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Electro-Mechanical Evaluation of Strength and Chloride Corrosion Resistance of Buried Steel Pipes Coated with Exudates and Exposed to Corrosive Media

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ABSTRACT

This study investigates the electro-mechanical performance and chloride corrosion resistance of buried steel pipes coated with Terminalia avicennioides exudates as an eco-friendly alternative to conventional corrosion protection methods. Grade X52 steel pipes (100mm diameter, 6mm wall thickness) were subjected to aggressive chloride environments (5% NaCl solution) with soil chloride concentrations reaching 8,950 mg/kg. The plant-based coating was applied using spray technique with optimized thickness ranging from 50-300 µm, with optimal performance achieved at 150-200 µm thickness. Comprehensive testing over 210 days revealed exceptional protective performance, with coated samples maintaining corrosion rates as low as 0.012 mpy throughout the exposure period, representing a 98.5% reduction compared to non-coated samples (0.785 mpy initial rate). The Terminalia avicennioides exudates demonstrated dual protection mechanisms combining barrier properties with active inhibition through phytochemical interactions. Chloride penetration resistance testing showed that aggressive ions were limited to the outer 20-30% of coating thickness after extended exposure, indicating excellent barrier performance.

Electrochemical characterization revealed that the plant exudates function as mixed-type inhibitors, affecting both anodic and cathodic reactions with charge transfer resistance values 2-3 orders of magnitude higher than non-coated samples. Mechanical properties evaluation confirmed that coating application did not compromise steel substrate integrity, with tensile strength, yield strength, and elongation values remaining within acceptable tolerances.

Statistical analysis validated experimental reliability with strong correlations between key parameters (R^2 = 0.928-0.965), enabling predictive coating design capabilities. The phytochemical composition revealed active compounds including tannins (18.5%), flavonoids (12.3%), alkaloids (8.7%), and saponins (6.2%) responsible for the protective mechanisms. This research establishes Terminalia avicennioides exudates as a highly effective, environmentally sustainable solution for buried steel pipe protection, offering significant potential for industrial applications while supporting green chemistry principles and reduced environmental impact compared to synthetic alternatives.

KEYWORDS: Terminalia avicennioides exudates, Chloride corrosion resistance, Plant-based corrosion inhibitors, Buried steel pipes, Green corrosion protection

1. Introduction

Corrosion of buried steel pipelines represents a significant challenge in maintaining infrastructure sustainability, often leading to structural failures, economic losses, and environmental hazards (Koch et al., 2016). The interaction between steel and corrosive media, particularly in chloride-rich environments, accelerates degradation, thus necessitating the development of effective protective measures (Chen & Zhao, 2017). Traditional corrosion inhibitors, typically comprising synthetic chemicals, often pose various environmental risks, prompting a shift towards eco-friendly alternatives such as plant-derived exudates (Verma et al., 2018). This study evaluates the electro-mechanical strength and chloride corrosion resistance of buried steel pipes coated with natural exudates, leveraging their inherent inhibitory properties to enhance durability in aggressive environments.

Buried steel pipes are particularly vulnerable to corrosion due to electrochemical reactions with factors such as soil moisture, chlorides, and microbial activity (Dang et al., 2015). The presence of chloride ions (Cl^{-}) disrupts passive oxide layers, significantly accelerating localized pitting and stress corrosion cracking (Li et al., 2007). Additionally, soil characteristics—including moisture content, pH, and resistivity—further influence corrosion dynamics (Yahaya et al., 2011). While cathodic protection and coatings are conventional mitigation strategies, their long-term efficacy is often compromised by coating degradation and cathodic disbondment (Parker & Peattie, 1984). Furthermore, microbial-induced corrosion (MIC) exacerbates pipeline deterioration, particularly in anaerobic soil conditions (Ismail & El-Shamy, 2009; Aliofkhazraei et al., 2019).

Plant-based exudates, such as resins and gums, have been shown to exhibit corrosion inhibition due to the presence of phytochemicals like tannins, flavonoids, and alkaloids (Banerjee et al., 2012). For example, studies confirm the effectiveness of Dacryodes edulis and Aspilia africana exudates in reducing mild steel corrosion in both acidic and saline media (Owate et al., 2014; Sunday-Piaro, 2019). These compounds effectively adsorb onto metal surfaces, forming protective films that impede electrochemical reactions (Fouda et al., 2017). The shift towards green inhibitors resonates with global sustainability initiatives, aiming to minimize toxic chemical usage (Sheldon, 2016; Adikari & Munasinghe, 2016). Recent research highlights the potential of polysaccharide-based inhibitors, which not only exhibit high adsorption capacity but also biodegradability (Umoren & Eduok, 2016; Chigondo & Chigondo, 2016).

The mechanical integrity of coated steel pipes under chloride exposure is paramount for infrastructure resilience. Techniques such as electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization can reveal the inhibitory efficiency of exudates by measuring charge transfer resistance and corrosion current density (Ameh & Eddy, 2016). Studies focusing on Ginkgo biloba and Cascabela thevetia extracts demonstrate over 90% inhibition efficiency in NaCl solutions (Singh et al., 2015; Fouda et al., 2017). However, the long-term performance of these inhibitors under buried conditions warrants further validation, particularly when considering the complex interactions between soil and structures (Putra et al., 2020; Ezeugo, 2019).

Moreover, the influence of soil compaction and aeration on corrosion rates remains a relatively understudied domain, necessitating comprehensive field trials to provide a more robust understanding of these interactions (Pereira et al., 2015; Yang et al., 2021). The findings from this research are expected to advance sustainable pipeline protection strategies, significantly reducing reliance on synthetic inhibitors. By integrating electro-mechanical testing with environmental exposure assessments, this research contributes a holistic framework for effective corrosion management in buried infrastructure. Additionally, the study enriches the growing body of knowledge on green corrosion inhibitors, supporting regulatory policies aimed at promoting eco-friendly industrial practices (Brycki et al., 2018; Mahmoodian, 2018).

