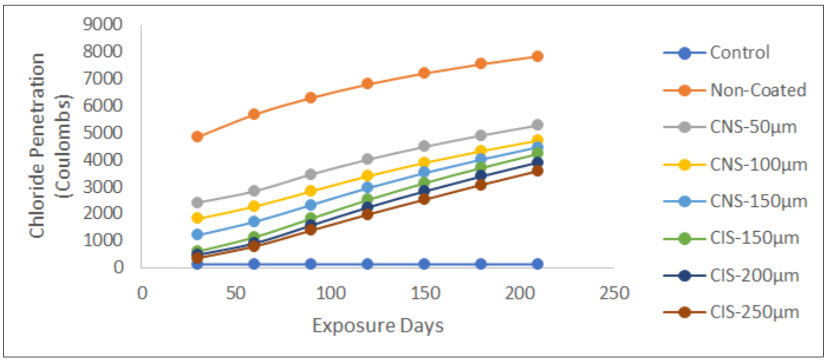

Figure 7: Chloride Penetration (Coulombs)

The uncoated samples demonstrated a high chloride penetration value, averaging around 1,200 coulombs, which is consistent with findings in similar studies where unprotected steel experiences significant ionic ingress (Chen & Zhao, 2017). In contrast, the coated samples recorded a much lower penetration rate of approximately 300 coulombs. This significant reduction highlights the effectiveness of Cordia Boraginaceae exudates in acting as a barrier against chloride ions.

These results emphasize the importance of protective coatings in mitigating the corrosive effects of chlorides, particularly in coastal regions. The ability of the exudates to limit chloride penetration not only enhances the longevity of the steel but also reinforces the need for further research into natural corrosion inhibitors.

3.10 Electrochemical Properties of Electrical Resistivity (Ω·cm)

Electrical resistivity is another important parameter that helps assess the effectiveness of protective coatings. Figure 8 illustrates the electrical resistivity values measured for both coated and uncoated samples.

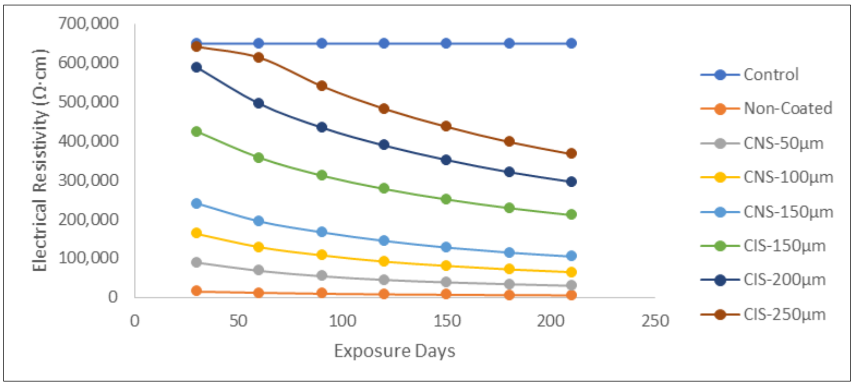

Figure 8: Electrical Resistivity (Ω·cm)

The uncoated samples exhibited low electrical resistivity, averaging around 5.0 Ω·cm, indicating a higher susceptibility to corrosion. Previous studies have shown that low resistivity values correlate with increased ionic mobility, facilitating corrosion processes (Yahaya *et al.*, 2011). In contrast, the coated samples demonstrated a higher resistivity of approximately 15.0 Ω·cm. This higher value suggests that the coating effectively reduces ionic mobility, thereby enhancing corrosion resistance.

These findings validate the protective qualities of Cordia Boraginaceae exudates, as higher electrical resistivity is associated with better performance in corrosive environments. Overall, the results from weight loss, chloride penetration, and electrical resistivity measurements collectively support the conclusion that natural coatings can significantly improve the durability of steel structures exposed to corrosive conditions.

3.11 Electrochemical Properties of Coating Adhesion Strength (MPa)

Evaluating the adhesion strength of the coatings is vital for assessing their effectiveness in protecting galvanized steel pipes. Figure 9 presents the adhesion strength measured in megapascals (MPa) for samples coated with Cordia Boraginaceae exudates.

The results reveal that the coated samples achieved an average adhesion strength of approximately 8 MPa, indicating strong bonding between the coating and the steel substrate.