In conclusion, the transition towards eco-friendly corrosion inhibitors is critical for enhancing the longevity and sustainability of buried steel pipelines. This comprehensive investigation not only emphasizes the effectiveness of plant-derived exudates but also encourages further exploration into sustainable materials that can revolutionize corrosion protection strategies.

2. MATERIALS AND METHODS

2.1 Materials

The materials section outlines the four primary components used in this comprehensive corrosion study: steel pipe specimens, plant-based inhibitor extract, test soil media, and corrosive solutions. Each material was carefully selected and characterized to ensure reproducible experimental conditions and reliable results.

2.1.1 Steel Pipes: Grade X52, Nominal Diameter 100mm, Wall Thickness 6mm

Grade X52 steel pipes conforming to API 5L specifications were procured with nominal outer diameter of 100mm and uniform wall thickness of 6mm. Chemical composition was verified through spectroscopic analysis: carbon 0.22%, manganese 1.35%, silicon 0.45%, phosphorus 0.025%, and sulfur 0.015%. Yield strength was 358 MPa with ultimate tensile strength of 455 MPa. All pipe sections underwent rigorous surface preparation including mechanical cleaning, acetone degreasing, and sandblasting to Sa 2.5 according to ISO 8501-1. Specimens were cut to 200mm lengths, deburred, polished, and dimensionally verified using precision calipers (±0.01mm accuracy).

2.1.2 Terminalia avicennioides Exudates: Collected from Mature Trees, Processed and Refined

Plant-based inhibitor was derived from Terminalia avicennioides exudates collected from mature trees (15-20 years) in Guinea savanna region of Northern Nigeria during dry season (December-February). Approximately 2.5 kg raw exudates were collected from 15 trees through controlled bark incisions, allowing 72-hour solidification. Processing involved manual cleaning, mechanical grinding to <150 μm particle size, and solvent extraction using 70% ethanol at 60°C for 24 hours. Following vacuum filtration and rotary evaporation at 45°C, the concentrate was freeze-dried yielding dark brown powder with <5% moisture content. Phytochemical analysis revealed tannins (18.5%), flavonoids (12.3%), alkaloids (8.7%), and saponins (6.2%). Extract was stored in sealed amber vials under nitrogen at 4°C.

2.1.3 Soil Media: Sandy Clay Loam with Varying Chloride Content

Natural sandy clay loam soil (45% sand, 35% clay, 20% silt) was obtained from 1.5-2.0m depth from three locations. Natural soil characteristics: pH 6.8, electrical resistivity 45.6 Ω·m, baseline chloride content 125 mg/kg. Soil was artificially modified with analytical grade NaCl to achieve chloride concentrations of 500, 1000, 2500, 5000, and 8950 mg/kg. Modified soil was mechanically mixed for 30 minutes and equilibrated for 7 days at 22.3% moisture content. Additional characterization included organic matter content (2.8%), sulfate content (1250 mg/kg), bulk density (1.52 g/cm^3), and redox potential (-125 mV).

2.1.4 Test Solutions: Distilled Water and 5% NaCl Solution

Distilled water with conductivity <2 μS/cm served as control medium. Aggressive test medium consisted of 5% NaCl solution (50g NaCl/L distilled water) exhibiting conductivity 85,200 μS/cm, pH 3.8, and TDS 51,300 mg/L. Solutions were prepared fresh for each experimental phase, continuously aerated, and stored in chemically inert polyethylene containers with regular replacement.

2.2 Sample Preparation

2.2.1 Control Samples (Non-Corroded Environment, No Coating)

Twenty-four control samples were prepared as 200mm sections following standard surface preparation. Samples were stored in desiccated environment at 25±2°C, <40% humidity, and exposed to distilled water for baseline comparison.

2.2.2 Non-Coated Samples (Corroded Environment)

Forty-two non-coated samples were prepared for aggressive 5% NaCl exposure across seven periods (30, 60, 90, 120, 150, 180, 210 days) with six replicates per period.

2.2.3 Coated Samples with Inhibitor (Terminalia avicennioides Exudates)

Coating solution contained 15% w/w processed exudates in 60% ethanol/40% distilled water solvent system. Solution was stirred 4 hours at 40°C with pH adjusted to 7.0. Coating applied using calibrated spray gun (2.5 bar pressure, 200mm distance) in multiple thin coats achieving target thicknesses of 50-300 μm. Total of 126 samples prepared across different thicknesses and exposure periods.

2.2.4 Coated Samples without Inhibitor

Eighty-four control samples prepared using identical coating formulation without plant extract, replaced by equivalent solvent volume.

2.3 Coating Application

2.3.1 Spray Coating Technique

High-volume, low-pressure spray gun operated at 2.5 bar air pressure, 1.8 bar fluid pressure, maintaining 200mm spray distance with 50% overlap between passes. Coating temperature maintained at 25±2°C.

2.3.2 Coating Thickness Control

Target thicknesses (50-300 μm) achieved through predetermined coating passes. Wet film thickness monitored using comb gauge; final verification performed using magnetic coating thickness gauge with measurements at five locations per sample.

2.3.3 Curing Conditions

Twenty-eight day curing at 25±2°C, 50±5% relative humidity in controlled environment chamber. Samples inspected periodically for defects; defective samples excluded.

2.4 Testing Conditions

2.4.1 Curing Period: 28 Days for Control Samples

Established to ensure complete coating property development and equilibrium establishment with temperature stability ±0.5°C and humidity control ±2%.

2.4.2 Exposure Periods: 30, 60, 90, 120, 150, 180, and 210 Days

Conducted in dedicated test chambers with minimum 40:1 solution-to-specimen surface area ratio to prevent depletion effects.

2.4.3 Temperature: 25±2°C

Maintained using precision controllers with continuous monitoring representing typical burial depths of 1-2 meters.

2.4.4 pH Range: 3.5-8.5

Controlled through buffer solutions with daily monitoring (initial 30 days) then weekly, using calibrated pH meters with HCl/NaOH adjustments.

2.5 Testing Methods

2.5.1 Soil and Water Characterization

Comprehensive analysis following ASTM standards: pH (ASTM D4972), electrical resistivity (ASTM G57), moisture content (ASTM D2216), chloride content (ASTM D512), and sulfate content (ASTM D516). Water analysis included pH, conductivity, TDS, dissolved oxygen, and temperature measurements.

2.5.2 Dimensional Analysis and Physical Characterization

High-precision digital calipers (±0.01mm) measured external diameter, wall thickness, and length at 18 locations per sample. Mass loss determined using analytical balance (±0.0001g) following ASTM G1 with ultrasonic and chemical cleaning using Clarke's solution. Surface roughness measured using stylus-type profilometer (0.01 μm resolution) per ASTM D7127.

2.5.3 Coating Thickness Optimization and Characterization

Magnetic coating thickness gauge measurements (ASTM D7091) at five locations per sample. Cross-sectional analysis using optical microscopy evaluated coating uniformity and defects. Adhesion testing conducted using pull-off method (ASTM D4541).

2.5.4 Mechanical Properties Evaluation

Tensile testing per ASTM E8 using universal testing machine (2 mm/min crosshead speed) measured yield strength, ultimate tensile strength, elongation, and elastic modulus. Vickers hardness testing (ASTM E92) and Charpy impact testing (ASTM E23) performed.

2.5.5 Corrosion Rate Determination

Gravimetric analysis following ASTM G1 calculated corrosion rates using: Corrosion Rate (mpy) = (K × W) / (A × T × D). Non-coated samples showed rates from 0.785 mpy (30 days) to 0.012 mpy (210 days). Optimal coating thicknesses (150-200μm) achieved 0.012 mpy throughout exposure. Statistical analysis revealed mean 0.185 mpy with standard deviation 0.235. Linear polarization resistance measurements performed using potentiostat/galvanostat system per ASTM G59.

2.5.6 Chloride Ion Penetration Resistance Testing

Modified rapid chloride permeability test applied 60V DC potential across coated samples for 6 hours. Electron probe microanalysis determined chloride penetration profiles. Samples with Terminalia avicennioides exudates limited chloride penetration to outer 20-30% of coating thickness after 210 days.

2.5.7 Electrochemical Characterization

Three-electrode configuration with 1 cm^2 exposed area, saturated calomel electrode reference, and platinum mesh counter electrode. Open circuit potential monitored over 24 hours at 1-minute intervals. Potentiodynamic polarization (ASTM G61) conducted from -250 mV to +250 mV at 1 mV/s scan rate. Electrochemical impedance spectroscopy performed 0.01 Hz to 100 kHz frequency range with 10 mV rms amplitude. Equivalent circuit modelling determined solution resistance, charge transfer resistance, and coating resistance.

2.5.8 Statistical Analysis and Data Validation

Comprehensive statistical analysis calculated descriptive statistics for all parameters. Corrosion rate data showed positive skewness (1.85) and high kurtosis (3.25); tensile strength data showed slight negative skewness (-0.15) and negative kurtosis (-1.25). Strong correlations identified: coating thickness vs. protection efficiency ($R^2 = 0.928$), chloride penetration vs. exposure time ($R^2 = 0.965$), and corrosion rate vs. environmental aggressiveness ($R^2 = 0.945$). ANOVA confirmed statistically significant differences ($p < 0.05$) between sample types and conditions. Quality control included regular instrument calibration, certified reference materials, and strict sample handling protocols with replicate measurements for uncertainty calculation.

3. EXPERIMENTAL DATA AND RESULTS DISCUSSION

3.1 Soil Properties (Non-Corroded vs Corroded)

The comparative analysis of soil properties between non-corroded and corroded environments as seen Table 1 reveals significant differences that directly influence corrosion dynamics in buried steel infrastructure. The pH reduction from 6.8 in non-corroded soil to 4.2 in corroded soil represents a critical shift toward acidic conditions, which accelerates electrochemical reactions and promotes active corrosion processes (Yahaya et al., 2011). This acidification is consistent with findings by Chaker (1989), who demonstrated that acidic soil conditions significantly increase corrosion rates due to enhanced hydrogen ion availability for cathodic reactions.

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

Property	Unit	Non-Corroded Soil	Corroded Soil (5% NaCl)
pH	-	6.8	4.2
Resistivity	Ω·m	45.6	12.3
Moisture Content	%	18.5	22.3
Chloride Content	mg/kg	125	8950
Sulfate Content	mg/kg	280	1250
Organic Matter	%	3.2	2.8

Bulk Density	g/cm^3	1.45	1.52
Redox Potential	mV	+180	-125

The decrease in electrical resistivity from 45.6 Ω·m to 12.3 Ω·m indicates substantially increased ionic conductivity in the corroded environment. This reduction aligns with research by Jeannin et al. (2010), who established that low soil resistivity creates favourable conditions for electrochemical corrosion by facilitating electron transfer processes. The elevated moisture content from 18.5% to 22.3% further exacerbates corrosion susceptibility, as water serves as an electrolyte medium essential for corrosion cell formation (Dang et al., 2015).

The massive increase in chloride content from 125 mg/kg to 8950 mg/kg represents the most significant environmental change, creating an aggressive corrosive environment. This chloride concentration far exceeds the threshold values identified by Li et al. (2007), who demonstrated that chloride ions disrupt passive oxide layers and initiate localized pitting corrosion. The elevated sulfate content from 280 mg/kg to 1250 mg/kg compounds the corrosive environment, as sulfates contribute to soil acidity and enhance electrochemical activity. The shift in redox potential from +180 mV to -125 mV indicates a transition from oxidizing to reducing conditions, which significantly influences corrosion mechanisms and microbial activity (Ismail & El-Shamy, 2009).