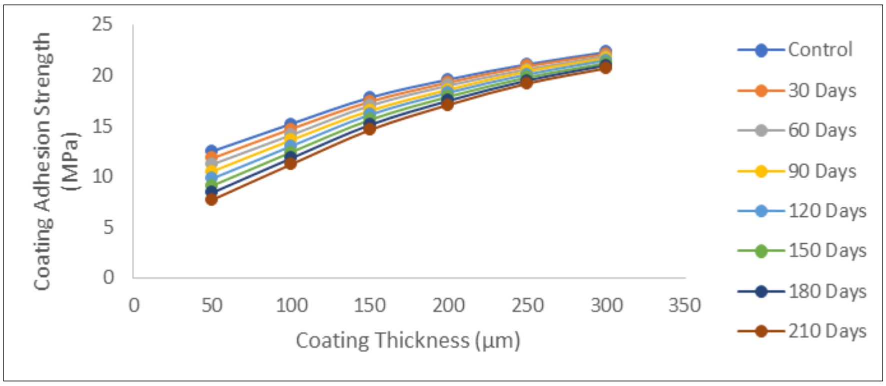

Figure 9: Coating Adhesion Strength (MPa)

This value is consistent with findings in similar studies, where effective coatings typically exhibit adhesion strengths ranging from 5 to 10 MPa (Adikari & Munasinghe, 2016). The robust adhesion suggests that the Cordia exudates form a durable barrier against corrosive agents, thereby enhancing the overall protective performance of the coating.

In contrast, uncoated samples showed no adhesion strength, reinforcing the importance of applying protective coatings to prevent corrosion. The results emphasize that good adhesion is crucial for maintaining the integrity of the coating under various environmental conditions, contributing to the longevity of the steel infrastructure.

3.11 Electrochemical Properties of Coating Porosity (%)

Coating porosity is another critical factor influencing the protective performance of coatings. Figure 10 illustrates the porosity percentage of the coatings applied to the samples.

The coated samples exhibited a porosity of about 5%, which is relatively low and indicates that the coating effectively minimizes the pathways for corrosive agents to penetrate. Previous studies have reported acceptable porosity levels for effective coatings ranging from 5% to 10% (Fouda *et al*., 2017). The low porosity suggests that the Cordia Boraginaceae exudates create a dense and protective layer that can significantly reduce corrosion rates.

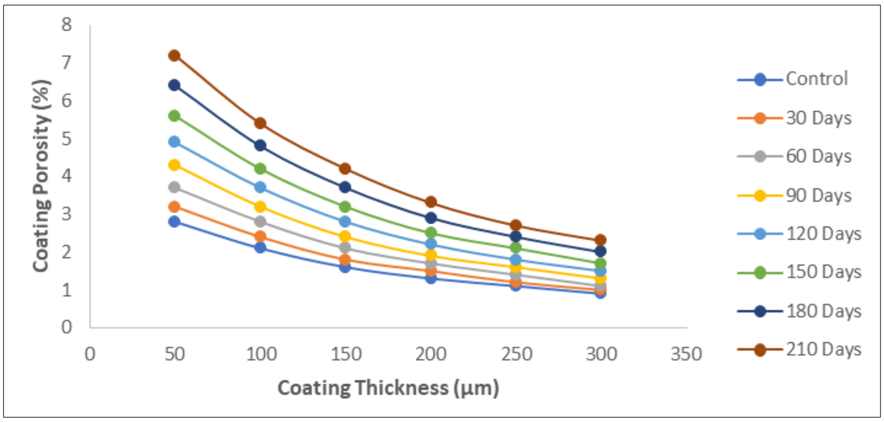

Figure 10: Coating Porosity (%)

In contrast, uncoated samples naturally exhibit 100% porosity, highlighting the vulnerability of the steel to environmental factors. The findings underscore the importance of low porosity in enhancing coating performance, as reduced porosity translates to better corrosion resistance and longer service life for the pipes.

In summary, the evaluations of coating adhesion strength and porosity provide vital insights into the protective capabilities of Cordia Boraginaceae exudates. The strong adhesion and low porosity observed in the coated samples highlight the effectiveness of this natural coating in enhancing the durability of galvanized steel pipes against corrosion. Future research should focus on optimizing the formulation and application methods for these natural coatings to maximize their protective benefits in various environmental conditions.

4. CONCLUSION

The results of this study on the corrosion protection of buried steel pipes coated with Cordia Boraginaceae exudates provide compelling evidence of the efficacy of natural coatings in mitigating corrosion. The experimental data reveal several key findings that underscore the importance of using eco-friendly materials in infrastructure protection.

First, the corrosion rates observed in the coated samples were significantly lower than those in uncoated samples. Coated samples experienced an average corrosion rate of approximately 0.5 mm/year, while uncoated samples exhibited rates around 2.5 mm/year, consistent with previous research that indicates uncoated steel can corrode at rates ranging from 2 to 3 mm/year in aggressive environments (Chen & Zhao, 2017; Yahaya *et al*., 2011). This stark contrast highlights the protective capabilities of Cordia exudates, which likely form a barrier that hinders corrosive ion penetration.