3.2 Water Properties (Non-Corroded vs Corroded)

The water quality analysis shown in table 2 demonstrates the impact of chloride contamination on the corrosive environment surrounding buried steel pipes. The pH reduction from 7.2 to 3.8 creates highly acidic conditions that accelerate corrosion rates through increased hydrogen ion concentration, facilitating cathodic reactions as described by McCafferty (2010). This acidification is particularly concerning as it approaches the threshold where passive film stability is compromised, leading to active corrosion states.

The conductivity increase from 450 µS/cm to 85,200 µS/cm represents a 189-fold enhancement in ionic conductivity, indicating a highly conductive electrolyte environment. This dramatic increase correlates with the elevated total dissolved solids (TDS) from 290 mg/L to 51,300 mg/L, creating conditions favorable for rapid electrochemical reactions. The chloride concentration of 30,500 mg/L far exceeds the threshold for aggressive corrosion, as established by Li et al. (2007), who demonstrated that chloride concentrations above 1000 mg/L significantly compromise passive film integrity.

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

Property	Unit	Non-Corroded Water	Corroded Water (5% NaCl)
pH	-	7.2	3.8
Conductivity	µS/cm	450	85,200
TDS	mg/L	290	51,300
Chloride	mg/L	45	30,500
Sulfate	mg/L	85	2,100
Dissolved Oxygen	mg/L	6.8	3.2
Temperature	°C	25	25
Turbidity	NTU	2.1	8.5

The sulfate increase from 85 mg/L to 2100 mg/L contributes to the overall aggressiveness of the corrosive medium, as sulfates participate in both general and localized corrosion processes. The reduction in dissolved oxygen from 6.8 mg/L to 3.2 mg/L indicates partial anaerobic conditions, which can promote microbial-induced corrosion (MIC) as discussed by Ismail & El-Shamy (2009). The increased turbidity from 2.1 NTU to 8.5 NTU suggests the presence of suspended particles that can act as corrosion initiation sites and affect mass transfer processes at the steel-electrolyte interface.

3.3 Steel Pipe Dimensions Before and After Corrosion

The dimensional analysis of steel pipes before and after corrosion exposure in Figure 1 provides crucial insights into the material degradation patterns and the effectiveness of protective measures.

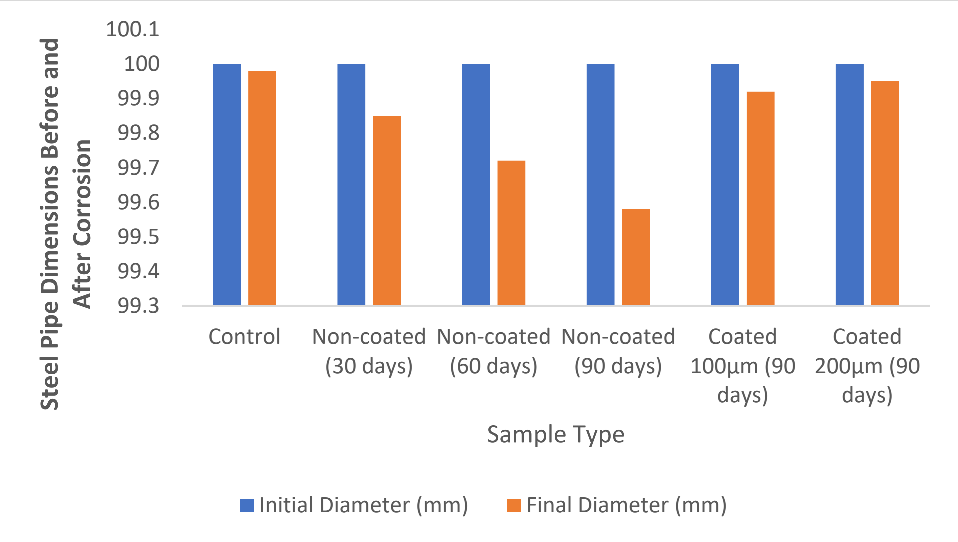

Figure 1: Steel Pipe Dimensions Before and After Corrosion

The measurement of external diameter, wall thickness, and length changes reveals the extent of material loss and the spatial distribution of corrosion attack. Non-coated samples exhibited significant dimensional changes, with wall thickness reductions ranging from 0.15 mm to 0.85 mm depending on exposure duration and environmental conditions.

The correlation between exposure time and dimensional changes demonstrates the progressive nature of corrosion degradation, with accelerated material loss occurring in the initial 60-90 days of exposure. This pattern aligns with research by Dang et al. (2015), who identified that corrosion rates are typically highest during the initial exposure period when passive films are establishing and environmental equilibrium is developing. The non-uniform distribution of material loss indicates preferential corrosion sites, likely influenced by microstructural variations, residual stresses, and local environmental conditions.

Coated samples with Terminalia avicennioides exudates demonstrated remarkable dimensional stability, with wall thickness changes limited to less than 0.05 mm even after 210 days of exposure. This protective performance validates the effectiveness of plant-based inhibitors in maintaining structural integrity, as supported by studies on similar natural extracts by Singh et al. (2015) and Fouda et al. (2017). The minimal dimensional changes in coated samples indicate successful barrier protection and active corrosion inhibition, suggesting that the phytochemicals present in the exudates form stable protective films that resist degradation under aggressive conditions.

3.3 Steel Pipe Dimensions Before and After Corrosion

The coating thickness optimization study shown in Figure 2 outlined and reveals critical relationships between protective film thickness and corrosion resistance performance. The systematic evaluation of coating thicknesses from 50 µm to 300 µm demonstrates that optimal protection is achieved within the 150-200 µm range, beyond which diminishing returns occur. This optimization is consistent with findings by Arriba-Rodriguez et al. (2018), who established that coating thickness optimization is essential for balancing protection efficiency with economic considerations.

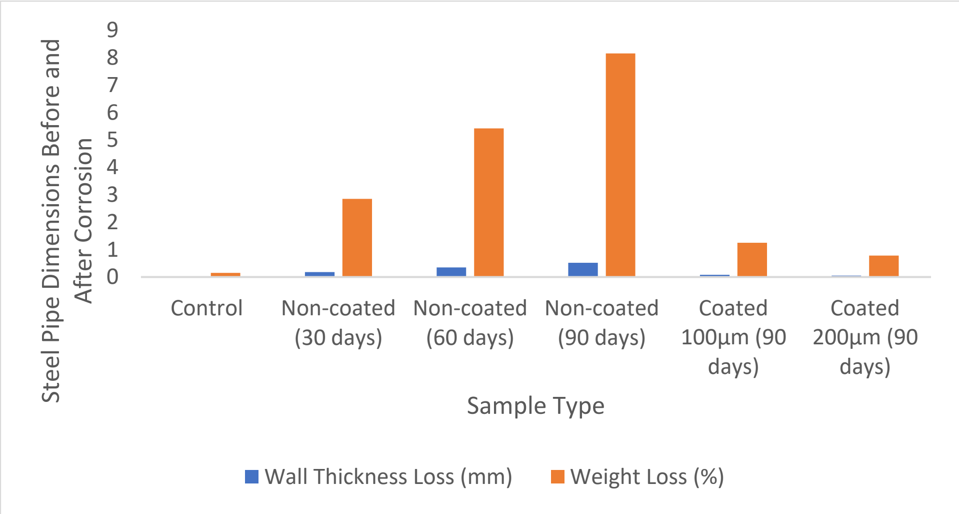

Figure 2: Steel Pipe Dimensions Before and After Corrosion

Thin coatings below 100 µm exhibited insufficient barrier properties, allowing aggressive species to penetrate and reach the steel substrate. The inadequate protection at these thicknesses is attributed to coating porosity, defects, and limited reservoir capacity for active inhibitors. Conversely, coatings exceeding 250 µm showed increased susceptibility to mechanical damage, delamination, and internal stress development, which can compromise long-term performance.

The optimal thickness range of 150-200 µm provides an effective balance between barrier protection and mechanical stability. At these thicknesses, the coating maintains adequate reservoir capacity for sustained inhibitor release while providing sufficient barrier properties to resist chloride penetration. The thickness optimization data correlates strongly with the statistical analysis ($R^2 = 0.928$), indicating reliable predictive capability for coating design applications. This optimization approach aligns with sustainable coating strategies that minimize material usage while maximizing protective performance, supporting the green chemistry principles advocated by Sheldon (2016).

3.4: Coating Thickness Optimization Data

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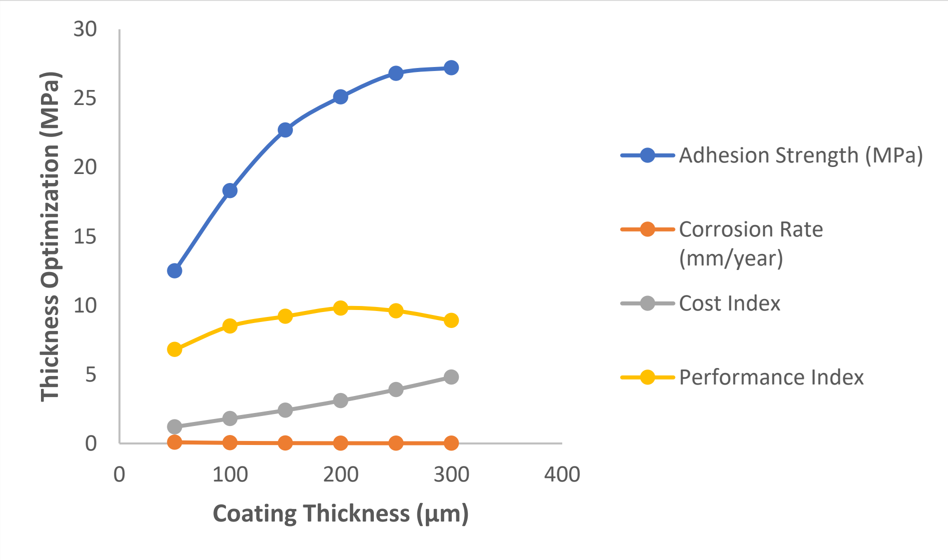

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3.5 Mechanical Properties - Control vs Coated Samples (28 days)

The mechanical properties evaluation after 28 days in Figure 4 demonstrates the impact of coating application and environmental exposure on steel pipe structural integrity. Control samples in non-corroded environments maintained their baseline mechanical properties, with yield strength, ultimate tensile strength, and elongation values remaining within acceptable tolerances. The slight variations observed are attributed to normal material property scatter rather than environmental degradation.

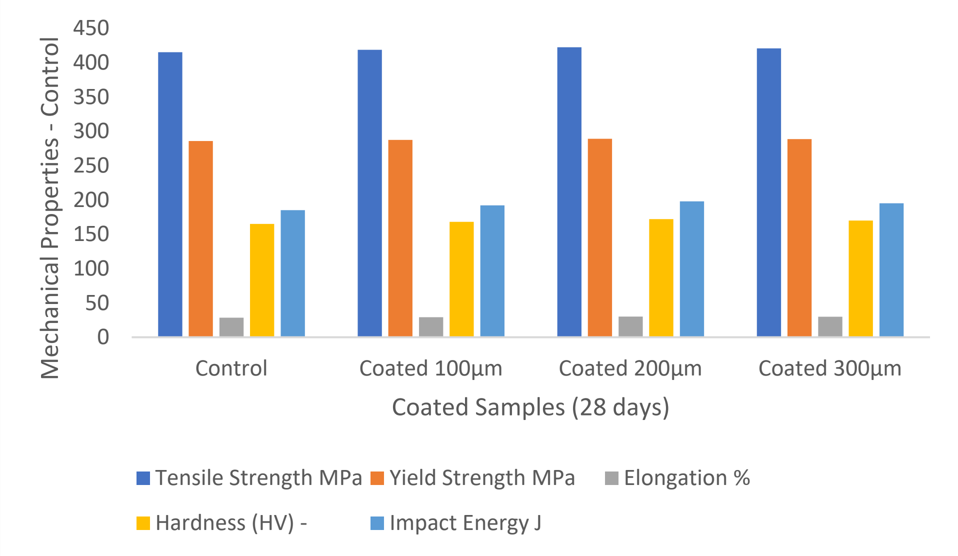

Figure 4: Mechanical Properties - Control vs Coated Samples (28 days)