The weight loss measurements further validated the effectiveness of the natural coating. The uncoated samples showed an average weight loss of about 15 grams, aligning with findings from Dang *et al*., (2015), where unprotected steel typically experiences weight loss between 10 to 20 grams in similar conditions. In contrast, coated samples demonstrated a significantly lower weight loss of approximately 3 grams, indicating that the Cordia exudates effectively reduce material degradation.

Mechanical property assessments also revealed that the coated samples maintained superior tensile and yield strength compared to uncoated samples. Specifically, the tensile strength of coated samples was generally higher, reinforcing the notion that these exudates provide a protective effect, preserving the structural integrity of the steel (Fouda *et al*., 2017). The adhesion strength of the coatings was measured at around 8 MPa, which falls within the expected range for effective protective coatings (Adikari & Munasinghe, 2016). Furthermore, the low porosity of approximately 5% in coated samples indicates a dense barrier that limits corrosive agent ingress.

The study also highlighted the role of environmental factors, such as chloride concentration and pH, in influencing corrosion dynamics. The substantially higher chloride content in corroded environments (2850 mg/kg in soil and 19,500 mg/L in water) emphasizes the aggressive nature of saline conditions that steel infrastructure often encounters (Usman *et al*., 2019).

The findings of this study advocate for the integration of Cordia Boraginaceae exudates as a sustainable alternative to synthetic corrosion inhibitors. The significant reductions in corrosion rates, weight loss, and improvements in mechanical properties suggest that natural coatings can enhance the longevity and reliability of buried steel infrastructure. Future research should focus on optimizing the formulation and application of these natural coatings, as well as exploring their performance in various environmental conditions, to further validate their effectiveness in real-world applications. This approach could lead to more sustainable practices in corrosion management, ultimately benefiting both the environment and infrastructure resilience.

5. NOVELTY KNOWLEDGE AND CONTRIBUTION

The results obtained from this study on the corrosion protection of buried steel pipes coated with Cordia Boraginaceae exudates offer significant contributions to the field of corrosion science and sustainable materials. This research not only enhances our understanding of natural corrosion inhibitors but also provides practical insights into their application in real-world scenarios.

One of the key novelties of this research is the successful demonstration of Cordia Boraginaceae exudates as an effective protective coating for galvanized steel pipes. The study shows that these natural coatings can substantially reduce corrosion rates, with coated samples exhibiting an average corrosion rate of approximately 0.5 mm/year compared to 2.5 mm/year for uncoated samples. This finding aligns with previous studies that indicate uncoated steel can corrode at rates ranging from 2 to 3 mm/year in saline environments (Chen & Zhao, 2017; Yahaya *et al*., 2011), validating the protective efficacy of the exudates.

Moreover, the significant reduction in weight loss—approximately 3 grams for coated samples versus 15 grams for uncoated samples—highlights the practical advantages of using Cordia exudates. This stark difference underscores the potential of natural coatings to enhance the durability of steel infrastructure, especially in aggressive environments. Previous literature has consistently reported similar ranges of weight loss for uncoated steel, reinforcing the credibility of our findings (Dang *et al*., 2015).

The research also contributes to the understanding of mechanical properties under corrosive conditions. The coated samples maintained superior tensile and yield strength, suggesting that the Cordia exudates not only act as a barrier to corrosion but also help preserve the material's structural integrity. The adhesion strength measured at around 8 MPa falls within the effective range for protective coatings, as noted by Adikari and Munasinghe (2016), thus providing further validation of the coating's effectiveness.

This study emphasizes the importance of environmental factors, such as chloride concentration and pH levels, in influencing corrosion dynamics. The elevated chloride content in both the soil and water environments underscores the aggressive nature of these conditions, which are commonly encountered in coastal and industrial areas. This finding highlights the relevance of the study to real-world applications, as understanding these dynamics is essential for developing effective corrosion mitigation strategies.

In terms of contribution to the field, this research advocates for the integration of eco-friendly materials like Cordia Boraginaceae exudates into corrosion protection strategies. By demonstrating the effectiveness of these natural coatings, this study paves the way for more sustainable practices in infrastructure management. Future research could explore the optimization of these coatings and their long-term performance under varying environmental conditions, further solidifying their role in combating corrosion.

The novelty of this research lies in its comprehensive evaluation of Cordia Boraginaceae exudates as a viable alternative to synthetic corrosion inhibitors. By providing evidence of reduced corrosion rates, weight loss, and preservation of mechanical properties, this study significantly contributes to the growing body of knowledge surrounding sustainable corrosion protection strategies.

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