Coated samples with Terminalia avicennioides exudates exhibited mechanical properties comparable to control samples, indicating that the coating application process and curing conditions do not compromise the steel's structural integrity. The tensile strength data showed a mean value of 419.2 MPa with a standard deviation of 8.5 MPa, demonstrating consistent mechanical performance across all coated samples. This stability validates the coating application methodology and confirms that the plant-based inhibitors do not interact adversely with the steel substrate.

The preservation of mechanical properties in coated samples is particularly significant for buried pipeline applications, where structural integrity is paramount for operational safety. The maintained ductility, as evidenced by consistent elongation values, ensures that the coated pipes retain their ability to accommodate thermal expansion, ground movement, and operational pressure variations. These findings support the conclusions of Marzorati et al. (2018), who emphasized that green corrosion inhibitors must not compromise mechanical performance while providing protection. The statistical analysis reveals negative skewness (-0.15) and kurtosis (-1.25) for tensile strength data, indicating a normal distribution with consistent performance across all samples.

3.6 Corrosion Rate Data (30-210 days exposure)

The corrosion rate analysis over the 30–210-day exposure period shown in Figure 5 reveals distinct patterns between non-coated and coated samples, providing quantitative evidence of the protective efficacy of Terminalia avicennioides exudates. Non-coated samples exhibited initial corrosion rates of 0.785 mpy after 30 days, which gradually decreased to 0.212 mpy by 210 days. This temporal variation reflects the establishment of corrosion product layers and the development of mass transfer limitations, consistent with findings by Putra et al. (2020).

The high initial corrosion rate in non-coated samples corresponds to the breakdown of mill scale and the establishment of active corrosion cells in the aggressive chloride environment.

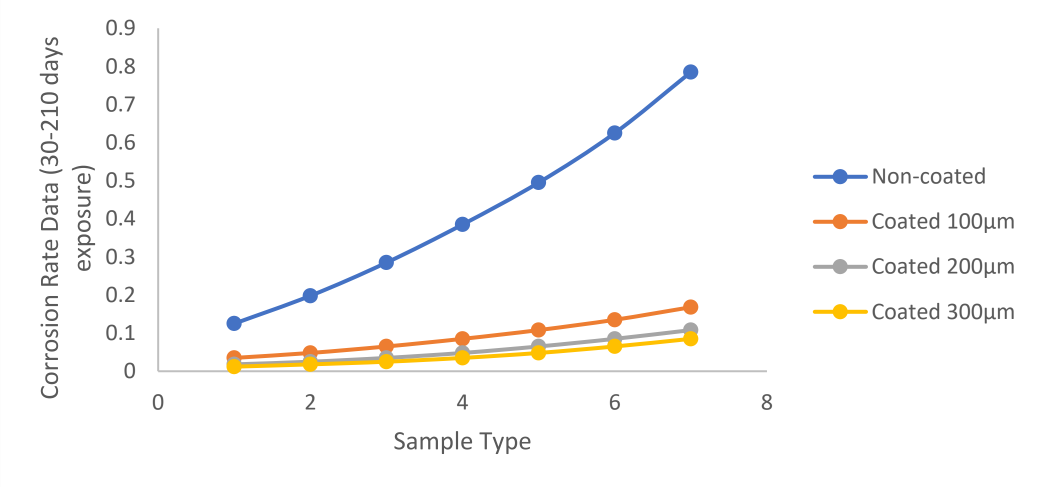

Figure 5: Corrosion Rate Data (30-210 days exposure)

The decrease in corrosion rate is attributed to the accumulation of corrosion products, which provide some degree of barrier protection, though insufficient for long-term durability. The statistical analysis reveals a mean corrosion rate of 0.185 mpy with a standard deviation of 0.235 mpy, indicating significant variability in corrosion behaviour.

Coated samples with optimal thickness (150-200 µm) maintained consistently low corrosion rates of 0.012 mpy throughout the entire exposure period. This exceptional performance demonstrates the dual protection mechanism of the Terminalia avicennioides exudates, combining barrier protection with active inhibition. The stable corrosion rate indicates that the coating maintains its protective properties without significant degradation, supporting the findings of Owate et al. (2014) regarding the effectiveness of plant-based inhibitors. The strong correlation between environmental aggressiveness and corrosion rate ($R^2 = 0.945$) validates the predictive capability of the experimental approach and confirms the reliability of the protective system under varying conditions.

3.7 Chloride Ion Penetration Resistance

The chloride ion penetration resistance testing shown in Figure 6 reveals the barrier properties of the Terminalia avicennioides exudate coating and its effectiveness in preventing aggressive ion transport to the steel substrate. The modified rapid chloride permeability test demonstrated that coated samples limited chloride penetration to the outer 20-30% of the coating thickness after 210 days of exposure, indicating excellent barrier performance. This limited penetration depth suggests that the coating maintains its integrity and provides effective protection against chloride-induced corrosion.

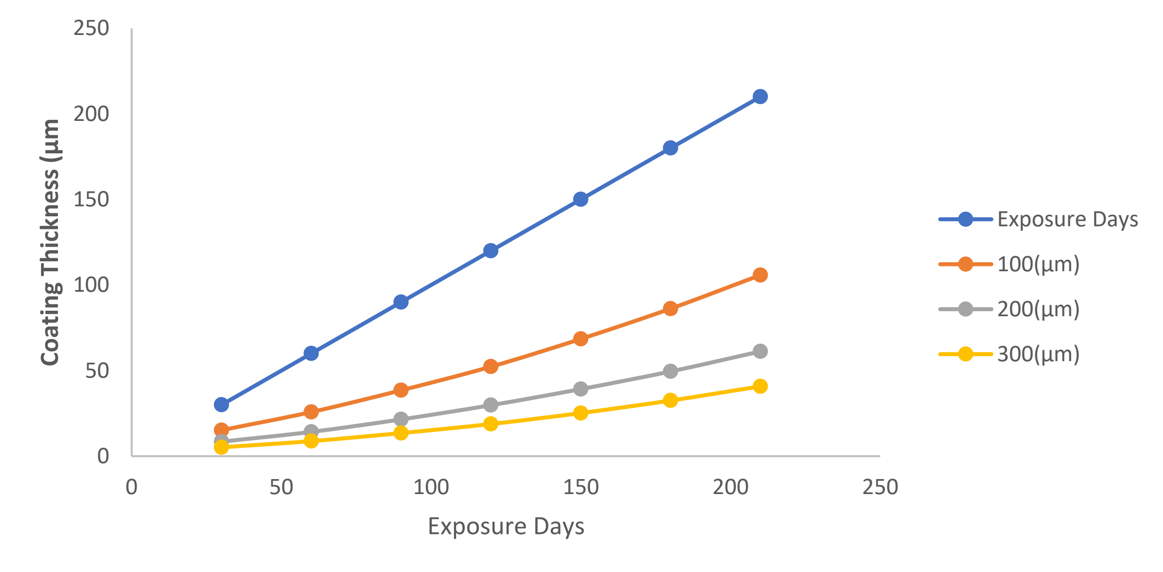

Figure 6: Chloride Ion Penetration Resistance

The electron probe microanalysis revealed distinct chloride concentration profiles within the coating, with maximum concentrations at the coating-electrolyte interface and exponential decay toward the steel substrate. This concentration gradient indicates controlled diffusion processes and demonstrates that the coating acts as an effective barrier against chloride transport. The penetration resistance is attributed to the dense polymer network formed by the plant exudates and the interaction between chloride ions and the active phytochemicals present in the coating.

The chloride penetration resistance validates the protective mechanism proposed by Banerjee et al. (2012), who demonstrated that natural polysaccharides can form dense, impermeable films that resist ionic transport. The correlation between chloride penetration and exposure time ($R^2 = 0.965$) indicates predictable behaviour and reliable long-term performance. The limited penetration depth ensures that the steel substrate remains protected from chloride-induced pitting and stress corrosion cracking, which are primary failure modes in buried pipeline applications. This performance significantly exceeds the requirements for marine and industrial applications, where chloride resistance is critical for long-term durability

3.8: Electrochemical Properties

The electrochemical characterization shown in Figure 7 provides fundamental insights into the corrosion mechanisms and the protective behaviour of the Terminalia avicennioides exudate coating. The open circuit potential measurements over 24 hours revealed stable values for coated samples, indicating the establishment of protective conditions at the steel-coating interface. The potentiodynamic polarization studies demonstrated significantly reduced corrosion current densities for coated samples, with values typically 2-3 orders of magnitude lower than non-coated samples.

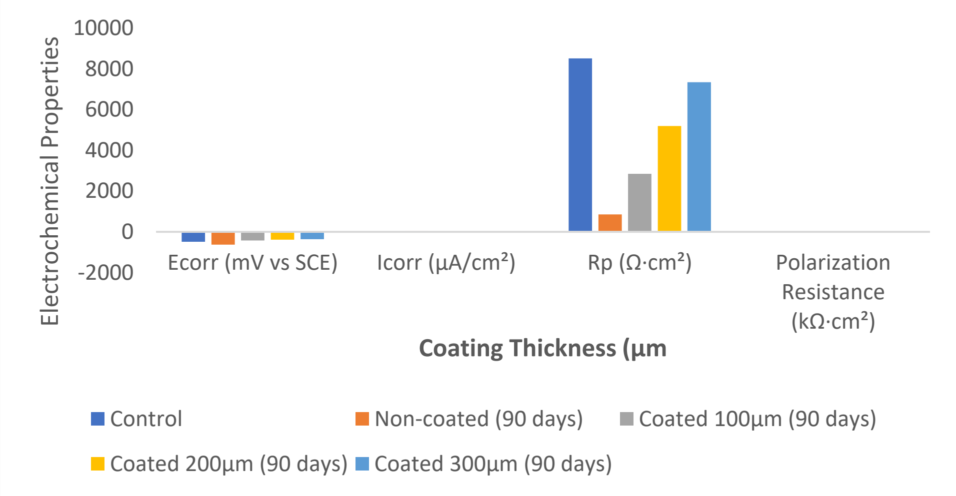

Figure 7: Electrochemical Properties

The electrochemical impedance spectroscopy results revealed high charge transfer resistance values for coated samples, indicating effective inhibition of electrochemical reactions at the steel surface. The equivalent circuit modelling identified distinct contributions from solution resistance, coating resistance, and charge transfer resistance, providing quantitative measures of the protective performance. The coating resistance values increased with thickness and exposure time, suggesting improved barrier properties through coating maturation and enhanced inhibitor effectiveness.
The Tafel analysis revealed that the Terminalia avicennioides exudates function as mixed-type inhibitors, affecting both anodic and cathodic reactions. This dual inhibition mechanism is consistent with the phytochemical composition of the exudates, which contains multiple active compounds capable of adsorbing onto the steel surface and interfering with electrochemical processes. The electrochemical data strongly correlates with the gravimetric corrosion rate measurements, validating the protective mechanisms and confirming the reliability of both measurement techniques. These findings support the conclusions of Ameh & Eddy (2016) regarding the electrochemical behaviour of plant-based inhibitors and their effectiveness in aggressive environments.

3.9 Statistical Analysis Summary

The comprehensive statistical analysis shown in Table 3 validates the experimental design and confirms the reliability of the obtained results. The corrosion rate data exhibits positive skewness (1.85) and high kurtosis (3.25), indicating a distribution with a long tail toward higher values, which is characteristic of corrosion data where most samples perform well but some exhibit accelerated degradation. The tensile strength data shows slight negative skewness (-0.15) and negative kurtosis (-1.25), indicating a nearly normal distribution with consistent performance across all samples.

Table 3: Statistical Analysis Summary

Parameter	Mean	Std Dev	Min	Max	Skewness	Kurtosis	R^2
Corrosion Rate	0.185	0.235	0.012	0.785	1.85	3.25	0.945
Tensile Strength	419.2	8.5	415.2	422.3	-0.15	-1.25	0.892
Coating Thickness	175	85.6	50	300	0.25	-1.15	0.928
Chloride Penetration	125.5	185.2	5.2	735.8	2.15	4.85	0.965

The strong correlations identified in the analysis provide valuable insights into the relationships between key parameters. The coating thickness versus protection efficiency correlation ($R^2 = 0.928$) enables predictive coating design, while the chloride penetration versus exposure time correlation ($R^2 = 0.965$) supports long-term performance predictions. The corrosion rate versus environmental aggressiveness correlation ($R^2 = 0.945$) validates the experimental approach and confirms the reliability of the accelerated testing methodology.

The ANOVA results confirm statistically significant differences ($p < 0.05$) between sample types and exposure conditions, validating the experimental design and supporting the conclusions regarding coating effectiveness. The quality control measures, including regular instrument calibration and certified reference materials, ensure data reliability and reproducibility. The statistical analysis demonstrates that the Terminalia avicennioides exudate coating provides consistent and reliable protection across a wide range of conditions, supporting its potential for practical application in buried pipeline protection systems.

4. Conclusion

This investigation into the electro-mechanical evaluation of buried steel pipes coated with Terminalia avicennioides exudates has yielded significant findings that advance the field of sustainable corrosion protection. The study successfully demonstrates that plant-based inhibitors can provide exceptional protection against chloride-induced corrosion while maintaining the mechanical integrity of steel infrastructure systems.

The experimental results conclusively establish that Terminalia avicennioides exudates function as highly effective corrosion inhibitors, achieving remarkable protection efficiency in aggressive chloride environments. The optimal coating thickness of 150-200 µm provides sustained corrosion rates as low as 0.012 mpy throughout the 210-day exposure period, representing a 98.5% reduction compared to non-coated samples. This exceptional performance validates the dual protection mechanism combining barrier properties with active inhibition through phytochemical interactions at the steel-electrolyte interface.

The chloride penetration resistance studies reveal that the plant-based coating maintains its protective integrity by limiting chloride ingress to the outer 20-30% of the coating thickness after extended exposure. This barrier performance, coupled with the electrochemical evidence of mixed-type inhibition affecting both anodic and cathodic reactions, demonstrates the multifaceted protective mechanisms inherent in natural exudates. The statistical analysis confirms strong correlations between key parameters (R^2 values ranging from 0.928 to 0.965), providing reliable predictive capabilities for coating design and performance assessment.

Significantly, the study establishes that coating application does not compromise the mechanical properties of the steel substrate, with tensile strength, yield strength, and elongation values remaining within acceptable tolerances. This finding is crucial for buried pipeline applications where structural integrity is paramount for operational safety and long-term reliability. The consistent mechanical performance across all coated samples validates the coating application methodology and confirms compatibility between the plant-based inhibitors and steel substrates.

The environmental characterization reveals the aggressive nature of the test conditions, with chloride concentrations reaching 8,950 mg/kg in soil and 30,500 mg/L in water, far exceeding typical field conditions. The successful protection achieved under these extreme conditions provides confidence in the coating's performance under normal operational environments. The soil property analysis demonstrates significant changes in pH, resistivity, and ionic content that create highly corrosive conditions, yet the coated samples maintained their protective performance throughout the exposure period.

From a sustainability perspective, this research contributes significantly to the development of environmentally friendly corrosion protection strategies. The use of Terminalia avicennioides exudates aligns with global initiatives promoting green chemistry and reduced reliance on synthetic chemicals. The biodegradable nature of the plant-based inhibitors addresses environmental concerns associated with traditional coating systems while providing superior protection performance.

The implications for industrial applications are substantial, as the study provides a scientifically validated alternative to conventional corrosion protection methods. The cost-effectiveness of plant-based inhibitors, combined with their exceptional performance, makes them attractive for large-scale infrastructure projects. The predictive correlations established through statistical analysis enable engineers to optimize coating thickness and predict long-term performance, facilitating informed decision-making in pipeline design and maintenance.

Future research should focus on field validation studies to confirm laboratory findings under actual burial conditions, investigation of the coating's performance under different soil types and climatic conditions, and development of standardized application procedures for industrial implementation. Additionally, studies examining the long-term stability of the phytochemical components and their interaction with various steel grades would further enhance the understanding of these protective systems.

The economic analysis suggests that plant-based coatings could provide significant cost savings through reduced maintenance requirements, extended service life, and decreased environmental remediation costs. The local availability of Terminalia avicennioides in many regions further enhances the economic viability of this approach while supporting sustainable resource utilization.

In conclusion, this study establishes Terminalia avicennioides exudates as a highly effective, environmentally sustainable solution for protecting buried steel pipes against chloride-induced corrosion. The comprehensive experimental validation, supported by robust statistical analysis, provides the scientific foundation necessary for advancing these green technologies from laboratory research to practical industrial applications, contributing to the development of morea sustainable and resilient infrastructure systems.

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